The effect of in-stream wood on channel morphology and sediment deposition in headwater streams of the Oldman River Basin, Alberta

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Headwater streams provide diverse habitat for aquatic organisms, drinking water for downstream communities and abundant recreational activities. The addition of in-stream wood to headwater channels can influence the hydrology, morphology and ecology of the system. The recruitment of wood to the channel and the export mechanisms determine the wood load and structure types formed in-stream, thus altering the channel's morphological response. This research examined the effects of in stream wood on channel morphology in two headwater streams along the eastern slopes of the Canadian Rocky Mountains; Lyons East (LE) and Corolla Creek (CC). Lyons East has natural and anthropogenic disturbance (burned and salvage-logged) in the watershed, while Corolla Creek has anthropogenic (grazing and recreation) disturbances in the watershed. An assessment of the longitudinal spatial distribution and a reach-scale geomorphic classification were conducted to investigate the impacts of in-stream wood on channel morphology, pool formation and sediment storage. The spatial distribution of in-stream wood was 1.49 sites/100m for both watersheds, results that are comparable to previously conducted studies in similar geographic watersheds. The types of structures found in both watersheds were predominately jam formations (LE - 43%, CC - 47%), which is consistent with the wood loading and spatial distribution conceptual model previously developed by Whol and Jaeger (2009) for in-stream wood accumulations in mountain streams.

At the reach-scale level of analysis, in-stream wood was found to impact channel morphology and pool forming processes. The addition of wood to the stream caused half of the studied reaches to have forced pool-riffle morphology. For all six selected study reaches, there was a decrease in expected pool spacing and an increase in the diversity of pool types. The relationship between wood-affected pools and sediment storage was examined and the results show that more sediment was stored in the burned/salvage logged reaches. Cohesive sediment was stored only in pools influenced by wood structures for half of the studied reaches. V* was generally higher in wood-affected pools for five of the six study reaches. The weighted average (V^*_w), which provides information regarding the storage of cohesive at the reach scale, was greater in Lyons East than in Corolla Creek. The presence of both exposed bedrock in the channel as well as the amount of vegetation are possible reasons for the smaller amounts of sediment observed in Corolla Creek. The observations from this reach scale investigation led to the development of a conceptual model, which can be used to predict the location of cohesive sediment storage in headwater streams of the Oldman River Basin. This

model highlights the relationship between simultaneous recruitment of in-stream wood and sediment from local sources as a mechanism for protecting and storing cohesive sediment deposits.

This research examined channel responses to in-stream wood within the context of land-use planning and Alberta's *Water for Life Strategy*. There was evidence of lateral channel migration in the floodplain of both watersheds. At some sites, the channel shifted up to 30 metres while in other sections of the watershed, the channel was confined within a narrow valley. Accordingly, it is recommended that the current salvage logging guidelines be changed to include a flexible riparian buffer that would more appropriately reflect the diversity in riparian widths throughout the watersheds. In addition the best management practice is to allow natural in-stream wood processes to evolve and not to remove in-stream wood from the channel. The in-stream wood provides diverse aquatic habitat and the cycle of wood being recruited and being in the stream is part of the natural ecosystem in forested environments.

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Dedication

I would like to dedicate this thesis to my Grandmothers, who taught me to follow my passion and explore the world around me.

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List of Variables and Abbreviations

List of variables used in the project

D_{AC}	Mean active channel depth
D_{BF}	Bankfull depth
D_{Thal}	Thalweg depth
ER	Entrenchment ratio
P_{AC}	Wetted perimeter of the active channel
R_h	Hydraulic Radius
V*	fraction of residual-pool volume occupied by fine sediment (during period of low streamflow)
V^*_W	reach-mean fraction of residual-pool volume occupied by fine sediment (during period of low streamflow)
W:D	Width:depth ratio
W_{AC}	Active channel width
W_{BF}	Bankfull width
W_{FP}	Floodprone width

List of abbreviations used in the thesis

Avg.	Average
CC	Corolla Creek
CC#	Corolla Creek at a particular site
DEM	Digital Elevation Model
DS	Downstream
GIS	Geographic Information Systems
LE	Lyons East
LE#	Lyons East at a particular site
n	Number of observations
St. Dev	Standard deviation
US	Upstream

Chapter 1
Introduction

1.1 Problem statement

Approximately 60% to 80% of the total stream length within a forested southern Rockies catchment is located in the headwaters (Bladon et al., 2008). This large proportion of stream length generates the majority of stream flow to downstream reaches, directly connecting the upstream and riparian landscape to downstream communities (Bladon et al., 2008). Forests are an important ecosystem and over one-fourth of the world's forests grow in cool-to-cold temperate zones (Frelich, 2002). Western North American forests are critical for biodiversity, ecological integrity and economic development (Hauer et al., 2007). These forested stream networks provide drinking water to more than 180 million people within local and downstream communities (Furniss et al., 2010). This interconnection of stream networks means a disturbance that impacts the headwater system, can affect downstream water quantity and quality (Fetherston et al., 1995, Gurnell et al., 1995, Whol & Jaeger, 2009, Vannote et al., 1980).

Landscape disturbances originate from either natural or anthropogenic sources. Natural sources in forested watersheds include debris flows, flooding, avalanches, drought, sedimentation, windthrow and fire (Fetherston et al., 1995). Over the past millennia, fires have been one of the most important disturbance types in western forests (Agee, 1998; Hessburg & Agee, 2003). Fire regimes shape the structure and composition of cool-to-cold forest mosaics (Flannigan et al., 2000; Frelich, 2002). Recent studies conclude that climate change and past management efforts have transformed forest structure and composition, thus promoting fire behaviour beyond the natural range of variability (Bergeron & Flannigan, 1995; Reeves et al., 2006). Due to the consequences of wildfire on the abiotic and biotic environment, interest in the effects of fires on forested catchments has dramatically increased (Ice et al., 2004; Robinson et al., 2005).

The increased sensitivity of forests post-fire can be further impacted by anthropogenic influences, for example salvage logging. The two main effects of these harvest operations are (1) those related to the practice of logging (e.g. machinery) and (2) structural effects from removing material (McIver & Starr, 2000). Post-fire soils are vulnerable and research has shown salvage logging generally leads to increased erosion, sediment transport to streams and the removal of trees that serve an ecological function within the natural ecosystem (McIver & Ottmar, 2007). Generally salvage logging compacts and damages the soils, increasing erosion and runoff rates (Karr et al., 2004). The resulting change in runoff rates and magnitudes can impact river hydrology by increasing the frequency and magnitude of critical discharges that increase sediment and water yields (Karr et al., 2004).

Anthropogenic impacts can occur independently of natural disturbances and include land-use changes such as roads, trails and recreational activities. The impact of anthropogenic activities can be minimal, such as with tent camping, fishing and hiking, or it can be much higher, such as with RV camping and all-terrain vehicle (ATV) use. Other activities including domestic animal grazing, logging, oil and gas exploration and mining can cause landscape disturbances in forest ecosystems (Beschta & Platts, 1986). Research has concluded that a century of anthropogenic influences within forested environments has led to the degradation of watersheds, modified stream flows and water quality, altered ecosystem processes and decreased biodiversity (Beschta et al., 2004).

Landscape disturbances alter natural processes within physical and biotic environments, particularly in rivers (Beschta & Platts, 1986). When a disturbance affects the riparian area, it can cause a cascade effect of change. Headwater streams typically experience a more direct impact and geomorphic response to disturbances (Nakamura & Inahara, 2007; Nakamura et al., 2007; Nakamura et al., 2000). The connection between streams and adjacent terrestrial landscape and upper and lower reaches within the watershed, make it important for researchers to understand processes affecting the morphology and ecology of headwater streams, particularly following a disturbance.

In a forested environment, vegetation affects the hydrological cycle and impacts hillslope stability. Therefore, a landscape disturbance that removes vegetative cover can decrease infiltration and increase runoff rates, leading to soil erosion processes. This in turn accelerates hillslope failure (Shakesby & Doerr, 2006). Often, in disturbed areas, these changes in hydrology contribute to an increase in fine-grained sediment entering streams, as the smaller size particles (sand, silt and clay) are more easily eroded through overland flow processes (Malmon et al., 2007; Meyer & Wells, 1997). The changes to soil structure and associated slope stability subsequently influence geomorphic stream characteristics, such as sediment yields, streamflow, channel morphology and channel loading of in-stream wood (Brady & Weil, 2002; DeBano et al., 1998, Robichaud & Waldrop, 1994). The addition of in-stream wood deposits can further impact channel morphology and the sediment regime.

To help ensure that aquatic health is maintained in the headwater systems, it is important to understand how landscape disturbances shift stream morphology and ecology. Following a disturbance by wildfire the amount of wood recruited to the stream channel can be modified, thus impacting hydrology, channel morphology and aquatic ecology (Abbe & Montgomery, 2003; Hart, 2003; Seo et al., 2010). The study of in-stream wood is necessary to understand the retention and stability of these structures and their influence on stream morphology (Robinson et al., 2005). The accumulation of wood regulates stream flow and water quality, which enhances biological diversity and the range of aquatic habitat (Gurnell & Sweet, 1998).

One of the most important functions of in-stream wood is the formation of different types of pools that provide a greater diversity in aquatic habitat (Kreutzweiser et al., 2005). In-stream wood can decrease the spacing between and increase the width, depth and volume of pools (Montgomery et al., 1995). Dammed pools created by woody deposits provide more cover for aquatic life offering protection and regulating temperature (Hawkins et al., 1993). The change in the number and type of pools subsequently impacts stream hydraulics and the sediment regime, which alters stream diversity (Gurnell et al., 2002). These modifications to the stream channel can alter the sediment-water balance within the fluvial system.

The hydraulic characteristics of a stream impact transport and storage of sediment and organic material within the active channel and floodplain (Gurnell et al., 2002). The storage of sediment can change channel morphology, smother the riverbed, kill aquatic flora, clog pore space between substrate clasts and reduce habitat for benthic organisms, which can negatively impact aquatic food chains (Wood & Armitage, 1997). In particular, a rise in fine-grained sediment "increases turbidity, limits light penetration and potentially reduces primary productivity impacting the food chain" (Wood & Armitage, 1997, p.203). In order to make the necessary decisions to ensure a healthy ecosystem, planners and managers should better understand the consequences of increased cohesive sediment stored in headwater streams. This will allow for the more effective development and implementation of integrated watershed management plans.

A healthy ecosystem requires diverse habitat for aquatic organisms to survive within the stream throughout their lifespans. Morphological changes induced by in-stream wood increase channel diversity. Accordingly, these diverse pool types provide a variety of conditions necessary for the lifecycle of fish; shallow pools for younger years and larger pools for as they grow (Beschta & Platts, 1986). However, if a pool experiences infill of thick cohesive sediment, aquatic biodiversity could be hindered (Wood & Armitage, 1997; Zelt & Wohl, 2004). Since the headwater streams in the study area (Crowsnest Pass) have some of the best fishing in the province of Alberta, it is important for resource managers to understand these processes in order to protect the aquatic ecosystem health and ensure fish continue to thrive (Oldman Watershed Council, 2010).

This thesis examines the effect of in-stream wood deposits on channel morphology in two disturbed watersheds along the eastern slopes of the southwestern Alberta Rocky Mountains. In-stream wood deposits were characterized within the active channel and three representative sites were selected for detailed analysis in each of the two study catchments. The upstream and downstream channel reach morphology, in particular the formation of pools and associated cohesive sediment (< 63μm) deposits were quantified at each site. This information helps provide a better understanding of the dynamics and formational processes of in-stream wood deposits and their effect on channel morphology at the watershed scale and reach-scale. From a planning perspective, such information provides an understanding of the impact landscape disturbances have on the ecosystem structure and function, as it relates to recovery and downstream consequences.

1.2 Literature review

1.2.1 Introduction

This section will review literature related to spatial distribution of in-stream wood and its effect on channel morphology. It begins by defining and clarifying terminology used to describe in-stream wood. Then it will discuss conceptual models and the wood budget concept. The stability and arrangement of wood as it pertains to the formation of in-stream wood and the impact that disturbances have on in-stream wood processes are reviewed. Next, knowledge of the geomorphic impacts including pool formation and cohesive sediment storage and the management and planning implications are discussed in the context of the Alberta *Water for Life Strategy*. The literature review provides the context in which to interpret the results from the current study.

1.2.2 Inconsistencies in defining in-stream wood characteristics

The terminology and definitions for in-stream wood are inconsistent within the current published literature. This lack of consistency makes it difficult to compare research findings across studies (Baillie & Davies, 2002). The differences in terminology encompass the type and dimension characteristics of in-stream wood. Wohl et al. (2010) call for a standardization of terminology within in-stream wood research, allowing communication and comparisons to be made between researchers and studies.

The most common term to describe woody vegetation within the channel environment used in published literature is large woody debris (LWD); however woody debris (WD), coarse woody debris (CWD), large organic debris (LOD) and fine woody debris (FWD) are also used (see Table A-1 in Appendix A for references). Recently literature has begun to shift from the term "debris," which can have negative connotations, towards the term "in-stream" to describe wood at least partially lying within the bankfull channel (Wohl et al., In Press). For the purpose of this study the term "in-stream wood" will be used to be consistent with current trend in literature.

The type of woody vegetation included within the definition of in-stream wood varies between studies. Woody vegetation ranges from the broadest definition including snags, logs, pieces of wood, large branches and coarse roots (Webb & Erskine, 2003, 2005), to the narrowest inclusion of only isolated unbranched logs (Curran, 2010; Jones & Daniels, 2008; Bartlomiej et al., 2010). The type of vegetation included within a study is important to define as it allows for more accurate cross-study comparisons. The woody vegetation parameters are partially related to the research objectives, but can also be categorized by the size of in-stream wood included (and excluded) from a particular study.

The dimensions of in-stream wood are generally defined as a minimum diameter and length, with the most common dimensions being 10cm and 1m respectively (see Table A-1 in Appendix A for references). However these dimensions are not consistently defined in the literature as seen in Table A-1 in Appendix A. Within the literature reviewed, the diameter ranged from 2.5 to 60 centimetres. About half the papers reviewed define diameter as "equal to" or "equal to and greater than" 10cm. The length ranged from 0.25 to 5 m with 57% of the papers defining the length as either "equal to" or "equal to and greater than" 1m. Typically if research chose not to use the 10 cm diameter and 1 m length an explanation for the chosen dimension was provided. For example, in the work complete by Gomi et al. (2001) smaller wood dimensions were used due to their functionality within the smaller headwater streams. This example highlights the concern with using a single set of wood dimension parameters, as this may not be appropriate across stream sizes and may under- or over-estimate the amount of functional wood within the stream (Chen et al., 2006). The alternative is a scale-dependant method of defining wood (Abbe & Montgomery, 2003; Gurnell et al., 2002; Hassan et al., 2005).

Within a forested watershed, stream size is a controlling factor in the distribution of in-stream wood, because the influence wood has on a stream depends on the size of the wood piece (Hassan et al., 2005; Richmond & Fausch, 1995). The use of a scale dependant definition of in-stream wood would consider the dimensions of the wood compared to channel parameters; in particular the diameter and length to bankfull depth and width respectively (Abbe & Montgomery, 2003; Gurnell et al., 2002; Hassan et al., 2005). When wood pieces are shorter than the channel width, there is a decrease in their ability to stabilize along the bank or bed of the channel. The inability to anchor combined with the potentially higher stream power, provides a greater chance of mobility and transport of wood out of the stream reach (Gurnell et al., 2002; Richmond & Fausch, 1995). Defining in-stream wood as it relates to channel dimensions would allow for the comparison of functional wood abundance or volume across studies. However, the problem with this method is obtaining the accurate measurements of channel parameters as well as of in-stream wood. The relationship between stream size and wood abundance has been explored through frameworks and conceptual models, which are used to explain the change in wood distribution along the longitudinal profile.

1.2.3 Conceptual models for in-stream wood distribution

The spatial distribution of wood along the longitudinal stream profile can be highly variable. The patterns and amount of wood and its location reflect differences in the input, redistribution and output of in-stream wood (Swanson, 2003). Conceptual models have been developed to explain possible controls on wood arrangement and distribution along the longitudinal profile. The first model (Figure 1-1) uses the River Continuum Concept (Vannote et al., 1980) to explain both the recruitment and stability of in-stream wood along the river profile (Fetherston et al., 1995; Gurnell et al., 1995). This model has been supported by field studies, which found a higher stock of wood per unit area in headwater streams because of large input rates and limited transport capacity of these streams (Martin & Benda, 2001; Swanson, 2003). The conceptual model illustrated in Figure 1-2 was developed by Wohl and Jaeger (2009) and explains the distribution pattern of in-stream wood within the stream network, by considering the transport capacity of watershed and channel variables.

