Spatial and Temporal Patterns of Sediment Mobility and Storage in a Small Mountain Stream

by

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Abstract

The study was conducted in East Creek, a headwater gravel-bed channel in the Fraser Valley foothills of the Coastal Mountains of British Columbia. Sediment transport was measured at three spatial scales using two measurement techniques in a study reach containing three unique morphological reaches: rapids, riffle pool, and step pool. At the largest spatial scale, the channel scale, channel stability was assessed between 2003 and 2009 using longitudinal profiles of channel elevation obtained from digital elevation mapping. The longitudinal profiles suggest that East Creek was in a relatively stable state over the six year analysis period, with the majority of erosion and deposition limited to localized fluctuations that varied in magnitude and direction. At the intermediate spatial scale, the reach scale, sediment transport estimates obtained from pit trap and digital elevation mapping data were used to create a sediment budget for the rapids reach and riffle pool subreaches of the channel. Using both measurement techniques, erosion and deposition fluctuated and could not be linked to flow regime or sediment supply alone. It is hypothesized that in-stream sediment supply and bed conditioning are important controls on sediment storage, and were used to explain observed fluctuations in erosion and deposition. The magnitude and direction of reach scale sediment storage fluctuations were not consistent across the two measurement techniques; however, elevation mapping estimates were nearly always higher than pit trap estimates. This is likely a result of overpassing of fine material and pit trap inefficiency. At the smallest spatial scale, the unit scale, spatial patterns of sediment transport were assessed across riffles and pools using digital elevation and morphological mapping data. There was increased sediment mobility in pools compared to riffles, which is likely a result of pools containing finer more loosely interacting particles compared to those in riffles. The high resolution unit scale sediment storage data demonstrated conservation of mass and a tight coupling of erosion and deposition in East Creek.

Preface

This dissertation is based on data collected in East Creek between 2003 and 2011 under the direction of Marwan Hassan. Given the collaborative nature of the project and the high resolution and long term qualities of the data set, there were a number of people who made significant contributions to the data collection, compilation, and analysis.

Marwan Hassan led and coordinated the East Creek database creation and management. Marwan managed field personnel in the collection, compilation, and analysis of data in East Creek for the entire duration of the study period including the initial set up of equipment at East Creek.

Joshua Caulkins performed a large portion of the fieldwork that generated the database analyzed in this thesis, including total station surveying, sediment collection from traps, sediment weighing, aerial photography, and discharge measurements. Joshua Caulkins also performed analyses that I built upon in this thesis, including processing and analyzing survey data, rectifying aerial photographs, and creating the initial morphology map that I later modified and used to demarcate pools and riffles. Joshua Caulkins also provided details on field equipment specifications and extensive information on East Creek channel characteristics.

Dave Reid was heavily involved in field data collection including total station surveying, sediment collection from traps, sediment weighing, and aerial photography. Dave was also involved in survey data processing.

Other field personnel involved in collecting data used in this thesis include Andre Zimmermann, Tony Lagemaat, Sam Robinson, Michael More, and Tim Reid. There were additional research assistants who had varying degrees of involvement in field data collection over the eight year study period.

I used a MATLAB program created by Joseph Wheaton to generate difference maps of elevation change in East Creek available for public download from Joseph Wheaton's website at: http://gcd.joewheaton.org/.

I used a MATLAB program created by Shawn Chartrand to generate erosion and deposition histograms for pools and riffles in East Creek.

I participated in field data collection in East Creek between 2008 and 2011, including total station surveying, sediment collection from traps, sediment weighing, aerial photography, and discharge measurements. I contributed to the processing of data collected between 2006 and 2008, and processed the majority of data collected between 2008 and 2011, including survey data compilation, aerial photograph rectification, and pit trap data compilation. Unless otherwise noted, the analyses described in this document were performed by me.

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Acknowledgments

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Thank you very much to Brett Eaton for his technical guidance, support, and for being on my supervisory committee. Thank you so very much to Shawn Chartrand for his technical guidance, on-going support, and perspective - which has been pivotal to me developing a constructive approach to my thesis and beyond. Many thanks to Shawn for his compassion and for bringing out my rock warrior. Thank you so much to Joshua Caulkins for his wholehearted support, wealth of knowledge on East Creek, and superb teaching skills. Josh trained me on East Creek fieldwork and analysis and much of the data used in this thesis was collected, processed, and shared by Joshua Caulkins.

Thank you to Marwan Hassan's students through the years, especially Dave Reid, for conducting extensive East Creek fieldwork and contributing to building the database used in this thesis.

Thank you very much to my Mom and Dad for their eternal love and support and for providing me with the foundations to reach this point. Thanks to Mom for caring so deeply and embodying the principles of R.I.C.K. Thanks to Dad for teaching me integrity and the value of the scientific process. Thanks to my sisters Tamar and Naomi for their love, support, and advice. Thank you to my UBC Geography, Guelph, and Dundas friends for their love, humour, and encouragement.

Chapter 1

Introduction

1.1 Background Information

The study of stream channel stability and sediment storage is critical to our understanding of stream dynamics. At the broader scale, many resource extraction operations and urban developments depend on some capacity to predict stream behaviour to avoid damage to infrastructure from large sediment mobilizing events. Streams also hold ecological value as they provide specialized habitat to fish and other aquatic organisms. It is, therefore, important that the factors governing stream dynamics are explored and used to inform watershed planning decisions.

Knowledge of sediment transport processes in small streams comprises an important contribution to understanding watershed dynamics at a broader scale. Small streams are of particular interest within watersheds as they comprise a significant portion of drainage networks on a cumulative length basis (Strahler, 1957; Shreve, 1969) and can be more susceptible to small scale disturbances than large streams (Hassan et al., 2005; McCleary and Hassan, 2008). Further, the presence of complex morphologies in small steep mountain streams requires a unique approach to characterizing these environments. A major factor dictating morphology in mountain streams is sediment transport and deposition processes (Hassan et al., 2005). A more complete understanding of sediment transport in small mountain streams has the potential to substantially aid the development of effective watershed management policies.

1.1.1 Channel Stability and Adjustment

Streams are dynamic entities that adjust in response to external environmental conditions (Buffington et al., 2003; Hassan et al., 2005). Sediment supply regime and flow regime are two environmental factors that have a major impact on channel dynamics and morphology (Hassan et al., 2007). Streams tend towards an equilibrium state when they are subjected to changing external conditions so that energy is expended in an optimal way. There are several approaches to describing how streams respond to external conditions (Knighton, 2014). One approach to studying energy expenditures in streams is to focus on visible evidence of channel adjustments as indicators of stability, including channel gradient, bed material characteristics, and channel morphology (Church, 2006; Knighton, 2014; Frothingham et al., 2002).

Channel gradient is often assessed using longitudinal profiles (Knighton, 2014). Longitudinal profiles reveal changes in the elevation and slope of a channel over time (Hassan et al., 2005). This can be used to infer about sediment transport processes, erosion and deposition patterns, and about whether a channel is in a state of aggradation, degradation, or equilibrium (Lisle et al., 1992; Knighton, 2014; de Almeida and Rodríguez, 2011).

Bed material characteristics can be assessed by analyzing grain properties and configuration. Grain properties include the material, shape, and grain size distribution on the channel bed. Configuration includes bedforms and arrangement of particles on the bed of a channel. In gravel bed streams, changes to bed configuration tend to occur at a spatial scale of 10 to 100 m and at a time scale of around 10 to 100 years, roughly consistent with the timescale of interest in this study (Knighton, 2014; Hassan et al., 2007).

Channel morphology can be described using various classification schemes with Montgomery and Buffington's (1997) process based framework being a commonly referenced system. Channel morphology incorporates channel gradient and bed material characteristics in addition to channel planform, hydrological environment, sediment sources, and sediment storage elements, among other factors. Channel morphology is important for understanding channel stability because morphology adjusts in response to changing flow and sediment supply conditions and also impacts the rates and spatial distribution of sediment transport processes within a channel (Buffington and Montgomery, 1997; Hassan et al., 2005).

1.1.2 Channel Morphology

Montgomery and Buffington (1997) identify seven distinct channel reach morphologies based on slope, grain size, shear stress, and roughness. This paper will focus on those morphologies present in the East Creek study reach: rapids, riffle pool, and step pool morphologies.

Rapids

In this paper Zimmermann and Church's (2001) 'rapids' classification will be used interchangeably with Montgomery and Buffington's (1997) 'plane bed' classification. Rapids morphologies can occur in confined or unconfined channels with moderate to high gradients of 2 to 10 percent (Buffington and Montgomery, 1997; Hassan et al., 2005; Clifford, 1993). Rapids commonly occur in gravel to cobble bed streams; however, they can also occur in sand bed streams. The source of sediment is usually from fluvial sources, bank failure, or debris flow and is stored in overbank deposits. Rapids are characterized by long nearly featureless stretches of bed. The primary roughness elements that produce flow resistance in rapids reaches are the channel banks and grain scale features (Montgomery and Buffington, 1997). Grain scale features in rapids include clusters, stone lines, and stone nets along well-armoured bed surfaces. The characteristically well-armoured beds of rapids morphologies are suggestive of sediment supply limited conditions; however, transport limited conditions have also been commonly observed in armoured gravel bed channels. This implies that rapids may represent a unique transitional morphology between supply and transport limited states (Montgomery and Buffington, 1997; Hassan et al., 2005).

Riffle Pools

In this paper 'riffle pool' and 'pool riffle' will be used interchangeably to describe the 'pool-riffle' morphology presented by Montgomery and Buffington (1997). Riffle pool sequences occur in unconfined channels with moderate to low gradients of around 1 percent (Buffington and Montgomery, 1997; Hassan et al., 2005;

Clifford, 1993). They commonly occur in gravel bed streams; however, grain sizes may range from sand to cobble. The source of sediment in pool riffle sequences is usually from fluvial sources or from bank failure and is stored in bedforms. These bedforms and grain roughness are the dominant roughness elements which produce flow resistance (Montgomery and Buffington, 1997). The riffles in riffle pool sequences are characterized as flat areas made of gravel, commonly in a lobate shape, and tend to contain coarse tightly interacting particles. In contrast, pools are deep areas with finer material that have looser interactions (Hassan et al., 2005; Clifford, 1993; Thompson, 2011). The spacing of riffles and pools has been observed to range from 1.5 to 23.3 channel widths apart, but on average they are typically spaced at about 5 to 7 channel widths apart. The range in spacing may partly be attributed to the presence of large wood inputs which decrease pool spacing (Hassan et al., 2005; Buffington and Montgomery, 1997).

Step Pools

Step pool sequences occur in confined channels with moderate to high gradients of greater than 3 percent (Buffington and Montgomery, 1997; Hassan et al., 2005). Step pools commonly occur in cobble boulder streams, but require heterogeneous bed mixtures to form. The source of sediment in step pools is usually from fluvial sources, hillslopes, or debris flows and is stored in bedforms. These bedforms, channel banks, and grain roughness are the dominant roughness elements which produce flow resistance. The steps in step pool sequences are characterized as discrete channel-spanning features associated with an elevation drop (Montgomery and Buffington, 1997). They can be comprised of large boulders or an accumulation of large grains that create local flow resistance and vary in height. Steps are spaced every one to four channel widths and separate pools (Montgomery and Buffington, 1997; Hassan et al., 2005). In contrast, pools are deep areas with finer material that have looser interactions (Hassan et al., 2005; Clifford, 1993; Thompson, 2011). Step pools have been proposed to form during sediment supply limited conditions and offer bed stability (Montgomery and Buffington, 1997).

1.1.3 Sediment Transport and Storage

Sediment transport and changes in sediment supply and discharge dictate the presence of various stream morphologies including rapids, riffle pools, and step pools (Lenzi et al., 1999). Sediment transport mechanisms are the product of interactions between sediment grain properties, bed composition, flow velocity, flow depth, and energy gradient, among other factors (Gomez and Church, 1989; Kondolf and Piégay, 2003; Wilcock, 2001; Hassan and Reid, 1990). The complex and confounded nature of such interactions both complicates measurement and modeling efforts and creates great potential for future exploration. To better understand sediment transport and storage patterns, it is important to recognize classifications and mechanisms of sediment transport.

Sediment Transport Classification

Sediment transported through water may be divided into different categories depending on the classification principle used. The two most commonly used classification principles are: (1) mechanism and (2) morphology.

(1) Using mechanism as a classification principle, sediment load can be categorized into bed load and suspended load. Suspended load is comprised of fine sediment that moves in suspension in water and is supported by fluid forces; whereas, bed load is comprised of coarse sediment that travels in contact with the bed of the channel and is supported by both fluid forces and the channel bed (Leopold, 1994; Gomez and Church, 1989). Bed load is collected using a bed load trap sampler. A bed load trap sampler captures the coarser sediment that is transported by rolling, sliding, or saltation.

(2) Using morphology as a classification principle, sediment load can be categorized into wash load and bed material load. Wash load can be distinguished from bed material load using the size of the sediment. Wash load consists of the finer fractions of sediment and bed material load consists of the coarser fractions of sediment. Bed material load can be measured using digital elevation model analyses. Bed material load may contribute to some of the bed load; however, bed load typically does not encompass all of the bed material load.

This study will focus on the coarser fractions of sediment - the bed load and bed material load.

Bed load Transport Mechanisms

Depending on sediment supply, discharge, grain size distribution, and grain interactions, sediment in a stream may experience various states of mobility (Dietrich et al., 2006; Lisle et al., 2000; Venditti et al., 2010). Venditti et al. (2010) identify three states of sediment mobility: partial transport, selective transport, and equal mobility. When a channel is in a state of partial transport, all particle sizes are mobilized but more fine material is mobilized compared to that on the bed surface (Venditti et al., 2010). In selective transport, only a fraction of sediment sizes are mobilized with the material on the bed surface containing coarser material not found in the mobilized bed load (Venditti et al., 2010). Which particles are mobilized and which particles remain on the bed during a selective transport situation depends on the size of the particles. As a result of selective transport, sediment sorting by size may occur and may produce distinct patterns on the channel bed (Wittenberg et al., 2007). In equal mobility, the grain size distribution on the bed surface is the same as that of the bed load (Venditti et al., 2010; Parker, 2008; Yuill et al., 2010).

The relationship between grain size distribution and mobility is complex. In order for large grains on the bed of a channel to be moved, the shear stress exerted on a particle by the fluid must be greater than the opposing frictional forces. Once the threshold of motion is overcome, the bed load becomes mobile and may be transported through sliding, rolling, or saltation processes (Leopold, 1994). However, as implied by the phenomenon of selective transport, grain size is not the sole determinant of force required to move a grain. Interlocking of particles, armouring of coarser particles on top of finer particles, and spatial variability of bed shear stress can also impact the conditions required for initiation of motion. For instance, using flume experiments Nelson et al. (2009) found that sediment flux estimations may be inaccurate because of variability in shear stress and grain size across the width of the channel. To further complicate matters, although Lisle et al. (2000) observed that variations in boundary shear stress control bed load transport; in an earlier study, Garcia et al. (2000) found that there was not a direct relationship between grain shear stress and bed load flux because of variations in mobility thresholds and variation in bed characteristics. Oldmeadow and Church (2006) confirmed the relevance of bed characteristics to sediment transport through their findings that surface armouring has an observable impact on sediment transport rates and that gravel bed rivers tend to be in a partial transport regime such that some bed material may be stationary and other bed material may be mobile. Additionally, Paola and Seal (1995) proposed that even during equal mobility conditions, selective deposition can still occur which leads to sediment sorting.

In addition to grain size distribution and configuration, sediment supply is also an important consideration in predicting sediment mobility. Iseya and Ikeda (1987) observed that the availability of sediment particles is a key influence on the magnitude and occurrence of bed load transport. Lisle et al.'s (2000) findings that in sediment poor channels there are small areas of concentrated high mobility and large areas of low mobility and partial mobility supports the observation that sediment availability can affect the state of mobility of sediment. Also, Lamarre and Roy (2008) found that sedimentary structures influence sediment transport. Studies on sediment transport in gravel bed rivers have largely focused on discharge at which particle entrainment occurs (Wittenberg and Newson, 2005); however, sediment transport depends on a complex array of factors including sediment supply, grain size distribution, and grain interactions (Frey and Church, 2011; Yuill et al., 2010).

1.1.4 Bed load Storage Quantification

Bed load transport and storage is typically quantified by taking measurements in the field and applying bed load transport formulae to the field data. Common field measurement techniques include using handheld bed load samplers, pit traps, tracers, scour chains, and magnetic detection systems. These techniques offer varying levels of cost and accuracy for different time and spatial scales. Similarly, bed load transport formulae range in level of accuracy. Bed load transport formulae are typically a function of some combination of water discharge, velocity, water surface slope, grain density, water density, grain size, and grain shape. Common bed load transport formulae include the DuBoy, Shields, Meyer-Peter and Muller, Bagnold, and Wilcock and Crowe equations. These formulae can offer useful insights into bed load transport processes; however, they are not applicable for all contexts and without careful consideration of the characteristics of the watershed in question they can be used inappropriately. Even when conscientiously applied, sediment transport functions often vary from measured rates by more than an order of magnitude (Hassan et al., 2007). Consequently, it could be worthwhile to explore non-classical methods of predicting sediment transport and storage patterns.

Church (2006) recommends using an inverse approach to investigate sediment transport and storage. In the inverse approach, the morphological properties of a stream are used as a starting point to infer about sediment transport processes occurring through riffles and pools. Given that bed load transport is a key predictor of sediment balance and channel morphology, analysing a sediment budget in connection with changes in channel form can, in turn, be telling of sediment transport rates (Church, 2006). There are many examples of applying the inverse approach for braided sand bed rivers; however, despite it's unique ability to capture variability in sediment transport, it has received only modest attention in gravel bed streams (Ham and Church, 2000).

1.2 Research Gap and Study Objectives

In spite of research previously conducted on sediment transport, we lack basic understanding of sediment storage, supply, morphology, and flow regime. To better understand sediment transport processes, it is important to know how channel morphology responds to changes in flow and sediment supply. This thesis will utilize data from East Creek, a small mountain stream in Coastal British Columbia, to discuss spatial and temporal patterns of sediment mobility and storage. The objectives of this study are to address the questions:

1. How does annual sediment storage relate to channel morphology at the channel, reach, and unit spatial scales in East Creek?

2. How does reach-scale sediment storage relate to annual peak discharge in East Creek?

Chapter 2

Study Site

The study was conducted in a small second-order gravel bed mountain stream located in the UBC Malcolm Knapp Research Forest in the Fraser Valley foothills of the Coast Mountains in British Columbia, Canada (Figure 2.1). The East Creek watershed is approximately 100 ha and the area receives between 2000 and 2500 mm of mean annual precipitation. The upper portion of the East Creek study area where the study site is located is dominated by young Douglas-fir trees (*Pseudotrsuga menziesii*), Red Alder (*Alnus rubra*), and Salmonberry bushes (*Rubus spectabilis*). The channel ranges in width from 2 to 5 m and has an average gradient of 3% (Caulkins).

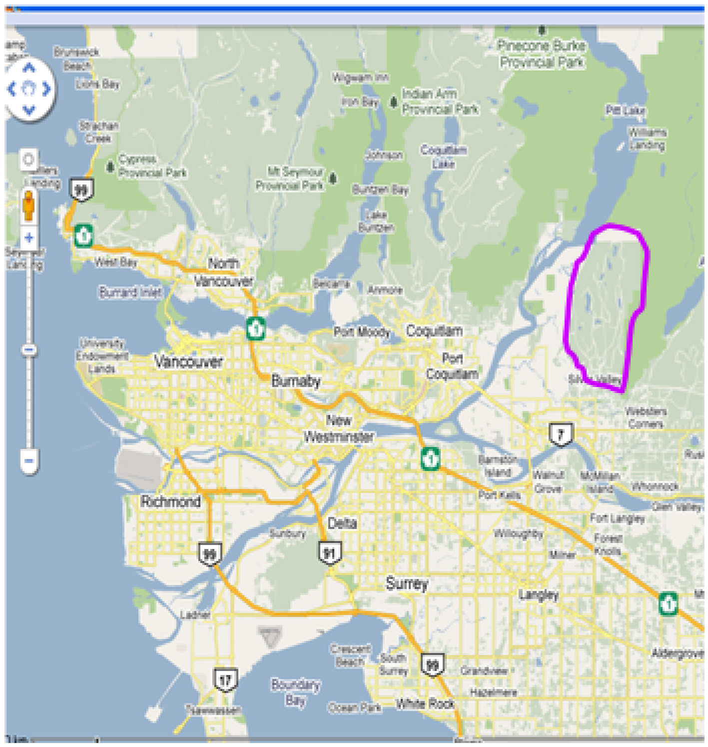


Figure 2.1: Location of UBC Malcolm Knapp Research Forest in Fraser Valley Foothills, British Columbia. The research forest is outlined in purple. (adapted from Google Maps)

The study reach extends approximately 600 m in length and encompasses three distinct morphologies: rapids, riffle pool, and step pool (Figure 2.2). The entire study channel is bounded by a culvert at the upstream end of the top of the rapids and by a pit trap at the downstream end of the step pool. A road named "M road" lies between the riffle pool and step pool sub-reaches, which are, consequently, connected via culvert. In this thesis, at the channel scale, analyses are presented that extend from the upstream end of the top of rapids reach to the downstream end of the step pool reach. At the reach and unit scales, additional, more detailed analyses are presented for the rapids and riffle pool morphologies.

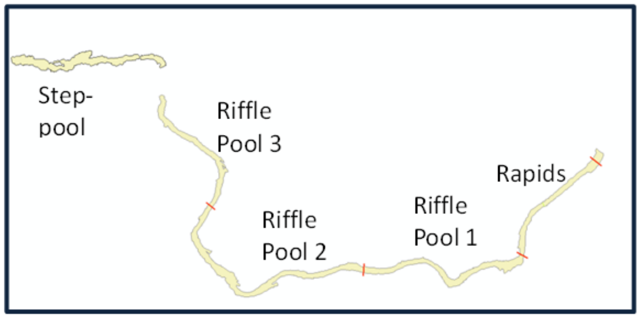


Figure 2.2: Location of rapids, riffle pool 1, riffle pool 2, riffle pool 3, and step pool in East Creek, British Columbia

2.1 Top of Rapids

"Top of rapids" refers to a short (5.9 m) length of channel upstream of the rapids reach, bounded by a culvert at the upstream end and a pit trap at the downstream end. The top of rapids (TOR) exhibits similar morphology to the rapids reach but contains a distinct plunge pool created by the culvert discharge. The plunge pool spans nearly half of the TOR and has a substantial impact on sediment transport and storage in this reach. For the purposes of the sediment budget element of this study, the TOR reach is effectively treated as a buffer zone so as not to confound the relationship between sediment storage and morphology with culvert induced impacts on sediment storage.

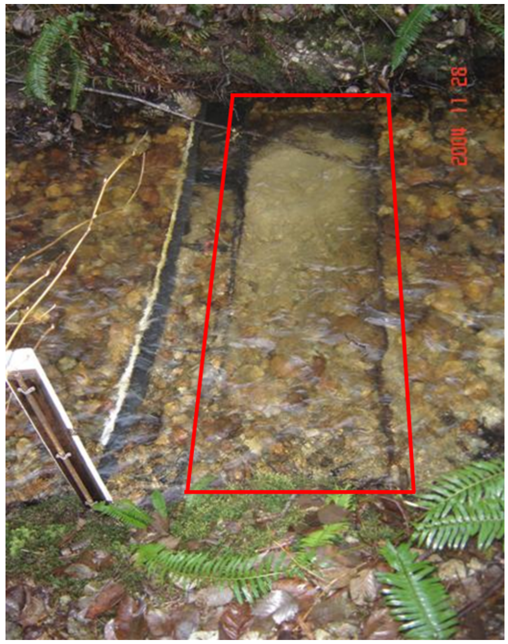
2.2 Rapids

The rapids reach is 84 metres in length and lies between the top of rapids and riffle pool reaches. It is bounded by pit traps at its upstream and downstream ends. A relatively shallow gradient (2.7%) and coarse bed material characterize the rapids reach, with a surface D50 of 57 mm and a subsurface D50 of 31 mm. Steep overhanging banks, patches of exposed till, and discontinuous sediment structures including stone lines and stone cells can be observed in the rapids (RAP).

2.3 Riffle Pool

The riffle pool reach (381 m) is significantly longer than the rapids (84 m) and step pool (approx. 120 m) reaches. To improve comparability with the other reaches, the riffle pool reach was divided into three smaller sub-reaches: riffle pool 1 (121 m), riffle pool 2 (163 m), and riffle pool 3 (97 m). These sub-reaches have shallow gradients of 1.8%, 1.5%, and 0.9%, respectively, and exhibit an intermediate grain size distribution as compared to the rapids and step pool reaches.