Both models show that smaller channels have a more abundant supply of in-stream wood with the frequency decreasing downstream. The River Continuum Concept (Figure 1-1) illustrates the in-stream wood structure relationship in terms of proximity to adjacent riparian zones and suggests that smaller pieces are more easily transported in larger channels, which results in a lower frequency of more complex structures in higher order channels (Fetherston et al., 1995; Keller & Swanson, 1979). The conceptual model in Figure 1-2 shows that upper headwater streams are transport limited; there is a transition zone of maximum wood distribution in intermediate reaches;

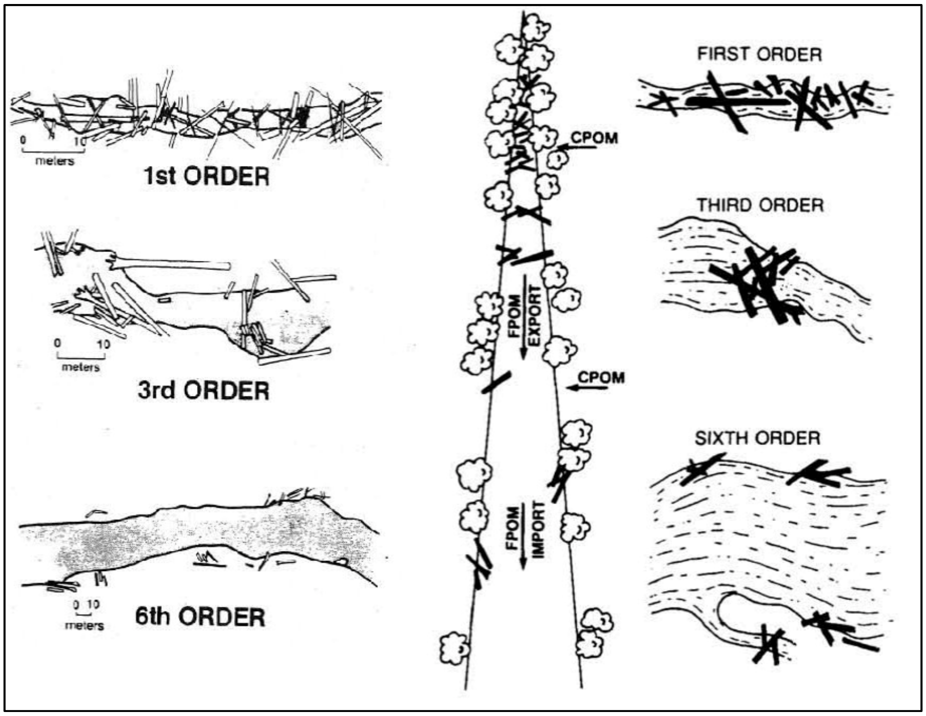


Figure 1-1: The downstream changes in distribution and abundance of in-stream wood and movement of organic matter (Fetherston et al., 1995; Gurnell et al., 1995)

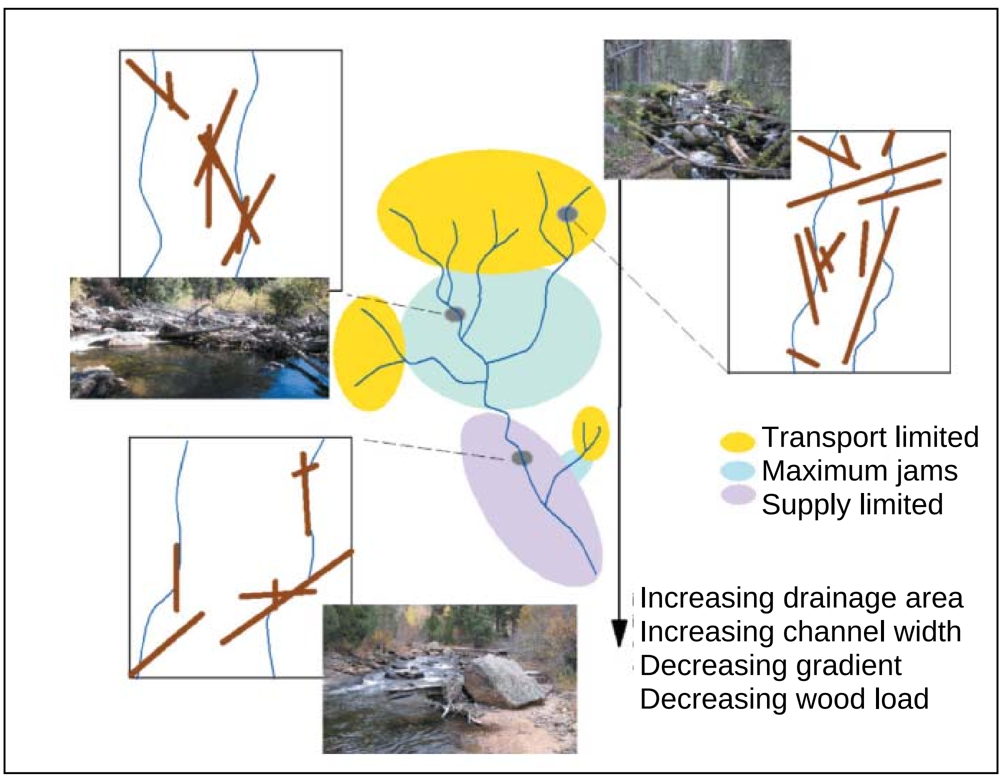


Figure 1-2: Conceptual model of wood load and spatial distribution for Colorado Front Range streams (Wohl & Jaeger, 2009)

and downstream reaches have a limited supply of wood (Wohl & Jaeger, 2009). This distribution has been observed in the Colorado Front Range (Wohl & Jaeger, 2009), the Pacific Northwest (Abbe & Montgomery, 2003; Montgomery & Buffington, 1997) and Montana (Marcus et al., 2002). Although the longitudinal distribution of in-stream wood within forested systems is an important process, little research has been conducted along the length of the river profile (Wohl & Jaeger, 2009). The current study is designed to provide information on the longitudinal distribution of in-stream wood within the forested headwater system of the eastern slopes of the southwestern Alberta Rocky Mountains.

1.2.4 Wood budget

When completing a study on the spatial distribution of in-stream wood, it is important to acknowledge the input and output processes involved. These processes control the wood budget, which are important in understanding the geomorphologic and ecological role of in-stream wood. Since in-stream wood influences morphology and ecology, it has been suggested that a wood regime similar to the sediment and discharge regimes be used to explain the morphology and dynamics of a river system (Benda, 2003; Faustini & Jones, 2003). This concept led to the creation of the wood budget framework, which explains the processes, controls, storage dynamics and material fluxes of wood. The dynamics of in-stream wood can be explained by five processes: recruitment, transport, decay/fragmentation, export and storage (Fremier et al., 2010). These processes determine the characteristics and distribution of in-stream wood (Benda & Sias, 2003).

The wood budget concept is presented in equation form to explain the changes in wood storage over the length of a channel during a set period of time. The volumetric mass balance equation is

$$\Delta S_c = [L_i - L_o + Q_i/\Delta x - Q_o/\Delta x - D]\Delta t \qquad (1)$$

where ΔS_c is the change in storage within a reach of length Δx over the time interval Δt. The budget accounts for input from lateral recruitment (L_i) and fluvial transport (Q_i) as well as loss from overbank deposition (L_o), fluvial transport out of the segment (Q_o) and decay (D) (Benda & Sias, 2003). The lateral wood recruitment represents numerous types of supply, including chronic forest mortality, toppling trees, bank erosion, landslides and exhumation of buried wood (Benda & Sias, 2003). This concept has been explored by a number of researchers (see Benda et al., 2002; Cadol et al., 2009; Martin & Benda, 2001; Warren & Kraft, 2008; Wohl et al., In Press). The dynamics of the input and output processes serve as a control mechanism in the formation of in-stream wood structures and their stability.

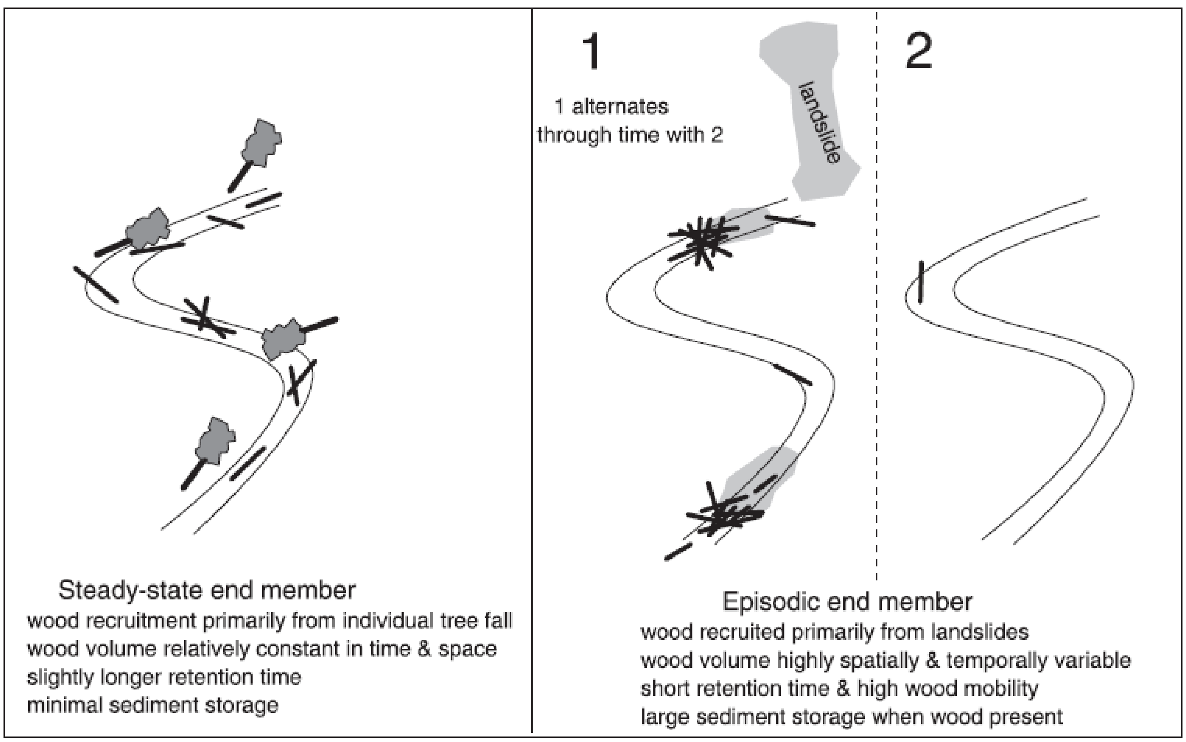
The pattern and form of in-stream wood is controlled through the recruitment process of wood from the adjacent riparian stands (Gregory et al., 1993; Mao et al., 2008). Two dominant recruitment mechanisms contribute wood to streams; chronic and episodic. Chronic mechanisms are the regular introduction of wood through tree mortality and gradual bank undercutting processes (Fetherston et al., 1995; Gurnell et al., 2002; Nakamura & Swanson, 1993; Webb & Erskine, 2003). Episodic wood recruitment results from catastrophic events such as floods, mass wasting (landslides and debris flows), fires, insect outbreaks, ice storms and windthrows. Episodic events cause a punctuated delivery of wood to occur (Chen et al., 2005; Fetherston et al., 1995; Webb & Erskine, 2003). The recruitment process also determines the position and orientation of in-stream wood, which can impact the stability and retention of wood in the system.

After wood is recruited to the channel, it is either exported out of the channel reach or it becomes stable. The export of in-stream wood occurs through both physical and biological mechanisms, such as decay, abrasion and fragmentation (Manners & Doyle, 2008). Biological processes involved in the rate of decay include invertebrate consumption and microbial decay (Harmon et al., 1986). In addition big geographic control factors such as climate, tree species, wood size and position along with the site conditions of temperature, moisture and oxygen levels, control decay (Harmon et al., 1986).

1.2.5 In-stream wood stability

The wood loading equation is used to quantify the amount of wood recruited and exported from a channel segment. For in-stream wood to become stable, it must remain stored within the channel. Pieces not stored will be transported downstream where they are either exported out of the system or become trapped as fluvial input in other complex structures.

The stability of in-stream wood is influenced by a balance between the physical characteristics of the valley, channel and wood. Valley form has been found to explain more variability of wood loading than channel characteristics, as the availability and stability of wood is determined by hillslope processes (Comiti et al., 2008; Nowakowski & Wohl, 2008). Wohl et al. (In Press) used the wood budget concept to explain the significance of variables and their influence on the distribution of in-stream wood (Figure 1-3). The steady-state end-member has a gradual but steady recruitment of individual trees, which generally produces individual logs or small jams (Wohl et al., In Press). In contrast, episodic bulk recruitment events such as blowdown or landslides create non-uniform wood storage, typically in the form of jams which store sediment (Wohl et al., In Press). Episodic structures tend to form at sites with reduced velocity. Therefore, steady-state end members are typically more stable as in-stream wood and remain in the channel longer than episodic structures (May & Gresswell, 2003b; Wohl et al., In Press; Wohl & Goode, 2008). The concepts of steady versus episodic recruitment are important to understand when examining the formation of jams and the associated impacts of in-stream wood on channel morphology and sediment storage.



$\Delta S_c = [L_i - L_o + Q_i/\Delta x - Q_o/\Delta x - D]\Delta t$ $\quad$ $\mathbf{\Delta S_c} = [\mathbf{L_i} - L_o + \mathbf{Q_i}/\Delta x - \mathbf{Q_o}/\Delta x - D]\Delta t$

Figure 1-3: Schematic illustration of the two end-member model of wood dynamics. The size of symbols for variables from equation 1 represents their relative importance in the respective end-members. The grey shaded area represents sediment storage (Wohl et al., In Press)

Channel characteristics such as stream order, stream dimensions, channel type, bed substrate type, gradient, sinuosity and flow rate influence the storage volume of in-stream wood (Bragg, 2000; Young et al., 2006). In addition, the magnitude, frequency an duration of hydraulic forces also impacts the storage of in-stream wood (Cadol et al., 2009). Both channel characteristics and hydraulic controls are typically determined by channel size and gradient. As illustrated in Figures 1-1 and 1-2, stream size tends to be the key factor in the storage of in-stream wood (Keller & Swanson, 1979; Mao et al., 2008; Richmond & Fausch, 1995).

The storage of in-stream wood depends on wood pieces and structures that remain stable over time. Wood characteristics that provide stability include: abundance, piece size, length of piece submerged in the water column, orientation, degree buried and ability to become anchored (Baillie & Davies, 2002; Bisson et al., 1987; Harmon et al., 1986). Stable wood pieces tend to be longer with a larger diameter (Berg et al., 1998; Gurnell & Petts, 2002; Wohl & Goode, 2008; Young, 1994), oriented parallel to the flow, (Braudrick & Grant, 2001), anchored with a rootwad in the bed or the banks (Abbe & Montgomery, 1996; Iroume et al., 2010) or buried at least partially within the substrate (Berg et al., 1998) or jam structure (Gurnell et al., 2002; Wohl & Goode, 2008). In particular, the ratio of wood piece length to bankfull width and the ratio of wood piece diameter to bankfull depth both appear to influence the storage of in-stream wood and its ability to form more complex jam and dam structures (Abbe & Montgomery, 2003; Iroume et al., 2010; Martin & Benda, 2001).

1.2.5.1 In-stream wood arrangement

The location and wood loading (input and export) processes create an arrangement of wood within the stream network. These processes determine the architecture of wood accumulations in terms of position, orientation, decay rate and degree of contact among pieces (Abbe & Montgomery, 1996; Abbe & Montgomery, 2003; Swanson, 2003). The characteristics of in-stream wood generally determine the retention and stability of the structures and their associated impacts on channel morphology (Chen et al., 2006; Jones & Daniels, 2008). The function of in-stream wood on the channel is determined by the characteristics of wood and its composition as either free wood or jammed.

The position of in-stream wood can be reported by describing (1) the vertical distribution and (2) the location of wood within the stream. The vertical classification is typically defined by four zones, two within the bankfull channel and two outside the channel surface (Robison & Beschta, 1990). Zone 1 is within the wetted low flow channel, Zone 2 is between low flow and bankfull flow, Zone 3 lays above the active channel (Zones 1 and 2) and Zone 4 is the terrestrial portion of wood (Robison & Beschta, 1990). The location of wood within the stream is generally identified by four common categories; bridge, ramp (partial bridge), buried or loose (unattached). These descriptive classifications make it easy for a reader to visualize the position of wood within the channel. Table B-1 in Appendix B illustrates the slight variations and general trends between definitions in current literature for each position. The position of in-stream wood provides information on the interactions between the wood and the banks, bed and stream flow of the channel.

The orientation of in-stream wood is used as a predictor of structural stability and its impact on fluvial morphology. The orientation is defined as the angle of wood in relation to the bank or the stream flow. Wood orientation is generally divided into three categories; perpendicular, parallel and intermediate. Some researchers further define the intermediate category based on the small end facing either upstream or downstream (see Table B-2 in Appendix B for references). Orientation can also be measured more precisely using a handheld compass to determine the angle in degrees. The majority of researchers do not use degrees for the orientation, but instead use descriptive classifications. Table B-2 in Appendix B provides more detailed definitions of the orientation categories found in current literature.

The use of decay classification for wood pieces is less prominent in the literature, but is generally categorized into three or four classifications based on physical stages of decomposition. However, the decay classification in current literature can range from three to seven categories, which are described in Table B-3 in Appendix B. The lack of consistency among the few studies using decay as a functional characteristic makes comparisons difficult to achieve (Chen et al., 2006; Jones & Daniels, 2008; Martin & Benda, 2001). Although the classification of the position, orientation and decay of in-stream wood is inconsistent across studies, they are important factors in determining the stability and functionality of in-stream wood.

1.2.6 The structure of wood deposits

The structure of wood formations within the stream channel determines their functionality and is generally categorized in a descriptive manner that includes single pieces, jams and dams. A single piece of wood creates a diversion to flow or a step in the channel profile; a jam causes a larger diversion impacting stream hydraulics and morphology and a dam cause an impediment to flow (Abbe & Montgomery, 2003; Keller & Swanson, 1979; Wohl & Jaeger, 2009). Definitions for different single piece structures can be found in Table C-1(Appendix C), and definitions for multiple piece structures (jams and dams) can be found in Tables C-2 and C-3, respectively. The complexity of the structure found in the system is primarily controlled through wood loading processes (Keller & Swanson, 1979).

The transport processes and characteristics of wood are important in determining the formation and evolution of jams illustrated in Figure 1-4 (Manners & Doyle, 2008). The evolution of a single piece of wood into a jam structure allows for greater stability and a longer residence time (Gurnell & Sweet, 1998; Wohl & Jaeger, 2009). The process begins with recruitment of a key member, which is defined as a relatively large log with or without branches and with or without a rootwad that obstructs the transport of additional wood pieces (Abbe & Montgomery, 1996; 2003). A relatively large log is operationally defined as a log that will remain stable within the channel due to its length or diameter, or both. The stability of the key member is typically determined by its size, shape, density, presence of a rootwad or branches and the probability of it lodging against a stable element (Manners & Doyle, 2008). The retention of a jam is often due to a stable key member that traps smaller wood fragments, which protects individual wood pieces from physical abrasion or fragmentation (Andreoli et al., 2007; Gurnell et al., 2002; Raikow et al., 1995). The export of in-stream wood generally occurs through the process of decay and fragmentation (Manners & Doyle, 2008).