The riffle pool 1 (RP1) sub-reach is bounded by pit traps at the upstream and downstream ends (Figure 2.3). The sediment observed in RP1 is finer than that of the rapids reach directly upstream and is coarser than that of the riffle pool 2 reach directly downstream, with a surface D50 of 42 mm and a subsurface D50 of 21 mm (Caulkins). Like RP1, the riffle pool 2 (RP2) sub-reach is bounded by pit traps at the upstream and downstream ends. The sediment observed in RP2 has a surface D50 of 32 mm and a subsurface D50 of 14 mm (Caulkins). The riffle pool 3 (RP3) sub-reach is bounded by a pit trap at the upstream end and by a culvert that runs under M Road at the downstream end. Grain size distribution data for riffle pool 3 is not available. Given that there is no pit trap at the downstream end of RP3, comparatively more attention is given to RP1 and RP2 in the sediment budget. The three riffle pool sub-reaches are collectively characterized by heterogeneous bed material with bed structures including alternating sequences of riffles, pools, runs, and bars (Figure 2.4).



Credit: *Joshua Caulkins*

Figure 2.3: Photograph of a pit trap outlined in red, located at the boundary between the rapids and riffle pool 1 in East Creek, British Columbia

Credit: *Tony Lagemaat and Dave Reid*

Figure 2.4: Aerial photograph of riffle pool 1 sub-reach in East Creek taken using pole photography method

2.4 Step Pool

The step pool reach roughly spans a length of 120 metres and is the most downstream reach of the study area. The step pool (SP) reach is bounded by a culvert that runs under M Road at the upstream end and by a pit trap at the downstream end. The grain size distribution in the step-pool reach is visibly more coarse than in the other reaches; however, complications due to sediment mixing prevent accurate sampling of particle size in this area. The step pool reach has the steepest gradient (8.8%) and contains steps formed from woody debris and heterogeneous grain mixtures (Caulkins). The sediment budget element of this study does not include the step pool reach; however, the step pool is included in channel scale analyses.

Chapter 3

Methods

3.1 Data Collection

There is an extensive dataset on channel morphology, sediment transport, and discharge in East Creek that extends from 2003 to 2011. This dataset has been collected, compiled, and analyzed by a number of different people over the years under the supervision and direction of Marwan Hassan. I participated in the later years of the data collection towards building this database; however, the majority of the data used in this thesis comes from the existing data set and builds on the data processing and analyses of other students and researchers. The remainder of this section will focus on the methods that were used by a number of individuals to collectively gather the existing data and the methods that I used to analyze the data provided to me.

3.1.1 Pit Traps

Pit traps were used in East Creek as a measure of discrete event-scale sediment storage. Sediment deposited in the traps was collected and weighed after each storm event. Storm events occurred during the winter and early spring. The impact of the traps to sediment transport dynamics was minimized by returning all collected sediment to the channel just below the trap immediately after recording its weight. This facilitated the re-entry of the material into the stream system and returned the trap to an empty state to allow for sediment capture in the next storm event. In this way, the impact of the temporary removal of sediment from the system via the traps was limited to the event scale, with no seasonal or annual impacts.

There were five wooden pit traps in total, each of which spanned the width of the channel. They were located at the upper bound of the rapids, the rapids-riffle pool 1 interface, the riffle pool 1-riffle pool 2 interface, the riffle pool 2-riffle pool 3 interface, and at the lower bound of the step pool. There was no pit trap located at the interface between riffle pool 3 and the step pool. This boundary was demarcated by M Road. Each pit trap was dug into the bed of the channel to a depth of 0.24 m - 0.3 m, such that the top of each trap lay flush with the surface of the channel bed (Caulkins). The pit trap volumes and estimated sediment trapping capacities are given in Table 3.1.

Table 3.1: Pit trap volumes and estimated sediment trapping capacities

Location	**Volume (m^3)**	**Estimated Capacity (kg)**
Rapids Upper Bound	1.07	1853
Riffle Pool 1 Upper Bound	0.27	473
Riffle Pool 2 Upper Bound	0.67	1162
Riffle Pool 3 Upper Bound	0.30	515
Step Pool Lower Bound	0.63	1093

3.1.2 Ground Surveys

Annual mapping of the channel topography of East Creek from 2003 to 2011 was carried out using a theodolite-based total station equipped with an electronic distance meter (EDM) (Caulkins). Operation of the total station involved one person focusing an eyepiece within the total station on an optical prism held by a second person at a predetermined location. With the eyepiece focused on the prism, the total station operator prompted the emission of a laser beam, which hit the prism and was reflected back to the station. Using the theodolite and EDM, the total station internally calculated the horizontal angle, vertical angle, and distance to the prism creating X, Y, and Z coordinates for the data point.

Data points were collected at 0.5 m intervals across the width of the channel bed and at 0.5 m intervals along the length of the channel bed for the 600 m reach, creating a 0.5 by 0.5 m grid of elevations, corresponding to a point density of 9 points per square meter. Channel banks were also surveyed at 0.5 m intervals to a distance of approximately 1 m out from the edge of the bed on either side of the channel. Unique characteristics such as bed, banks, woody debris, till, and islands were distinguished from each other by entering codes on the keypad of the total station. Boulders and large stationary rocks distributed throughout the channel were spray painted and also were surveyed to be used as control points for later photograph rectification.

The locations of seventy-four sets of stationary rebar pins spaced along the left and right channel banks at 5 to 15 m intervals had been established in a previous year of the study (Caulkins). Some of these pins were re-surveyed and comparison of surveyed pin locations to known pin locations were used to estimate and correct surveying errors.

3.1.3 Aerial Photography

Aerial photographs of the channel were taken to enable channel mapping. A camera suspended atop a 10 m metal pole was raised in the air by field personnel to obtain an aerial frame of the creek. The pole and camera were carried downstream along the length of the creek with photographs taken by remote control at an overlap of approximately one half to one third of a frame between successive photographs. These photographs were taken annually at the end of the summer corresponding to low flow conditions for optimal visibility of bed features.

3.2 Data Analysis

As with the field data collection, data cleaning and analysis had been conducted on much of the field data prior to this study. I have built on the analyses performed by others by conducting the analyses described below.

3.2.1 Storage Estimates using Pit Traps

Bed load flux estimates between the 2008 and 2010 water years were generated for each reach using data from the pit traps and aluminum traps located at the downstream boundary of each reach. From this point onwards, water year (WY) is defined as the period from October 1 in the prior year to September 30 of the given year. For example, WY09 refers to the period from October 1 2008 to September 30 2009 and WY10 refers to the period from October 1 2009 to September 2010.

Since some reaches were bounded by both a pit trap and an aluminum trap and others were bounded only by a pit trap, two different measures of volume of sediment exported were calculated. Bed load export values as calculated from the pit traps alone are presented for all reaches to allow for greater consistency in comparisons across reaches. In reaches where there was both an aluminum trap and a pit trap, bed load export values taken as the sum of bed load retrieved from both traps combined is presented. The combined results were used to create the sediment budget because the coarser sediment fractions that were trapped in the aluminum traps would have been difficult to re-mobilize once trapped, and therefore, once in the trap this material was effectively, temporarily, removed from the stream. Bed load transport rates were not calculated for the riffle pool 3 sub-reach because there was no pit trap at the downstream end of this sub-reach.

Bed load storage was calculated using equation 3.1.

$$\Delta S_B = S_i - S_o \tag{3.1}$$

where S_i is bed load input into a reach as given by the mass of sediment in the trap at the upstream bound of the reach and S_o is bed load output from a reach as given by the mass of sediment in the trap at the downstream bound of the reach.

3.2.2 Storage Estimates using Ground Surveys

Bed material erosion and storage estimates were generated for the rapids reach, and the riffle pool 1, 2, and 3 sub-reaches of East Creek from WY04-11 using elevation change mapping data.

Surveyed elevation data was imported into ArcGIS and used to create shape-files that displayed the annual surveyed data on a point by point basis; triangulated irregular networks (TINs) of the study reach to annually interpolate elevation values between surveyed points; and annual digital elevation models (DEMs) to create smooth elevation surfaces that could be compared for consecutive water years. Although bank points were surveyed, they were removed for the analysis of erosion and deposition patterns because there was a high degree of uncertainty associated with elevation change estimates along the banks. This high uncertainty can be attributed to the comparatively lower point density and sharper topographic changes around the banks.

Difference maps were created from the DEMs using A MATLAB program created by Joseph Wheaton to quantify annual bed elevation changes and the level of uncertainty associated with those changes (Wheaton et al., 2010). A brief description of the program follows; however, Wheaton's (2008) thesis provides a far more comprehensive description of the program. Wheaton describes multiple pathways that may be used in this program depending on the objectives of the study. This study used pathway 4 (Wheaton, 2008).

The difference maps (DoDs) were created by subtracting the elevations of one year from the elevations of the following year on a cell by cell basis. Similarly, the uncertainties associated with elevation estimates were calculated on a cell by cell basis. The uncertainties were determined using a fuzzy inference system which used multiple qualitative criteria to create a final quantitative estimate of the uncertainty (Jang and Gulley, 1995). The qualitative criteria used in this study were point density and slope, where a high point density corresponded to a low level of uncertainty and a high slope corresponded to a high level of uncertainty. The quality of the point density and slope were represented by categories of low, medium, and high. The category of point density and slope for each cell together were used to determine an uncertainty estimate for that cell. The point density and slope inputs into the program were created in ArcGIS and were derived from the original surveyed bed elevation data. A confidence interval of 95% was used as a threshold to propagate the calculated uncertainties onto the map. The gross elevation change estimates and the uncertainty-adjusted elevation change estimates were used to create two sets of difference maps for 2003 to 2010. The MATLAB program output also included numerical distributions of the gross elevation changes and the uncertainty-adjusted elevation changes for each pair of years.

Annual bed material erosion volumes obtained from the difference maps were converted into annual bed material erosion masses using equation 3.2 and using the constants indicated in Table 3.2.

$$Q_m = V_e \phi \rho \frac{L_t/L_r}{t} \tag{3.2}$$

in which V_e is volumetric bed material erosion , ϕ is the porosity of the bed material, ρ is the density of the bed material approximated by the density of granite, L_t is the distance of travel of mobilized bed material approximated by the average step length obtained from tracer stones, L_r is the distance over which V_e is determined which is equivalent to the reach length, and t is the time interval between surveys.

Table 3.2: Values of constants used to calculate bed material erosion masses

Constant	Value	Units
Porosity of Sediment (ϕ):	0.25	
Density of Granite (ρ):	2600	kg/m^3
Average Step Length (L_t):	7.56	m
Rapids Length (L_{r1}):	84.2	m
Riffle Pool 1 Length (L_{r2}):	120.6	m
Riffle Pool 2 Length (L_{r3}):	163.4	m
Riffle Pool 3 Length (L_{r4}):	97	m

Bed material storage was calculated using equation 3.3.

$$\Delta S_M = S_d - S_e \tag{3.3}$$

where S_d is bed material deposition within a reach as calculated from digital elevation difference maps and S_e is bed material erosion within a reach as calculated from digital elevation difference maps.

In addition to using the survey data to create a bed material budget, the survey data was also used to create longitudinal profiles. A grid subtraction between DEMs for 2003 and 2009 was conducted using GIS to calculate the elevation differences between 2003 and 2009 on a cell by cell basis. A line running through the centre of the channel was created as a surrogate for the channel thalweg. Elevations and downstream distances were recorded at the intersection of this centreline and each cross section to create longitudinal profiles of the channel.

3.2.3 Morphology Mapping using Aerial Photography

Aerial photographs of the channel were spatially rectified in ArcGIS and used to generate a map of morphological features in the channel. Each annual set of aerial photographs was rectified using surveyed points that included large stationary control point boulders, rebar pins, and trap boundaries. The morphology map used in this study was created by Caulkins (personal communication, 2010) based on the morphological features visible in the rectified 2005 aerial photographs and an intimate knowledge of the channel acquired from multiple years of fieldwork experience at the East Creek study reach. The 2005 morphology map was used to demarcate morphological features for all years within the study period to more easily accommodate comparisons over time. The potential for error that could arise from extrapolating morphological feature locations over multiple years was gauged by overlaying the morphology map generated using the 2005 aerial photographs on maps of rectified aerial photographs for each year of the study period. There were little to no changes observed between the location and extent of the features demarcated in the 2005 morphology map and those observed in the rectified photographs for the remaining years, suggesting that there would have been only minimal errors associated with using the 2005 map for all years, given the scale and scope of this study.

Chapter 4

Results

The results section presents sediment storage and transport trends observed in East Creek organized using spatial scale. First, flow regime data for East Creek are provided. Next, sediment storage and transport trends at the largest scale analyzed in this study, the channel scale, are presented. Reach scale results follow, allowing for comparison across the distinct channel morphologies: rapids and riffle pool. Third, unit scale results, the smallest scale analyzed in this study, are reported, allowing for comparison across pools and riffles within the rapids and riffle pool reaches.

4.1 Flow Regime

Annual peak discharge was used as an indication of flow regime in East Creek. Figure 4.1 shows the fluctuations in peak discharge for WY04-11. The highest peak discharges occurred in WY09 (4.5 m^3/s) and WY07 (4.3 m^3/s) and the lowest peak discharge occurred in WY06 (1.0 m^3/s).

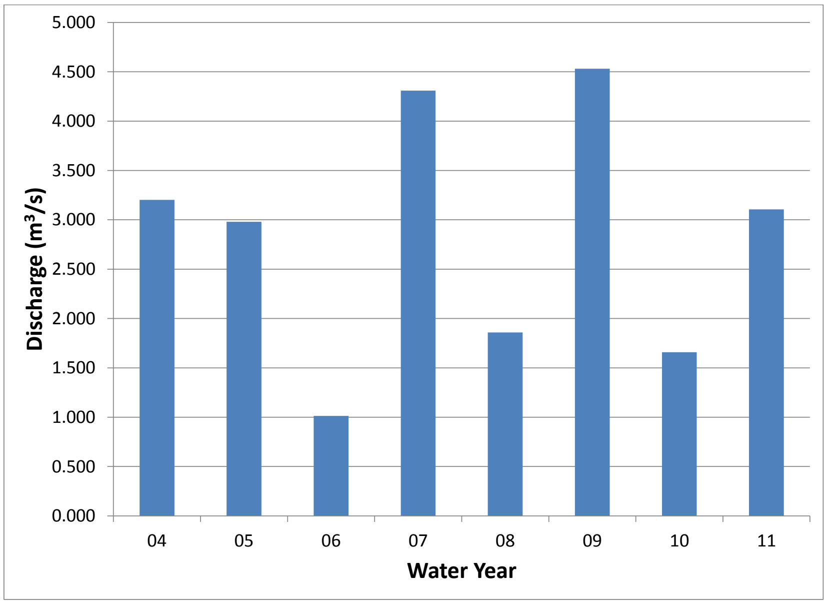


Figure 4.1: Annual peak discharge in East Creek for WY04-11

4.2 Channel Scale: Trends in Sediment Storage

At the channel scale, sediment storage will be assessed using longitudinal profiles. Longitudinal profiles allow for inferences to be made about the vertical stability of a channel because they provide one dimensional estimates of changes in sediment storage and longitudinal adjustments to changes in sediment supply and flow regimes.

Figure 4.2 presents the longitudinal adjustment of the channel to flow and sediment supply at the channel scale for the rapids and riffle pool reaches of East Creek between 2003 and 2009. At this coarse scale, the annual profiles are very similar and show little change over time.

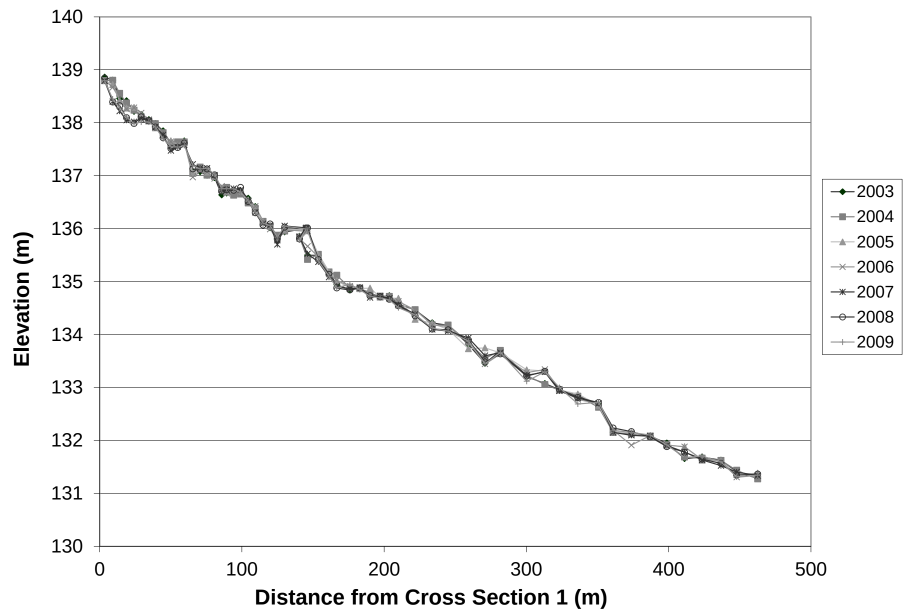
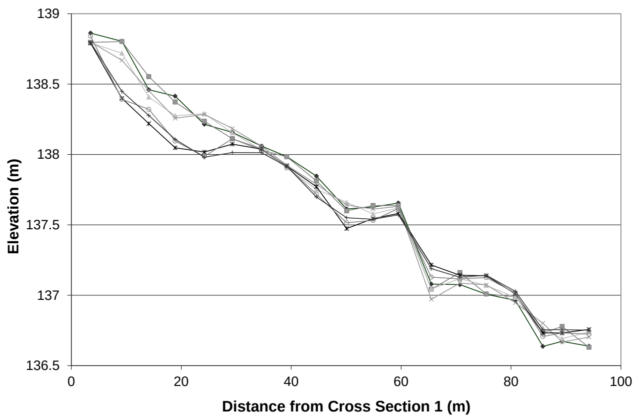
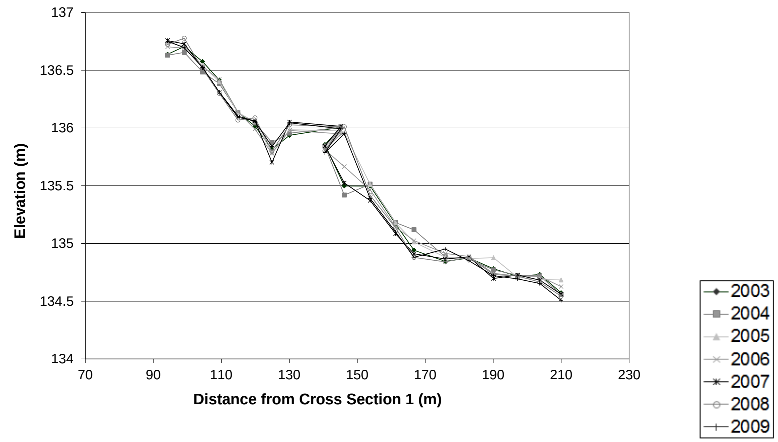


Figure 4.2: Longitudinal profile at the channel scale for the rapids and riffle pool reaches of East Creek for 2003 to 2009

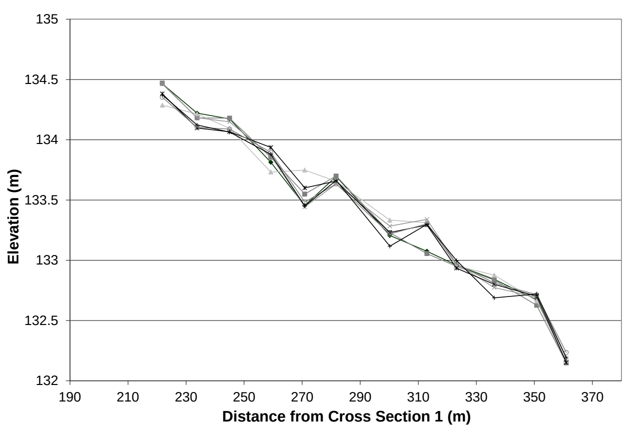
Longitudinal profiles are also presented separately, at a more resolved level, for the rapids, riffle pool 1, riffle pool 2, and riffle pool 3 to discern changes at the fine scale that cannot be observed at the coarse scale (Figure 4.3).



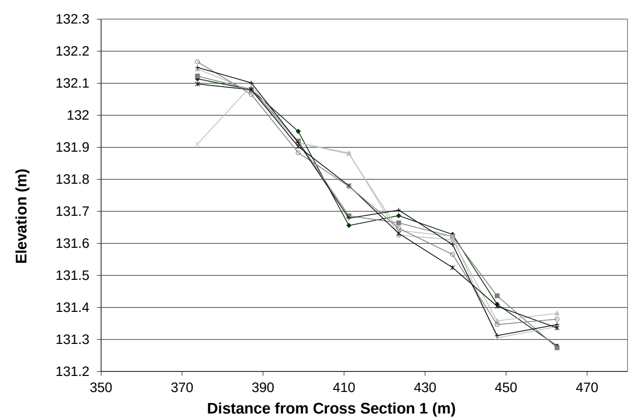
(a) Rapids



(b) Riffle Pool 1



(c) Riffle Pool 2



(d) Riffle Pool 3

Figure 4.3: Longitudinal profiles at the reach scale for the rapids and riffle pool reaches of East Creek for 2003 to 2009

Locations within the channel where the greatest range in elevation change occurred are identified as areas of interest. The morphology, width, and channel pattern at these locations are summarized in Table 4.1. The presence of large wood and its upstream (US) or downstream (DS) location, corresponding to the distances on the longitudinal profiles are also noted. The most substantial elevation change over the six year period corresponded to the upper part of the rapids reach, from 9.2 m to 24.2 m downstream. The average bed elevation change over this area was 0.36 m. The channel width in this section was measured at the section midpoint of 15.2 m downstream. For all other areas in the channel highlighted in Table 4.1, substantial bed elevation change was more localized around a shorter length of channel. In these cases, the reported distance downstream and channel width were measured directly at the noted distance downstream.

Table 4.1: Morphology at areas of interest based on longitudinal profiles of East Creek upper reaches between 2003 and 2009

Distance Downstream (*m*)	Range of Elevation Change (*m*)	Reach	Morphological Unit	Channel Width (*m*)	Channel Pattern	Notes
2.9 - 24.2	0.36	rapid	run	3	straight	DS of plunge pool
65.5	0.24	rapid	pool	3.4	very wide bend	DS of LW
146.2	0.59	riffle pool 1	side bar	4.9	sharp bend	LW intersects XS
166.7	0.24	riffle pool 1	pool	3.3	wide bend	–
270.9	0.31	riffle pool 2	pool	1.9	very wide bend	DS of LW; US of LW and back channel
313	0.28	riffle pool 2	side bar	6.2	straight	US of LW and back channel
373.8	0.26	riffle pool 2	run	2.8	straight	US of pit trap

In all reaches, the annual elevation profiles are fairly consistent. Of the few areas that experienced notable changes in bed elevation, these changes fluctuated between aggradation and degradation over the six year period.

Figure 4.4 shows the change in channel gradient in each of the upper reaches over the 2003 to 2009 period. The rapids experienced the largest change in channel slope (0.0008 m/m) over time compared to the relatively stable slopes observed in the riffle pool sub-reaches (all $\leq$0.0002 m/m). The greatest annual changes in channel slope (calculated as the percentage difference from the average slope in that sub-reach) occurred in the rapids in WY07 (14%), in riffle pool 1 in WY07 (3%), in riffle pool 2 in WY05 (8%), and in riffle pool 3 in WY06 (11%) closely followed by WY07 (9%).

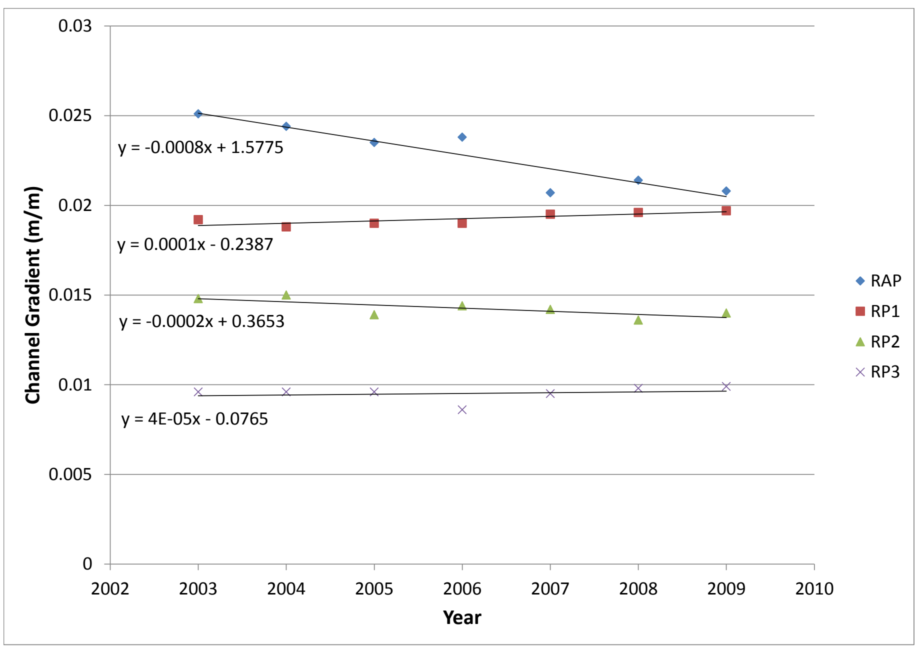


Figure 4.4: Change in channel gradient over time across the upper reaches of East Creek from 2003 to 2009

4.3 Reach Scale: Sediment Flux and Storage

4.3.1 Bed load Transport from Pit Traps

Bed load flux and storage estimates were generated for the upper sub-reaches of East Creek for WY09-11 using sediment trap data. Bed load data is also available for East Creek for additional years. It was selected to limit the focus of the bed load flux component of this study to the water years listed above in favour of conducting a more comprehensive analysis of bed material transfer (Subsection 4.3.2) while maintaining a feasible study scope .