When in-stream wood is dislodged from the reach, it can become trapped in other complex structures. In-stream transport of wood from one channel reach to another influences the retention and formation of complex in-stream wood structures (Cadol et al., 2009; Nakamura & Swanson, 1993). The transport of in-stream wood is dependent on channel width in relation to piece size, wood density, channel stability, flood intensity, frequency and forest composition (Berg et al., 1998; Harmon et al., 1986; Montgomery & Piégay, 2003; Naiman et al., 2002; Webb & Erskine, 2003). The rate of wood transport from a channel reach through fluvial processes is positively related to watershed size, due to increasing streamflow volume (Fremier et al., 2010; Martin & Benda, 2001). Fluvial transport of wood generally occurs during flood events where a critical threshold is exceeded and immobile wood is subsequently transported downstream (Bilby & Ward, 1989; Manners & Doyle, 2008; Montgomery et al., 1995; Piégay & Gurnell, 1997).

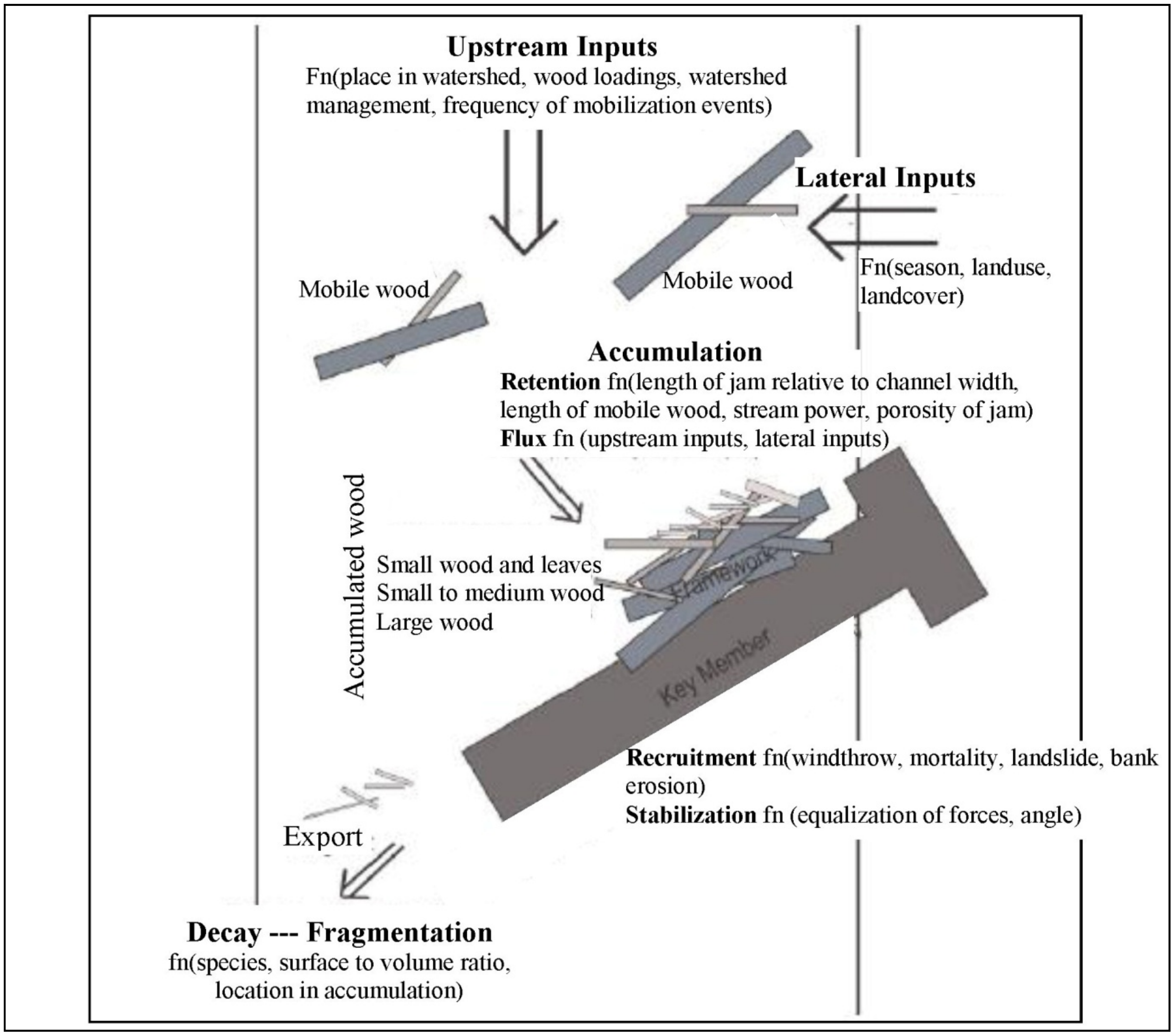


Figure 1-4: Schematic model of the evolution of a jam modified from Manners & Doyle (2008)

1.2.7 Impact of disturbances on in-stream wood

The change in landscape following a disturbance has both an immediate and future impact on wood availability. Immediately following a wildfire, the amount of in-stream wood often declines because the wood has been consumed as fuel by the fire (Berg et al., 2002; Reeves et al., 2006). The average annual rate of recruitment then increases over the next few years as remaining dead wood falls (Jones & Daniels, 2008). After this temporary increase of wood recruitment to the stream, there is a continuous decline of available wood (Chen et al., 2006; Zelt & Wohl, 2004). The decrease occurs as the riparian forest regenerates to produce enough wood of significant size and character to replace the natural recruitment balance. In some watersheds this process can take over a hundred years depending on several factors including fire characteristics, dominant tree species and climate (Chen et al., 2005; Chen et al., 2006; Reeves et al., 2006). Forests can be further impacted by salvage logging that removes standing and downed wood, eliminating the wood's ability to enter the stream channel (May & Gresswell, 2003b; Swanson, 1981; Trotter, 1990).

Disturbances within a forested watershed, whether natural or anthropogenic, can impact the loading and spatial distribution of in-stream wood. Nakamura and Swanson (2003) concluded that disturbances affect wood availability and recruitment in three ways. First, a direct or indirect alteration of wood delivery to the stream can occur. Second, the hydrological cycle may be impacted, altering the frequency and magnitude of streamflow and sediment entering the stream channel. This alteration in hydrology can change wood transport dynamics and quantity. Finally, a change in the storage, deposition and transport of wood can affect the physical and biological components of the aquatic ecosystem (Nakamura & Swanson, 2003). Therefore, disturbances have the potential to alter sediment, streamflow and wood dynamics, which can in turn impact the morphology of a stream channel (Montgomery & Buffington, 1997).

1.2.8 Impacts of in-stream wood on channel morphology

There is a relationship between the presence of wood (type and distribution) and fluvial geomorphology due to the impacts of wood retention on stream shape (Gurnell et al., 2002; Tinker & Knight, 2000). The recruitment and transfer of wood to streams significantly and systematically affects the fluvial geomorphology at a range of spatial and temporal scales. In-stream wood deposits can cause the formation of flood plains and valley floor landforms (Abbe & Montgomery, 1996; Gurnell et al., 2001; Piégay & Gurnell, 1997); large scale control on channel patterns (Nakamura & Swanson, 1993; Piégay & Marston, 1998); increased channel width and creation of side channels (Raikow et al., 1995); the creation of in-channel features including the formation of pools, riffles and steps (Lisle, 1995; Montgomery et al., 1995; Nakamura & Swanson, 1993); and changes in channel roughness and bed surface grain size (Buffington & Montgomery, 1999; Lisle, 1995; Shields & Gippel, 1995). At the site scale, research has examined in-stream wood as a storage instrument for sediment (Nakamura & Swanson, 1993), organic matter (Bilby & Ward, 1991) and associate nutrient dynamics (Aumen et al., 1990). The changes to stream form occur through shifts in channel processes that include stream hydraulics, flow patterns and scouring and deposition of sediment (Bisson et al., 1987; Keller & Swanson, 1979; Montgomery et al., 1995).

In-stream wood dissipates stream energy, particularly during high flow periods (Abbe & Montgomery, 1996), which influences channel morphology and stability (Lisle, 1986; Montgomery et al., 1995) and the associated ecological function of the stream (Richmond & Fausch, 1995). A number of studies report energy dissipation is associated with in-stream wood increasing the bed roughness, which reduces transport of sediment and organic material causing a loss in bed elevation (Andreoli et al., 2007; Bilby & Ward, 1989; Curran & Wohl, 2003; Fetherston et al., 1995; Gurnell et al., 2005; Montgomery et al., 1996; Webb & Erskine, 2003). This loss in elevation caused by increased sediment can shift the channel from bedrock dominant to forced alluvial (Massong & Montgomery, 2000). Accordingly, the shift in channel form can change the sediment regime and create areas of local deposition and scour (Beschta & Platts, 1986).

Channel type classifications are based on the planform pattern (scour and depositional features) and geometry characteristics (radius of curvature, meander amplitude, width and depth). Channel patterns are described based on their planform shape as straight, meandering, braided, anastomosing and anabranching (Leopold & Wolman, 1957; Nanson & Knighton, 1996; Smith & Smith, 1980). The addition of wood to the channel can cause deposition on the downstream side, creating a bar formation and shifting the channel towards a braided or anastomosing system (Gurnell & Petts, 2002; Gurnell et al., 2005). In meandering streams the input of wood can cause meander chute cut-offs, creating abandoned channels (Gurnell et al., 2002). As wood accumulated on the outside of meander curves it protects the bank, decreases the radius of curvature and increases the meander amplitude. The channel alteration subsequently tightens the curve, restricting flow and raising upstream water levels. The channel width can also respond to changes in wood load. As the frequency of wood input decreases, an increase in bank erosion occurs, causing the channel to widen and become shallower. However, if an increase in wood causes an increase in sediment storage, it can lead to a narrowing of the channel (Beschta & Platts, 1986; Zelt & Wohl, 2004). The subsequent change in sediment regime further impacts the channel planform in terms of bar and pool formations.

The dissipation of energy due to in-stream wood creates an altered channel form by altering scour and deposition processes (Bisson et al., 1987; Keller & Swanson, 1979; Montgomery et al., 1995). These geomorphic changes can occur upstream, downstream or on both sides of the obstruction as the water encounters a change in channel roughness (Beschta & Platts, 1986). Lower stream gradients stabilize wood accumulations that retain and sort bed materials within gravel-bed streams (Gurnell & Sweet, 1998). This stability of in-stream wood can allow for the gradual fill upstream of the obstruction with coarser sediment (gravel, pebbles and cobbles), generating irregular streambed topography and non-regularly spaced bars (Gurnell et al., 2002; Kraft & Warren, 2003; Wallace et al., 1995). The change in sediment regime can also shift scouring processes, to obtain a stable state between an excess or limited amount of sediment. In channel reaches with an excess of total sediment, deposition occurs; whereas in sediment limited sections, erosion occurs contributing additional sediment to the channel (Schumm, 1977). Equilibrium is achieved through a balance between discharge, sediment load and slope (Lane, 1955). The shift in scouring processes due to changes in the sediment regime subsequently impact the spacing, type and formation of pools in the active channel.

The distribution of wood within the channel impacts not only the formation, but the frequency of pools. Pool frequency is defined as the number of pools per channel width or stream length and has been found to be directly related to in-stream wood (Montgomery et al., 1995). Pool spacing typically averages five to seven channel widths (Leopold et al., 1964); however in-stream wood generally decreases this rate due to associated flow convergence and bed scour (Gregory et al., 1994; Montgomery et al., 1995). Previous research found pool spacing can range from 0.2 to 13 channel widths in forested channels, with the lowest values associated with the highest wood loading (Gurnell & Sweet, 1998; Montgomery et al., 1995). The strong correlation between pool spacing and in-stream wood loading has been found to occur in small to moderately sized gravel-bed channels (Abbe & Montgomery, 1996; Piégay et al., 1999).

1.2.9 Effect of in-stream wood on pool formation and cohesive sediment storage

There is currently no accepted definition for a minimum pool size (Webb & Erskine, 2005). Within the reviewed literature there were two general definitions for pools; the first based on the related depth, with pools being a closed topographic depression with a residual depth greater than 0.1 meter (Abbe & Montgomery, 1996; Lisle, 1987). The second pool definition allowed for a quicker visual estimate, with a pool being defined as an area of intense turbulence (energy dissipation) with slow or standing water occupying at least 10% of the bankfull width (Kreutzweiser et al., 2005; Montgomery et al., 1995). The formation of pools typically occurs through scour or damming processes, which allows the water depth to increase. Channel processes within scour and dammed pools differ in terms of their location within the channel, longitudinal and cross-sectional depth profile, characteristics of substrate and constraining features (Hawkins et al., 1993). Classification schemes are used by researchers to define and explain the different pool formations found within stream reaches and are generally tailored to the study objectives.

Several pool classifications have been proposed in the literature and there are similarities among the definitions. However, there is no universally accepted scheme and modifications to existing classifications have occurred for different types of systems and studies (Webb & Erskine, 2005). Often the classification schemes are based on aquatic habitat (Bisson et al., 1982; Hawkins et al., 1993) or in-stream wood (Buffington et al., 2002; Montgomery et al., 1995; Montgomery et al., 2003; Robison & Beschta, 1990; Webb & Erskine, 2005). Pool classifications are typically divided into two general categories. For example, Hawkins et al. (1993) use scour or dammed pool categories, while Webb and Erskine (2005) use log-affected or non-log-affected and Montgomery et al. (1995) use self-forming or forced categories. Accordingly, the general category used depends on the research objectives. The types of pools are then further classified within these general sub-divisions, providing further information on the forms and processes involved in their creation. There are both similarities and differences found between pool type classifications. Four of the more commonly cited classifications from in-stream wood literature are presented in Table 1-1. These classifications are generally defined broadly as either scouring or damming processes, with the majority of the classifications in Table 1-1 formed through scouring processes.

Table 1-1: A comparison of four pool type classifications. The pool types in bold font are wood-affected; in italic font are both wood-affected and non-wood affected and regular font represent non-wood affected pools, based on information provided within each research paper

	Webb & Erskine, 2005	**Hawkins et al., 1993**	**Robison & Beschta, 1990**	**Bisson et al. 1982**
Vertical obstruction				
	Longitudinal scour			
Vertical – Pier obstruction				
	Pendant scour			
Vertical – Abutment obstruction				
	Trench scour	*Trench scour*		Trench
	Mid-channel	*Mid-channel*		
		Lateral scour	*Lateral scour*	**Lateral scour – rootwad**
			Deflector	
Pitched obstruction				
		Lateral scour	*Lateral scour*	**Lateral scour – debris**
			Underflow	
Horizontal obstruction				
	Transverse scour		**Underflow**	
Step				
	Transverse scour			
	Eddy scour	*Eddy scour*		
	Step	*Plunge*	*Plunge*	*Plunge*
	Disconnected			
Dammed				
	Debris dammed	**Debris dammed**	*Dammed*	*Dammed*
		Beaver dammed (not naturally formed)		
		Landslide dammed		
		Backwater		**Backwater – rootwad**
				Backwater – debris
				Backwater – boulder
		Abandoned channel		Secondary channel
Non-log affected				
	Convergence	Convergence	Convergence	
	Bedrock			Lateral scour – bedrock
	Boulder			Backwater – boulder
	Free-formed alluvial	*Lateral scour*	*Lateral scour*	
	Compound		Combination	

One of the most influential functions of wood on stream morphology is the formation of pools (Kreutzweiser et al., 2005). The pool type is dependent on the relationship between in-stream wood and flow (Robison & Beschta, 1990). In particular, wood alters channel roughness, which creates a zone of high turbulence and forms a pool (Beschta & Platts, 1986; Nakamura & Swanson, 1993). In general, scour pools are more common as the addition of wood creates small scour pools between planform controlled pools (Webb & Erskine, 2005). The wood characteristics and its relationship to flow determine the location of channel scouring, which could be around, beside, under or over the wood. The location and type of scouring processes determines the type of pool formed (Robison & Beschta, 1990; Webb & Erskine, 2003). The basic mechanisms of scour (flow convergence and turbulence) are still common with in-stream wood; however, the orientation, structure and strength of those mechanisms differ with obstruction types (Buffington et al., 2002).

Researchers examining pool formation in relation to in-stream wood tend to use the characteristics of wood to determine the scour processes and associated pool types (Bisson et al., 2006; Buffington et al., 2002; Webb & Erskine, 2005). Buffington et al. (2002) identify four natural obstruction types: (1) vertical obstruction, such as abutments and piers, (2) pitched obstructions, (3) horizontal obstructions and (4) steps. The relationship between scour pool classification and obstruction type are found in Table 1-1. For example a horizontal obstruction, which is perpendicular to flow and touching both banks (bridged), deflects flow downwards against the bed creating a transverse or underflow pool (Buffington et al., 2002; Montgomery et al., 2003; Robison & Beschta, 1990). However, if a wood structure has the same horizontal position and orientation but the flow breeches the top of the structure, it becomes a step obstruction. Step obstructions are associated with plunge pool formations downstream of the structure (Richmond & Fausch, 1995). When channel substrate cannot be scoured, and the in-stream wood structure does not permit water to flow over it, a dammed pool is created on the upstream side of the obstruction (Beschta & Platts, 1986; Bilby, 1981; Gurnell & Sweet, 1998; Robison & Beschta, 1990).