Bed load Flux

Table 4.2 presents bed load flux estimates from the pit traps alone and from the pit and aluminum traps combined for WY09-11 for the upper reaches of East Creek. The mass of bed load transported ranged from 431 kg to 2576 kg. The average mass of bed load transported per reach per year was 1102 kg. Of the reaches listed in Table 4.2, the top of rapids reach experienced the largest annual bed load transport fluxes averaging 1547 kg/yr. Of the remaining reaches, the rapids reach experienced the largest annual bed load transport flux averaging at 1295 kg/yr and the riffle pool 2 sub-reach experienced the smallest annual bed load transport flux averaging at 732 kg/yr.

Bed load Storage

Annual bed load storage estimates are presented in Table 4.3 for the rapids, riffle pool 1, and riffle pool 2 sub-reaches for WY09-11. Storage estimates for the top of rapids and riffle pool 3 are not given because the top of rapids reach did not have a pit trap on its upper bound and the riffle pool 3 sub-reach did not have a pit trap on its lower bound.

Over the three year period, the rapids reach exhibited the largest storage (1252 kg), and riffle pool 2 exhibited the smallest storage (29 kg). Of the nine bed load storage estimates obtained from the pit traps, seven demonstrate net deposition as indicated by positive storage values and two demonstrate net erosion as indicated by negative values. The cases of net erosion occurred in the rapids reach in WY11

Table 4.2: Bed load flux estimates using pit traps for WY09-11

Reach	Water Year	Pit Trap Flux *(kg)*	Combined Pit and Aluminum Trap Flux *(kg)*
TOR	WY09	**992**	n/a
TOR	WY10	**2576**	n/a
TOR	WY11	**1074***	n/a
RAP	WY09	**768**	836
RAP	WY10	**1224***	1324*
RAP	WY11	**1603**	1725*
RP1	WY09	**560**	573
RP1	WY10	**400**	431
RP1	WY11	**1152**	1193*
RP2	WY09	**544***	n/a
RP2	WY10	**1280***	n/a
RP2	WY11	**1046***	n/a
SP	WY09	**992**	1019
SP	WY10	**552**	598
SP	WY11	**1290**	1315*

*A complete record of bed load mobilizing events could not be obtained because of either equipment malfunctioning or overfull trap events. n/a refers to no aluminum trap present at the bottom of the reach.

and in the riffle pool 2 sub-reach in WY10.

4.3.2 Bed Material Transfer from Morphological Method

Bed material erosion and storage estimates were generated for the rapids reach, and the riffle pool 1, 2, and 3 sub-reaches, of East Creek from WY04-11 using elevation change mapping data.

Bed Material Erosion

Table (4.4) shows that the annual mass of bed material transported ranged from 57 kg to 767 kg, where erosion mass was derived from erosion volume using equation

Table 4.3: Bed load storage based on pit traps for WY09-11

Station	Water Year	Bed load Storage (*kg*)
RAP	WY09	156
RAP	WY10	1252
RAP	WY11	-651
RP1	WY09	263
RP1	WY10	893
RP1	WY11	532
RP2	WY09	29
RP2	WY10	-849
RP2	WY11	147

(3.2). The average mass of bed material transported per reach per year was 218 kg. Listed in descending order, the average bed material transport fluxes over the eight year period for the rapids, riffle pool 2, riffle pool 1, and riffle pool 3 are 254 kg/yr, 245 kg/yr, 197 kg/yr, and 176 kg/yr.

Bed Material Storage

Bed material storage estimates were derived using summed differences from digital elevation models. The differences between deposition and erosion as indicated by Equation 3.3 are shown for WY04-11 in Figure 4.5 for the rapids and riffle pools 1, 2, and 3.

Bed material storage estimates were used to analyze temporal patterns within each morphology. Within the rapids reach, the largest (-9.67 m^3) and smallest (-0.05 m^3) magnitudes of net change occurred in WY07 and WY11, respectively (Figure 4.5a). Sediment storage fluctuated over the eight year study period with larger magnitude changes more concentrated in the first half of the study period.

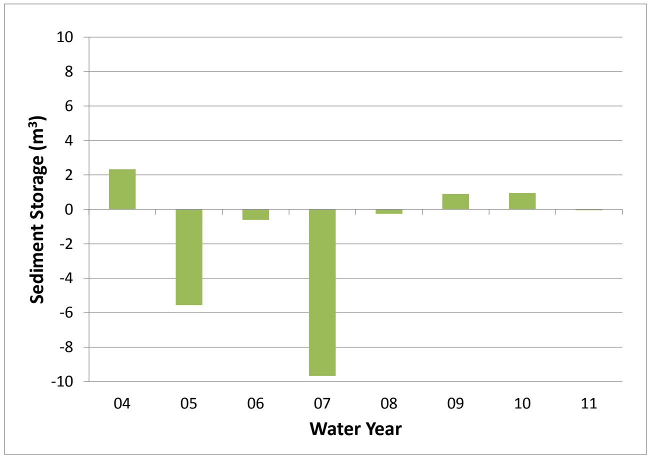
Within the riffle pool 1 sub-reach, the largest (-3.62 m^3) and smallest (0.03 m^3) magnitudes of net change occurred in WY07 and WY08, respectively (Figure 4.5b). Sediment storage fluctuated over the eight year study period with larger magnitude changes more concentrated in the first half of the study period.

Table 4.4: Bed material export estimates using morphological methods for WY04-11

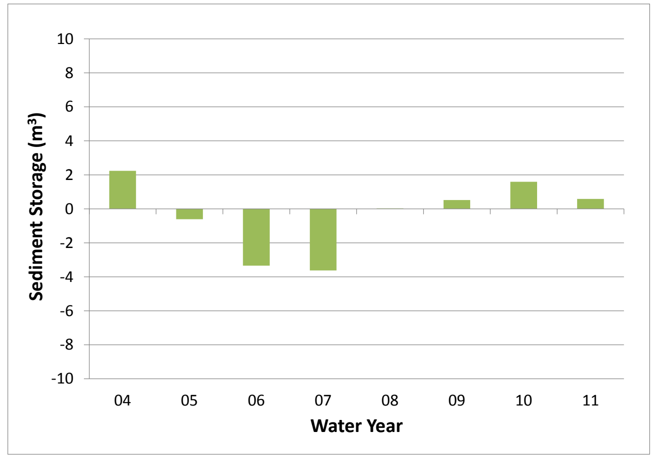
Reach	**Water Year**	**Bed Material Erosion Volume (m^3)**	**Bed Material Erosion Mass (Se) (*kg*)**
RAP	WY04	2.1	124
	WY05	8.1	474
	WY06	2.7	156
	WY07	13.1	767
	WY08	2.1	121
	WY09	1.6	96
	WY10	2.5	148
	WY11	2.5	147
RP1	WY04	4.0	163
	WY05	7.9	322
	WY06	5.7	233
	WY07	9.3	377
	WY08	3.8	153
	WY09	3.3	133
	WY10	1.7	70
	WY11	3.0	123
RP2	WY04	7.3	220
	WY05	15.1	455
	WY06	4.6	139
	WY07	15.4	462
	WY08	5.0	151
	WY09	4.8	144
	WY10	7.6	229
	WY11	5.3	160
RP3	WY04	4.9	248
	WY05	5.3	270
	WY06	3.3	168
	WY07	3.9	200
	WY08	4.3	217
	WY09	2.0	100
	WY10	2.9	147
	WY11	1.1	57

Within the riffle pool 2 sub-reach, the largest (-3.17 m^3) and smallest (0.02 m^3) magnitudes of net change occurred in WY10 and WY06, respectively (Figure 4.5c). Sediment storage fluctuated over the eight year study period with larger magnitude changes distributed throughout the study period.

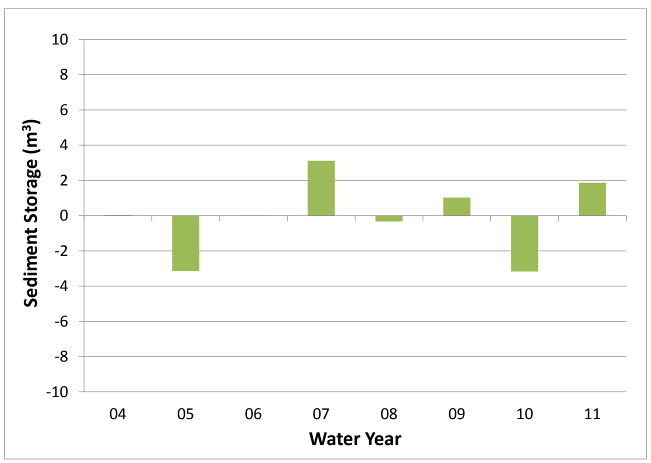
Within the riffle pool 3 sub-reach, the largest (5.11 m^3) and smallest (1.3 m^3) magnitudes of net change occurred in WY11 and WY09, respectively (Figure 4.5d). Sediment storage fluctuated over the eight year study period with a distinct and repeated alternation between erosional and depositional environments between consecutive years.



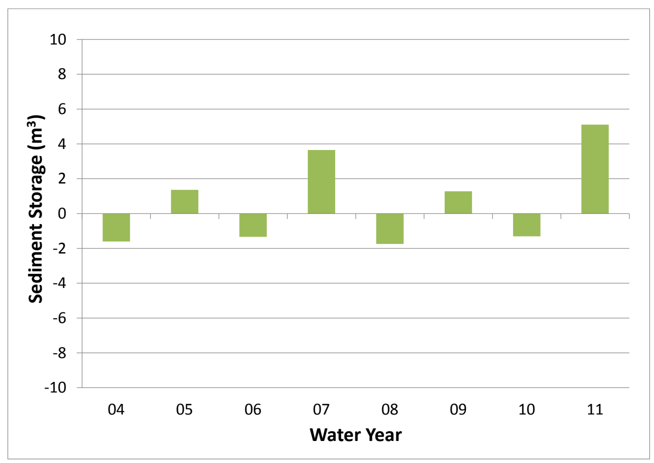
(a) Rapids



(b) Riffle Pool 1



(c) Riffle Pool 2

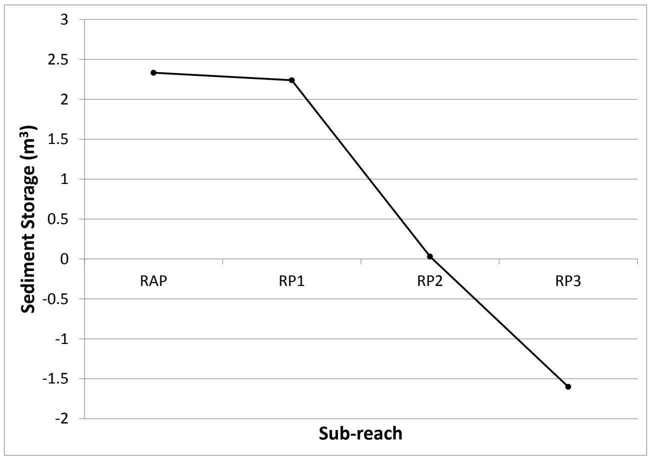


(d) Riffle Pool 3

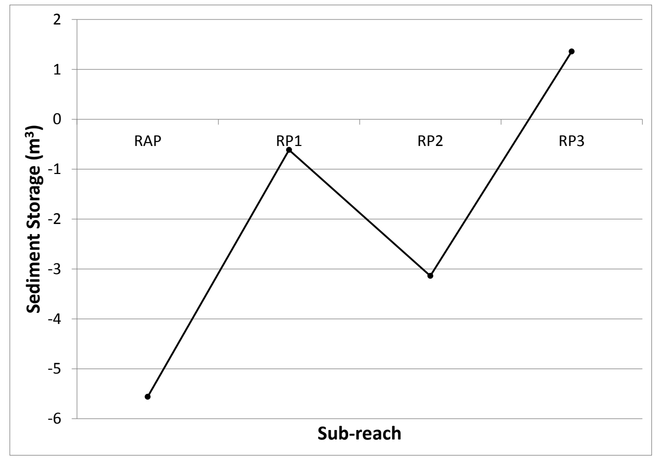
Figure 4.5: Volumetric change in sediment storage in the rapids reach and riffle pool sub-reaches of East Creek for WY04-11

Spatial patterns of sediment storage moving downstream along the length of the channel are shown separately for each water year in Figures 4.6 and 4.7 for WY04-7 and WY08-11, respectively.

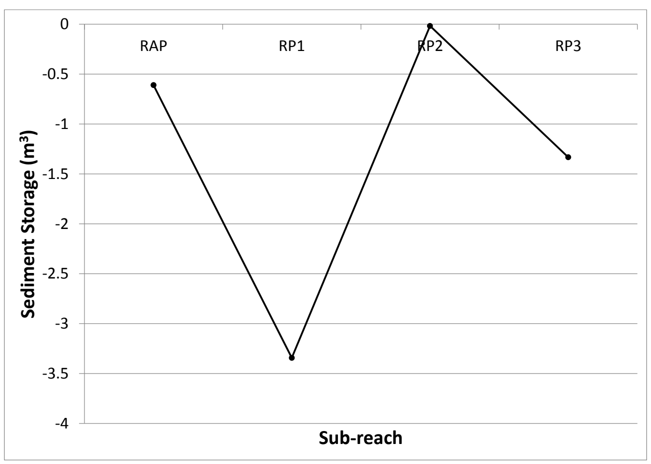
In WY04 net storage decreased moving downstream along the channel with deposition in the rapids reach and erosion in the riffle pool 3 sub-reach. In WY07 and WY11, net storage increased moving downstream along the channel with erosion in the rapids reach and deposition in the riffle pool 3 sub-reach. In all other years, net storage fluctuated between aggradation and degradation moving downstream along the channel.



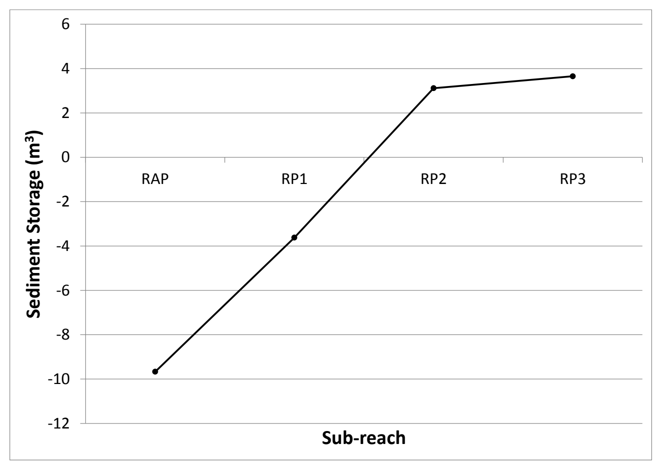
(a) WY04



(b) WY05

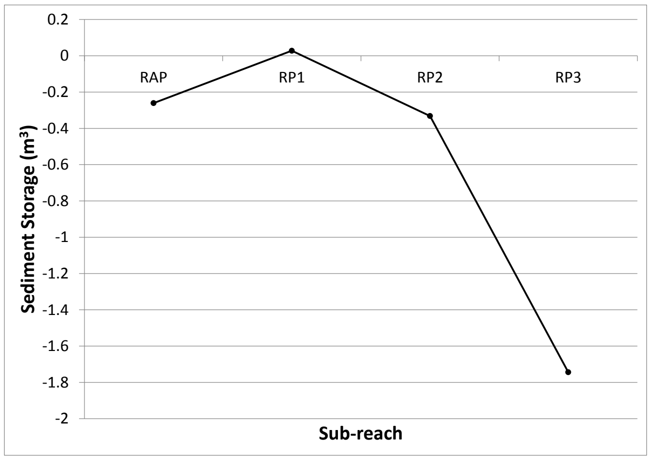


(c) WY06

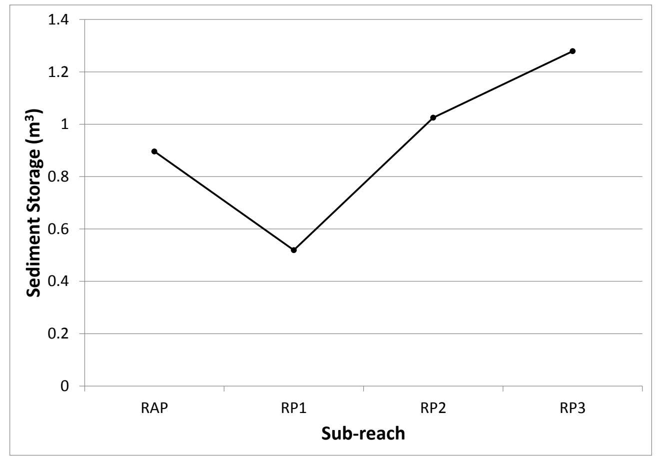


(d) WY07

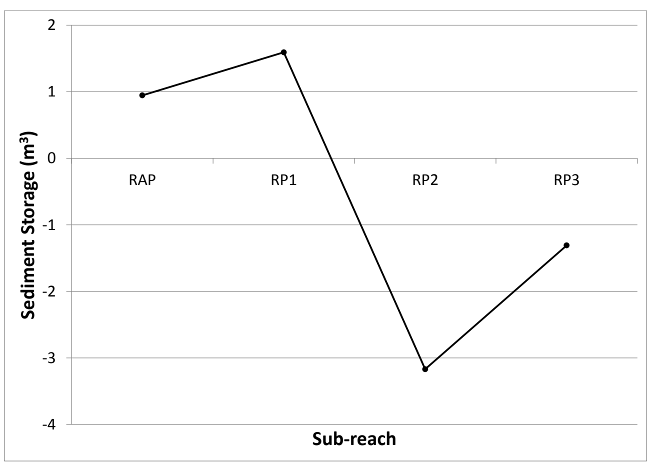
Figure 4.6: Volumetric change in sediment storage moving downstream along the bed of the East Creek study reach for WY04-07



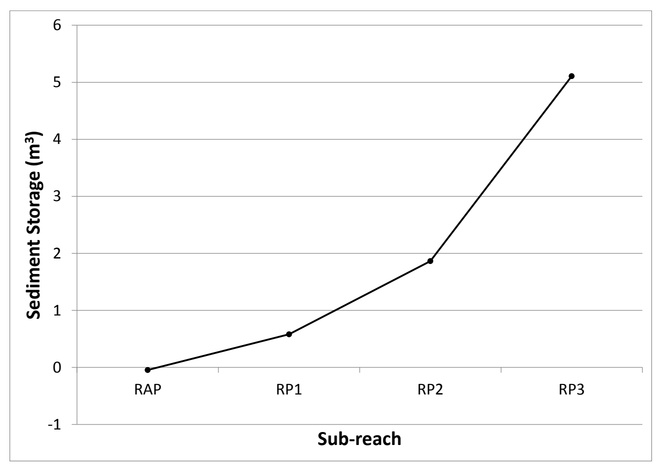
(a) WY08



(b) WY09



(c) WY10



(d) WY11

Figure 4.7: Volumetric change in sediment storage moving downstream along the bed of the East Creek study reach for WY08-11

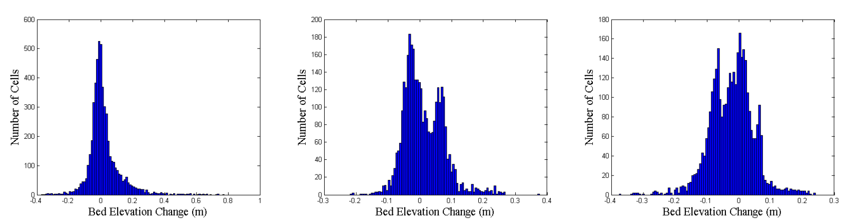
4.4 Unit-Scale: Distribution of Sediment Storage

4.4.1 Bed Elevation Change Histograms

Sediment storage and mobility was analyzed separately for the riffle and pool units in East Creek, and reported for the rapids reach and the riffle pool 1, 2, and 3 sub-reaches.

Riffles

Net bed elevation change histograms for the riffles were generally uni-modal with only a few cases of multi-modal histograms. These consisted of one bimodal histogram in the rapids in WY07; two multi-modal histograms in riffle pool 2 in WY05 and WY07; and two bimodal histograms in riffle pool 3 in WY06 and WY07. Figure 4.8 shows examples of a uni-modal histogram typical of most years and sub-reaches (4.8a), a rare bimodal histogram (4.8b), and a very rare multimodal histogram (4.8c) for the riffles. Net bed elevation change histograms for all reaches and all years can be found in Appendix B in Figures A.1, A.2, A.3, and A.4 for the rapids, riffle pool 1, riffle pool 2, and riffle pool 3, respectively.



(a) A Uni-modal histogram in rapids for riffles in WY04

(b) A Bi-modal histogram in riffle pool 3 for riffles in WY07

(c) A Multimodal histogram in riffle pool 2 for riffles in WY05

Figure 4.8: Examples of types of bed elevation change histograms in riffles in East Creek

The means and medians of net bed elevation change in the riffles were close to zero in all years in all sub-reaches, with an average mean of 0.00 m and an average median of 0.00 m. The means ranged from -0.04 m to 0.03 m and the medians ranged from -0.02 m to 0.03 m. Rounded to the nearest tenth of a decimal, the range of means was equal to the range of medians in riffle pool 2 and riffle pool 3.

The average variance in the riffles was 0.005 m^2. The largest variance in each reach usually occurred during WY07 with the exception of the rapids reach where the largest variance occurred in WY05. The variance ranged from 0.001 m^2 to 0.022 m^2.

The majority of histograms were slightly skewed and there were fluctuations between positively and negatively skewed histograms. The most extreme negative skews occurred in WY05 in the rapids, riffle pool 1, and riffle pool 3. The most extreme positive skews were not consistent with the water year. The average skew was -0.081 and the skews ranged from -4.76 to 3.66. The former occurred in riffle pool 2 and the latter occurred in the rapids.

There was a wide range in kurtosis values of the histograms, with an average kurtosis of 10.0. The minimum (0.37) and maximum (40.25) kurtosis values both occurred in riffle pool 2.

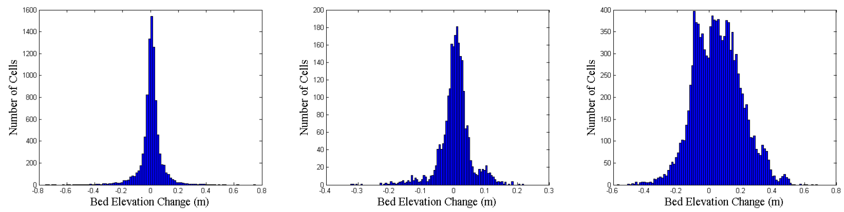
The summary statistics for riffles in riffle pool 3 are shown as representative for the other sub-reaches (Table 4.5). Summary statistics for the remaining reaches can be found in Appendix B in Tables A.1, A.2, A.3 for the rapids, riffle pool 1, and riffle pool 2, respectively.

Table 4.5: Summary statistics for bed elevation change in riffles in riffle pool 3 sub-reach

Year	Mean (m)	Median (m)	Variance (m^2)	Skew	Kurtosis
WY04	0.00	-0.01	0.00	0.93	7.79
WY05	-0.01	0.00	0.00	-1.20	5.57
WY06	0.01	0.00	0.00	1.27	6.70
WY07	0.01	0.00	0.00	0.77	1.56
WY08	-0.01	0.00	0.00	-1.18	11.18
WY09	0.00	0.01	0.00	-0.49	6.29
WY10	-0.01	-0.01	0.00	-0.81	4.35
WY11	0.01	0.01	0.00	1.16	8.52
Average	**0.00**	**0.00**	**0.00**	**0.06**	**6.49**

Pools

Net bed elevation change histograms for the pools were generally uni-modal with only a few cases of multi-modal histograms. These consisted of three multi-modal histograms in the rapids in WY06, WY07, and WY09 and two multi-modal histograms in riffle pool 2 in WY05 and WY07. Figure 4.9 shows examples of a typical uni-modal histogram (4.9a), a rare bimodal histogram (4.9b), and a rare multimodal histogram (4.9c) for the pools.