The ability to restrict the flow of water in the channel is based on the porosity of the in-stream wood structure. A high porosity structure causes little impoundment, whereas a well sealed dam with low porosity causes the water to crest and spill over the top (Bisson et al., 2006). The deepening of pools has been found to occur as leaves and sediment accumulate, which prevents water and sediment from transporting downstream (Wallace et al., 1995). Abbe and Montgomery (1996) found forced pools associated with in-stream wood averaged greater variance in depth than free forming pools. This variance was due in part to the diversity of wood structures. The diameter has been found to control the jam/dam height, which has an associated impact on pool volume. Studies on the relationship between in-stream wood and pool formation report a positive correlation between pool volume and in-stream wood deposits (Jackson & Strum, 2002; Mao et al., 2008; Montgomery et al., 1995).

The diversity of pool types associated with in-stream wood provides aquatic organisms with suitable habitat throughout their lifecycles. For example, fish require shallow pools for younger years and larger pools as they grow and need a better food supply (Beschta & Platts, 1986). In-stream wood creates pools that are favoured by fish because the pools offer low velocity pockets with shaded areas and cover that provide diverse fish habitat (Bisson et al., 1987; Piégay et al., 1999). Woody obstructions slow the flow of water and provide fish with a zone for feeding from wood-related sources and protection from predators (Berg et al, 1998). This thesis will provide information on the types of pools found in the headwaters of the Oldman River Basin, an area known for its fishing (Oldman Watershed Council, 2010). The information will allow for a more complete understanding of the ecological link between in-stream wood, channel form and biodiversity, providing insight into healthy aquatic ecosystems necessary to achieve the goals outlined in the *Water for Life Strategy*.

The change in wood-affected pool volume affects aquatic ecosystems by altering the stream hydraulics. A reduced flow causes sediment and organic material to be trapped and slowly released to the downstream system (Fetherston et al., 1995; Jackson & Strum, 2002). Generally pools upstream of in-stream wood dissipate kinetic energy, decreasing sediment transport and causing sediment to store within the pool. The increase in stored sediment can cause part of the pool to infill, which then reduces the pool volume (Bilby, 1981; Hawkins et al., 1993). Zelt and Wohl (2004) found pool infill was primarily coarse sand and very fine gravel, with finer sediment deposits occurring in disturbed catchment. Further study was recommended to better understand in-stream wood as a mechanism for fine sediment storage in various stream types and geographic areas (Zelt & Wohl, 2004). The research conducted in this thesis will provide information regarding the relationship between cohesive sediment storage and in-stream wood structures found along the eastern slopes of the Rocky Mountains of southwest Alberta, Canada.

1.2.9.1 Cohesive sediment storage

When sediment is delivered to the channel network it can be stored within the channel and on the floodplain or routed to downstream reaches. Following a disturbance by wildfire, loss in vegetation increases the erosion of smaller sediment (sand, silt and clay) during overland flow. This process contributes to an increase in fine-grained sediment entering the local stream system (Malmon et al., 2007; Meyer & Wells, 1997; Thomas et al., 1999). In areas of low water velocity, such as in pools, fine particles settle out of suspension and deposit along the channel. The term fine sediment can be used to describe sediment less than 2000μm in size and incorporates sand (<2000 to >62μm), silt (<62 to 4μm) and clay (<4μm) (Wood & Armitage, 1997). Of particular interest is cohesive sediment, which is defined as particles less than 63μm; the most important size fraction for contaminant transport because of its large surface area and high cation exchange capacity (Owens et al., 2005; Stone & Droppo, 1994).

The biogeochemical sink of cohesive sediment makes it a potential source for toxins. When cohesive sediment increases within a channel, levels of associated nutrients and contaminants can increase, causing eutrophication and increasing eco-toxicological risks (Petticrew et al., 2007). The storage of cohesive sediment is significant because the deposition and associated nutrients could constitute environmental problems (Petticrew et al., 2007). Water quality has implications on river ecology (turbidity and eutrophication) and human health (pathogens and radionuclides) (Owens et al., 2005; Petticrew et al., 2007). The remobilisation of cohesive sediment could release large amounts of nutrients and contaminants into the stream, thus changing both the sediment quantity and water quality within the aquatic ecosystem (Owens et al., 2005; Walling, 1999).

Cohesive sediment can cause changes not only in the chemical and biological conditions but also in the physical conditions of a gravel stream, which can impact habitat (Petticrew et al., 2007). When cohesive sediment is stored on the channel bed, it can infiltrate into the pore space of the gravel bed and negatively impact the aquatic ecosystem (Lachance & Dubé, 2004). An alteration in the quantity of cohesive sediment also impacts turbidity in the water column (Owens et al., 2005). Wood and Armitage (1997) found that cohesive sediment can smother the riverbed, killing aquatic flora, clogging space between substrate clasts and reducing habitat for benthic organisms. The change in accumulation, storage and potential remobilisation of cohesive sediment due to landscape disturbance, including the removal or addition of in-stream wood obstructions are important to understand because of the implications to the larger stream system (Walling, 1999).

1.2.9.2 The impact of in-stream wood on cohesive sediment storage

Typically there is a more efficient retention of particulate matter in streams containing in-stream wood deposits compared to streams lacking wood deposits (Trotter, 1990). The input of wood to the active channel can cause a shift in flow direction towards the banks, which increases erosion thus contributing additional sediment to the channel (Beschta & Platts, 1986; Bilby, 1981; Hart, 2003). Bank erosion can lead to additional wood input through undercutting and bank failure, increasing the frequency or complexity of structures within the active channel (Benda, 2003; Wohl & Jaeger, 2009). The change in sediment storage related to in-stream wood is due to the increase in channel roughness. Low-velocity pools upstream of in-stream wood can dissipate stream energy causing cohesive sediment to deposit (Andreoli et al., 2007; Bilby & Ward, 1989; Curran & Wohl, 2003; Fetherston et al., 1995; Gurnell et al., 2005; Montgomery et al., 1996; Webb & Erskine, 2003).

The relationship between in-stream wood and cohesive sediment storage is connected, as the size and complexity of wood structures generally control the type and amount of sediment stored (Gomi et al., 2001; Jackson & Strum, 2002; May & Gresswell, 2003b). For example, complex structures (jams and dams) tend to store larger volumes of sediment due to their greater influence on flow (Hart, 2003). The stability of in-stream wood exerts control on the retention of cohesive sediment storage (Faustini & Jones, 2003; Montgomery et al., 1996). The retention of finer sediment can shift a channel from a coarse bedload dominated reach to a more cohesive sediment dominated reach, which subsequently could impact the morphology and ecology of the stream (Hart, 2003).

The importance of cohesive sediment storage is related to the biological changes it can initiate within the stream. In-stream wood is critical for the retention of sediment and nutrients in steep headwater streams, through trapping colluvium and fluvial sediment (Bilby, 1981; Curran & Wohl, 2003; Fetherston et al., 1995). The influence of wood in the active channel causes changes to the flow and cycling of energy, nutrient and food (Seo et al., 2010). Research shows wood in headwater streams is effective at retaining cohesive sediment, particulate organic matter and associated nutrients (Aumen et al., 1990; Faustini & Jones, 2003; Wohl & Jaeger, 2009). When an in-stream wood structure breaks, cohesive sediment and associated nutrients are transported downstream, creating a deficiency in one location and an excess in another. This shift could lead to undesirable effects because of the change in the sediment and nutrient balance (Bilby, 1981).

The ecological impact of cohesive sediment and the impact in-stream wood has on its distribution and retention makes this an important topic to consider. In the Oldman River Basin, the reach scale impacts on aquatic organisms, particularly fish, are important to understand, because the Basin is considered to have some of the best fishing in the province of Alberta (Oldman Watershed Council, 2010). In addition, the potential destruction of a wood structure could release large amounts of cohesive sediment and associated nutrients and contaminants to downstream reaches. The headwaters of the Oldman River Basin supply drinking water to downstream communities and the potential pathogens and increased turbidity associated with a large cohesive sediment release could overwhelm municipal drinking water treatment facilities. Therefore, it is important to understand the relationship of in-stream wood and cohesive sediment storage within headwater streams. This thesis will examine the relationship between in-stream wood and cohesive sediment storage in two headwater streams of the Oldman River Basin.

1.2.10 Planning and management for headwater systems

To best manage forested watersheds an understanding of stream processes is necessary (Richmond & Fausch, 1995). Current literature recommends researchers provide sound scientific knowledge for decision makers regarding the interconnection of the terrestrial and aquatic systems in forested watersheds (Karr et al., 2004; Reeves et al., 2006; Zelt & Wohl, 2004). If an effective management plan and regulations are to be implemented, forest practices in headwater streams should reflect a better understanding of the geomorphological processes, hydrology and riparian vegetation dynamics (Gomi et al., 2001). The policies created should reflect the ecological importance of in-stream wood, ensuring at least partial conservation of wood input, transfer and deposition in river systems (Nowakowski & Wohl, 2008; Piégay et al., 1999; Young, 1994).

Logging (including salvage logging) of riparian areas typically reduces the rate of in-stream wood for several decades, impacting the aquatic ecology (Beechie & Sibley, 1997; Bilby & Ward, 1991). A forestry management plan should reflect the natural composition of wood and ensure its long term availability (Abbe & Montgomery, 1996; Gurnell et al., 1995; Montgomery et al., 1995; Robison & Beschta, 1990). The management strategy most commonly cited was to implement a riparian buffer zone (Beechie & Sibley, 1997; Beschta et al., 2004; Chen et al., 2005; Gurnell et al., 1995; Jones & Daniels, 2008; Laiho & Prescott, 1999; Murphy & Koski, 1989; Swanson & Lienkaemper, 1978). Although the buffer zone typically has a standard distance, managers should understand standard targets do not always work and adaptive management or conceptual frameworks are recommended for small streams (Beschta & Platts, 1986; Buffington et al., 2002). Changes within the forest ecosystem will impact channel conditions, therefore management efforts should attempt to mitigate potential adverse affects (Lancaster et al., 2001).

To promote a healthy aquatic ecosystem through management guidelines, it is necessary to understand wood dynamics within the channel (Gurnell et al., 1995; Gurnell & Sweet, 1998). When possible, wood should not be removed as it impacts not only the local channel, but the downstream reaches due to changes in channel dynamics (Gregory et al., 1993; Swanson & Lienkaemper, 1978; Wohl & Jaeger, 2009). In particular, management decisions should allow jams and dams to evolve and stabilize due to their role in controlling organic matter movement and providing diverse habitat (Gurnell & Sweet, 1998; Manners & Doyle, 2008). In order to maintain habitat over a range of stream orders, research results should have a direct affect on riparian forest management guidelines at the watershed level (Chen et al., 2006; Richmond & Fausch, 1995).

1.2.10.1 Water for Life

In 2003, the province of Alberta responded to concerns over the increasing pressure on its water resources by introducing the document *Water for Life: Alberta's Strategy for Sustainability* (Alberta Environment, 2003). Three primary goals emerged from this: "safe, secure drinking water, healthy aquatic ecosystems, and reliable quality water supplies for a sustainable economy" (Alberta Environment, 2003, p. 7). Albertans focused on three key directions and actions necessary for the strategy to succeed; knowledge and research, partnerships, and water conservation (Alberta Environment, 2003). The *Water for Life* strategy highlighted the unpredictability of water supply due to climate variability and the effects of land use activities on water quality. Additionally, the strategy identifies many concerns requiring further investigation in order to improve water management (Alberta Environment, 2003). As a long term plan, the Government of Alberta wants to understand the state of the province's aquatic ecosystems and use an adaptive management system to complete watershed management plans (Alberta Environment, 2003).

The strategy was reviewed by the Alberta Water Council (2008) who concluded the goal of achieving healthy aquatic ecosystems was behind schedule, due to less emphasis compared to the other two goals. The review also noted a gap in sharing information and translating the collected data and research into useful information for land and water managers. The review highlighted that due to the three goals being interrelated a failure to progress in one goal limits the ability to achieve all the goals (Alberta Water Council, 2008). A recommendation for immediate action to address degradation of aquatic ecosystems was proposed (Alberta Water Council, 2008). Upon this advice, the report *Water for Life: A renewal,* completed in 2008, has an increased focus on healthy aquatic ecosystems (Government of Alberta, 2008). The final objective of this thesis project is to discuss potential planning and management implications for achieving healthy aquatic ecosystems within disturbed catchments, focusing on the headwater streams of the eastern slopes of the Alberta Rocky Mountains.

1.3 Objectives

The goal of the present research project is to examine landscape disturbance impacts on the characteristics of in-stream wood deposits and their effect on stream morphology along the eastern slopes of the southwestern Rocky Mountains in Alberta, Canada. Specific objectives are to:

1. Conduct a literature review on the structure of in-stream wood deposits in rivers and their impact on stream morphology and sediment deposition.

2. Evaluate the spatial distribution and type of in-stream wood structures found in streams draining watersheds of contrasting disturbances (wildfire/salvage logging /recreation versus recreation/grazing).

3. Characterize three representative in-stream wood structures and their geomorphic impacts at the reach scale within each disturbance type (six selected sites total).

4. Determine the effect of in-stream wood on pool formation and associated impact on the storage of cohesive sediment.

5. Discuss planning and management implications for headwater ecosystems within the eastern slopes of the southwestern Rocky Mountains

1.4 Thesis organization

There are five chapters presented in this thesis. Chapter 1 summarizes literature pertaining to the impact of land-use disturbance on the hydrologic and geomorphic processes and the effect in-stream wood formations have on stream morphology and ecology in order to provide a context for the thesis. Chapter 2 provides a description of the experimental design, study area characteristics and methods for the project. The results for in-stream wood characteristics and associated stream morphology data are presented in Chapter 3. In Chapter 4, trends of in-stream wood site frequency and structure type, along with reach scale morphology, are discussed within the context of the current literature. Chapter 4 also discusses the implications of the current study on watershed management and planning. Finally, in Chapter 5 the conclusion of the study and recommendations for future research are presented.

Chapter 2
Methods

2.1 Experimental design

Based on the literature review, a conceptual diagram (Figure 2-1) of the current research is presented to illustrate key processes that influence in-stream wood structures and their impacts on channel morphology. Within this conceptual diagram specific aspects which form the basis of this thesis are shaded and bolded. The thesis was conducted to examine the spatial distribution and type of in-stream wood located along the main stem of two headwater streams impacted by different land-use disturbances. The second goal of this project was to understand the reach scale impact of wood structures on depositional and scour features in the channel morphology. In particular the study focused on the formation of pools and associated cohesive sediment storage (Figure 2-1).

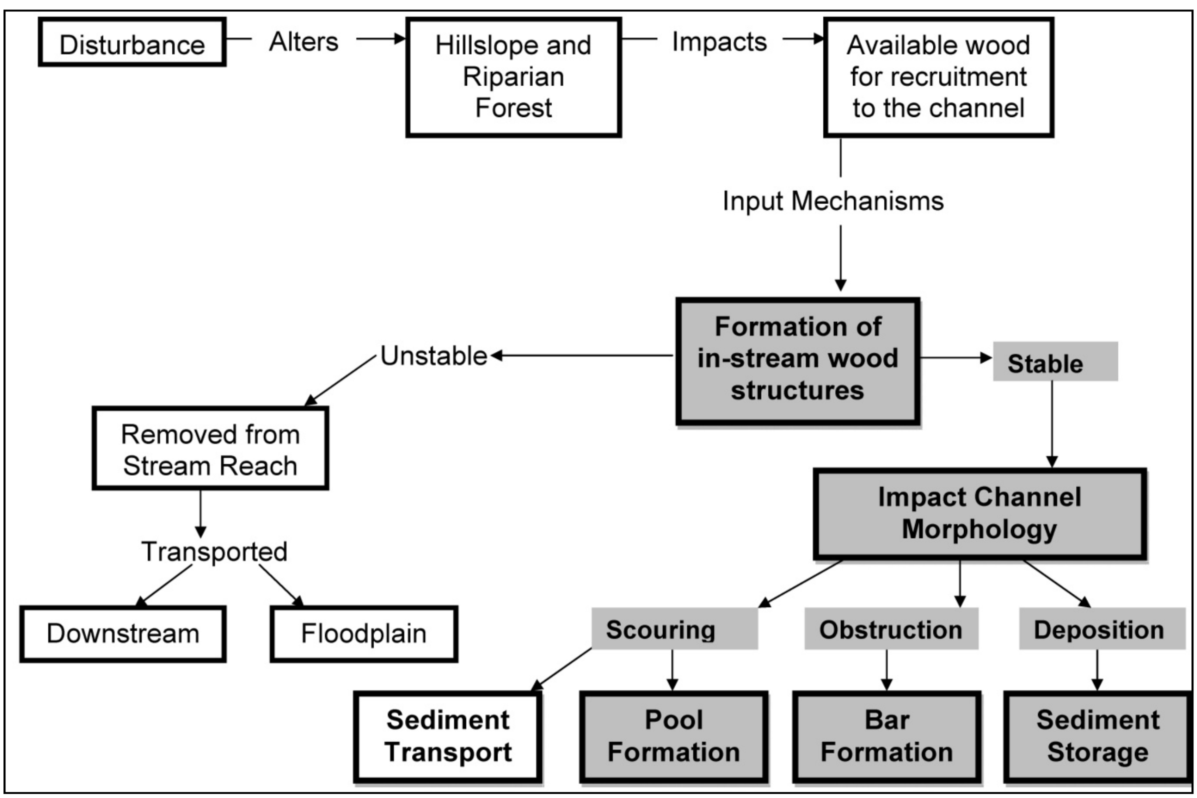


Figure 2-1: Conceptual diagram illustrating the formation and impact of in-stream wood structures on channel morphology. This thesis will explore the concepts contained within the bold and shaded boxes.

Two representative watersheds, Lyons East and Corolla Creek (a previously unnamed tributary), were selected for analysis of the spatial distribution and function of in-stream wood along the main stem channel. For the purpose of this study, only wood considered functional within the active channel was recorded. Functional wood was operationally defined as wood having morphological impact on channel processes during low flow conditions (Berg et al., 1998; May & Gresswell, 2003a; Trotter, 1990). Accordingly, an in-stream wood structure had to be at least partially located within the active low flow channel during the 2009 field season. The location, structure type and general morphological characteristics were surveyed and photographed for each site.

The second phase of the project examined the reach scale impact of in-stream wood structures within each watershed. Using the findings from the initial phase, six representative sites were selected based on general trends of structure type, wood characteristics and stream morphology. The reach scale research allowed for a more detailed analysis of the relationship between deposit type and stream morphology. For each of the six sites, the geomorphic features upstream from, at and downstream of the in-stream wood structure were surveyed. The information collected in the field was used to classify the channel reach morphology based on the methods of Montgomery and Buffington (1997). The pools were classified based on a combination of methods presented by Montgomery et al. (1995), Webb and Erskine (2005), Hawkin et al. (1993) and Robison and Beschta (1990). During the field investigation, detailed analysis of pool characteristics and cohesive sediment storage were completed based on the methods of Lisle and Hilton (1992). This information was used to calculate water and sediment volume for each pool.

2.2 Description of the study region

This study was conducted within the headwaters of the Oldman River Basin, which includes three large sub-basins: Oldman, Castle and Crowsnest. Located in southwestern Alberta (Figure 2-2), the Oldman River Basin originates in the Rocky Mountains and extends eastward through the foothills. The Oldman Watershed Council (2010) has divided the basins into five zones; Mountain, Foothills, Southern Tributaries and Prairies along with the Oldman River main stem. This thesis research was conducted within the Mountain zone of the Castle and Crowsnest sub-basins.

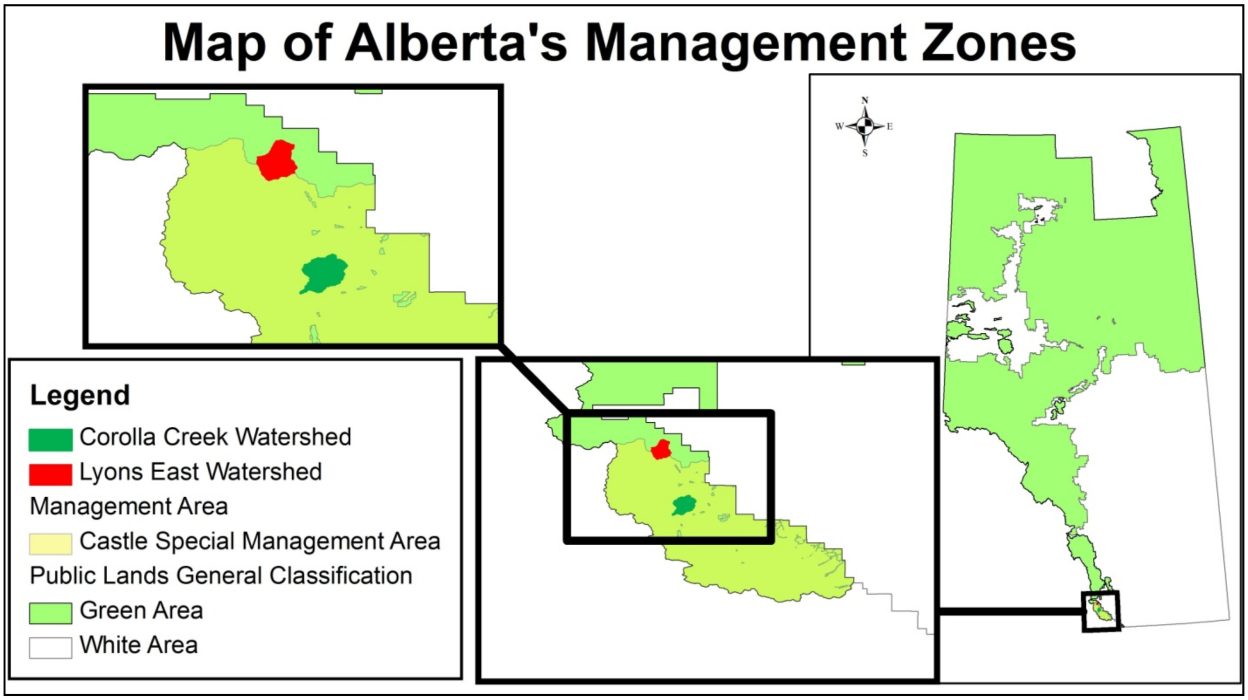


Figure 2-2: Public land classification and location of the two research watersheds in relation to the Castle Special Management Area in Alberta, Canada

The annual flow regime has a distinct peak in flow occurring around June for both the Crowsnest and Castle sub-basin streams. This reflects the seasonality of precipitation with spring freshet occurring together with snow melt. The Castle sub-basin typically has a higher amount of precipitation due to a greater proportion of the drainage area located within alpine and sub-alpine eco-regions. These higher precipitation rates can lead to increased water yields. Streams in these watersheds typically have a rocky substrate of large cobbles and boulders, which require high flow events associated with spring-freshet for transport to occur along these steep gradient systems (Oldman Watershed Council, 2010).

The topography and valley form of the study watersheds are characteristic of the sub-alpine and montane eco-regions found in the Mountain zone. Sub-alpine topography generally consists of rolling to inclined hills, whereas the montane eco-region is comprised of gentler rolling hills and hilly foothills. The elevation of the study area ranges from 1429m to 2028m with a mean of 1638m for Lyons East and 1568m for Corolla Creek (Figure 2-3 and Table 2-1). The topography has been shaped by previous glaciation, forming both wider U-shaped and more narrow V-shaped valleys. The primary surficial geology within the study area is continuous glacial till consisting of glacio-lacustrine deposits (Table 2-1). The geology is overlain by well to imperfectly drained soils, characteristic of the northern coniferous forest environment (Bladon et al., 2008). Soils within the upper headwater reaches include thin gray luvisol and brunisols soils with weak horizon development (Bladon et al., 2008; Oldman Watershed Council, 2010). The local soils are a factor in influencing the type of vegetation found in the Mountain zone eco-regions.

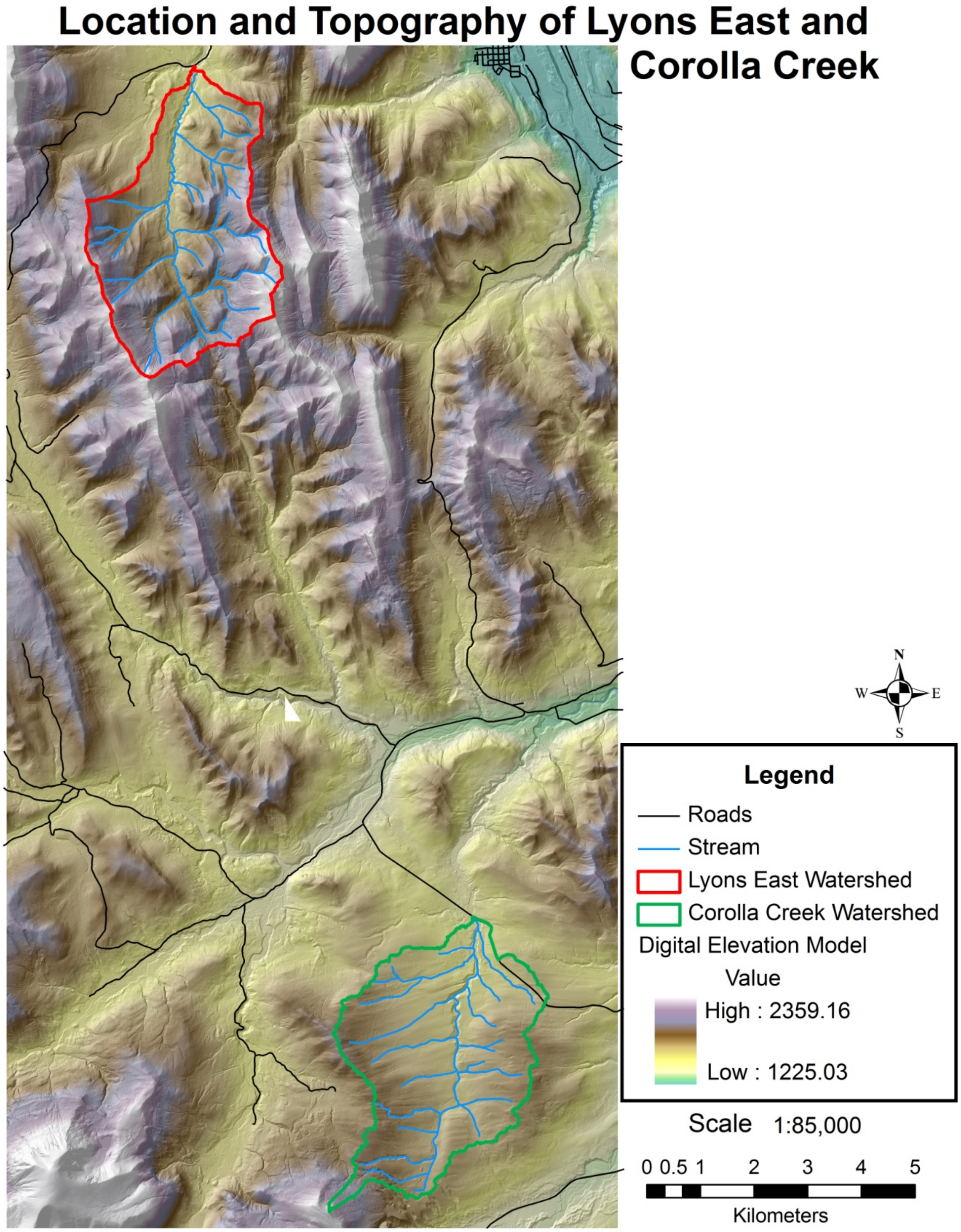


Figure 2-3: Location and topography of the two study watersheds

Table 2-1: The physical characteristics of the studied watershed catchments

Watershed	Watershed drainage area (km^2)	Watershed perimeter (km)	Elevation (mean/ range; m)	Catchment slope (%)	Channel slope	Mean annual precipitation (mm)*	Mean annual precipitation 2004-2008 (mm)	Geology
Lyons East	13.06	17.2	1683 (1441-2028)	31.4	0.04	576.5	852	Cretaceous Colluvium Slightly leached till Cordilleran provenance
Corolla Creek	13.15	20.3	1568 (1429-1963)	11.4	0.03	654.4	1236	Cretaceous Mostly Moderately leached till Cordilleran provenance Some Colluvium and slightly leached till Cordilleran provenance

*Annual precipitation is based on Environment Canada Climate Normal's for 1971-2000 for the closest station to each watershed

The type of dominant vegetation shapes the forest and is a factor in the impact a disturbance has on the watershed. Forests cover approximately 64% of the Mountain zone of the Oldman River Basin. There are three eco-regions within the mountain zone - alpine, sub-alpine and montane (Oldman Watershed Council, 2010). The alpine eco-region is the highest elevation in the basin, located above the tree line. The sub-alpine eco-region is marked with a transition to coniferous forest below the alpine zone. The coniferous forest is comprised of englemann spruce (*Picea englemannii*), white spruce, (*Picea glauca*) and douglas fir (*Pseudotsuga menziesii*) in higher elevations and primarily lodgepole pine (*Pinus contorta*) in lower elevations. The montane eco-region is comprised of lodgepole pine (*Pinus contorta*) and douglas fir (*Pseudotsuga menziesii*). Aspen mixed forests are found on the eastern and north facing slopes of the montane eco-region (Oldman Watershed Council, 2010).

Forested watersheds within the Crowsnest and Castle basins have been shaped through natural disturbances and land use practices. This area of Alberta is part of the "leading edge" zone for mountain pine beetle (MPB) infestations, which are found scattered throughout the watersheds (Oldman Watershed Council, 2010). Forest fires have shaped the landscape throughout history with over four-hundred fires being reported between 1961 and 2002 (Oldman Watershed Council, 2010). In the summer of 2003, the Lost Creek fire burned more than 21,000 hectares and was one of the most severe fires in the area's history (Bladon et al., 2008). Only about 30% of fires in the basin are caused by natural sources such as lightning, with the other 70% caused by anthropogenic factors, primarily recreational users (Oldman Watershed Council, 2010).

Anthropogenic activities within the Mountain zone of the basins are recreational, livestock grazing and logging (Oldman Watershed Council, 2010). Recreational activities, such as camping, fishing and hiking, are extensive throughout the front and back-country. Although there are some designated campsites complete with infrastructure, there are a number of non-designated campsites created throughout the season. Fishing is a popular activity in the Oldman River Basin, because it has some of the finest trout streams in Alberta. The use of all-terrain vehicles (ATVs) is common within both the Crowsnest and Castle sub-basins. A network of ATV trails, complete with bridged stream crossings, has been created to decrease the impact of ATVs on the natural ecosystem. Within the Castle Special Management Area (Figure 2-2), ATV use is permitted only on designated trails from 1 April to 30 November (Oldman Watershed Council, 2010). The characteristics of the trail network, including length and number of stream crossings, are presented in Table 2-2 for both watersheds.

Table 2-2: The stream and trail characteristics and interactions found in the two studied watersheds

Watershed	Stream length (km)	Trail length (km)	Ratio S:T* length	Number of crossings	Trail density ($km/100km^2$)
Lyons East	31	14	2.2	13	107
Corolla Creek	29	47	0.6	31	357

*S:T is defined as the stream to trail ratio

The other types of anthropogenic activities are industrial uses, which include grazing and logging. Grazing is permitted in 'green zones' designated areas (Figure 2-2) which cover over 315,000 hectares of the Mountain zone. Small commercial forest harvest operations are conducted by a local sawmill and governed by a forest management plan (Oldman Watershed Council, 2010). Salvage logging was permitted in some of the area burned in the Lost Creek fire, to recover economic losses (Government of Alberta, 2010). In addition to salvage logging, firewood permits are available within designated areas, which allow residents to harvest an allotment of wood for personal use.

2.2.1 Description of study watersheds

The land-use practices in the two study watersheds are representative of land-use practices commonly found within the eastern slopes of the southern Canadian Rocky Mountains. The characteristics of the permitted activities and natural disturbance impacts can be found in Table 2-3. Lyons East (LE) was initially disturbed in the 2003 Lost Creek fire and subsequently salvage logged. The land-use disturbances found in Corolla Creek (CC) are anthropogenic and include livestock grazing and a network of hiking and all-terrain vehicle (ATV) trails (Table 2-2). Recreational activities, including camping and trail use are permitted in both watersheds. The length and number of crossings found within Lyons East and Corolla Creek are outlined in Table 2-2 and Figures 2-4 and 2-5 respectively. These two watersheds characterize the general activities permitted within the geographical region.

Table 2-3: Natural and anthropogenic disturbance activities occurring within the selected study watersheds

Watershed	Management category	Permitted activities	Watershed drainage area (km^2)	Burned (km^2, %)	Salvage logged (km^2, %)
Lyons East	Burned Salvage - Logged	Logging Recreation ATV Trails	13.06	10.72 (82)	2.62 (20)
Corolla Creek	Unburned	Recreation ATV Trails Hiking Trails Grazing - Cattle	13.15	0	0

This research was completed within the sub-alpine and montane eco-regions of the Mountain zone found in the larger sub-basins. The valley constriction and type varies between the two watersheds. Lyons East has a more constricted channel in a "V" shaped valley; whereas Corolla Creek is less constricted, typically with a floodplain on one side and a "U" shaped valley. Based on the stream order classification of Strahler (1952) both Lyons East and Corolla Creek main stem channels are third order streams (Figures 2-4 and 2-5 respectively). The two watersheds are comprised of a dendritic stream network pattern and meandering stream type. Additional morphometric descriptions of the watersheds are presented in Table 2-1.

The vegetation in Lyons East and Corolla Creek varied slightly. In Lyons East, the vegetation consisted of standing burned trees from the 2003 wildfire, tree re-growth, shrubs, flowers and grasses. Corolla Creek was primarily a coniferous forest, typical of the region with some sections of Aspen mixed forest. Meadows and sections of the stream bank in Corolla Creek are dominated by shrubs, flowers and grasses.