(a) A Uni-modal histogram in riffle pool 1 for pools in WY09

(b) A Bi-modal histogram in rapids for pools in WY06

(c) A Multimodal histogram in riffle pool 2 for pools in WY07

Figure 4.9: Examples of types of bed elevation change histograms in pools in East Creek

The means and medians of net bed elevation change in the riffles were close to zero in all years in all sub-reaches, with an average mean of 0.00 m and an average median of 0.00 m. The means ranged from -0.063 m to 0.055 m and the medians ranged from -0.046 m to 0.051 m. Rounded to the nearest tenth of a decimal, the range of means was equal to the range of medians in the rapids.

The average variance in the pools was 0.008 m^2. The largest variances occurred in WY05 and WY07. The variance ranged from 0.002 m^2 to 0.023 m^2.

The majority of histograms were slightly skewed and there were fluctuations between positively and negatively skewed histograms. The most extreme negative skews occurred in WY10 in the rapids, riffle pool 2, and riffle pool 3. The most extreme positive skews occurred in WY11 in riffle pool 1, riffle pool 2, and riffle pool 3. The average skew was 0.015 and the skews ranged from -1.60 to 2.25. The former occurred in riffle pool 3 and the latter occurred in riffle pool 1.

The kurtosis values were lower in pools than in riffles, with an average kurtosis of 5.99 in pools. As with riffles, the minimum (0.23) and maximum (14.14) kurtosis values in pools both occurred in riffle pool 2.

The summary statistics for pools in riffle pool 3 are shown as representative for the other sub-reaches (Table 4.6). Summary statistics for the remaining reaches can be found in Appendix B in Tables A.4, A.5, A.6 for the rapids, riffle pool 1, and riffle pool 2, respectively.

Table 4.6: Summary statistics for bed elevation change in pools in riffle pool 3 sub-reach

Year	Mean (m)	Median (m)	Variance (m^2)	Skew	Kurtosis
WY04	-0.01	0.00	0.01	-0.87	3.74
WY05	-0.02	-0.02	0.02	0.32	1.73
WY06	0.00	0.00	0.01	-0.26	7.36
WY07	0.03	0.02	0.01	0.42	2.83
WY08	-0.01	0.00	0.01	-0.33	7.33
WY09	0.01	0.01	0.01	0.35	6.36
WY10	-0.02	0.00	0.01	-1.60	5.85
WY11	0.02	0.01	0.01	0.90	5.95
Average	**0.00**	**0.00**	**0.01**	**-0.13**	**5.14**

4.4.2 Erosion and Deposition Histograms

Bed material erosion and deposition were analyzed separately for the riffle and pool units in East Creek in the rapids reach and in all riffle pool sub-reaches for WY04-10.

Riffles

Erosion histograms for the riffles were generally uni-modal with a few cases of multi-modal histograms in each sub-reach. These consisted of three multi-modal histograms in the rapids in WY07, WY08, and WY10; three multi-modal histograms in riffle pool 1 in WY07, WY09, and WY10; three multi-modal histograms in riffle pool 2 in WY04, WY07, and WY10; and one multi-modal histogram in riffle pool 3 in WY05. Deposition histograms for the riffles were generally uni-modal; however, there was a higher occurrence of multi-modal histograms of deposition compared with erosion. These multi-modal deposition histograms consisted of four cases in the rapids in WY04, WY08, WY09, and WY10; one case in riffle pool 1 in WY04; four cases in riffle pool 2 in WY04, WY05, WY07, and WY11; and three cases in riffle pool 3 in WY04, WY06, and WY07.

Figure 4.10 shows the erosion and deposition histograms in riffle pool 3 in WY09 as an example of a uni-modal erosion histogram concurrent with a uni-modal deposition histogram. Figure 4.11 shows the erosion and deposition histograms in riffle pool 1 in WY07 as an example of a bimodal erosion histogram concurrent with a uni-modal deposition histogram Figure 4.12 shows the erosion and deposition histograms in the rapids in WY10 as an example of a multimodal erosion histogram concurrent with a multi-modal deposition histogram. Multi-modal histograms occurred most commonly in WY07 and WY10 for erosion and in WY04 for deposition. Occurrence of a multi-modal erosion histogram was not consistent with the occurrence of a multi-modal deposition histogram for the same given year and sub-reach.

Erosion and deposition histograms for all reaches and all years can be found in Appendix B in Figures B.1, B.2, B.3, and B.4 for the rapids, riffle pool 1, riffle pool 2, and riffle pool 3, respectively.

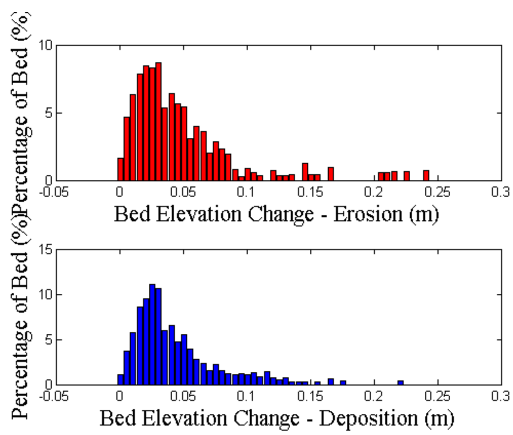


Figure 4.10: Uni-modal erosion and deposition histograms in riffle pool 3 for riffles in WY09

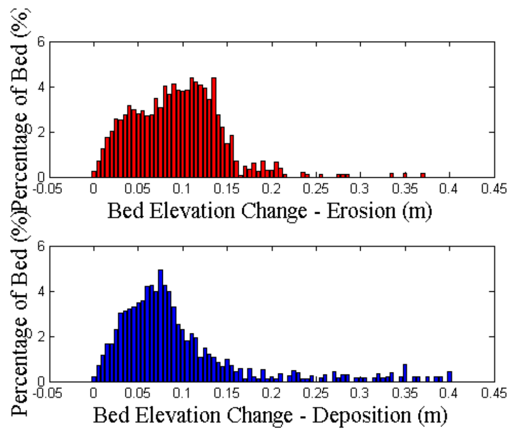


Figure 4.11: A bi-modal erosion histogram concurrent with a uni-modal deposition histogram in riffle pool 1 for riffles in WY07

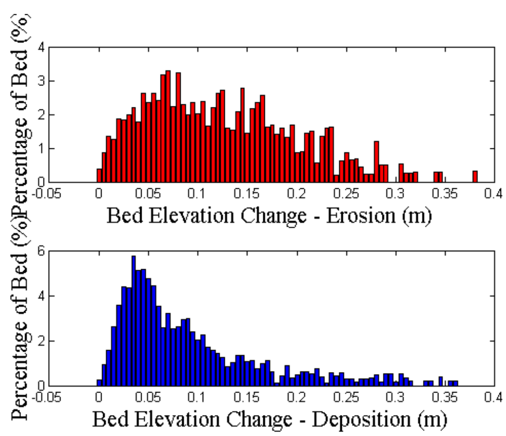


Figure 4.12: Multimodal erosion and deposition histograms in the rapids for riffles in WY10

The average mean erosion (-0.04 m) was equal in absolute magnitude to the average mean deposition (0.04 m) in riffles. Similarly, the average median erosion (-0.03 m) was equal in absolute magnitude to the average median deposition (0.03 m) in riffles. The mean erosion ranged from -0.12 m to -0.02 m and the mean deposition ranged from 0.02 m to 0.08 m. The median erosion ranged from -0.06 m to -0.02 m and the median deposition ranged from 0.01 m to 0.07 m.

The average variances of both the erosion and deposition histograms were 0.003 m^2. The largest variances in the erosion histograms occurred during WY05 for three of four sub-reaches and the largest variances in the deposition histograms occurred in WY07 for three of four sub-reaches. The channel experienced large storm events in WY07. The variance for erosion ranged from 0.000 m^2 to 0.029 m^2 and the variance for deposition ranged from 0.000 m^2 to 0.012 m^2.

All erosion histograms were negatively skewed and all deposition histograms were positively skewed for the riffles. The average skew of the erosion histograms was -2.84 and the average skew of the deposition histograms was 2.96. The largest skews for the erosion histograms occurred in WY08 in the rapids, riffle pool 2, and riffle pool 3. The smallest skews for the erosion histograms occurred in WY07 in the riffle pool 1, riffle pool 2, and riffle pool 3 sub-reaches. Unlike the erosion histograms, the most extreme skews for the deposition histograms did not repeatedly occur in the same water year across the sub-reaches. Rather, the smallest skews and the largest skews for the deposition histograms occurred in different water years across the sub-reaches.

There was a wide range in histogram kurtosis, with an average kurtosis of 13.9 for erosion histograms and an average kurtosis of 13.8 for deposition histograms. The minimum (-0.70) and maximum (39.36) kurtosis values for erosion both occurred in riffle pool 2. The minimum (2.12) and maximum (46.25) kurtosis values for deposition occurred in riffle pool 2 and riffle pool 1, respectively.

The summary statistics for erosion in riffles in riffle pool 2 are shown as a representative for other sub-reaches (Table 4.7). Summary statistics for erosion for the remaining reaches can be found in Appendix B in Tables B.1, B.2, B.3 for the rapids, riffle pool 1, and riffle pool 3, respectively.

Table 4.7: Summary statistics for erosion in riffles in riffle pool 2 sub-reach

Year	Mean (m)	Median (m)	Variance (m^2)	Skew	Kurtosis
WY04	-0.04	-0.03	0.00	-1.22	1.14
WY05	-0.06	-0.06	0.00	-1.63	4.94
WY06	-0.02	-0.02	0.00	-4.53	33.36
WY07	-0.07	-0.06	0.00	-0.46	-0.70
WY08	-0.03	-0.02	0.00	-5.51	39.36
WY09	-0.03	-0.02	0.00	-3.60	26.73
WY10	-0.04	-0.02	0.00	-2.49	8.30
WY11	-0.03	-0.02	0.00	-2.04	8.07
Average	**-0.04**	**-0.03**	**0.00**	**-2.69**	**15.15**

The summary statistics for deposition in riffles in riffle pool 2 are shown as a representative for the other sub-reaches (Table 4.8). Summary statistics for deposition for the remaining reaches can be found in Appendix B in Tables B.4, B.5, B.6 for the rapids, riffle pool 1, and riffle pool 3, respectively.

Table 4.8: Summary statistics for deposition in riffles in riffle pool 2 sub-reach

Year	Mean (m)	Median (m)	Variance (m^2)	Skew	Kurtosis
WY04	0.04	0.02	0.00	2.74	8.32
WY05	0.04	0.03	0.00	1.34	4.38
WY06	0.02	0.02	0.00	2.95	15.08
WY07	0.08	0.07	0.00	1.37	2.12
WY08	0.02	0.01	0.00	3.73	22.63
WY09	0.03	0.02	0.00	3.19	15.76
WY10	0.02	0.02	0.00	3.25	20.75
WY11	0.03	0.02	0.00	3.30	15.43
Average	**0.04**	**0.03**	**0.00**	**2.73**	**13.06**

Pools

Erosion histograms for the pools were generally uni-modal with a few cases of multi-modal histograms in each sub-reach. These consisted of four multi-modal histograms in the rapids in WY04, WY06, WY08, and WY10; two multi-modal histograms in riffle pool 1 in WY07 and WY08; three multi-modal histograms in riffle pool 2 in WY05, WY06, and WY08; and two multi-modal histograms in riffle pool 3 in WY04 and WY11. Deposition histograms for the pools were generally uni-modal with a few cases of multi-modal histograms in each sub-reach. These multi-modal deposition histograms consisted of four cases in the rapids in WY04, WY06, WY07, and WY10; one case in riffle pool 1 in WY11; two cases in riffle pool 2 in WY07 and WY09; and one case in riffle pool 3 in WY05.

Figure 4.13 shows the erosion and deposition histograms in riffle pool 3 in WY09 as an example of a uni-modal erosion histogram concurrent with a uni-modal deposition histogram. Figure 4.14 shows the erosion and deposition histograms in the rapids in WY06 as an example of a multi-modal erosion histogram concurrent with a bi-modal deposition histogram. Figure 4.15 shows the erosion and deposition histograms in riffle pool 2 in WY05 as an example of a multimodal erosion histogram concurrent with a uni-modal deposition histogram. Occurrence of multi-modal erosion and deposition histograms was fairly spread out across the years of study, with W09 being the only water year in which all histograms were uni-modal. Occurrence of a multi-modal erosion histogram was not consistent with the occurrence of a multi-modal deposition histogram for the same given year and sub-reach.

Erosion and deposition change histograms for all reaches and all years can be found in Appendix B in Figures B.1, B.2, B.3, and B.4 for the rapids, riffle pool 1, riffle pool 2, and riffle pool 3, respectively.

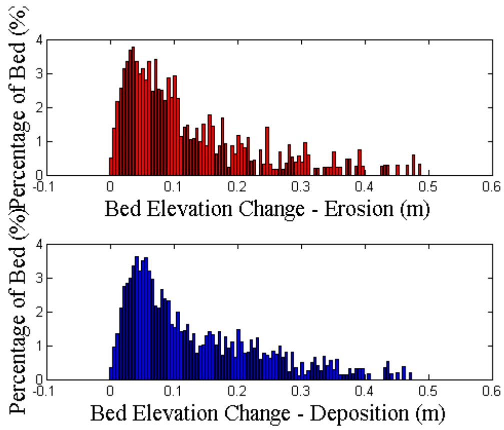


Figure 4.13: Uni-modal erosion and deposition histograms in riffle pool 3 for pools in WY09

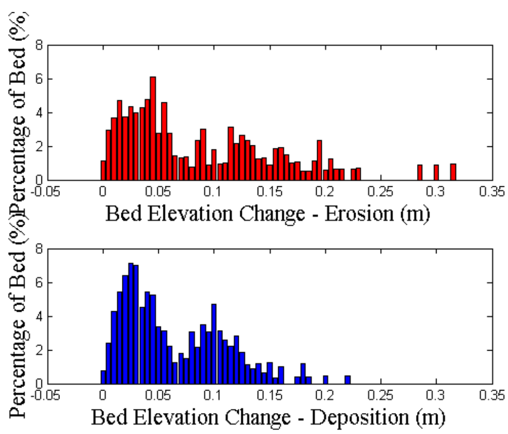


Figure 4.14: A multi-modal erosion histogram concurrent with a bi-modal deposition histogram in the rapids for pools in WY06

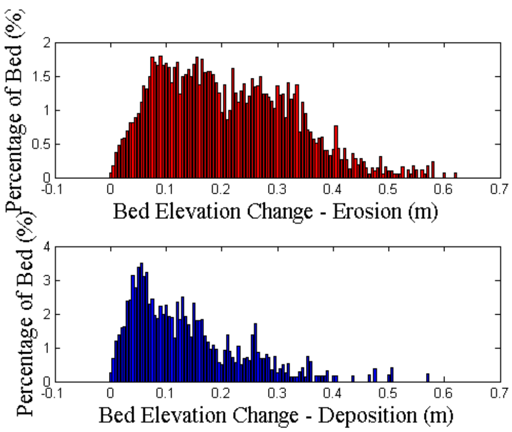


Figure 4.15: Multi-modal erosion and uni-modal deposition histograms in riffle pool 2 for pools in WY05

The average mean erosion (-0.06 m) was equal in absolute magnitude to the average mean deposition (0.06 m) in riffles. Similarly, the average median erosion (-0.04 m) was equal in absolute magnitude to the average median deposition (0.04 m) in riffles. The mean erosion ranged from -0.12 m to -0.03 m and the mean deposition ranged from 0.03 m to 0.14 m. The median erosion ranged from -0.09 m to -0.02 m and the median deposition ranged from 0.02 m to 0.12 m.

The average variance of erosion and deposition histograms were 0.005 m^2 and 0.004 m^2, respectively. The largest variances in erosion and deposition histograms were not consistent with water year. The variance for erosion ranged from 0.001 m^2 to 0.012 m^2 and the variance for deposition ranged from 0.001 m^2 to 0.011 m^2.

All erosion histograms were negatively skewed and all deposition histograms were positively skewed for the riffles. The average skew of the erosion histograms was -2.36 and the average skew of the deposition histograms was 2.46. The most extreme skews for both erosion and deposition histograms for pools occurred in different water years across the sub-reaches.

There was a wide range in histogram kurtosis, with average kurtosis values of 8.2 and 9.0 for erosion and deposition histograms, respectively. The minimum kurtosis for erosion (0.74) occurred in the rapids in WY07 and the maximum kurtosis for erosion (19.06) occurred in riffle pool 1 in WY11. The minimum (0.71) and maximum (24.67) kurtosis values for deposition both occurred in riffle pool 2 in

WY07 and WY11, respectively.

The summary statistics for erosion in pools in riffle pool 2 are shown as a representative for other sub-reaches (Table 4.9). Summary statistics for erosion for the remaining reaches can be found in Appendix B in Tables B.7, B.8, B.9 for the rapids, riffle pool 1, and riffle pool 3, respectively.

Table 4.9: Summary statistics for erosion in pools in riffle pool 2 sub-reach

Year	Mean (m)	Median (m)	Variance (m^2)	Skew	Kurtosis
WY04	-0.07	-0.04	0.01	-3.44	16.13
WY05	-0.12	-0.09	0.01	-1.20	1.19
WY06	-0.06	-0.03	0.01	-2.44	7.87
WY07	-0.10	-0.08	0.01	-1.67	3.91
WY08	-0.06	-0.03	0.00	-2.56	10.60
WY09	-0.05	-0.03	0.00	-2.58	9.17
WY10	-0.05	-0.02	0.01	-3.02	11.32
WY11	-0.05	-0.03	0.00	-1.84	4.49
Average	**-0.07**	**-0.04**	**0.01**	**-2.34**	**8.09**

The summary statistics for deposition in pools in riffle pool 2 are shown as a representative for the other sub-reaches (Table 4.10). Summary statistics for deposition for the remaining reaches can be found in Appendix B in Tables B.10, B.11, B.12 for the rapids, riffle pool 1, and riffle pool 3, respectively.

4.4.3 Bed Storage, Erosion, and Deposition

Bed material erosion and deposition were compared to bed material storage separately for the riffle and pool units in East Creek for WY04-11 both distinctly for each of the upper reaches and in the upper reaches combined. It was hypothesized that storage should track trends in the erosion/deposition balance for each sub-reach.

Figure 4.16 shows weak correlations between net change in bed elevation and mean bed erosion and deposition in riffles. Similarly, Figure 4.17 shows weak correlations between net change in bed elevation and mean bed erosion and deposition in pools.

Table 4.10: Summary statistics for deposition in pools in riffle pool 2 subreach

Year	Mean (m)	Median (m)	Variance (m^2)	Skew	Kurtosis
WY04	0.07	0.05	0.01	2.03	5.13
WY05	0.07	0.05	0.00	2.08	5.76
WY06	0.05	0.03	0.00	2.90	10.47
WY07	0.14	0.12	0.01	0.95	0.71
WY08	0.05	0.03	0.00	2.10	5.90
WY09	0.07	0.04	0.01	2.93	12.43
WY10	0.05	0.03	0.00	2.12	6.60
WY11	0.05	0.03	0.01	4.13	24.67
Average	**0.07**	**0.05**	**0.01**	**2.41**	**8.96**

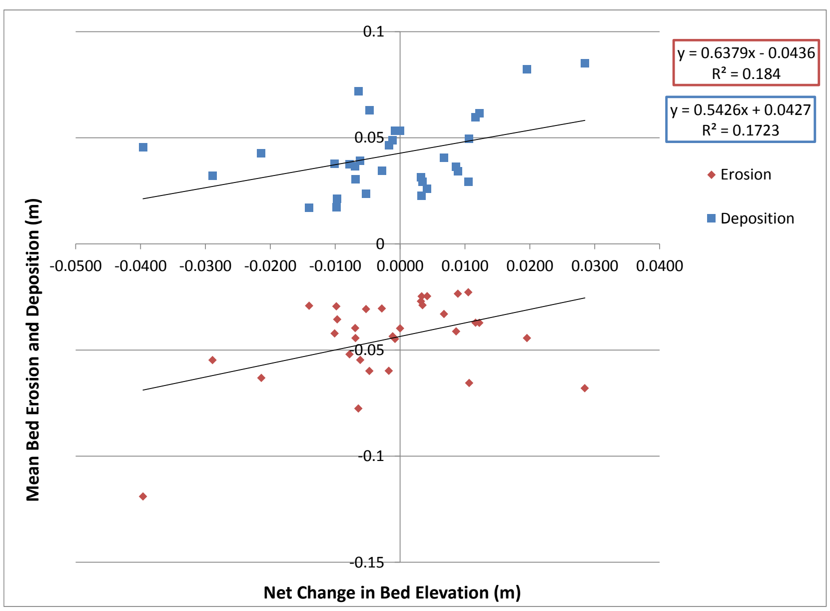


Figure 4.16: Sediment storage vs. erosion and deposition in riffles in combined upper reaches of East Creek

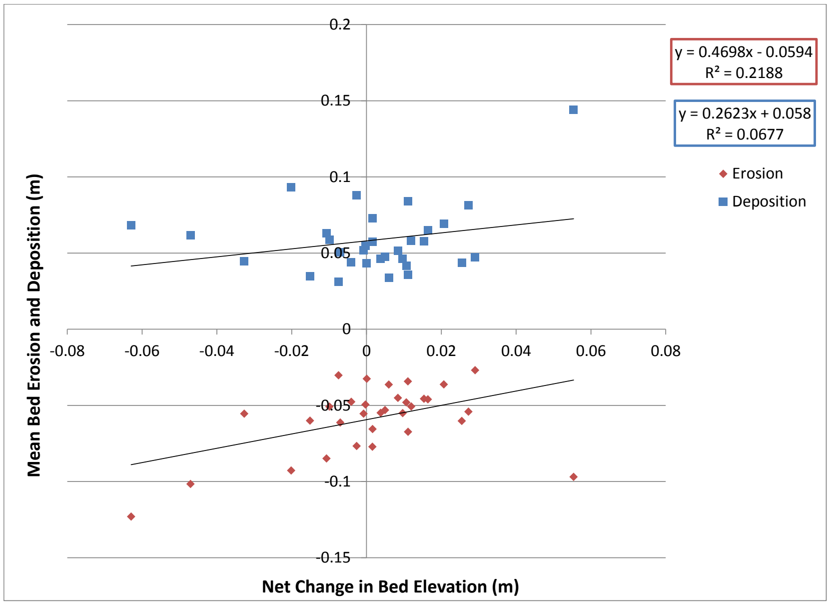


Figure 4.17: Sediment storage vs. erosion and deposition in pools in combined upper reaches of East Creek

4.4.4 Peak Discharge, Erosion, and Deposition

Bed material erosion and deposition were compared to annual peak discharge separately for the riffle and pool units in the rapids reach and riffle pool 1, 2, and 3 sub-reaches of East Creek for WY04-11.

In most sub-reaches as peak discharge increased, the magnitude of erosion and deposition increased. Figure 4.18 shows the relationship between peak discharge and mean bed erosion and the relationship between peak discharge and mean bed deposition for riffles in the riffle pool 3 sub-reach. This location is shown because the slopes and R^2 values are fairly representative of those observed in the other units and sub-reaches analyzed. Figure 4.19 shows an exception to this trend in the pools in the rapids reach. In this case, as peak discharge increased, the magnitude of erosion decreased slightly.