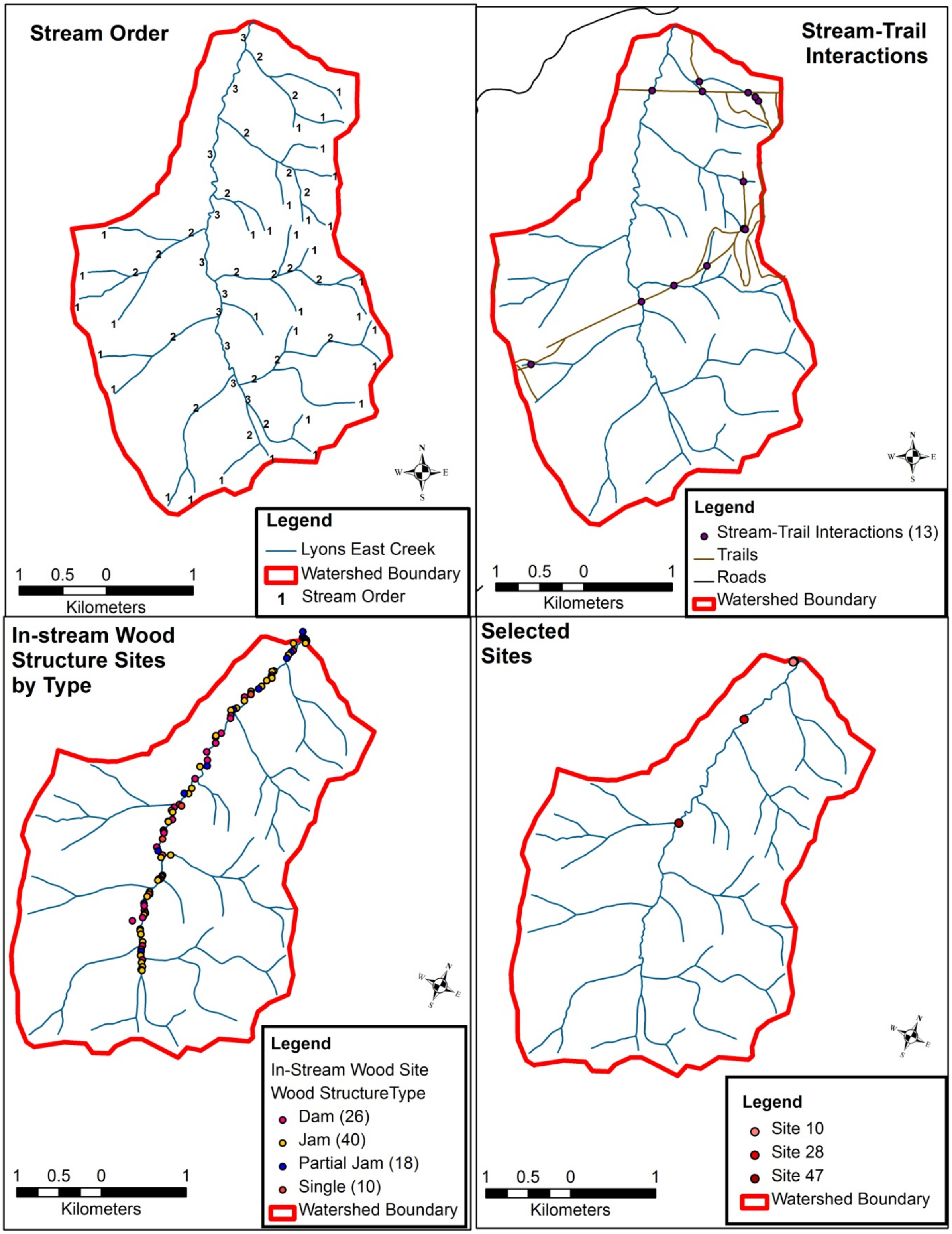


Figure 2-4: Four maps illustrating the watershed and wood characteristics for Lyons East. The stream order was completed based on Strahler (1952). The lower two maps illustrate the type of in-stream wood found and the location of the sites chosen for reach scale analysis

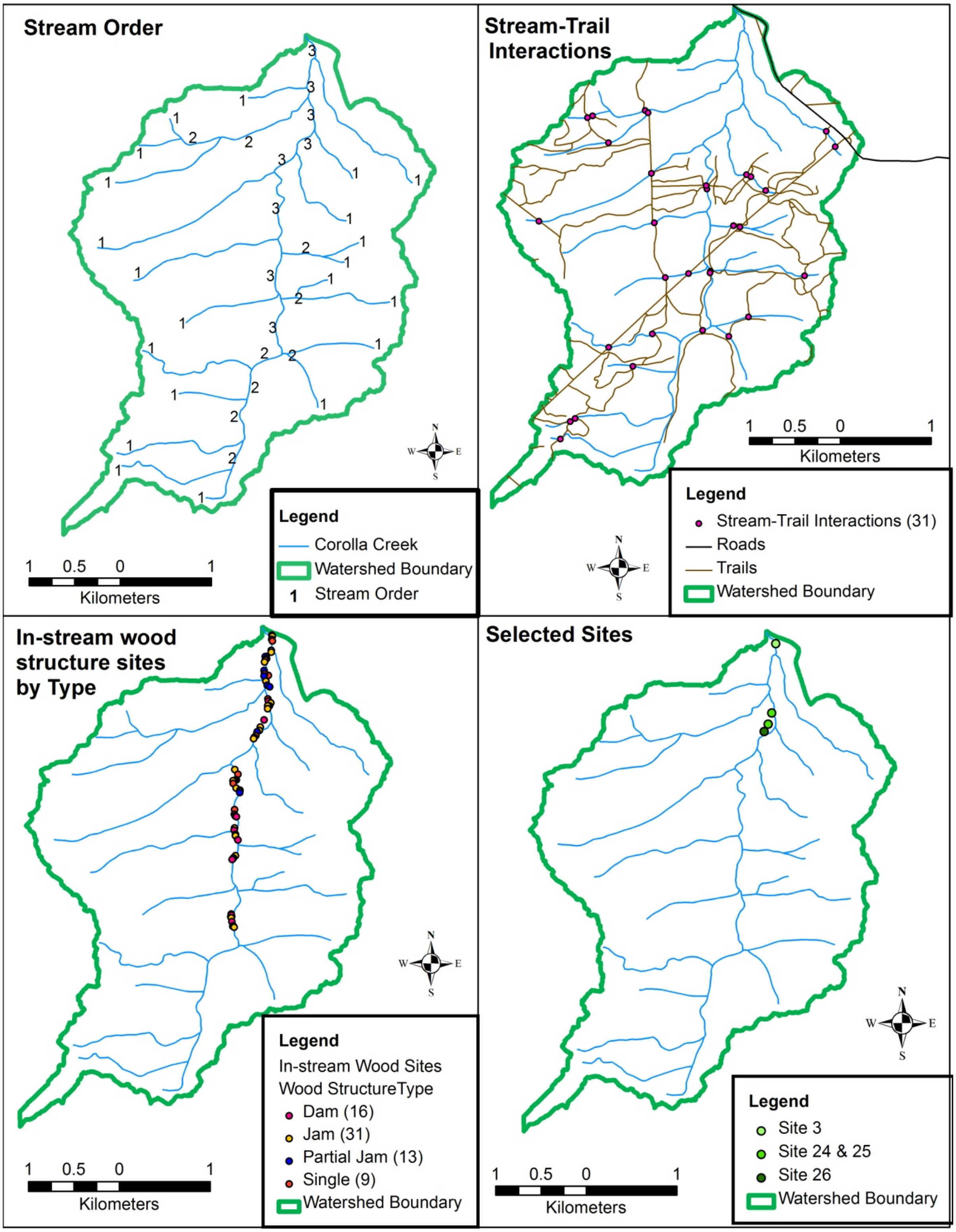


Figure 2-5: Four maps illustrating the watershed and wood characteristics for Corolla Creek. The stream order was completed based on Strahler (1952). The lower two maps illustrate the type of in-stream wood found and the location of the sites chosen for reach scale analysis.

2.3 Phase 1 – Spatial distribution and types of in-stream wood

2.3.1 Longitudinal profile

A longitudinal profile for each stream was created to determine the spatial distribution of in-stream wood along the main stem channel. The start locations were based on natural watershed boundaries and accessibility. For Corolla Creek, research began on the upstream side of a road bridge, to decrease anthropogenic influence and was terminated where the defined channel disappeared. Research in Lyons East was initiated on the upstream side of a road and was terminated at the confluence of the upper forks of the main stem channel. This termination point was used to minimize possible bias arising from the question of which tributary to analyse.

A longitudinal profile was created using a handheld Garmin GPSmap 60 unit. The GPS was securely attached to the researcher while walking upstream within the active channel. Using the tracking function a point was taken every ten seconds, recording the northing, easting and elevation. At each functional wood site, a waypoint was taken using the GPS and recorded with the accuracy in field books. The researcher waited for the best plus/minus accuracy before taking the waypoint. This was accomplished by leaving the GPS in one spot while completing the site analysis and taking the waypoint when the accuracy was within plus/minus 3 metres or less. If accuracy was not within three metres, multiple waypoints were taken to compensate for the inaccuracy. The elevation data may not have been within the three meter accuracy, as elevation measurements appeared to fluctuate more than northing and easting readings. The tracking points and waypoints were downloaded into MapSource and any outlying points were removed. The outlier points included travel to and from the stream location, and points taken where it was necessary to leave the active channel to traverse large obstructions.

2.3.1.1 GIS analysis of the longitudinal profile

Digital Elevation Model (DEM) data with one meter resolution was obtained from the University of Alberta courtesy of Dr. U. Silins after the field component of the study was completed. The DEM data has a 1m by 1m resolution and is complimentary to the data collected using the handheld GPS. The DEM data was used to create a longitudinal profile using the geographical information systems (GIS) program ArcMap 9.3. The spatial analysis hydrology toolbox in ArcMap 9.3 was used to create a watershed boundary for each of the studied watersheds using flow direction and accumulation data (see Figure 2-6). The GPS waypoint taken at the start location of each study stream was used to create the “pour point” feature. Once the watershed was defined, the main stem of each stream was determined based on the flow accumulation raster. A line feature was created for the main stem of each channel. The final step involved creating a line using the “interpolate shape” tool to extract elevation data from the filled DEM. This process provided a line showing the change in elevation over distance for each main stem channel, which was graphed as a longitudinal profile.

The data was compiled in ArcMap 9.3 and used to determine the location of in-stream wood sites along the main stem channel for each watershed. ArcMap 9.3 was used to calculate the length of the stream line feature, which was necessary to determine the spatial distribution of the in-stream wood sites along the channel profile. The GPS waypoint data were added to the map to show in-stream wood sites. For any in-stream wood site with more than one waypoint, accuracy records were consulted and the point closest to the stream was kept. If the waypoint was obviously an outlier, such that it did not follow the stream channel, it was discarded. The outliers were due to inaccuracy of GPS readings obtained during field work. The compiling of GPS data into ArcMap 9.3 allowed for a visual planform of in-stream wood structure distribution. The frequency of in-stream wood sites and each category of wood structure type for both watersheds were computed using the statistical program SPSS.

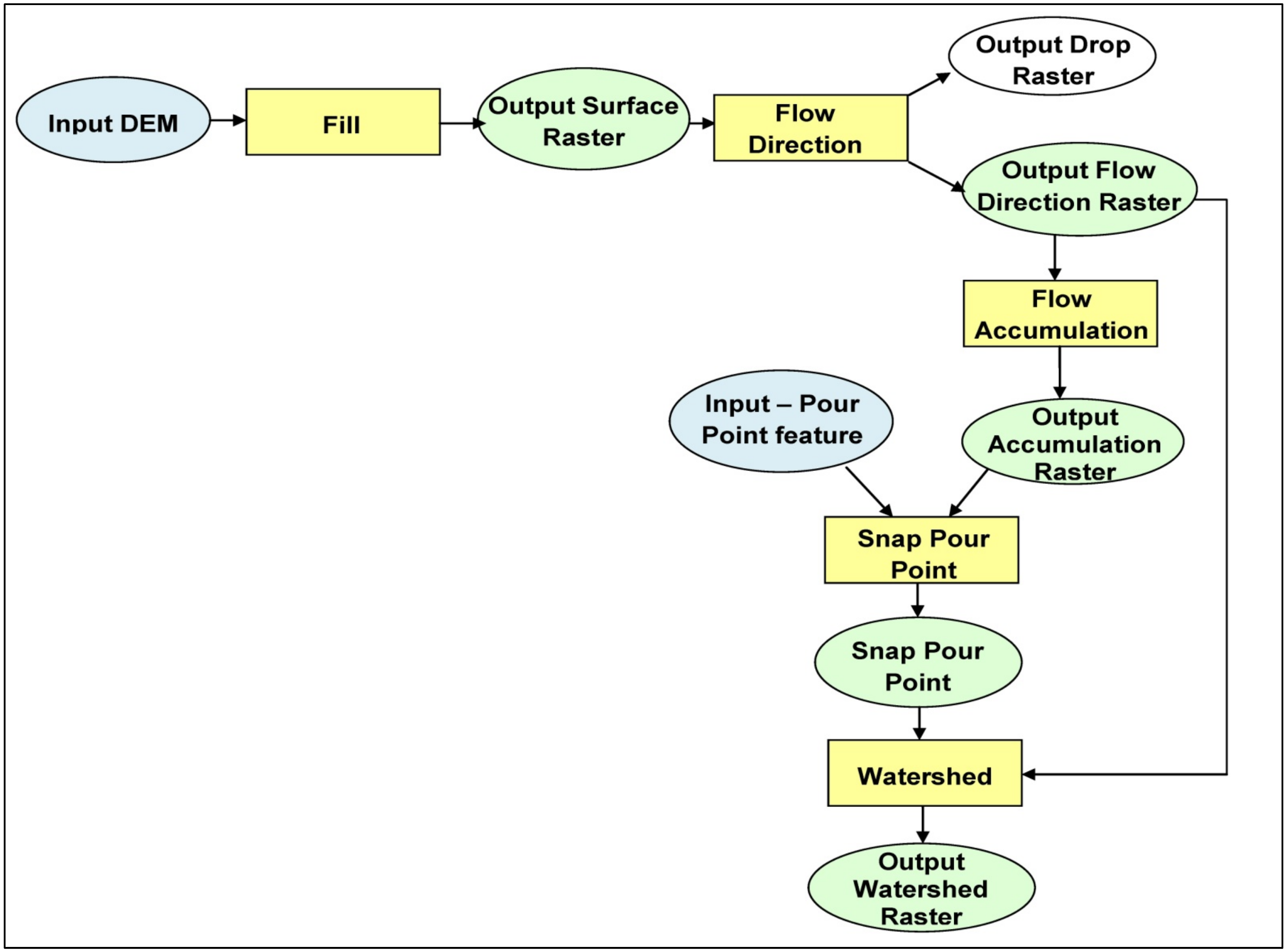


Figure 2-6: The ArcMap 9.3 ModelBuilder process used to create the watershed boundary raster for each watershed using the spatial analyst hydrology toolbox.

2.3.2 In-stream wood classification

For the purpose of this study, in-stream wood was defined as logs, pieces of wood, large branches, coarse roots and rootwads (Webb & Erskine, 2003, 2005). Typically researchers use a size requirement to categorize in-stream wood into large, fine and organic; however these size requirements were not explicitly used within this study. A Colorado study found small pieces are important in small mountain streams and it is inappropriate to exclude them from analysis; however this use of different definitions complicates result comparison across studies (Richmond & Fausch, 1995). This study focused on functional wood impacting the channel morphology, which is the reason for not restricting wood based on size. Previous research recommends this technique when examining the geomorphic function of in-stream wood (Chen et al., 2006). Therefore, functionality was used instead of size for dictating the relevance of in-stream wood. Functional wood was operationally defined as wood interacting directly with the active channel at low-flow conditions for the 2009 summer field season. Therefore wood suspended above the channel and not within the wetted channel at low flow conditions, was deemed non-functional (Gomi et al., 2001). Functional wood was further defined as any piece of woody vegetation, single or part of a structure that scoured, trapped or sorted sediment or protected the banks from erosion (Jackson & Strum, 2002). For the purpose of this research only pieces of wood that were functional according to the defined criteria were recorded.

At each study site with functional wood, the structure and wood characteristics were recorded. The description of in-stream wood included the structure type, orientation and position of key pieces. Wood characteristics surveyed included the presence of a rootwad and the complexity of branches. The key member of an in-stream wood structure was operationally defined as a log providing stability and influencing the shape of an in-stream wood structure. The structure was first classified based on the number of pieces it contained. A structure with one piece was classified as single whereas structures with two or more pieces touching were classified as a partial jam, jam or dam, depending on the impact on flow or channel morphology. The definitions used for each category of wood structure type are described in Table 2-4. The orientation and position were recorded for visible key member pieces of in-stream wood based on the definitions in Table 2-4.

Table 2-4: Descriptive definitions of woody deposit type, position and orientation used for the initial phase of the research project

	Descriptive definition	References
Wood structure type		
Single	A single piece of in-stream wood within the active channel	(Long, 1987)
Partial jam	Two or more pieces of in-stream wood, partially blocking the channel due to being incomplete or partly destroyed. Sometimes referred to as a passive dam.	(Gregory et al., 1993; Gregory et al., 1985; Gurnell et al., 1995)
Jam	Two or more pieces of in-stream wood, completely spanning the channel, but does not form a complete barrier due to "leaky" conditions within the structure.	(Gregory et al., 1993; Gregory et al., 1985; Gurnell et al., 1995)
Dam	Two or more pieces of in-stream wood, completely spanning the channel forming a barrier to water and sediment.	(Gregory et al., 1993; Gregory et al., 1985; Gurnell et al., 1995)
Position		
Bridge	The piece of wood is suspended across the stream channel	(Baillie & Davies, 2002; Jones & Daniels, 2008)
Partial bridge	The piece of wood is partially spanning the channel or spanning the channel and has broken in one or more places within the stream	Combination of definitions from (Baillie & Davies, 2002; Jones & Daniels, 2008)
Buried	The piece of wood is buried or partially buried in the substrate	(Baillie & Davies, 2002)
Submerged	The piece of wood is completely covered by water at low flow conditions.	
Loose	The piece of wood does not touch either bank and is not buried within the bed or banks	(Cadol et al., 2009; Wohl & Cadol, 2011; Wohl & Goode, 2008; Wohl & Jaeger, 2009; Wohl et al., 2009; Wohl et al., 2011)
Orientation		
Parallel	Parallel or close to parallel (0˚) to stream flow	(Andreoli et al., 2007; Baillie & Davies, 2002; Comiti et al., 2008; Richmond & Fausch, 1995)
Intermediate	Any angle between perpendicular and parallel to flow	(Andreoli et al., 2007; Comiti et al., 2008; Piégay et al., 1999)
Perpendicular	Perpendicular or close to perpendicular (90°) to stream flow	(Andreoli et al., 2007; Baillie & Davies, 2002; Comiti et al., 2008; Piégay et al., 1999; Richmond & Fausch, 1995)

Wood characteristics surveyed for the visible key member pieces in each functional wood structure included the presence of a rootwad and branch complexity. The presence of a rootwad was recorded as yes, no or unknown. The unknown category was used if the log extended too far onto the floodplain or up the hillslope to determine if a rootwad was still attached. The unknown category was also recorded if the rootwad end was not visible due to being buried in the stream bank or within the wood structure. A simplified version of Jones and Daniels' (2008) branch classification was used, reducing the five original categories to three; no branches, simple branches and complex branches.