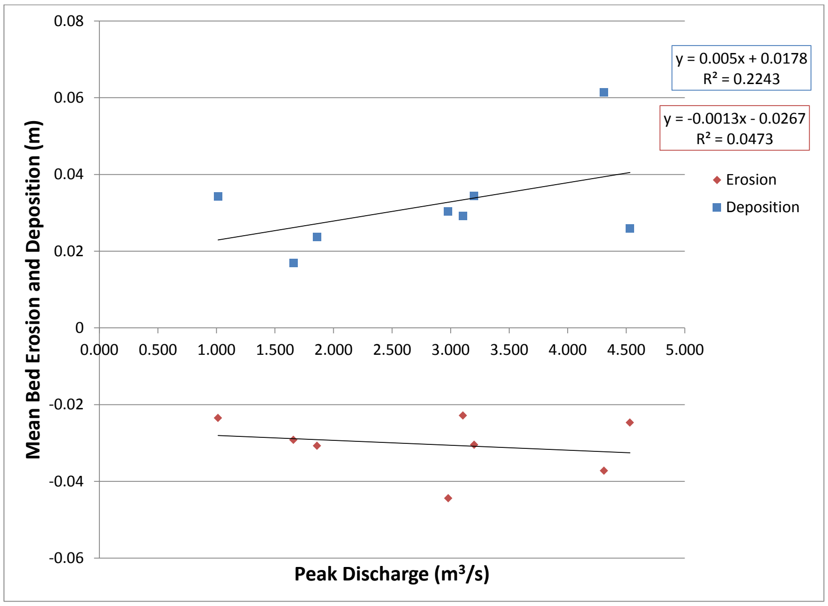


Figure 4.18: Peak discharge vs. mean bed erosion and mean bed deposition in riffles of riffle pool 3 sub-reach in East Creek

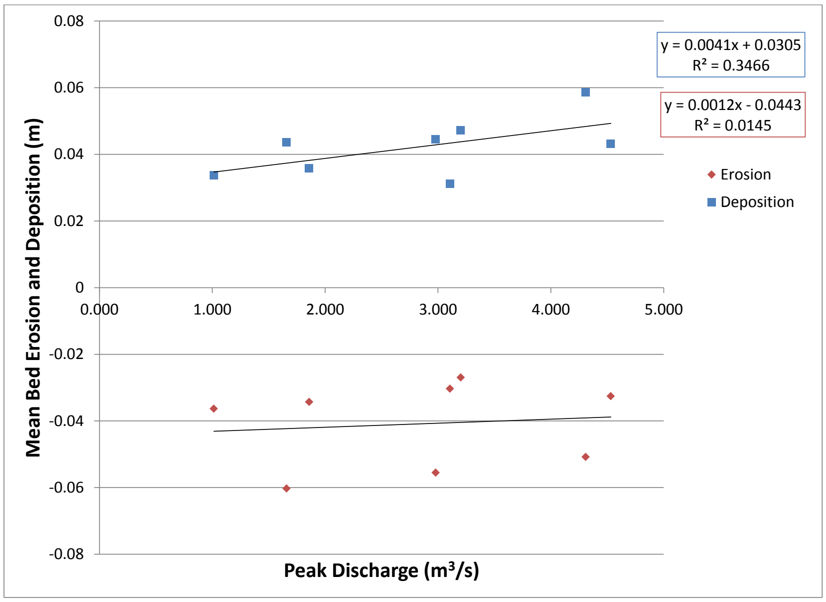


Figure 4.19: Peak discharge vs. mean bed erosion and mean bed deposition in pools of rapids reach in East Creek

The correlations between peak discharge and mean bed deposition (Table 4.11) were higher than the correlations between peak discharge and mean bed erosion (Table 4.12) in all sub-reaches. The largest correlations for deposition and for erosion occurred in riffle pool 2 as highlighted by the bolded font.

Table 4.11: Correlation between peak discharge and mean bed deposition

Morphological Unit	Rapids	Riffle Pool 1	Riffle Pool 2	Riffle Pool 3
Pools	0.3466	0.1864	**0.4278**	0.3692
Riffles	0.1883	0.3924	**0.4287**	0.2243

Table 4.12: Correlation between peak discharge and mean bed erosion

Morphological Unit	Rapids	Riffle Pool 1	Riffle Pool 2	Riffle Pool 3
Pools	0.0145	0.0358	0.0602	0.002
Riffles	0.0242	0.0659	**0.1832**	0.0473

The correlations between peak discharge and median bed erosion and the correlations between peak discharge and median bed deposition were also low ($R^2 \leq 0.5451$) in all sub-reaches of East Creek.

Chapter 5

Discussion

The discussion section proposes possible explanations and offers comments on the sediment storage and transport trends presented in Chapter 4: Results. First, flow regime is briefly discussed. Next, sediment storage and transport processes in East Creek at the channel, reach, and unit scales are discussed. At the channel scale, bed elevation changes in East Creek throughout the study period are described. At the reach scale, emphasis is given to analyzing sediment storage trends over time and space. At the unit scale, the ability of the data to demonstrate conservation of mass in East Creek is discussed.

5.1 Flow Regime

In considering the relationship between discharge and sediment transport in the sections that follow, it is important to acknowledge the scale and scope at which the flow regime was analyzed in this study. Consistent with the annual scale of the sediment budget, discharge was also analyzed at the annual scale where annual peak discharge was used as a coarse reflection of annual flow regime. Since discharge is not resolved at the event scale, the impact of event scale features of flow regime are not considered. For example, number of storm events per year; storm duration; and sediment mobilizing flow duration per storm event are not addressed. Despite this limitation, annual peak discharge does provide valuable information about the sediment mobilizing conditions in East Creek. In particular, the 2007 and 2009 water years experienced the highest annual peak discharges (4.3 m^3/s and 4.5 m^3/s, respectively), suggesting high sediment mobilizing capacity in these years. In comparison, the 2006 water year experienced the lowest peak discharge (1.0 m^3/s) (Figure 4.1). Overall, the peak flows fluctuated over time between high and low values.

5.2 Channel Scale: Long Profile

Bed elevation in the upper reaches fluctuated between 2003 and 2009. At the coarser scale, the long profile of East Creek suggested relative channel stability (Figure 4.2); whereas, at the finer scale additional bed elevation changes could be discerned (Figure 4.3). In the rapids reach, the greatest amount of fluctuations occurred in the upper 20 m of the reach (Figure 4.3a). The channel was scoured down to the bedrock in the upper 20 m during WY07, the year with the greatest storm events. Downstream sediment accumulation in subsequent years in riffle pools 2 and 3 can likely be attributed to the re-mobilization of the sediment scoured from the upper 20 m of the rapids (Figures 4.3c and 4.3d). Fluctuations in bed elevation were of similar magnitude across the sub-reaches. There were, however, localized areas distributed throughout the upper reaches in which more substantial fluctuations in bed elevation occurred. These large fluctuations occurred across various bedforms: runs, pools, and bars, and across varying channel widths ranging from 1.9 m to 6.2 m. Large bed elevation fluctuations frequently occurred in close proximity to a channel obstruction downstream of the culvert and associated plunge pool at the top of the rapids section and around large wood in the riffle pool sub-reaches. It is well established that wood modulates sediment flux and storage through a coupled cycle of storage-erosion and release (Eaton et al., 2012). Sediment is stored upstream of wood, the presence of wood leads to bed erosion alongside and downstream of the wood, and when wood decays stored sediment is released to downstream reaches.

5.3 Reach Scale: Closing the Sediment Budget

5.3.1 Bed Load Flux and Storage

There was considerable variation in the magnitude of bed load flux, with no consistent connections to sub-reach or water year, suggesting that channel morphology and water discharge are not the only factors controlling bed load flux in East Creek.

The TOR, the sub-reach just upstream of the rapids sub-reach (Figure 5.1), experienced the greatest annual bed load flux, which can likely be attributed to the presence of a culvert at its upper bound.

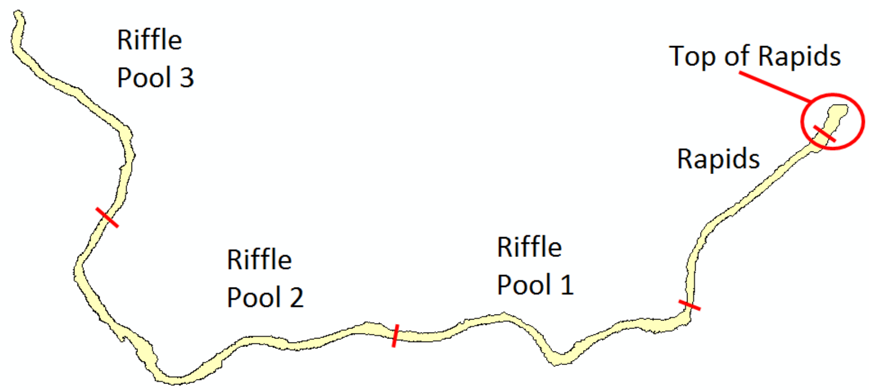


Figure 5.1: Upper reaches of East Creek with location of top of rapids (TOR) sub-reach highlighted in red circle

The narrow diameter of the culvert in comparison to the channel width results in a localized increase in water velocity, and consequently an increase in sediment mobilizing capacity in this short stretch of the channel. This localized increase in velocity is also evidenced by the presence of a large scoured out plunge pool at the base of the culvert (Figure 5.2). It is likely that some of the material scoured from the plunge pool contributed to the material captured in the trap a mere 11.9 m downstream.

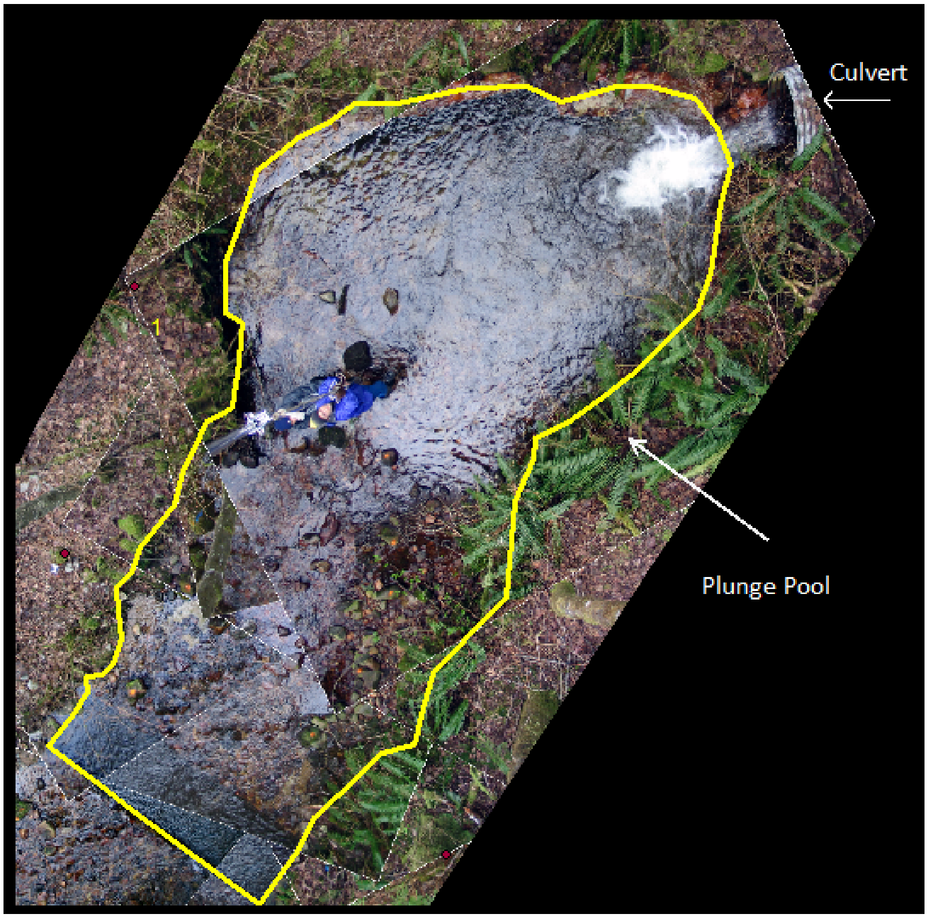


Photo Credit: *Joshua Caulkins*

Figure 5.2: Plunge pool at base of culvert in top of rapids (TOR) sub-reach of East Creek

Both the largest average annual bed load flux and the largest bed load storage over the 3 year period occurred in the rapids reach. This dynamism within the rapids reach is consistent with the earlier observation that the rapids reach underwent the largest amount of change in the thalweg elevation over the nine year period (Section 5.2).

The majority of sub-reaches experienced positive net bed load storage suggesting that during WY09-11 East Creek may have been in a state of aggradation 4.3. The exceptions to this occurred in the rapids in WY11 (-651 kg) and in riffle pool

2 in WY10 (-849 kg). The uncharacteristic negative storage observed in the rapids in WY11 may have been a response to the particularly large positive sediment storage (1252 kg) in WY10. That is, to balance out the large gain in sediment in the previous year, more sediment than usual was excavated from the reach in the following year. With regards to the uncharacteristic negative storage observed in riffle pool 2 in WY10, it is possible that this is a reflection of a reduction in sediment supply to this sub-reach. Since riffle pool 2 is downstream of riffle pool 1 and the rapids, sediment excavated from these more upstream reaches is often transported downstream and deposited in riffle pool 3. In the 2010 water year, there were particularly low peak flows; and, correspondingly, particularly high bed load storage values in the rapids and riffle pool 1. With this increase in sediment retention in the upper reaches, less sediment would have been available to travel downstream and be deposited in the riffle pool 3 sub-reach, resulting in negative bed load storage.

5.3.2 Bed Material Erosion and Storage

Similar to bed load flux and storage, there was considerable variation in the magnitude of bed material erosion and storage, with no consistent connection to sub-reach or water year, suggesting that channel morphology and water discharge are not the only factors controlling bed material erosion and storage in East Creek. It is likely that a third, and important, control on bed material erosion and storage in East Creek is sediment supply and storage within the channel. Sediment scoured from upstream reaches becomes a sediment source in downstream reaches, and sediment storage fluctuations in a given sub-reach and year can be more easily explained by examining bed conditioning. Given that a longer record of bed material erosion and storage is available compared to bed load flux and storage, a more detailed analysis of bed material storage changes over time and space is possible.

Over the eight year period analyzed, all sub-reaches fluctuated between aggradational and degradational states (Figures 4.5a - 4.5d). The rapids were dominated by degradation during the early years and transitioned towards being slightly dominated by aggradation in the latter half of the study (Figure 4.5a). Consistent with the rapids being the reach where the largest bed load flux and storage occurred, the rapids was also the reach where the largest average bed material flux and storage occurred. Given that (1) the thalweg elevation in the rapids was relatively stable in the lower part of the reach, but fluctuated substantially in the upper part of the reach (Figure 4.3a) and (2) in the upper part of the reach, there was scouring to such an extent that the bedrock was exposed (Figure 5.3), it is likely that the large bed material flux values in the rapids, too, were localized in the upper part of the reach. The bed material scoured from the upper part of the reach was likely transported and deposited in the lower part of the reach contributing to the large bed material storage values in the rapids. Similar to the storage patterns over time in the rapids, riffle pool 1 was also dominated by degradation in the early years and transitioned towards being slightly dominated by aggradation in the latter half of the study (Figure 4.5b). Like the rapids, the greatest change in storage (negative storage in both cases) occurred in WY07, corresponding to the second highest annual peak discharge.

Photo Credit: *Joshua Caulkins*

Figure 5.3: Exposure of till on bed of rapids reach of East Creek in WY07 following high magnitude scouring

In contrast to the trend from degradation to aggradation over time observed in the rapids and riffle pool 1, riffle pools 2 and 3 fluctuated back and forth between aggradational and degradational states throughout the entire duration of the study period. The magnitudes of annual storage in riffle pool 2 spanned a narrower range than that of the other sub-reaches, with no water year experiencing a drastically higher storage than the others (Figure 4.5c). Similar to riffle pool 2, in riffle pool 3, storage values were closer in magnitude to each other over time compared to that of the rapids and riffle pool 1. The greatest storage in riffle pool 3 (positive storage) occurred in WY11, a year without a particularly high annual peak discharge (Figure 4.5d).

Analyzing the spatial trends across the length of the channel for each water year may offer more insight into some of the temporal trends noted above (Figures 4.6 - 4.7). Moving downstream along the length of the channel, there was increasing degradation approaching riffle pool 3 in WY04. This was followed by fluctuating storage values in WY04 along the length of the channel. In the following year, WY05 there were also storage fluctuations along the length of the channel, but in the opposite directions as the previous year, suggesting a possible internal balancing of storage occurring in the study reach. For example, in WY05 there were peaks in storage in RP1 and RP3 and troughs in the RAP and RP2, whereas in WY05 there were peaks in storage in the RAP and RP2 and troughs in RP1 and RP3. In WY07, the year with the second highest annual peak discharge, there was an exceptionally large amount of scour in the rapids and moving downstream along the length of the channel increasing aggradation, suggesting that some of the material scoured out from the rapids may have been transported downstream and deposited in riffle pools 2 and 3. This increasing trend towards aggradation moving downstream along the channel was then balanced out the following year, in WY08, with a trend towards increasing degradation moving downstream along the length of the channel. It is presumable that the degradation in riffle pools 2 and 3 in WY08 may be a consequence of the large input of sediment in the previous year. The large load of sediment input to the downstream reaches from the rapids in WY07 was likely then excavated in WY08, producing negative sediment storage values. In WY09, the entire channel shifted to a state of aggradation, with a particularly large increase in storage in the more downstream sub-reaches. This is surprising given that the greatest annual peak flow occurred in WY09 and suggests that (1) annual peak flow cannot be used as a sole predictor of sediment storage and/or (2) the annual peak flow values used in this study may be suspect. In WY09, the storage values returned to fluctuating between aggradation and degradational states moving downstream along the length of the channel implying in-stream balancing out of sediment storage. Finally, in WY11 the channel was in a state of aggradation with increasing positive storage values moving downstream along the length of the channel.

5.3.3 Comparison of Methods

There was high discrepancy between sediment storage estimates obtained from traps compared to those obtained from surveyed difference maps, with the percentage differences between these two methods ranging from -88% to 6030% (Table 5.1). With the exception of the rapids in WY11 (percentage difference of -88%), in all other sub-reaches and water years analyzed the pit trap method yielded smaller magnitudes of sediment storage than the difference mapping method. Since the pit trap method measures bed load and the difference mapping method measures bed material load, this suggests that there was more bed material load compared to bed load. This can be explained in at least two ways. First, when the traps become full or almost full finer material that is coupled to the flow overpasses the traps and does not contribute to the pit trap sediment collections. That same fine material likely would have settled out elsewhere in the channel, perhaps in bars or riffles, contributing to the higher values of bed material load calculated. Second, the bed load traps have storage volumes that reflect a fraction of the bed material that is actually transported during any given storm or runoff period. Hence, the trap records will always underestimate bed material flux.

Table 5.1: Sediment budget from traps and survey data for East Creek for W09-11

Station	**Water Year**	**Sediment Storage from Traps (I-E)** ***(kg)***	**Sediment Storage from Surveys (ΔS)** ***(kg)***	**Difference between (I-E) and ΔS** ***(kg)***	**% Difference between (I-E) and (ΔS)** ***(%)***
RAP	WY09	156	1554	1398	896
RAP	WY10	1252	1641	389	31
RAP	WY11	-651	-80	572	-88
RP1	WY09	264	900	636	241
RP1	WY10	893	2763	1870	209
RP1	WY11	532	1006	474	89
RP2	WY09	29	1778	1749	6030
RP2	WY10	-849	-5497	-4648	548
RP2	WY11	147	3233	3086	2105

Figure 5.4 shows that in all but two cases, the sediment storage estimates obtained from the morphological mapping method are equal to or greater than double those obtained from the pit trap method. This highlights the extent to which the pit trap method comparatively underestimates sediment storage, regardless of year or morphological reach. This is consistent with the earlier supposition of pit trap inefficiency.

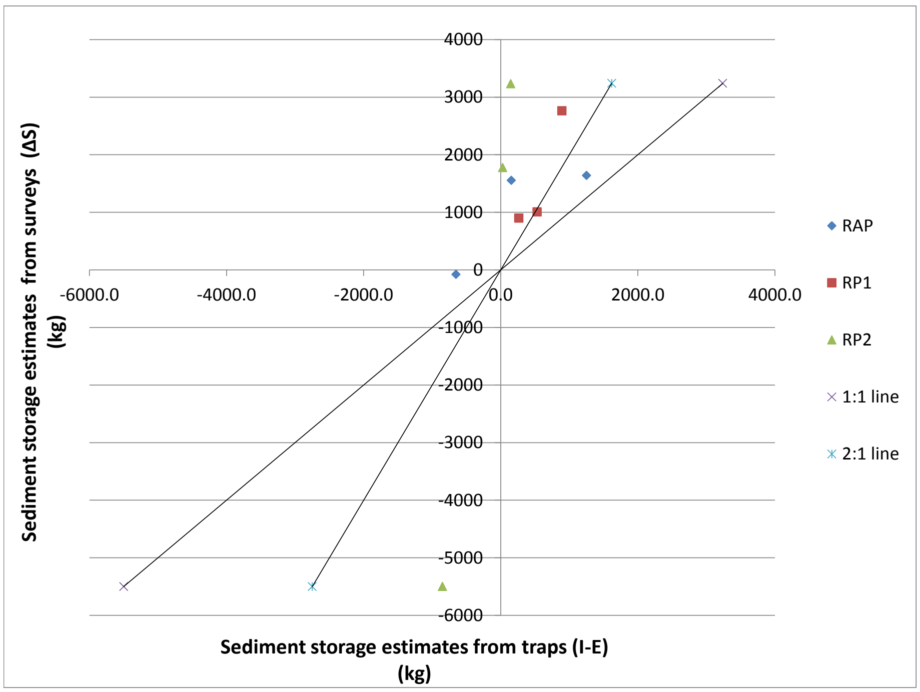


Figure 5.4: Sediment storage estimates from surveys compared to sediment storage estimates from traps

A closer look at the two exceptions to this trend of the pit trap method greatly underestimating storage compared to the morphological mapping method may offer more insight or create further questions about pit trap efficiency. The first case in which the sediment storage estimate obtained from the morphological mapping method was less than double that obtained from the pit trap method occurred in the rapids in WY10. This coincided with the highest recorded sediment storage estimates as obtained using the pit trap method of all sub-reaches and water years within the given study period, explaining why this estimate may have more closely approached that of the morphological mapping method. In WY10 there were documented trap overflow events in the rapids making for an incomplete accounting of sediment storage using the pit traps. It is impossible to draw absolute conclusions from a single case, but this may suggest that limitations in trap capacity contribute to underestimates of sediment storage, but cannot fully explain the more than two-fold differences observed between the two methods. The second exception to the pit trap underestimates trend occurred in riffle pool 2 in WY10. This was the only case in which the sediment storage estimates from the pit trap were greater than those obtained from the morphological mapping method. This coincided with the lowest recorded sediment storage estimate obtained from the morphological mapping method of all sub-reaches and water years analyzed and represented one of only two cases of negative sediment storage estimates. Framed another way - that the morphological mapping method captured the erosion of a larger fraction of bed material than the pit trap could be capable of doing - it becomes less surprising that the pit trap estimate of storage was higher than that of the morphological mapping method in this case.

Figure 5.5 shows that the difference in sediment storage estimates between the morphological mapping and pit trap method can be scaled to the sediment storage estimates obtained from the morphological mapping method with a correlation of 0.95. This suggests that it might be possible to somewhat standardize the magnitude of discrepancy between these two methods. This could be very valuable for (1) increasing the comprehensiveness of a sediment budget and (2) more accurately estimating the magnitude of over- or under- estimation of sediment storage when only one of these two methods is available.

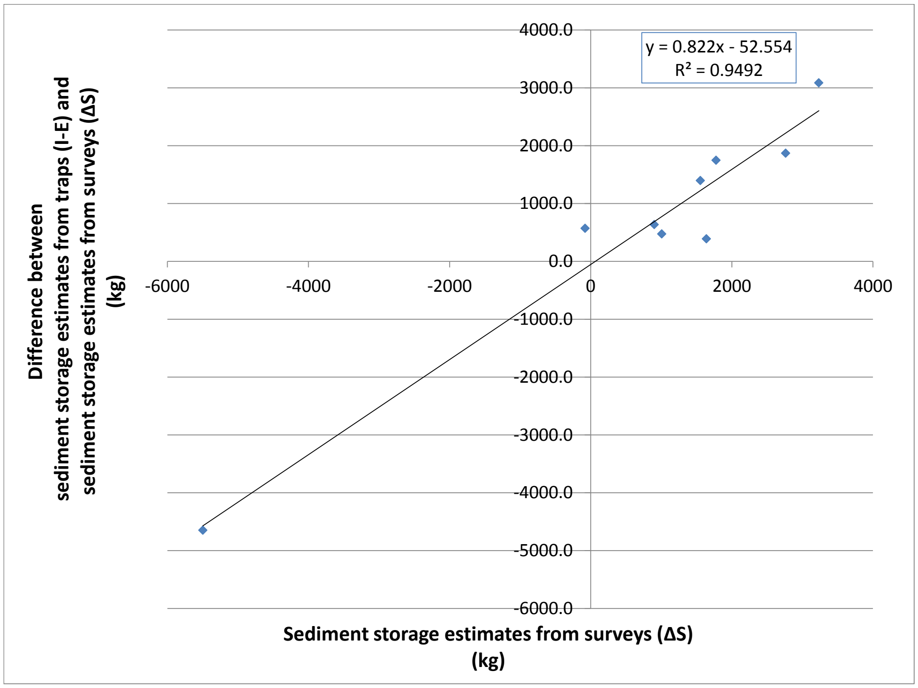


Figure 5.5: Difference in sediment storage estimates between two distinct methods (surveys and traps) scaled to sediment storage estimates from surveys

5.4 Unit Scale: Sediment Storage and Bedforms

5.4.1 Bed Elevation Change in Riffles and Pools

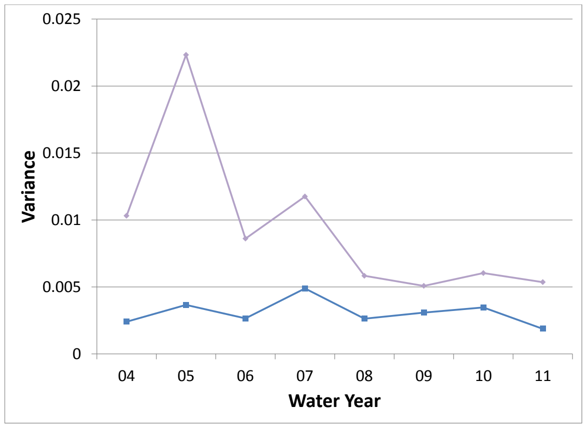
In most cases, the bed elevation change histograms were relatively symmetrical with means and medians falling close to 0.0 m. This suggests that erosion and deposition were balanced, demonstrating mass conservation at the reach scale and more importantly that erosion and deposition are coupled. The level of detail presented in the histograms provides a unique opportunity to observe conservation of mass at the unit scale over an extended time period that is typically not seen in studies on sediment transport.

The level of detail presented in the data also allows for spatial patterns of bed elevation change across riffles and pools to be discerned. The means and medians of bed elevation change were close to 0.0 m in most cases in both the riffle and pool units. There were positive linear correlations between mean bed elevation change in riffles and mean bed elevation change in pools in all sub-reaches except riffle pool 1. This is likely a reflection of the discharge and sediment supply conditions in the channel. There were only two years of the study period during which particularly high annual peak flows capable of causing extreme scouring were observed. Consequently, during the majority of the study period, mean scour and fill were relatively balanced across the channel, producing similarly low mean bed elevation change in both riffles and pools. There were, however, weak or no correlations between median bed elevation change in riffles and median bed elevation change in pools in all reaches (Table 5.2), suggesting that finer scale bed elevation changes vary across riffles and pools.

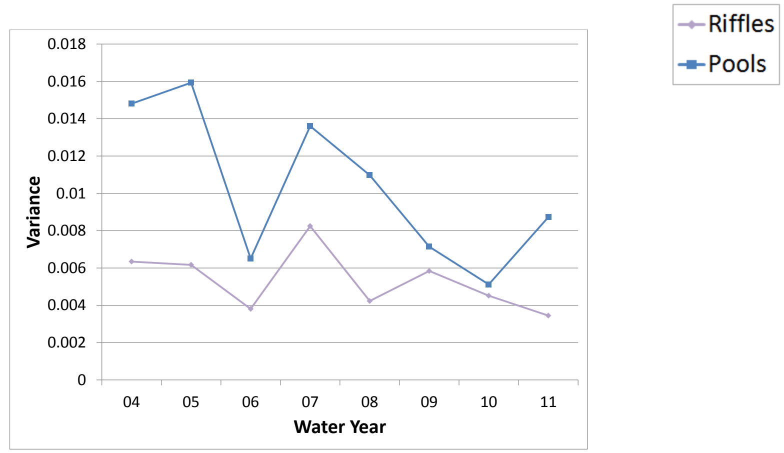
Table 5.2: Correlation between bed elevation change in riffles and bed elevation change in pools in upper reaches of East Creek

Measure of Bed Elevation Change	**Rapids**	**Riffle Pool 1**	**Riffle Pool 2**	**Riffle Pool 3**
Mean	0.82	0.05	0.81	0.70
Median	0.38	0.00	0.90	0.09

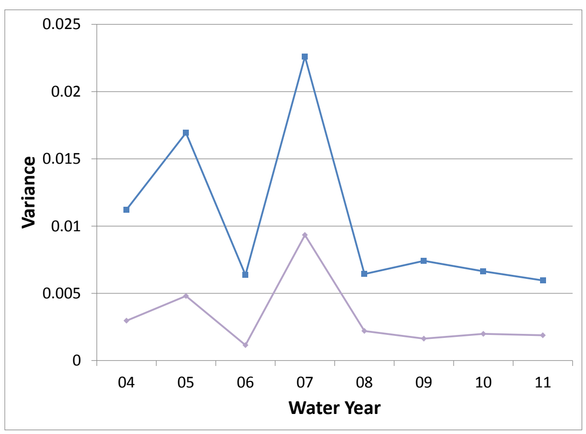
In the rapids reach, variances in bed elevation change were higher in riffles than in pools. In contrast, in all riffle pool sub-reaches, variances in bed elevation change were greater in pools than in riffles (Figure 5.6). There may have been increased variance in bed elevation change in pools compared to riffles in the riffle pool morphology because pools characteristically contain finer more loosely interacting particles than riffles, allowing for increased sediment mobility and consequently, greater variance in bed elevation changes. The increased variance in bed elevation change in riffles compared to pools in the rapids morphology is more difficult to explain from the perspective of particle interactions; however, it can be explained by broadening consideration to include reach scale processes. The overwhelming majority of bed elevation changes in the rapids were localized in the upper 20 m of the reach, which primarily encompassed a riffle unit. This concentration of high magnitude, high variance, bed elevation change localized in a riffle unit likely masked smaller scale spatial variations in bed elevation change across riffle and pool units distributed throughout the reach.



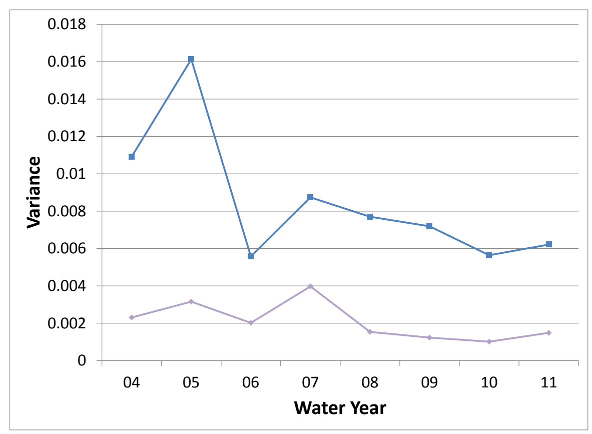
(a) Rapids



(b) Riffle Pool 1



(c) Riffle Pool 2



(d) Riffle Pool 3

Figure 5.6: Variance in bed elevation over time in riffles (purple line) and pools (blue line) in the rapids, riffle pool 1, riffle pool 2, and riffle pool 3 sub-reaches of East Creek

The direction of skew in both riffles and pools fluctuated over time, as would be expected for a channel in a relative state of equilibrium. In some cases the direction of skew of the pools very crudely appeared to oscillate in phase with the direction of skew in the riffles; however, this pattern was inconsistent and there were very weak or no correlations between skew in riffles and skew in pools for all sub-reaches ($R^2 \leq 0.2$). Figure 5.7 shows an example of the bed elevation histogram skew in riffles and pools in riffle pool 1, a case in which the crudely in-phase oscillation can be observed. Figure A.5 in Appendix B shows the skew of the bed elevation histograms over time for all sub-reaches. There were very weak ($R^2 = 0.02$) or no correlations between kurtosis in riffles and kurtosis in pools for all sub-reaches.

5.4.2 Erosion and Deposition in Riffles and Pools

With the exception of the riffle pool 2 sub-reach, there was very little correlation between annual deposition in riffles and annual deposition in pools. Similarly, with the exception of the riffle pool 2 sub-reach, there was also very little correlation between annual erosion in riffles and annual erosion in pools (Table 5.3). This observation strongly reinforces the importance of considering spatial heterogeneity in sediment transport at the unit scale. Even when a morphological reach was subjected to the same flow regime, bed conditioning, and sediment supply conditions, there were still localized differences in erosion and deposition patterns within the reach. These differences were likely in part governed by differing grain interactions in riffles and pools.

Table 5.3: Correlation between erosion/deposition in riffles and erosion/deposition in pools in upper reaches of East Creek

Type of Change	Rapids	Riffle Pool 1	Riffle Pool 2	Riffle Pool 3
Deposition	0.4178	0.7789	**0.9559**	0.3328
Erosion	0.5755	0.2937	**0.8512**	0.5481

In the riffle pool sub-reaches, the magnitude of deposition in pools was always higher than deposition in riffles. Whereas, in the rapids reach, the magnitude

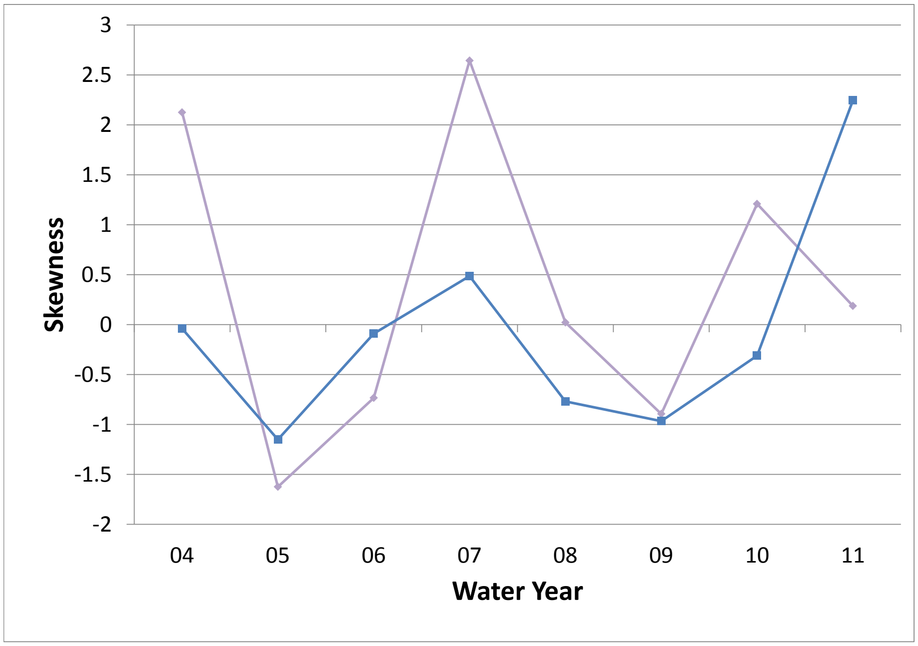
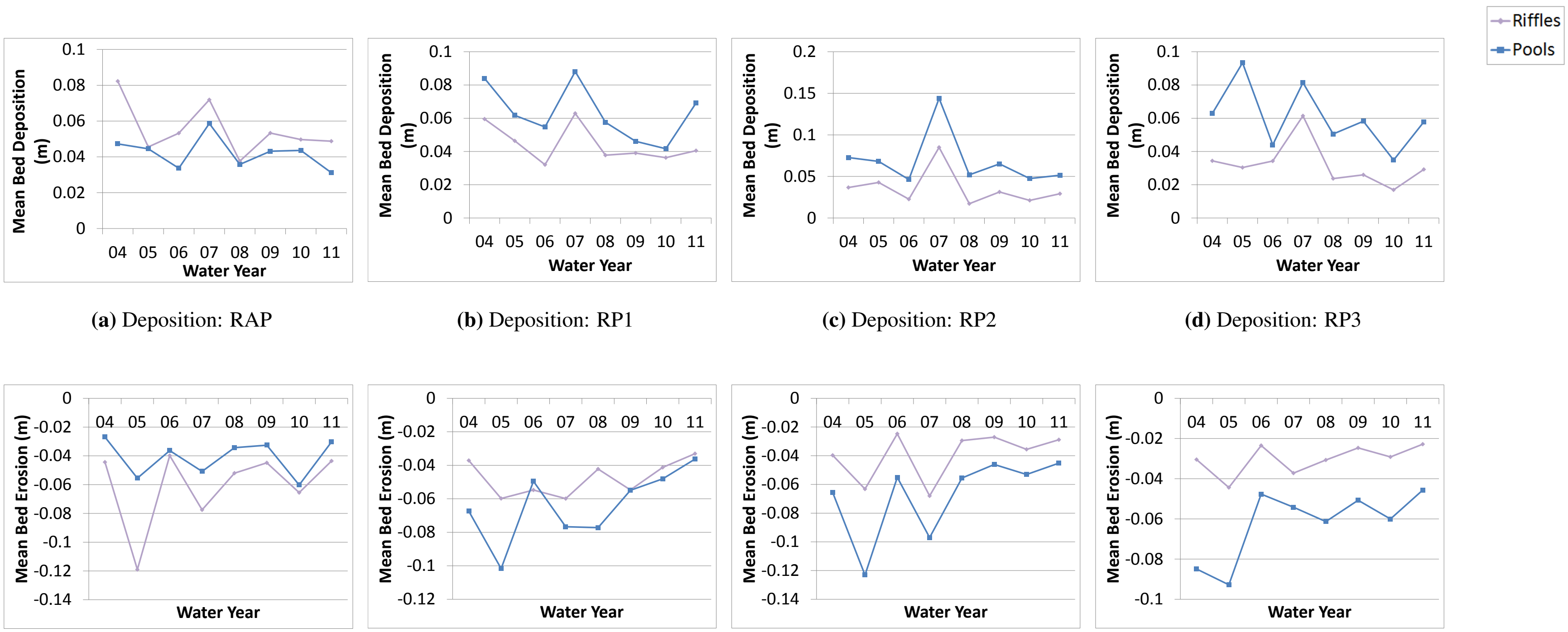


Figure 5.7: Skew of bed elevation histograms over time in riffles (purple line) and pools (blue line) in riffle pool 1 in East Creek

of deposition in pools was always lower than deposition in riffles. The erosion showed a similar pattern. In the riffle pool sub-reaches, the magnitude of erosion in pools was nearly always higher than erosion in riffles. Whereas, in the rapids reach, the magnitude of erosion in pools was always lower than erosion in riffles. These observations build on the earlier observation in Subsection 5.4.1 of increased variance in bed elevation change in pools compared to riffles in the riffle pool morphology. As with variance, greater magnitudes of deposition and erosion in pools compared to riffles in the riffle pool morphology are likely a reflection of comparatively increased sediment mobility in pools, where particles are finer and more loosely interacting than in riffles. As with variance, the opposite trend was observed for the rapids, where there was a smaller magnitude of deposition and erosion in pools compared to riffles. In the rapids morphology, reach scale processes were likely a greater determinant of spatial patterns of sediment transport; whereas, in the riffle pool morphology, unit scale processes were likely a greater determinant of spatial patterns of sediment transport. This is a wonderfully clear illustration of the necessity of integrating multiple spatial scales when predicting sediment transport patterns.

In riffles and pools in all upper reaches, deposition and erosion fluctuated inconsistently with respect to water year (Figure 5.8). In the majority of cases, the greatest magnitudes of erosion and deposition in riffles and pools occurred in WY07, the year of the second highest annual peak flows. There did not appear to be any other connections between water year and magnitude of deposition/erosion in riffle or pool units, a reinforcement that flow regime cannot alone be used as a reliable predictor of sediment transport patterns.



(a) Deposition: RAP
(b) Deposition: RP1
(c) Deposition: RP2
(d) Deposition: RP3
(e) Erosion: RAP
(f) Erosion: RP1
(g) Erosion: RP2
(h) Erosion: RP3

Figure 5.8: Mean bed deposition and mean bed erosion over time in the riffle units (purple line) and the pool units (blue line) in the rapids, riffle pool 1, riffle pool 2, and riffle pool 3 sub-reaches of East Creek

5.4.3 Bed Storage, Erosion, and Deposition

Although it was hypothesized that storage should track trends in erosion/deposition in riffles and pools, there were very weak correlations between net change in bed elevation and mean bed erosion/deposition. Taking riffles as an example, in years during which there was a large amount of storage in riffles, there was not necessarily an associated increase in mean deposition (Figure 4.16). For storage to increase independently of deposition, there must have been a decrease in erosion. Similarly, in years during which there was very little storage in riffles, there was not necessarily an associated increase in mean erosion. For storage to decrease independently of erosion, there must have been a decrease in deposition. A similar trend was observed for pools (Figure 4.17). This implies that erosion and deposition were closely coupled, an excellent demonstration of conservation of mass in East Creek.

5.4.4 Peak Discharge, Erosion, and Deposition

There were very low positive correlations between annual peak discharge and magnitude of bed material erosion/deposition in riffles and pools. This implies that when using annual peak discharge as a predictor of erosion and deposition patterns, one must also consider additional factors governing transport processes, such as sediment supply and bed conditioning. Additionally, the correlations between peak discharge and mean bed deposition were consistently higher than those between peak discharge and mean bed erosion (Tables 4.11 and 4.12). This difference is difficult to explain given that erosion and deposition are tightly coupled in East Creek (Subsection 5.4.3). However, it is distinctly possible that the correlations were so small that this difference had inconsequential physical significance, further emphasizing the importance of integrating multiple sediment transport governing factors in analyzing erosion and deposition trends.

Chapter 6

Conclusions

The sediment transport and storage trends observed in East Creek at the channel, reach, and unit scales for WY04-11 offer useful insights into the state of the study reach, factors governing sediment transport, and coupling of erosion and deposition processes.

At the channel scale, relative stability in channel grade and elevation was observed over the study period, with localized areas of large bed elevation fluctuations occurring primarily around large wood and other channel obstructions.

At the reach scale, there was considerable fluctuation in both bed load flux and storage as obtained from the pit trap method and in bed material storage and flux estimates as obtained from the morphological method. The pit trap method consistently underestimated storage compared to the morphological method as a result of overpassing of fine material and trap inefficiency. Both measurement methods estimated the same direction of storage (+ or -) in all cases. The highest magnitude bed load and bed material flux occurred during the year of the second highest annual peak flow; however, other trends in bed load and bed material flux could not be explained by flow regime. In-stream sediment supply conditions of the given and surrounding reaches in the given and previous years helped to explain annual reach scale fluctuations in erosion and deposition. Large inputs of sediment in downstream reaches (RP2, RP3) were repeatedly attributed to preceding evacuations of sediment in upstream reaches (RAP, RP1). Large evacuations of sediment in downstream reaches (RP2, RP3) repeatedly followed large inputs into these reaches in previous years. Large increases in storage in upstream reaches (RAP, RP1) typically followed large evacuations of sediment from these reaches in previous years. The somewhat balanced fluctuations in sediment storage in East Creek suggest a state of relative equilibrium within the study reach at the ten year scale of study.

At the unit spatial scale, the detailed net bed elevation change, erosion, and deposition histograms provided a unique opportunity to observe conservation of mass, and coupling of erosion and deposition in East Creek. Fine scale bed elevation changes varied across riffle and pools and could not be explained using flow regime and sediment supply alone. It is hypothesized that grain interactions might help explain differences in spatial distributions of erosion and deposition. There was typically higher variance in elevation change, higher magnitudes of erosion, and higher magnitudes of deposition in pools compared to riffles. Taking grain interactions into account, this spatial heterogeneity in sediment storage at the unit scale can easily be explained. Pools contain finer more loosely interacting particles that are, consequently, more easily mobilized compared to those in riffles.

Amassing the above conclusions, there are three salient points that can be drawn from this thesis:

1. In addition to flow and sediment supply regime, in-stream sediment supply and bed conditioning also govern sediment transport processes.

2. A detailed sediment budget using multiple measurement methods can have an amazing capacity to demonstrate conservation of mass and coupling of erosion and deposition.

3. Explaining the physical significance of observed erosion and deposition trends in a channel is tremendously aided by integrating spatial and temporal influences at multiple scales.

Additional research into sediment supply and storage that is spatially and temporally contextualized at multiple scales is recommended to continue unearthing the enigma of sediment transport.

Bibliography

J. M. Buffington and D. R. Montgomery. A systematic analysis of eight decades of incipient motion studies, with special reference to gravel-bedded rivers. *Water Resources Research*, 33(8):1993–2029, 1997. → pages 3, 4

J. M. Buffington, R. D. Woodsmith, D. B. Booth, D. R. Montgomery, et al. Fluvial processes in Puget Sound rivers and the Pacific Northwest. *Restoration of Puget Sound Rivers. University of Washington Press, Seattle, WA*, pages 46–78, 2003. → pages 2

J. Caulkins. Sediment transport and channel morphology within a small forested stream: East creek, British Columbia. Unpublished dissertation, University of British Columbia, Vancouver. → pages 9, 12, 14, 16, 17

M. Church. Bed material transport and the morphology of alluvial river channels. *Annu. Rev. Earth Planet. Sci.*, 34:325–354, 2006. → pages 2, 8

N. Clifford. Differential bed sedimentology and the maintenance of riffle-pool sequences. *Catena*, 20(5):447–468, 1993. → pages 3, 4

G. A. M. de Almeida and J. F. Rodríguez. Understanding pool-riffle dynamics through continuous morphological simulations. *Water Resources Research*, 47 (1), 2011. → pages 2

W. Dietrich, P. Nelson, E. Yager, J. Venditti, M. Lamb, and L. Collins. *River, Coastal, and Estuarine Morphodynamics*, Volume 1, Sediment patches, sediment supply, and channel morphology, pages 79–90. Taylor and Francis, 2006. → pages 6

B. Eaton, M. Hassan, and S. Davidson. Modeling wood dynamics, jam formation, and sediment storage in a gravel-bed stream. *Journal of Geophysical Research: Earth Surface (2003–2012)*, 117(F4), 2012. → pages 57

P. Frey and M. Church. Bedload: a granular phenomenon. *Earth Surface Processes and Landforms*, 36(1):58–69, 2011. → pages 7

K. M. Frothingham, B. L. Rhoads, and E. E. Herricks. A multiscale conceptual framework for integrated ecogeomorphological research to support stream naturalization in the agricultural midwest. *Environmental Management*, 29(1): 16–33, 2002. → pages 2

C. Garcia, J. B. Laronne, and M. Sala. Continuous monitoring of bedload flux in a mountain gravel-bed river. *Geomorphology*, 34(1):23–31, 2000. → pages 6

B. Gomez and M. Church. An assessment of bed load sediment transport formulae for gravel bed rivers. *Water Resources Research*, 25(6):1161–1186, 1989. → pages 5

D. G. Ham and M. Church. Bed-material transport estimated from channel morphodynamics: Chilliwack river, British Columbia. *Earth Surface Processes and Landforms*, 25(10):1123–1142, 2000. → pages 8

M. A. Hassan and I. Reid. The influence of microform bed roughness elements on flow and sediment transport in gravel bed rivers. *Earth Surface Processes and Landforms*, 15(8):739–750, 1990. → pages 5

M. A. Hassan, M. Church, T. E. Lisle, F. Brardinoni, L. Benda, and G. E. Grant. Sediment transport and channel morphology of small, forested streams. *Journal of the American Water Resources Association*, 41(4):853–876, 2005. → pages 1, 2, 3, 4

M. A. Hassan, B. J. Smith, D. L. Hogan, D. S. Luzi, A. E. Zimmermann, and B. C. Eaton. Sediment storage and transport in coarse bed streams: scale considerations. *Developments in Earth Surface Processes*, 11:473–496, 2007. → pages 2, 8

F. Iseya and H. Ikeda. Pulsations in bedload transport rates induced by a longitudinal sediment sorting: A flume study using sand and gravel mixtures. *Geografiska Annaler. Series A. Physical Geography*, 69:15–27, 1987. → pages 7

J. R. Jang and N. Gulley. Fuzzy logic toolbox users guide. *The Mathworks Inc*, 1: 995, 1995. → pages 19

D. Knighton. *Fluvial forms and processes: a new perspective*. Routledge, 2014. → pages 2

G. M. Kondolf and H. Piégay. *Tools in fluvial geomorphology*. Wiley Online Library, 2003. → pages 5

H. Lamarre and A. G. Roy. A field experiment on the development of sedimentary structures in a gravel-bed river. *Earth Surface Processes and Landforms*, 33(7): 1064–1081, 2008. → pages 7

M. A. Lenzi, V. D'Agostino, and P. Billi. Bedload transport in the instrumented catchment of the Rio Cordon: Part I: Analysis of bedload records, conditions and threshold of bedload entrainment. *Catena*, 36(3):171–190, 1999. → pages 5

L. B. Leopold. *A View of the River*. Harvard University Press, 1994. → pages 5, 6

T. E. Lisle, M. Madej, et al. Spatial variation in armouring in a channel with high sediment supply. *Dynamics of Gravel-Bed Rivers*, pages 277–293, 1992. → pages 2

T. E. Lisle, J. M. Nelson, J. Pitlick, M. A. Madej, and B. L. Barkett. Variability of bed mobility in natural, gravel-bed channels and adjustments to sediment load at local and reach scales. *Water Resources Research*, 36(12):3743–3755, 2000. → pages 6, 7

R. J. McCleary and M. A. Hassan. Predictive modeling and spatial mapping of fish distributions in small streams of the Canadian Rocky Mountain foothills. *Canadian Journal of Fisheries and Aquatic Sciences*, 65(2):319–333, 2008. → pages 1

D. R. Montgomery and J. M. Buffington. Channel-reach morphology in mountain drainage basins. *Geological Society of America Bulletin*, 109(5):596–611, 1997. → pages 2, 3, 4

P. A. Nelson, J. G. Venditti, W. E. Dietrich, J. W. Kirchner, H. Ikeda, F. Iseya, and L. S. Sklar. Response of bed surface patchiness to reductions in sediment supply. *Journal of Geophysical Research: Earth Surface (2003–2012)*, 114 (F2), 2009. → pages 6

D. F. Oldmeadow and M. Church. A field experiment on streambed stabilization by gravel structures. *Geomorphology*, 78(3):335–350, 2006. → pages 7

C. Paola and R. Seal. Grain size patchiness as a cause of selective deposition and downstream fining. *Water Resources Research*, 31(5):1395–1407, 1995. → pages 7

G. Parker. *Sedimentation Engineering*, Volume 110, Transport of Gravel and Sediment Mixtures, pages 165–251. American Society of Civil Engineers, 2008. doi:10.1061/9780784408148.ch03. URL http://ascelibrary.org/doi/abs/10.1061/9780784408148.ch03. → pages 6

R. L. Shreve. Stream lengths and basin areas in topologically random channel networks. *The Journal of Geology*, pages 397–414, 1969. → pages 1

A. N. Strahler. Quantitative analysis of watershed geomorphology. *Eos, Transactions American Geophysical Union*, 38(6):913–920, 1957. → pages 1

D. M. Thompson. The velocity-reversal hypothesis revisited. *Progress in Physical Geography*, 35(1):123–132, 2011. → pages 4

J. Venditti, W. Dietrich, P. Nelson, M. Wydzga, J. Fadde, and L. Sklar. Effect of sediment pulse grain size on sediment transport rates and bed mobility in gravel bed rivers. *Journal of Geophysical Research: Earth Surface (2003–2012)*, 115 (F3), 2010. → pages 6

J. M. Wheaton. *Uncertainty in morphological sediment budgeting of rivers*. PhD thesis, Centre for Ecology & Hydrology, 2008. → pages 19

J. M. Wheaton, J. Brasington, S. E. Darby, and D. A. Sear. Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets. *Earth Surface Processes and Landforms*, 35(2):136–156, 2010. → pages 19

P. R. Wilcock. Toward a practical method for estimating sediment-transport rates in gravel-bed rivers. *Earth Surface Processes and Landforms*, 26(13): 1395–1408, 2001. → pages 5

L. Wittenberg and M. D. Newson. Particle clusters in gravel-bed rivers: an experimental morphological approach to bed material transport and stability concepts. *Earth Surface Processes and Landforms*, 30(11):1351–1368, 2005. → pages 7

L. Wittenberg, J. Laronne, and M. Newson. Bed clusters in humid perennial and mediterranean ephemeral gravel-bed streams: The effect of clast size and bed material sorting. *Journal of Hydrology*, 334(3):312–318, 2007. → pages 6

B. Yuill, M. Nichols, and E. Yager. Coarse bed material patch evolution in low-order, ephemeral channels. *Catena*, 81(2):126–136, 2010. → pages 6, 7

A. Zimmermann and M. Church. Channel morphology, gradient profiles and bed stresses during flood in a step–pool channel. *Geomorphology*, 40(3):311–327, 2001. → pages 3

Appendix A

Supporting Results: Bed Elevation Change

Appendix A contains supporting figures and tables detailing bed elevation change patterns in riffles and pools in East Creek from WY04-11. Appendix A includes histograms (Figures A.1 - A.4), summary statistics (Tables A.1 - 4.6), and comparisons of skew between riffles and pools (Figure A.5).