A number of geomorphic characteristics based on visual observations along the longitudinal profile were obtained at each in-stream wood structure site. The valley shape and vegetation on both sides of the channel were recorded. The bank stability was qualitatively classified based on field observations as stable or compromised (slumping, undercut or incised). This classification was completed for both left and right banks, upstream and downstream of the wood structure. Morphological processes associated with functional wood, including pool formation, step formations, deflection of flow, armouring of banks and sediment storage, were recorded (Berg et al., 1998; May & Gresswell, 2003a; Trotter, 1990). These morphologic features were described and sketched in the field. The locations of pool formations and bars along the banks and within the channel were sketched in relation to the in-stream wood structure. Anthropogenic activities such as logging activity and trails parallel to or crossing the stream were recorded. Additional notes of possible external forces, primarily boulders and leaning trees, were recorded and sketched. The final step for the longitudinal profile analysis was a photographic catalogue of both the stream and the in-stream wood features directly upstream from, at and directly downstream of the structure. Each photograph included a scaled object for reference.

2.4 Phase 2 – Reach scale analysis of in-stream wood and stream morphology

2.4.1 Location of the in-stream wood sites selected for reach-scale analysis

The purpose of the second phase of this project was to characterize representative in-stream wood structures located in the two study streams at the reach level. Three sites were selected for each watershed (see Figures 2-4 and 2-5 for the site locations) based on field reconnaissance of the entire stream length. Each of the six study sites required the presence of a functional wood structure and the presence of at least one pool within the reach. The locations were chosen to represent typical in-stream wood structures and typical stream morphology characteristics found in the larger watersheds.

2.4.2 Survey techniques and measurements

Geomorphic characteristics of each study reach above, at and below selected wood structures were surveyed using a total station attached to a Ricon handheld computer and a prism attached to a rod. The prism had a constant of -30.0 mm. The survey team selected a location for the total station, which could be seen from the majority of features in the reach. The total station origin point was recorded and marked with a bright peg and survey tape. If the total station had more than one location in a reach, each origin point was marked with a peg and survey tape and numerically ordered. All pegs were left undisturbed until a survey of the stream reach was completed. The back sight was set at true North using a Brunton Compass, corrected for magnetic declination and marked with a survey pin and flagging tape. Prior to surveying the features, test points were marked with survey pins wrapped with flagging tape. These test points were shot each time the total station was started to ensure it functioned correctly. One member of the team operated the total station, shooting points and recorded point numbers for each feature. The total station operator was responsible for recording adjustments to rod height or total station location. The second team member positioned and levelled the rod and prism at each geomorphic feature along the study reach.

There were a number of features surveyed using the total station for each study reach. The right and left valleys were surveyed to determine channel confinement and extended approximately twenty to thirty metres perpendicular to the channel. The presence of abandoned channels within the surveyed valley was noted and points were recorded. Using visual changes in vegetation and slope as described in the USDA field technique guide (Harrelson et al., 1994), the bankfull width was surveyed. Next, cross-sections were completed directly above and below the wood structure, and then at approximately ten meter intervals extending upstream and downstream for the length of the reach. For each cross section, the survey points at the left and right water's edge were recorded in the field book. The left and right water's edge and thalweg were surveyed every couple of metres for the entire study reach. If a section had a defined feature occurring within a shorter distance, such as a boulder extending into the active channel, survey points were taken closer together. Next, the in-channel geomorphic features were surveyed, including riffles, pool perimeters and bar formations. The type of bar formation was recorded and classified as point bar, lateral accretion bar or mid-channel bar. Additional features, for example boulders and leaning trees, were also surveyed to provide information about possible influences on in-stream wood structure and channel morphology.

The in-stream wood structures were surveyed using the total station. The lengths of all accessible key member pieces were surveyed by placing the rod on top of either end of the log. To ensure the correct ends of in-stream wood were surveyed as the same code, flagging tape was numbered and attached to each piece. This technique allowed the rod holder to follow along each log to both ends and radio the code to the total station operator. The accumulation of smaller in-stream wood was surveyed around the structure's perimeter. There were some accessibility issues and safety concerns that restricted the researchers while surveying the perimeter of wood accumulation at some sites.

In addition to surveying each reach, a photographic catalogue was completed. These photographs provided additional information not captured by surveying and included an item for the purpose of scale. The in-stream wood was photographed looking upstream and downstream toward the structure and if possible from an overhead bird's eye view. This provided information on the three dimensional formation of the structure and its general characteristics. The general channel was photographed upstream and downstream of the in-stream wood structure. Any surveyed feature was included in these channel photos and noted in field books. All surveyed bar formations were photographed for further clast size analysis. The scale used was a pair of meter sticks with alternating bright orange and black intervals at ten centimetres. The orange was chosen to stand out against the neutral colours of the wood and the green of the vegetation. Prior to a feature being photographed an inventory card photo was taken. In addition as pictures were taken the associated photo number was recorded in field books with a description of the feature.

2.4.3 Channel classification

The channel reach morphology classification of each study site was completed using Montgomery and Buffington's (1997) methodology, which is based on bed form morphology in mountain streams. This classification was selected as it has been widely used in previously published in-stream wood research located in mountain systems. There are seven channel reach morphology types within the classification scheme: dune-ripple, pool-riffle, plan bed, step-pool, cascade, bedrock and colluvial. The information in Table 2-5 describes the patterns and processes necessary to classify each type of channel reach morphology.

For channel morphology parameters that could not be measured in the field, such as ratios (entrenchment and width:depth) and floodprone width, calculations and analysis were completed using computer software. After completing the 2009 field season, the data collected was used to calculate morphological features such as entrenchment ratio, floodprone width, bankfull width, bankfull depth, bankfull width:depth ratio, sinuosity and slope. These calculations were computed for each cross section in the study reach. In addition, the calculations for sinuosity and slope were computed for each study reach as a whole. The field survey did not include enough information for floodprone width calculations, so a combination of ArcMap 9.3 and ArcMap10 software was used to extract elevation data from longer transects. For all cross sectional calculations, the mean and standard deviation were calculated using SPSS Statistics19 and Excel 2007. These statistics were completed for the entire study reach as well as for above, within (where applicable) and below the in-stream wood structure. Based on Wentworth's (1922) size classification for clast sediment, bed material was estimated for each reach using field notes and visual estimates from field photographs with scale. The photographs used for the clast size analysis were bar formations with scale that allowed for an estimation of the average bed material size for each reach. The estimation of each clast size category was recorded as a percentage of the total area for each bar formation located within the selected reach.

Table 2-5: Characteristics of different channel reach morphology types based on the classification of Montgomery and Buffington (Source: (Montgomery & Buffington, 1997))

	Dune-Ripple	Pool Riffle	Plane Bed	Step Pool	Cascade	Bedrock	Colluvial
Typical bed material	Sand	Gravel	Gravel-cobble	Cobble-boulder	Boulder	Rock	Variable
Bedform pattern	Multi-layered	Laterally oscillatory	Featureless	Vertically oscillatory	Random	Irregular	Variable
Dominant roughness elements	Sinuosity, bedforms (dunes, ripples, bars) grains, banks	Bedforms (bars, pools) grains, sinuosity banks	Grains, banks	Bedforms (steps, pools), grains, banks	Grains, banks	Boundaries (bed and banks)	Grains
Dominant sediment sources	Fluvial, bank failure	Fluvial, bank failure	Fluvial, bank failure, in-stream wood flows	Fluvial, hillslope, in-stream wood flows	Fluvial, hillslope, in-stream wood flows	Fluvial, hillslope, in-stream wood flows	Hillslope, in-stream wood flows
Sediment storage elements	Overbank, bedforms	Overbank, bedforms	Overbank	Bedforms	Lee and stoss sides of flow obstructions	Pockets	Bed
Typical confinement	Unconfined	Unconfined	Variable	Confined	Confined	Confined	Confined
Typical pool spacing (per channel width)	5 to 7	5 to 7	none	1 to 4	<1	Variable	Unknown

2.4.4 Pool type classification

The location of a pool was recorded as upstream from, at or downstream of the in-stream wood structure. For the purpose of this research, pools were defined as areas with a nearly horizontal water surface within the main part of the channel occupying at least half the active channel width and included the thalweg (Hilton & Lisle, 1993; Lisle & Hilton, 1992). Pools were initially categorized as free form or forced based on their formational processes. Montgomery et al. (1995) defined free form pools as those occurring through natural interactions of flow and sediment transport processes; whereas forced pools are defined as forming due to local obstructions causing flow convergence and turbulence. If a pool was defined as a forced pool, the type of local obstruction was recorded. In particular if a log caused the obstruction, the pool was additionally classified as log-affected. Conversely, if the obstruction was not associated with in-stream wood it was classified as non-log-affected.

After determining the pools' formational processes as free or forced, log-affected or non-log-affected, all pools were classified based on the definition of Hawkins et al. (1993) as either scour or dammed. Scour pools were further categorized as trench, mid-channel, lateral, deflector, underflow, transverse, plunge, convergence or combination based on previously published definitions (Bisson et al., 1982; Hawkins et al., 1993; Robison & Beschta, 1990; Webb & Erskine, 2005). The combination of pool definitions was used since two were focused on ecology classifications (Bisson et al., 1982; Hawkins et al., 1993) and two were based on in-stream wood classifications (Robison & Beschta, 1990; Webb & Erskine, 2005). The use of one pool classification scheme did not encompass the variety of pools found within the study reaches, therefore multiple classifications were used to ensure accurate classification of pool formations**.** Dammed pools were not further categorized. The document *Stream habitat classification and inventory procedures for northern California* was used to clarify the detailed definitions of pool types found in the previously referenced papers (McCain et al., 1990).

2.4.5 Pool characteristic analysis

Pool parameters of length, width and depth for each pool found in the study reach were determined using the methods outlined by Hilton and Lisle (1993). Figure 2-7 illustrates this field method with one tape measure extended the length of the pool and the second tape measure extended across the pool. Any pool found along channel bends was divided into sections in order for the tape measure to remain straight and then added together to obtain the total pool length (Hilton & Lisle, 1993). The length of a pool is measured at the longest portion of the pool, however for some pools a visual estimate had to be used when in-stream wood obstructed the view of the entire pool. In addition, in-stream wood caused problems when measuring length as it was difficult to achieve a straight tape measure through more complicated structures. The length measurement was recorded in the field book for each pool located in a study reach.

Figure 2-7: Pool analysis field set up according to the methods presented in Hilton and Lisle (1993)

The width measurements were taken at set intervals (typically 0.5m or 1m apart) along the length of the pool. Hilton and Lisle (1993) state the first cross section should be located at a random number between zero and the distance between cross sections. The rationale for this is to have an unbiased, simple and systematic sampling technique. Within the modification section of the paper, the removal of systematic sampling is permitted to allow for improved accuracy of the estimate if necessary for the research project (Hilton & Lisle, 1993). Therefore, the location of cross sections was pre-determined to accommodate the obstruction of in-stream wood structures. This modification was used for all pools to maintain consistency. The pre-determined interval for pools with no in-stream wood was a cross section every meter or every half meter for smaller pools, starting at the most downstream end. When pools were formed due to in-stream wood the one meter transect was maintained where possible; however in cases where in-stream wood obstructed the transect line it was positioned within plus or minus ten centimetres of the intended location.

Depth measurements were obtained to determine cross sectional shape and pool volume. For each of the cross sectional transects used to measure width, depth measurements were taken. The depth measurements were completed at set intervals along the cross section based on the methods of Hilton and

Lisle (1993). The same modifications made to the simple and systematic sampling technique that was used for the width measurements, were used for depth measurements (Hilton & Lisle, 1993; Lisle & Hilton, 1999). Hilton and Lisle (1993) recommend increasing the frequency of depth measurements for more complicated pools. Therefore, a minimum of ten measurements across the stream were completed for simpler pools and then increased with pool complexity. A standard of 10cm intervals was used for complex pools.

The field technique for acquiring depth measurements were modified slightly based on available equipment. According to Hilton and Lisle's recommendations a graduated steel rod made of one-half diameter stainless steel was to be used for depth measurements (Hilton & Lisle, 1993; Lisle & Hilton, 1999). This equipment could not be obtained for the project and was replaced with an aluminum rod measuring one centimetre in diameter, with a metal meter stick zip-tied securely to the rod. The strength of the rod-meter stick was tested in shallow water to ensure bending did not occur. Depth measurements were taken at each interval by touching the rod to the stream bed and reading the value at the bottom of the meniscus. The field data for the length, width and depth measurements for each pool were used to calculate volume (Hilton & Lisle, 1993).

2.5 Sediment storage within pool feature analysis

The final component of this research project was to measure the thickness and volume of cohesive sediment deposits located in pools. For each pool found in the six study reaches, the thickness of surficial cohesive sediment in pools was measured. The same locations for water depth measurements were used to obtain the thickness of cohesive sediment measurements (Hilton & Lisle, 1993). After the water depth was recorded, the rod was probed into the sediment until an abrupt change in resistance occurred, indicating a transition from finer material to sand and gravel (Hilton & Lisle, 1993). The combined depth of water and sediment was recorded in the field and then water depth was subtracted from the measurement to determine sediment thickness.

The sediment data collected in the field was then used in calculations to obtain the volume of cohesive sediment within the residual pool. Using the procedure outlined by Hilton and Lisel (1993) the volume of cohesive sediment was calculated and then used to determine the ratio of fine-sediment volume to pool water volume plus fine-sediment volume (V*). The weighted average (V_w*) was calculated using the below formula proposed by Hilton and Lisle (1993).

$$V_w^* = \frac{\sum(residual\ fines\ volume)}{\sum(scoured\ residual\ pool\ volume)} \tag{2}$$

2.6 Planform and cross sectional analysis

After the 2009 field season, the collected data was compiled using computer software for further analysis. For the initial phase of this research project, a longitudinal profile for each channel was necessary. Two longitudinal profiles for each watershed were graphed using Microsoft Excel 2007. The first longitudinal profile was created using the waypoints taken at each in-stream wood location. This profile had a number of inaccurate waypoints, so the data was put into ArcMap10. The second longitudinal profile created used data extracted from the stream channel feature created in ArcMap10. This profile was created by extracting elevation data from the filled DEM along the stream feature using the interpolate shape tool. The waypoints were then added to the map and elevation data was extracted for each point using the interpolate shape tool. This point data was graphed as a longitudinal profile using ArcMap10. The reach scale longitudinal profiles were constructed using survey data for the first profile and extracted elevation data from the filled DEM for the second graphed profile. The reach scale longitudinal profile data was exported from ArcMap10 into Microsoft Excel 2007 to graph and add wood structure location or water surface information.

Additional graphs were created using the survey data to provide information on elevation changes within the study reaches. The survey data was used to graph the cross sectional profiles for the valley, bankfull and channel using Microsoft Excel 2007. These graphs were used to aid in the channel reach morphology classification. In addition to the channel cross sections, the pool cross sections were also graphed. The pool cross sectional graphs included the location and thickness of cohesive sediment storage. This provided a three dimensional illustration for each pool measured. All cross sectional graphs were completed using Microsoft Excel 2007.

Computer software was used for mapping and graphing the six reach scale sites studied during the second phase of field investigation. The survey data was compiled and sorted by feature for each site using Microsoft Excel 2007 and then added to ArcMap9.3 to create point shapefiles for each of the features. The points were used to create line and polygon features to map the planform view of each of the study reaches. If survey points were not in chronological order, which often occurred because of overlap from different total station origins, the order of points was determined and corrected. The correction was completed by adding a new column of identification numbers in the attribute table in ArcMap. The line features created were the thalweg, banks and cross sections. The polygon features created were bars, pools and cohesive sediment deposits. The process of creating features allowed for accurate length and area measurements to be calculated using ArcMap9.3 software for lines and polygons respectively.

2.7 Statistical analysis

Statistical analysis was completed for the data collected during the initial phase of investigation. The information collected for each variable in the field was given a nominal code associated with the description of the feature. Due to the number of sites in the current study, descriptive statistics were completed for the in-stream wood structure types for each of the studied watersheds. Cross tabulation statistics were computed using SPSS Statistical19 software to examine relationships between the type of disturbance and the in-stream wood structure formations. In addition multiple cross tabulation statistics were run for channel morphology, key member pieces and in-stream wood formation type variables. These statistics were used to determine if there were relationships between channel features and wood formations. For each statistical test, a chi-square analysis was completed to determine if the relationship was statistically independent (no relationship). The null hypothesis of independence was rejected if the asymptotic significance was reported as less than 0.05.

Calculations and statistical analysis were computed for the geomorphic data collected at the reach scale for each of the six sites. During the field investigation channel measurements were taken at multiple cross sections above and below (and within or between where applicable) the in-stream wood structures. These measurements provided information on the active channel width, thalweg depth, mean channel depth, wetted perimeter, bankfull width, bankfull depth and floodprone width. Using these measurements the cross sectional area, width:depth ratio, entrenchment ratio and hydraulic radius were calculated. For each of the above mentioned parameters the average and standard deviation were calculated for the entire reach and then for above and below (and within or between where applicable) the in-stream wood structure.

2.8 Limitations

A few limitations were encountered during this research project. Natural limitations included weather conditions and wildlife. Precipitation events often change the amount of water entering a stream system, which alters water level and flow in the active channel. To maintain consistency, the research project was conducted at reaches during low flow conditions. Therefore, if water levels rose, field work stopped until low flow conditions returned. The use of low flow conditions was particularly important for the sediment storage analysis to ensure sediment was not in suspension. The need for constant conditions meant weather conditions further impacted the already tight time constraints for the second phase of the project.

When working in remote wilderness areas, wildlife is a safety consideration. Signs of wildlife were noted throughout the duration of the project. During the final phase of research, there were increasing signs of a bear in the area, which had to be considered prior to completing further field research. An additional survey site was not completed due to fresh bear signs occurring within less than twelve hours of the team's arrival and the research team being outfitted with only simple bear protection. The safety and comfort level of the researcher and assistant had to be considered and the decision was made not to proceed.