A.1 Histograms

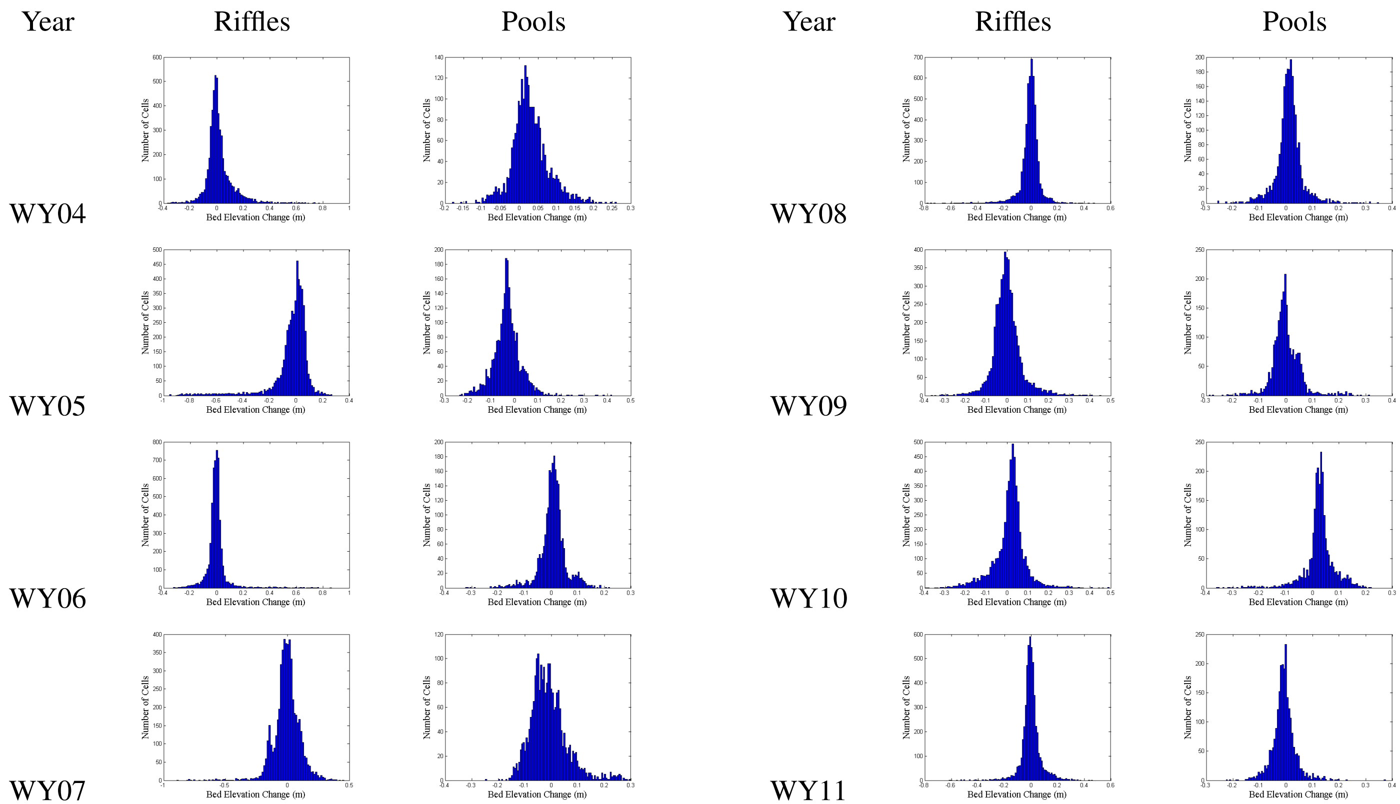


Figure A.1: Distribution of annual bed elevation changes in the riffles and pools within the rapids reach of East Creek from WY04 to WY11

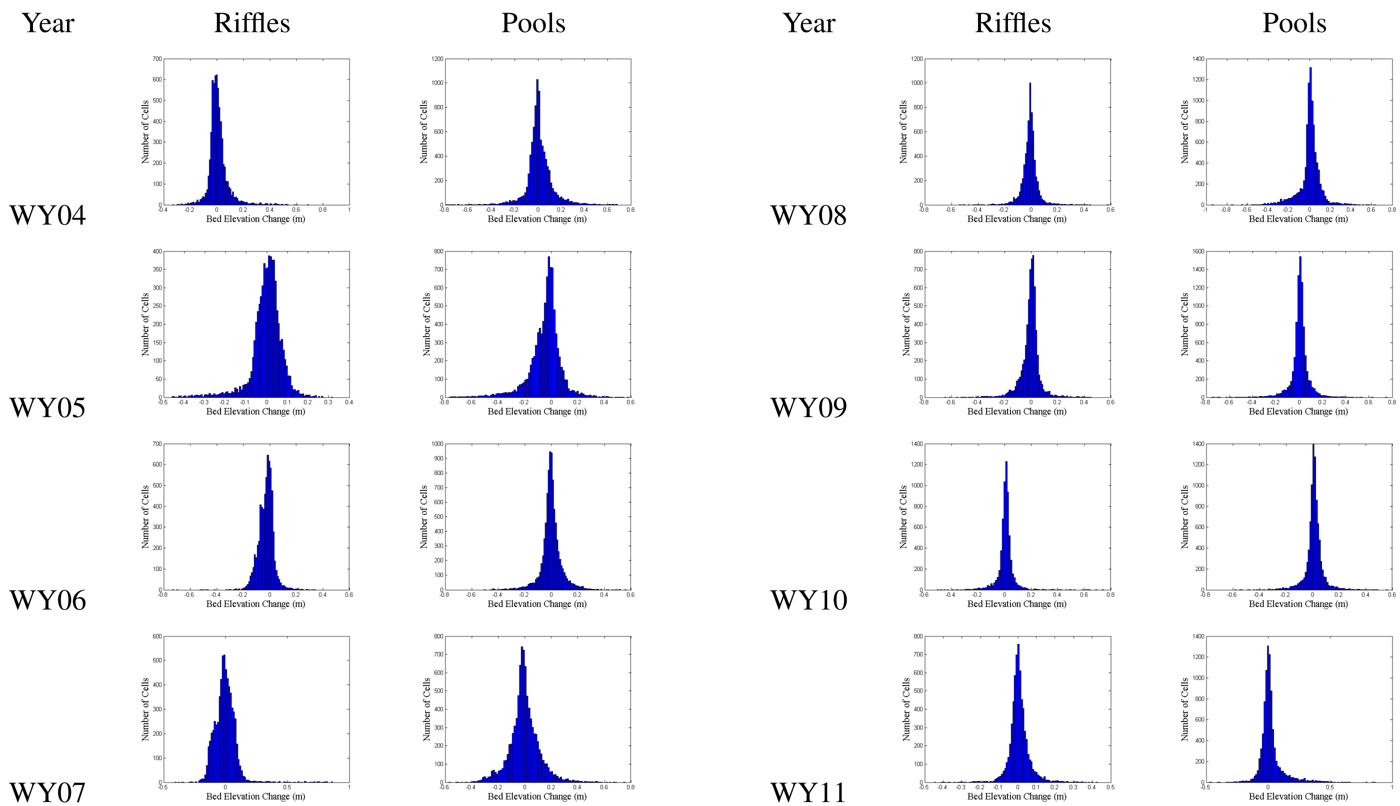


Figure A.2: Distribution of annual bed elevation changes in the riffles and pools within the riffle pool 1 sub-reach of East Creek from WY04 to WY11

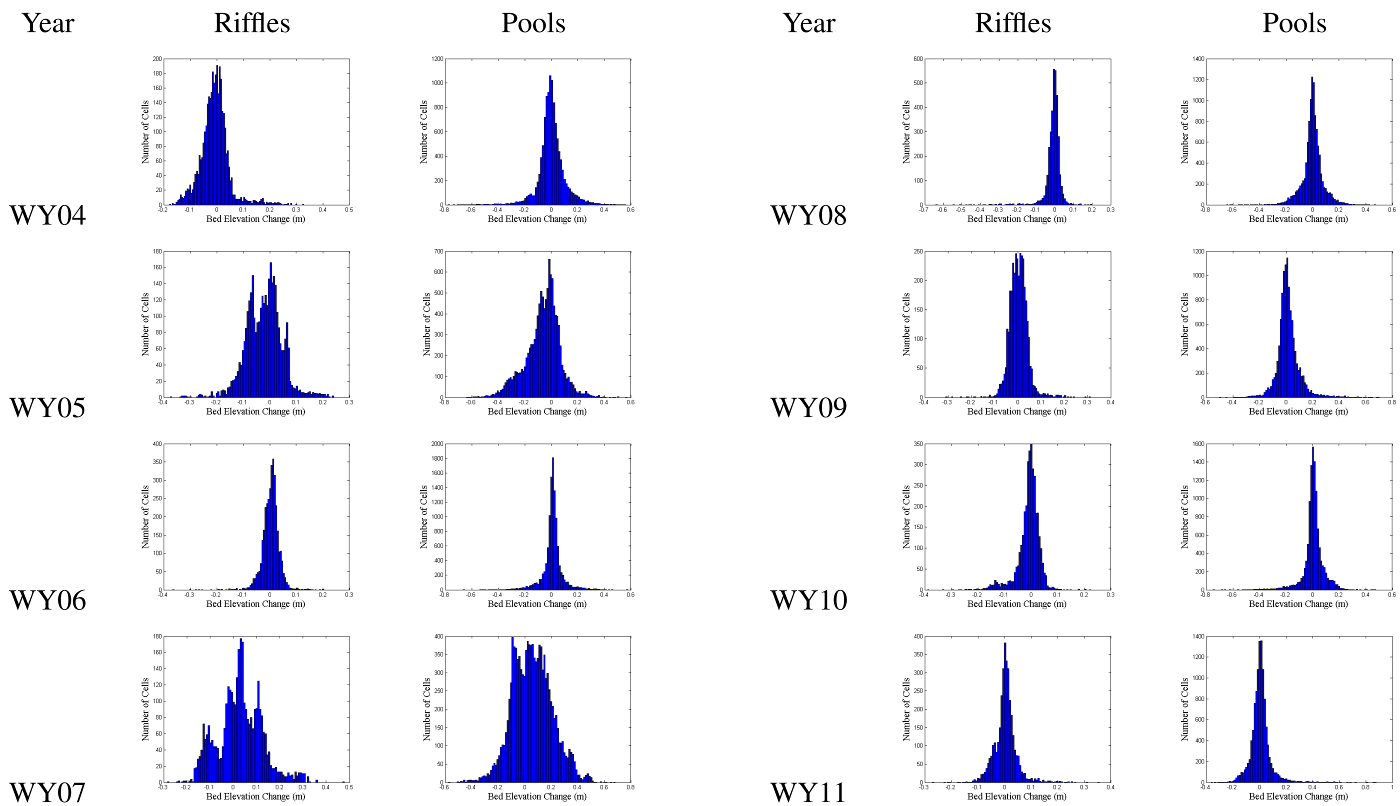


Figure A.3: Distribution of annual bed elevation changes in the riffles and pools within the riffle pool 2 sub-reach of East Creek from WY04 to WY11

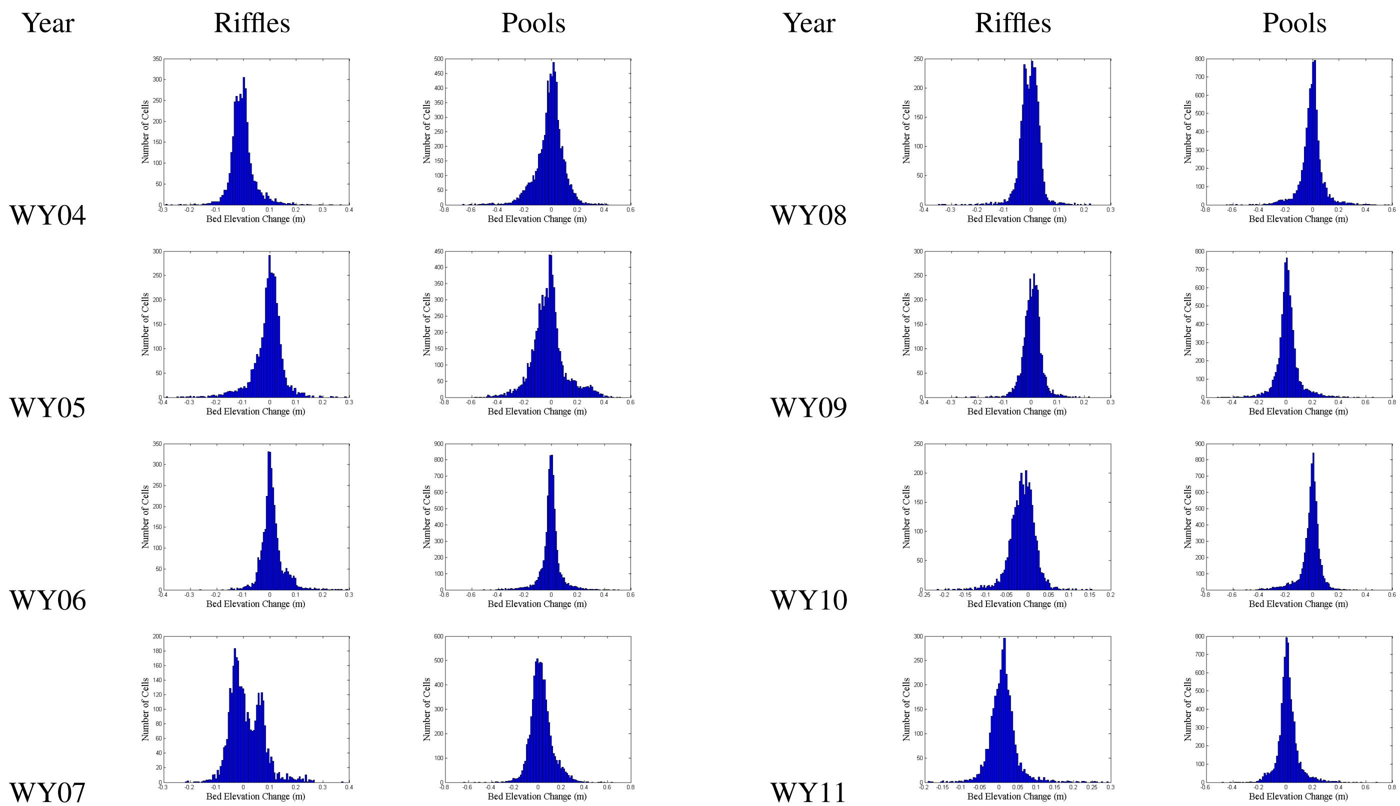


Figure A.4: Distribution of annual bed elevation changes in the riffles and pools within the riffle pool 3 sub-reach of East Creek from WY04 toWY11

A.2 Summary Statistics

Table A.1: Summary statistics for bed elevation change in riffles in rapids reach

Year	Mean (*m*)	Median (*m*)	Variance (*m*^{2})	Skew	Kurtosis
WY04	0.02	0.00	0.01	1.93	8.92
WY05	-0.04	0.00	0.02	-2.96	10.96
WY06	0.00	-0.01	0.01	**3.66**	24.04
WY07	-0.01	0.00	0.01	-1.20	8.11
WY08	-0.01	0.00	0.01	-2.26	17.72
WY09	0.00	-0.01	0.01	0.74	4.91
WY10	0.01	0.02	0.01	-0.27	4.00
WY11	0.00	0.00	0.01	-0.46	9.51
Average	**0.00**	**0.00**	**0.01**	**-0.10**	**11.02**

Table A.2: Summary statistics for bed elevation change in riffles in riffle pool 1 sub-reach

Year	Mean (*m*)	Median (*m*)	Variance (*m*^{2})	Skew	Kurtosis
WY04	0.01	0.00	0.01	2.12	11.26
WY05	0.00	0.01	0.01	-1.63	6.22
WY06	-0.03	-0.02	0.00	-0.73	10.94
WY07	0.00	-0.01	0.01	2.64	19.63
WY08	-0.01	-0.01	0.00	0.02	12.21
WY09	-0.01	0.00	0.01	-0.89	9.96
WY10	0.01	0.01	0.00	1.21	20.61
WY11	0.01	0.00	0.00	0.19	9.53
Average	**0.00**	**0.00**	**0.01**	**0.37**	**12.55**

Table A.3: Summary statistics for bed elevation change in riffles in riffle pool 2 sub-reach

Year	Mean (m)	Median (m)	Variance (m^2)	Skew	Kurtosis
WY04	-0.01	-0.01	0.00	1.04	4.43
WY05	-0.02	-0.02	0.00	-0.15	1.77
WY06	0.00	0.01	0.00	-1.28	13.58
WY07	0.03	0.03	0.01	0.27	**0.37**
WY08	-0.01	0.00	0.00	**-4.76**	**40.25**
WY09	0.00	0.00	0.00	0.49	7.18
WY10	-0.01	0.00	0.00	-1.68	7.38
WY11	0.00	0.00	0.00	0.90	7.15
Average	**0.00**	**0.00**	**0.00**	**-0.64**	**10.26**

Table A.4: Summary statistics for bed elevation change in pools in rapids reach

Year	Mean (m)	Median (m)	Variance (m^2)	Skew	Kurtosis
WY04	0.03	0.02	0.00	0.49	1.66
WY05	-0.03	-0.03	0.00	0.79	5.27
WY06	0.01	0.01	0.00	-0.83	5.10
WY07	-0.01	-0.02	0.00	1.08	2.34
WY08	0.01	0.01	0.00	0.31	6.26
WY09	0.00	-0.01	0.00	0.75	5.39
WY10	0.03	0.03	0.00	-1.47	7.43
WY11	-0.01	-0.01	0.00	0.68	5.74
Average	**0.00**	**0.00**	**0.00**	**0.23**	**4.90**

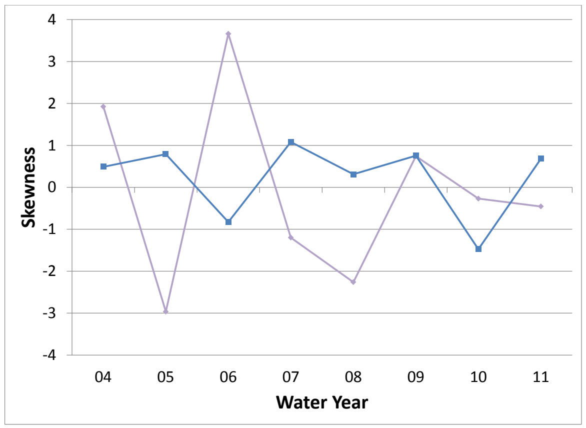
Table A.5: Summary statistics for bed elevation change in pools in riffle pool 1 sub-reach

Year	Mean (m)	Median (m)	Variance (m^2)	Skew	Kurtosis
WY04	0.01	0.00	0.01	-0.04	7.45
WY05	-0.05	-0.03	0.02	-1.15	5.14
WY06	0.00	0.00	0.01	-0.09	5.98
WY07	0.00	-0.01	0.01	0.49	3.12
WY08	0.00	0.01	0.01	-0.77	5.94
WY09	0.00	0.01	0.01	-0.97	11.88
WY10	0.01	0.01	0.01	-0.31	10.41
WY11	0.02	0.00	0.01	2.25	10.30
Average	**0.00**	**0.00**	**0.01**	**-0.07**	**7.53**

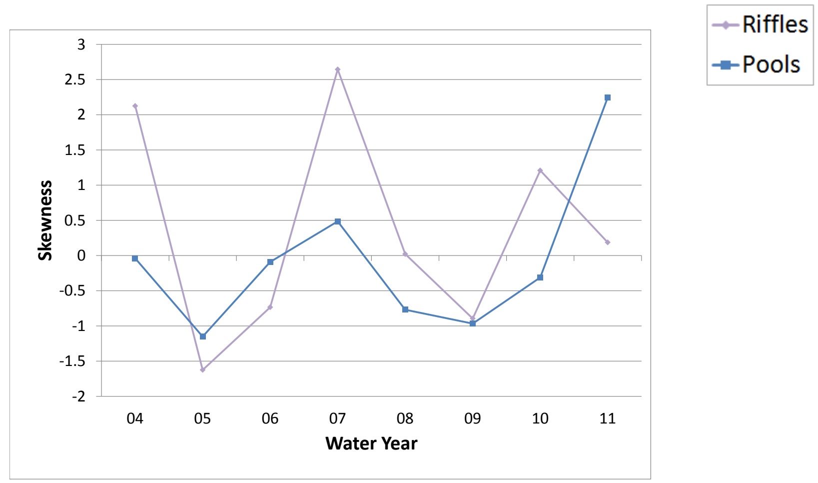
Table A.6: Summary statistics for bed elevation change in pools in riffle pool 2 sub-reach

Year	Mean (m)	Median (m)	Variance (m^2)	Skew	Kurtosis
WY04	0.00	0.00	0.01	-0.52	6.64
WY05	-0.06	-0.05	0.02	-0.41	1.12
WY06	0.01	0.01	0.01	-0.28	7.08
WY07	0.06	0.05	0.02	0.12	0.23
WY08	0.00	0.00	0.01	-0.44	5.03
WY09	0.02	0.01	0.01	1.27	7.68
WY10	0.00	0.01	0.01	-1.46	9.10
WY11	0.01	0.01	0.01	2.06	14.14
Average	**0.00**	**0.00**	**0.01**	**0.04**	**6.38**

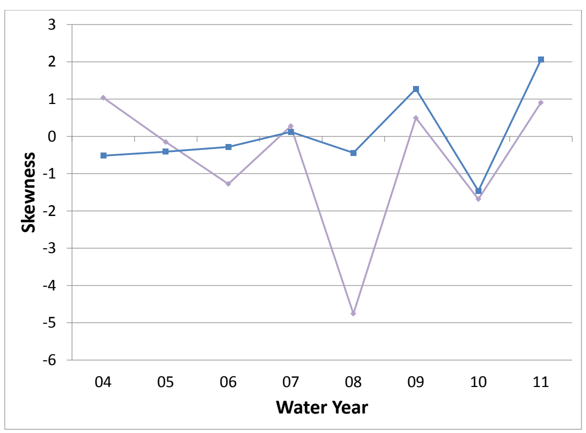
A.3 Skew



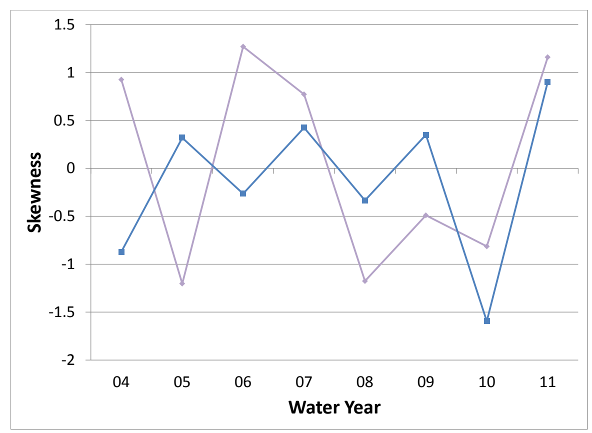
(a) Rapids



(b) Riffle Pool 1



(c) Riffle Pool 2



(d) Riffle Pool 3

Figure A.5: Skew in bed elevation over time in the riffle units (purple line) and the pool units (blue line) in the rapids, riffle pool 1, riffle pool 2, and riffle pool 3 sub-reaches of East Creek

Appendix B

Supporting Results: Erosion and Deposition

Appendix B contains supporting figures and tables detailing erosion and deposition patterns in riffles and pools in East Creek from WY04-11. Appendix B includes histograms (Figures B.1 - B.4) and summary statistics (Tables B.1 - B.12).

B.1 Histograms

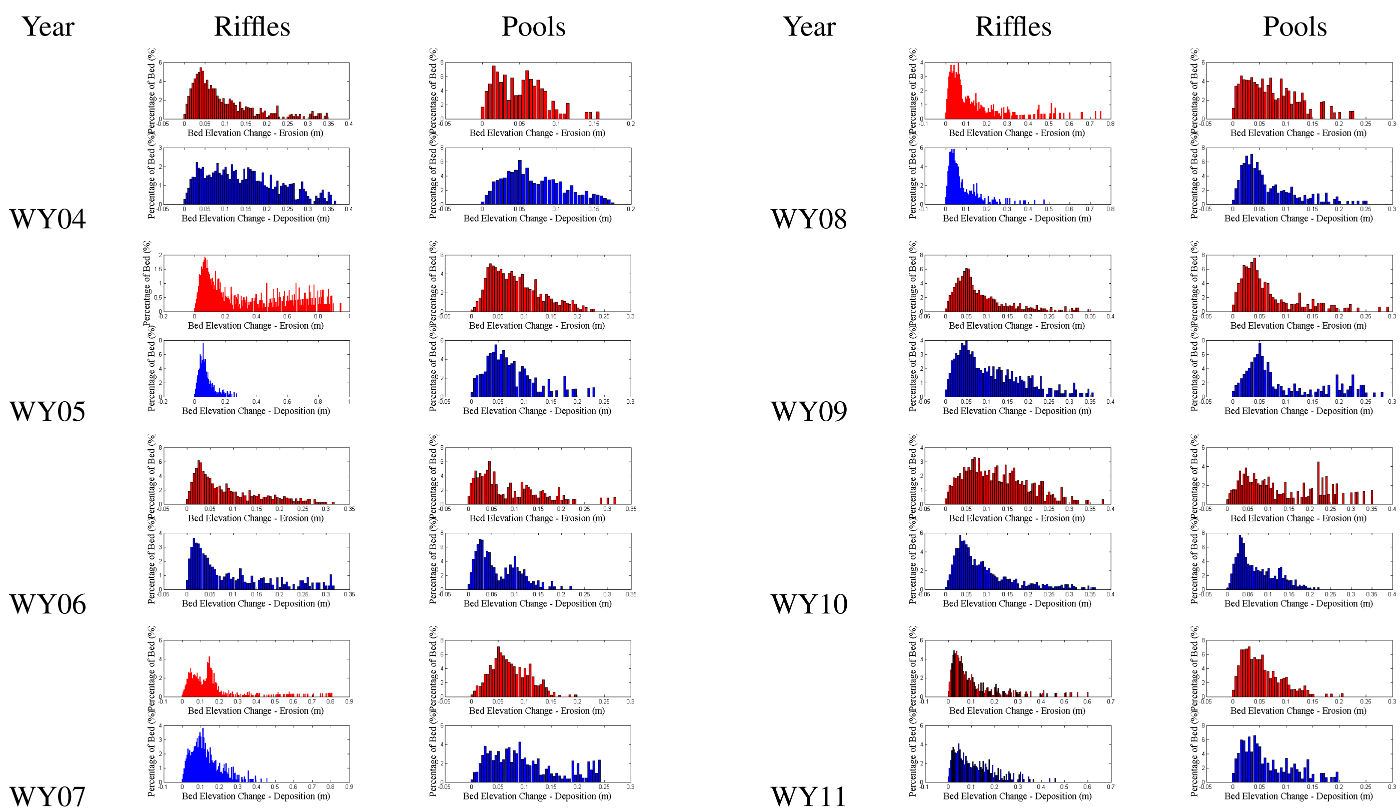


Figure B.1: Distribution of annual bed erosion and deposition in the riffles and pools in the rapids reach of East Creek from WY04 to WY11

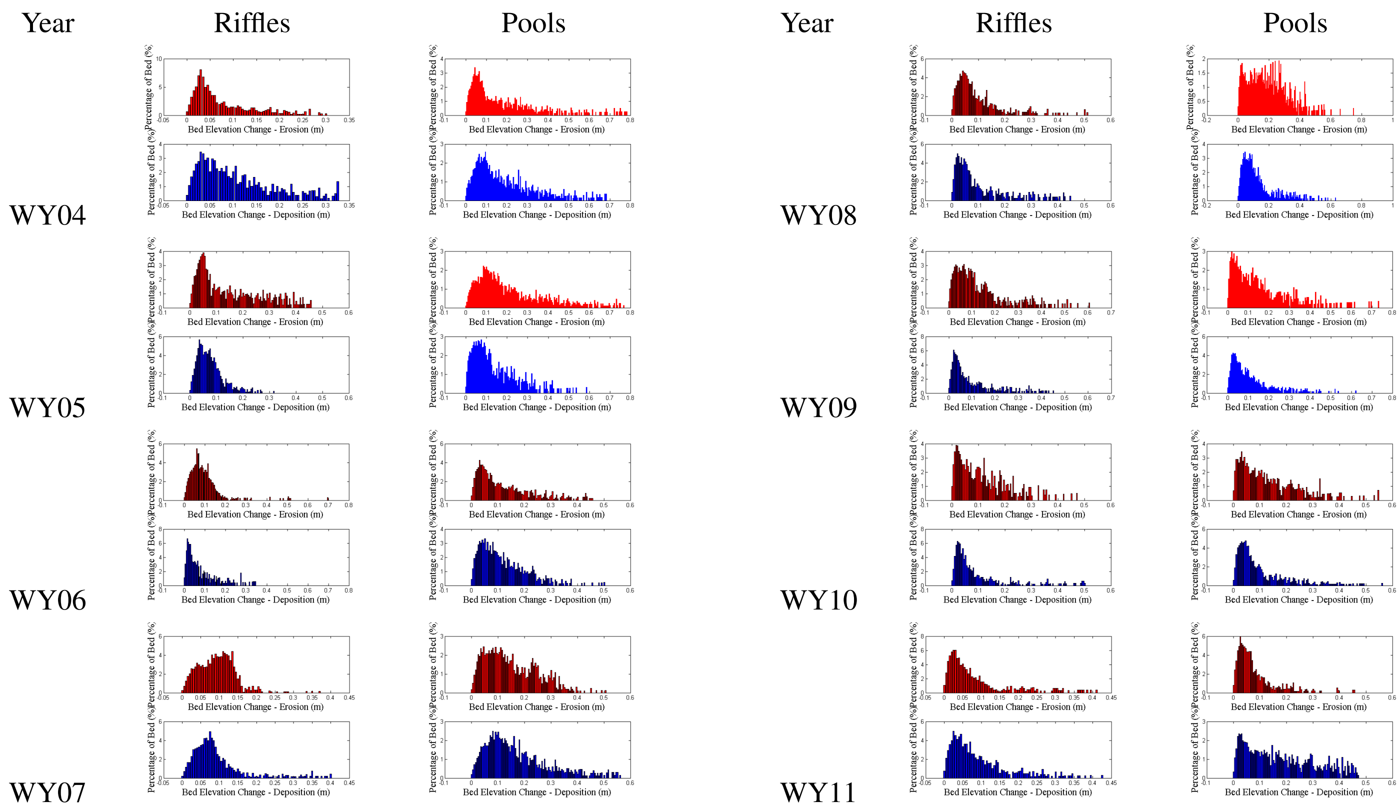


Figure B.2: Distribution of annual bed erosion and deposition in the riffles and pools within the riffle pool 1 sub-reach of East Creek from WY04 to WY11

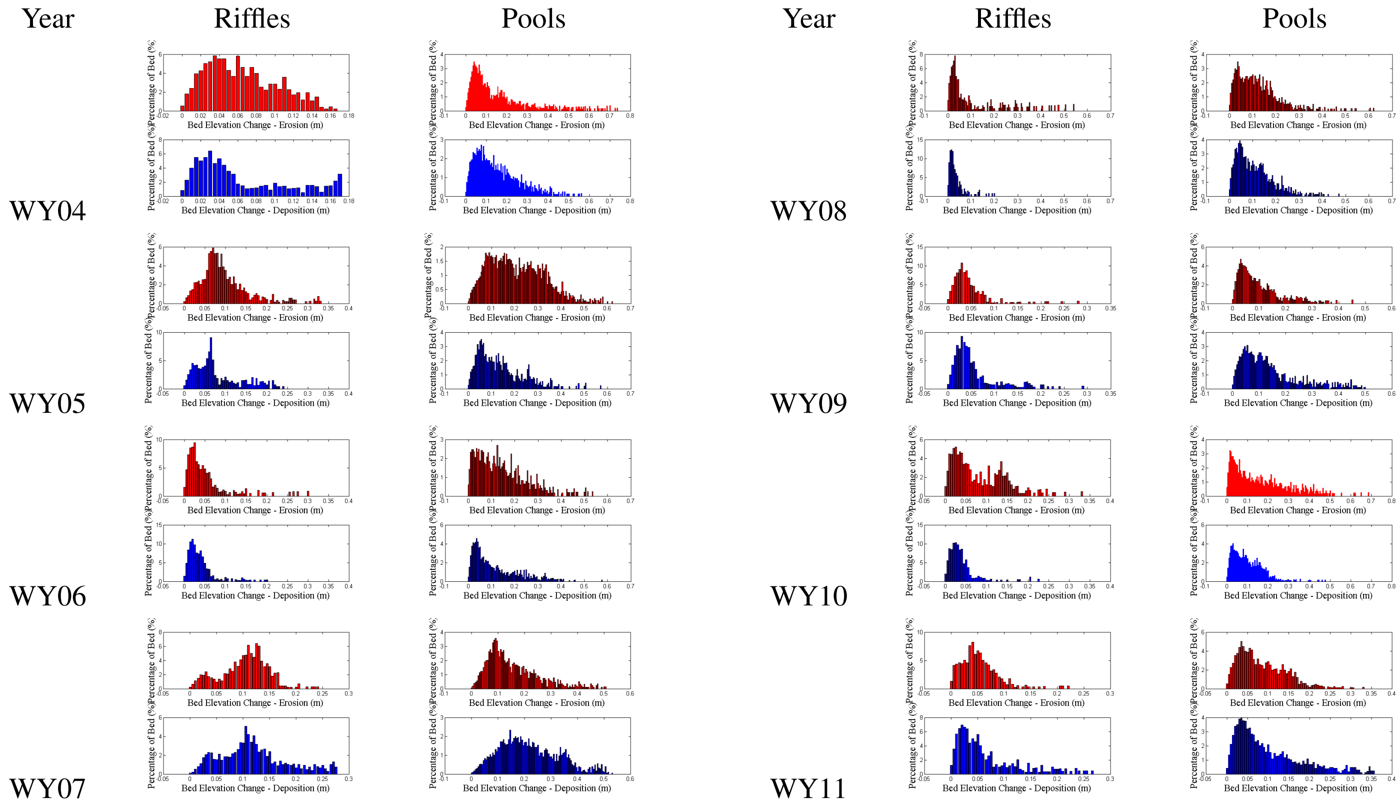


Figure B.3: Distribution of annual bed erosion and deposition in the riffles and pools within the riffle pool 2 sub-reach of East Creek from WY04 to WY11

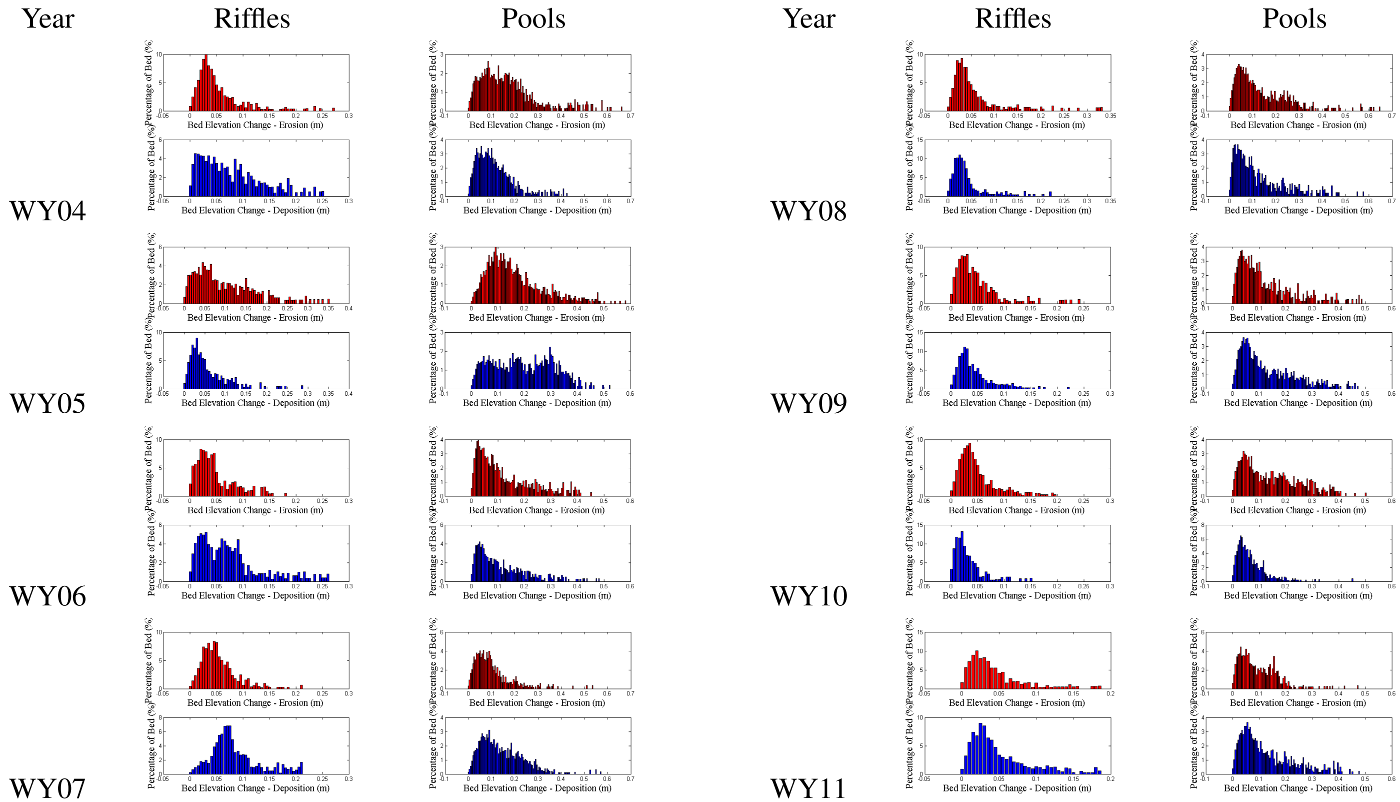


Figure B.4: Distribution of annual bed erosion and deposition in the riffles and pools within the riffle pool 3 sub-reach of East Creek from WY04 to WY11

B.2 Summary Statistics

Table B.1: Summary statistics for erosion in riffles in the rapids reach

Year	Mean (m)	Median (m)	Variance (m^2)	Skew	Kurtosis
WY04	-0.04	-0.03	0.00	-2.70	9.97
WY05	-0.12	-0.06	0.03	-2.64	6.84
WY06	-0.04	-0.03	0.00	-2.63	8.20
WY07	-0.08	-0.05	0.01	-3.71	20.98
WY08	-0.05	-0.03	0.01	-4.14	23.32
WY09	-0.04	-0.03	0.00	-2.51	9.39
WY10	-0.07	-0.05	0.00	-1.46	2.10
WY11	-0.04	-0.03	0.00	-4.12	24.93
Average	**-0.06**	**-0.04**	**0.01**	**-2.99**	**13.21**

Table B.2: Summary statistics for erosion in riffles in riffle pool 1 sub-reach

Year	Mean (m)	Median (m)	Variance (m^2)	Skew	Kurtosis
WY04	-0.04	-0.03	0.00	-2.81	10.25
WY05	-0.06	-0.04	0.01	-2.57	7.15
WY06	-0.05	-0.04	0.00	-3.15	25.18
WY07	-0.06	-0.05	0.00	-1.07	2.15
WY08	-0.04	-0.03	0.00	-3.48	18.87
WY09	-0.05	-0.03	0.00	-3.07	13.16
WY10	-0.04	-0.02	0.00	-2.88	10.83
WY11	-0.03	-0.02	0.00	-3.99	22.35
Average	**-0.05**	**-0.03**	**0.00**	**-2.88**	**13.75**

Table B.3: Summary statistics for erosion in riffles in riffle pool 3 sub-reach

Year	Mean (m)	Median (m)	Variance (m^2)	Skew	Kurtosis
WY04	-0.03	-0.02	0.00	-3.24	17.78
WY05	-0.04	-0.03	0.00	-2.31	6.93
WY06	-0.02	-0.02	0.00	-2.59	10.98
WY07	-0.04	-0.03	0.00	-1.66	5.25
WY08	-0.03	-0.02	0.00	-4.14	26.87
WY09	-0.02	-0.02	0.00	-3.41	19.92
WY10	-0.03	-0.02	0.00	-2.31	8.43
WY11	-0.02	-0.02	0.00	-2.83	12.14
Average	**-0.03**	**-0.02**	**0.00**	**-2.81**	**13.54**

Table B.4: Summary statistics for deposition in riffles in the rapids reach

Year	Mean (m)	Median (m)	Variance (m^2)	Skew	Kurtosis
WY04	0.08	0.04	0.01	2.68	9.74
WY05	0.05	0.04	0.00	1.91	5.44
WY06	0.05	0.02	0.01	4.06	17.86
WY07	0.07	0.05	0.00	1.61	3.37
WY08	0.04	0.03	0.00	3.46	18.49
WY09	0.05	0.03	0.00	2.36	7.09
WY10	0.05	0.04	0.00	2.98	13.60
WY11	0.05	0.03	0.00	2.34	6.83
Average	**0.06**	**0.03**	**0.00**	**2.68**	**10.30**

Table B.5: Summary statistics for deposition in riffles in riffle pool 1 sub-reach

Year	Mean (m)	Median (m)	Variance (m^2)	Skew	Kurtosis
WY04	0.06	0.03	0.01	3.17	12.68
WY05	0.05	0.04	0.00	1.75	4.69
WY06	0.03	0.02	0.00	3.36	14.83
WY07	0.06	0.05	0.01	5.38	36.95
WY08	0.04	0.02	0.00	3.88	20.12
WY09	0.04	0.02	0.00	3.63	17.08
WY10	0.04	0.02	0.00	5.78	46.25
WY11	0.04	0.03	0.00	2.89	11.68
Average	**0.04**	**0.03**	**0.00**	**3.73**	**20.53**

Table B.6: Summary statistics for deposition in riffles in riffle pool 3 sub-reach

Year	Mean (m)	Median (m)	Variance (m^2)	Skew	Kurtosis
WY04	0.03	0.02	0.00	2.73	10.63
WY05	0.03	0.02	0.00	2.69	11.59
WY06	0.03	0.02	0.00	2.64	9.44
WY07	0.06	0.06	0.00	1.67	4.15
WY08	0.02	0.02	0.00	3.35	17.85
WY09	0.03	0.02	0.00	2.38	9.11
WY10	0.02	0.01	0.00	2.75	12.43
WY11	0.03	0.02	0.00	3.40	16.46
Average	**0.03**	**0.02**	**0.00**	**2.70**	**11.46**

Table B.7: Summary statistics for erosion in pools in rapids reach

Year	Mean (m)	Median (m)	Variance (m^2)	Skew	Kurtosis
WY04	-0.03	-0.02	0.00	-1.70	3.48
WY05	-0.06	-0.04	0.00	-1.33	1.86
WY06	-0.04	-0.02	0.00	-2.54	8.02
WY07	-0.05	-0.05	0.00	-0.83	0.74
WY08	-0.03	-0.02	0.00	-2.17	6.03
WY09	-0.03	-0.02	0.00	-2.73	10.44
WY10	-0.06	-0.04	0.00	-1.96	3.81
WY11	-0.03	-0.02	0.00	-1.90	5.15
Average	**-0.04**	**-0.03**	**0.00**	**-1.89**	**4.94**

Table B.8: Summary statistics for erosion in pools in riffle pool 1 sub-reach

Year	Mean (m)	Median (m)	Variance (m^2)	Skew	Kurtosis
WY04	-0.07	-0.04	0.01	-3.48	16.14
WY05	-0.10	-0.07	0.01	-2.36	7.10
WY06	-0.05	-0.03	0.00	-2.84	10.28
WY07	-0.08	-0.05	0.01	-1.67	3.01
WY08	-0.08	-0.03	0.01	-2.05	5.38
WY09	-0.05	-0.03	0.01	-3.26	14.30
WY10	-0.05	-0.02	0.00	-2.86	10.81
WY11	-0.04	-0.02	0.00	-3.43	19.06
Average	**-0.06**	**-0.04**	**0.01**	**-2.75**	**10.76**

Table B.9: Summary statistics for erosion in pools in riffle pool 3 sub-reach

Year	**Mean** (*m*)	**Median** (*m*)	**Variance** (m^2)	**Skew**	**Kurtosis**
WY04	-0.08	-0.06	0.01	-2.15	6.72
WY05	-0.09	-0.07	0.01	-1.69	3.85
WY06	-0.05	-0.03	0.00	-2.84	9.87
WY07	-0.05	-0.04	0.00	-2.79	14.75
WY08	-0.06	-0.04	0.01	-2.84	11.94
WY09	-0.05	-0.03	0.00	-2.89	11.25
WY10	-0.06	-0.03	0.01	-2.23	5.59
WY11	-0.05	-0.03	0.00	-2.39	9.16
Average	**-0.06**	**-0.04**	**0.00**	**-2.48**	**9.14**

Table B.10: Summary statistics for deposition in pools in rapids reach

Year	**Mean** (*m*)	**Median** (*m*)	**Variance** (m^2)	**Skew**	**Kurtosis**
WY04	0.05	0.04	0.00	1.48	2.53
WY05	0.04	0.03	0.00	3.24	15.44
WY06	0.03	0.02	0.00	1.88	3.79
WY07	0.06	0.04	0.00	1.78	2.98
WY08	0.04	0.03	0.00	3.10	13.98
WY09	0.04	0.03	0.00	2.45	6.88
WY10	0.04	0.03	0.00	1.67	2.80
WY11	0.03	0.02	0.00	2.82	13.38
Average	**0.04**	**0.03**	**0.00**	**2.30**	**7.72**

Table B.11: Summary statistics for deposition in pools in riffle pool 1 sub-reach

Year	**Mean** (*m*)	**Median** (*m*)	**Variance** (m^2)	**Skew**	**Kurtosis**
WY04	0.08	0.05	0.01	2.44	7.66
WY05	0.06	0.04	0.01	2.47	8.01
WY06	0.05	0.03	0.00	2.44	8.80
WY07	0.09	0.06	0.01	2.18	6.68
WY08	0.06	0.04	0.00	2.95	12.14
WY09	0.05	0.03	0.00	3.45	18.42
WY10	0.04	0.03	0.00	3.59	18.25
WY11	0.07	0.03	0.01	2.69	9.08
Average	**0.06**	**0.04**	**0.01**	**2.78**	**11.13**

Table B.12: Summary statistics for deposition in pools in riffle pool 3 sub-reach

Year	**Mean** (*m*)	**Median** (*m*)	**Variance** (m^2)	**Skew**	**Kurtosis**
WY04	0.06	0.05	0.00	1.94	5.62
WY05	0.09	0.05	0.01	1.34	0.96
WY06	0.04	0.02	0.00	2.96	11.73
WY07	0.08	0.06	0.01	1.69	4.21
WY08	0.05	0.03	0.00	3.01	11.86
WY09	0.06	0.04	0.00	2.64	9.28
WY10	0.03	0.03	0.00	2.66	13.12
WY11	0.06	0.04	0.00	2.66	9.83
Average	**0.06**	**0.04**	**0.00**	**2.36**	**8.33**