An additional limitation to the field component of this research project was the travel time to, and accessibility of, sites. The travel time for the first phase of the study restricted the number of remote backcountry sites completed within a day. The second phase of research had to be conducted at sites accessible by foot with the equipment, as access through other modes of transport was limited or restricted.

Limitations were associated not only with the physical environment, but with the equipment used. Equipment limitations occurred with the handheld GPS unit and the survey equipment. The hilly terrain and tree cover contributed to limited accuracy while using the handheld GPS unit. Since GPS relies on access to orbiting satellites, a thick tree canopy such as occurs in parts of Corolla Creek made it difficult to obtain accurate tracking and waypoint readings. The hilly terrain could have also caused some obstruction for accurate GPS readings. Even with these constraints, there were minimal sites where accuracy of plus or minus three metres could not be obtained.

The surveying knowledge of the research team was a limiting factor during the second phase of data collection. In addition to the lack of knowledge, physical constraints of the natural environment imposed restrictions on the ability to survey. For example, the ability to survey straight transect lines over the distance of the valley cross section was restricted by tree density. In reaches with increased tree density transects were limited to shorter distances across the valley. This was particularly noticeable within Corolla Creek where tree and branch density caused numerous obstructions. The reflective water surface caused scattering within the prism, which led to false survey points. These problems were compounded due to the team's lack of experience and minimal knowledge of the equipment and survey techniques. In addition, malfunctioning equipment further complicated the surveying process and required consultation with experts as problems arose.

Chapter 3
Results

3.1 Spatial distribution of in-stream wood deposits

This research project examines the spatial distribution of in-stream wood structures along the longitudinal profile of two headwater streams in the Alberta Rocky Mountains. Within the two study watersheds, 160 functional in-stream wood deposits were identified; 94 in Lyons East and 66 in Corolla Creek. Figure 3-1 illustrates the shape, channel network and spatial distribution of in-stream wood deposits along the main stem channel of each studied watershed. In Lyons East, the distribution of in-stream wood appears to be more uniform along the channel, whereas in Corolla Creek wood deposits tended to cluster together along the channel with gaps in between the clusters. The clustering of in-stream wood deposits in Corolla Creek occurs throughout the longitudinal profile; however there is a more uniform distribution at the downstream end of the channel, with clusters occurring in the middle section after an initial gap (Figure 3-1). For example, the upper section of in-stream wood sites is clustered together with gaps of no wood

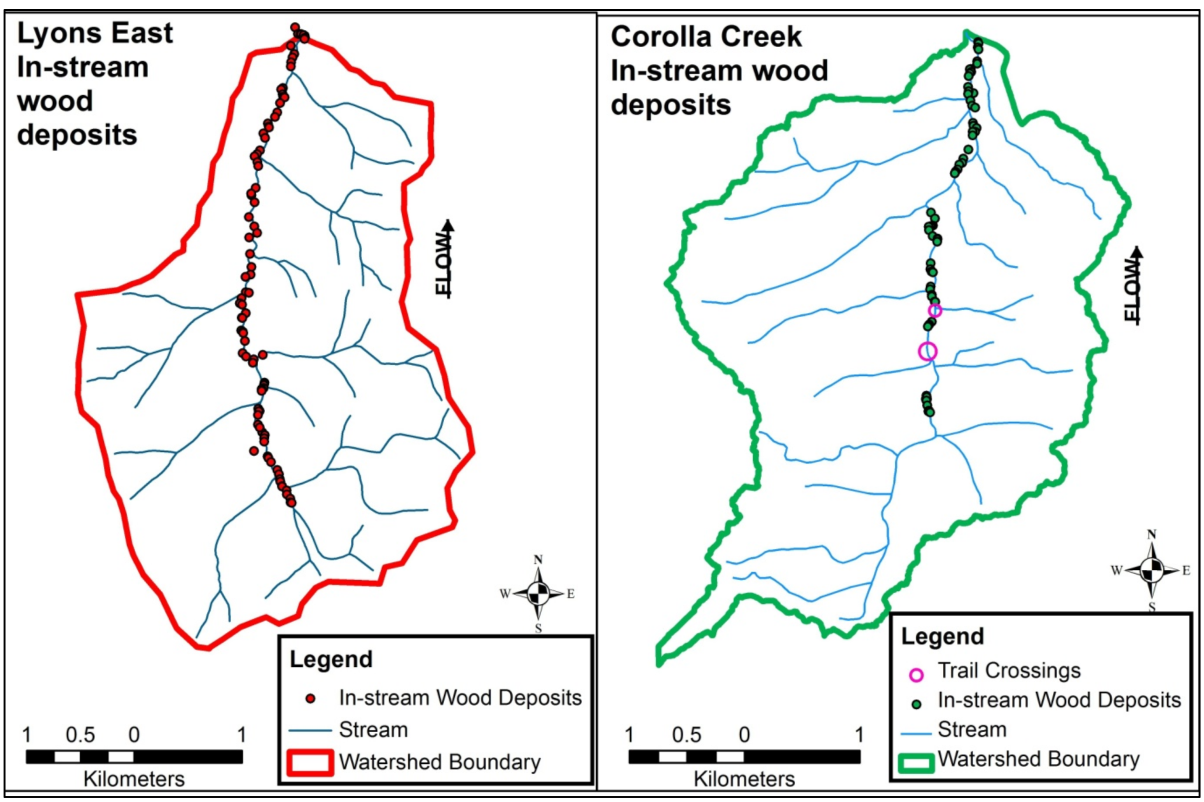


Figure 3-1: Distribution of in-stream wood deposits in Lyons East (left) and Corolla Creek (right). In Corolla Creek, trail crossing buffers are represented by pink circles.

found on either side (Figure 3-1). Two trail crossings occur along the main stem channel in Corolla Creek and are illustrated by pink circles (Figure 3-1). The trail network is primarily used by all-terrain vehicles (ATVs). These trails can have wood deposits that are deliberately placed near the stream banks to provide traction at non-bridged stream crossings. Since the in-stream wood deposited near these trails may not be from a natural source, the researcher chose to maintain a buffer on either side of the channel. The buffer zone was defined as 200m on either side of any trail crossing found in the basin. This buffer maintained the selection of only naturally-occurring, functional in-stream wood structures for both watersheds. Since information was eliminated based on the researcher's decision to buffer trail crossings and not natural variation, the pink circles indicate these buffer zones.

Longitudinal profiles of the main stem of each channel are illustrated in Figures 3-2 and 3-3 for Lyons East and Corolla Creek, respectively. The top profile in both figures illustrates the main stem gradient of the entire channel. The bottom profile in both figures (3-2B and 3-3B) illustrates the main stem channel gradient initiating at the first deposit site and terminating at the last in-stream wood deposit site, for Lyons East and Corolla Creek respectively. These bottom graphs show the location of all functional in-stream wood deposits in relation to the longitudinal profile and the location of the reach scale sites selected for the second phase of the project. It is important to note that the x-axis scale is different between the longitudinal graphs for each watershed. The graph illustrating the woody deposits along the profile for Corolla Creek (Figure 3-3B) is marked with two pink circles, these correspond to the circles on the planform map (Figure 3-1) and represent trail crossing buffers. These circles show where gaps in the spatial distribution of woody deposits occur based on defined buffers instead of natural variation. Differences in defined and natural gaps along the spatial distribution are important to note prior to further analysis. For example, in Corolla Creek (Figure 3-3B) the long gap around 2,000 metres was located within a bedrock section of the channel that naturally lacked the presence of in-stream wood deposits. To gain further understanding of the distribution and characteristics of in-stream wood each location was categorized by structure type based on definitions from current literature.

The categories of in-stream wood structures for the purpose of this research are: single, partial jam, jam and dam. Each site within the watersheds is classified according to one of four structures based on the number of wood pieces, restriction to flow and proportion of the channel obstructed. The criterion for the structure type is outlined in Chapter 2 in Table 2-4. To illustrate the wide natural variety of in-stream wood, representative photos for each type of structure are presented in Appendix D for Lyons East and in Appendix E for Corolla Creek. The photographs provide information on the channel, riparian environments and wood characteristics found in each studied watershed. The order of photographs (figures) located in the appendices increase with increasing structure complexity. Figure D-1 and Figure

E-1 are photographs representing a single wood structure; Figures D-2, D-3, E-2 and E-3 represent partial jams; Figures D-4 and D-5 and Figures E-4 through E-6 represent jams; and Figures D-6 though D-8 and Figures E-7 and E-8 represent dams. Each of the photographs includes a site number in the upper left corner corresponding to the site number recorded during field investigation. The photographs presented in both Appendix D and Appendix E were selected to represent the common structure types and provide examples along the entire longitudinal profile.

The two study watersheds represent different land use disturbances (natural and anthropogenic). For each watershed, the number of functional wood sites is divided by structure type and presented in Table 3-1. To evaluate impact land use has on the distribution of in-stream wood structures, the frequency of each category was calculated (Table 3-1). The sites were located along the main stem of each watershed, with a recorded length of just over 6295 m (~6.3km) for Lyons East and just under 4444 m (~4.4km) for Corolla Creek. Despite the difference in the number of sites along the channel, the total frequency of in-stream wood structures for both watersheds is the same at 1.49 sites per 100m, as shown in Table 3-1. The values for each type of in-stream wood structure are expressed in Table 3-1 as a frequency per 100m for both Lyons East and Corolla Creek. Although the total frequency of in-stream wood structures is the same for both watersheds, there are variations between the four sub-categories of structure types. The frequency of jams is the highest of the in-stream wood structure types in both watersheds; Lyons East has 0.64 jams per 100m compared to Corolla Creek, which has 0.70 jams per100m.

Table 3-1: Number and frequency of in-stream wood structure types along the main stem of Lyons East and Corolla Creek

Wood structure type	Lyons East Count	Lyons East Frequency (/100m)	Corolla Creek Count	Corolla Creek Frequency (/100m)
Single	10	0.16	9	0.20
Partial jam	18	0.29	13	0.29
Jam	40	0.64	31	0.70
Dam	26	0.41	13	0.29
Total	**94**	**1.49**	**66**	**1.49**

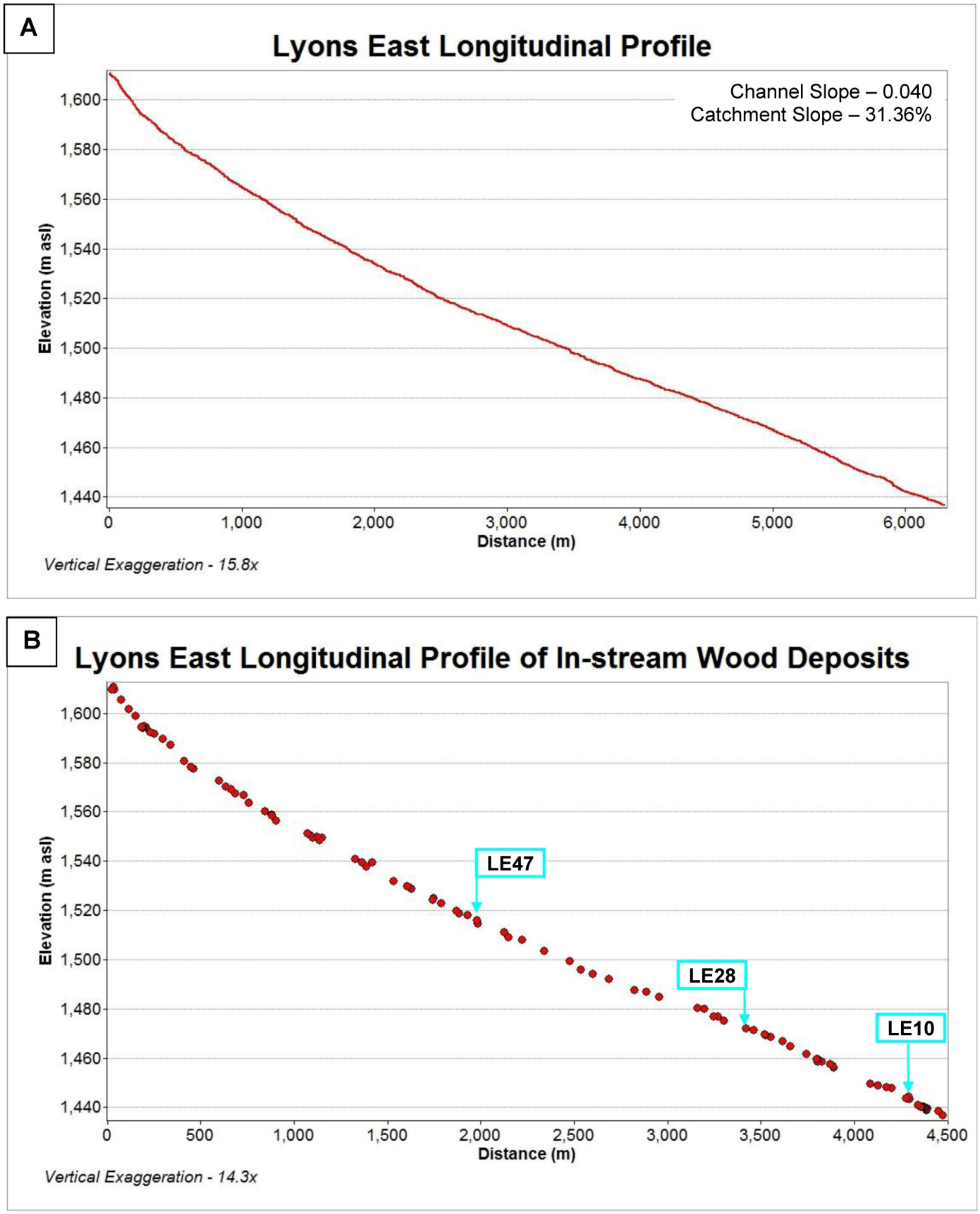


Figure 3-2: Longitudinal profile for Lyons East illustrating the channel main stem (2A) and location of in-stream wood deposits (2B). Note the different vertical exaggerations and x-axis scale.

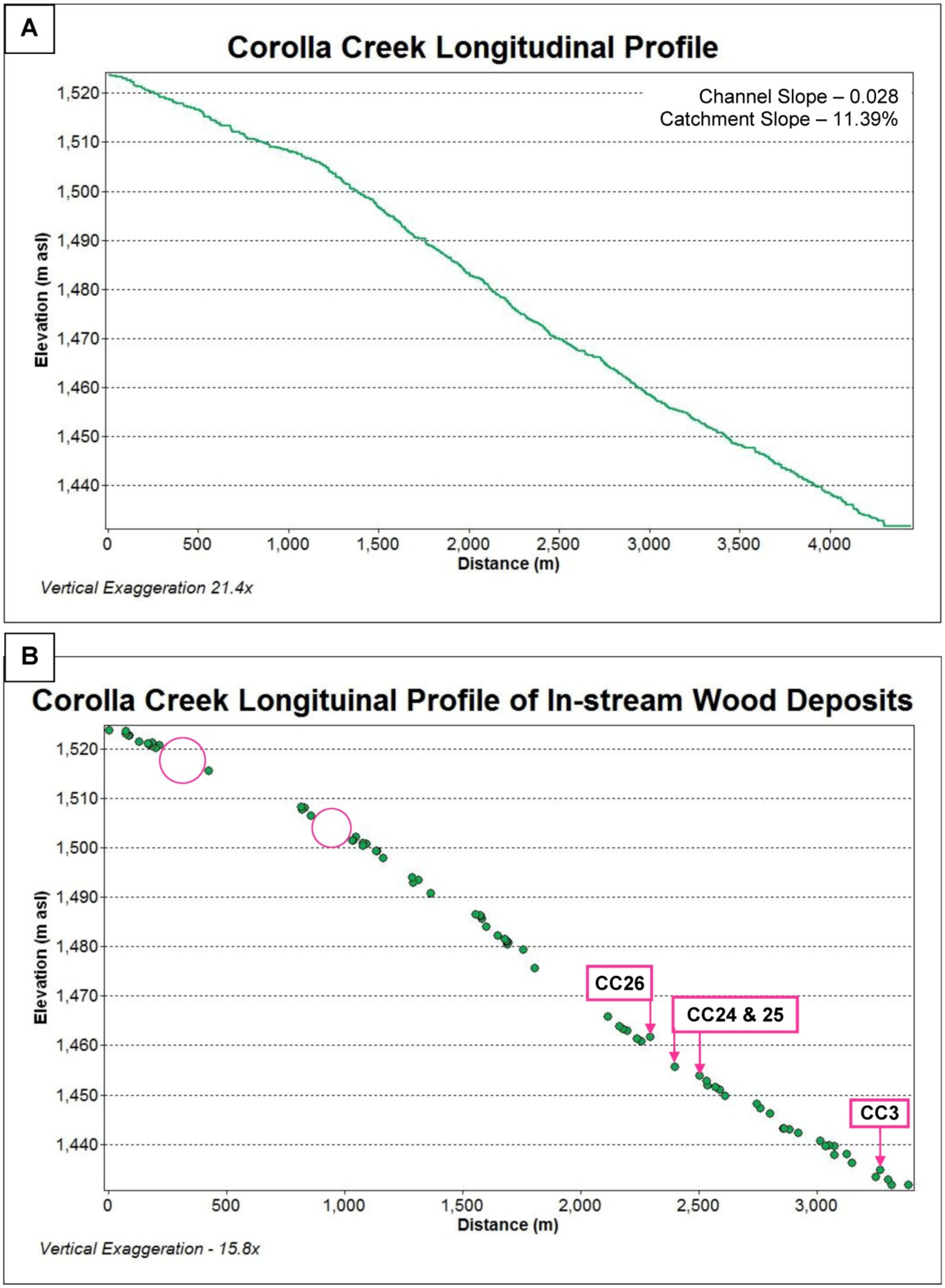


Figure 3-3: Longitudinal profile for Corolla Creek illustrating the channel main stem (3A) and location of in-stream wood deposits (3B). Note the different vertical exaggerations and x-axis scales.

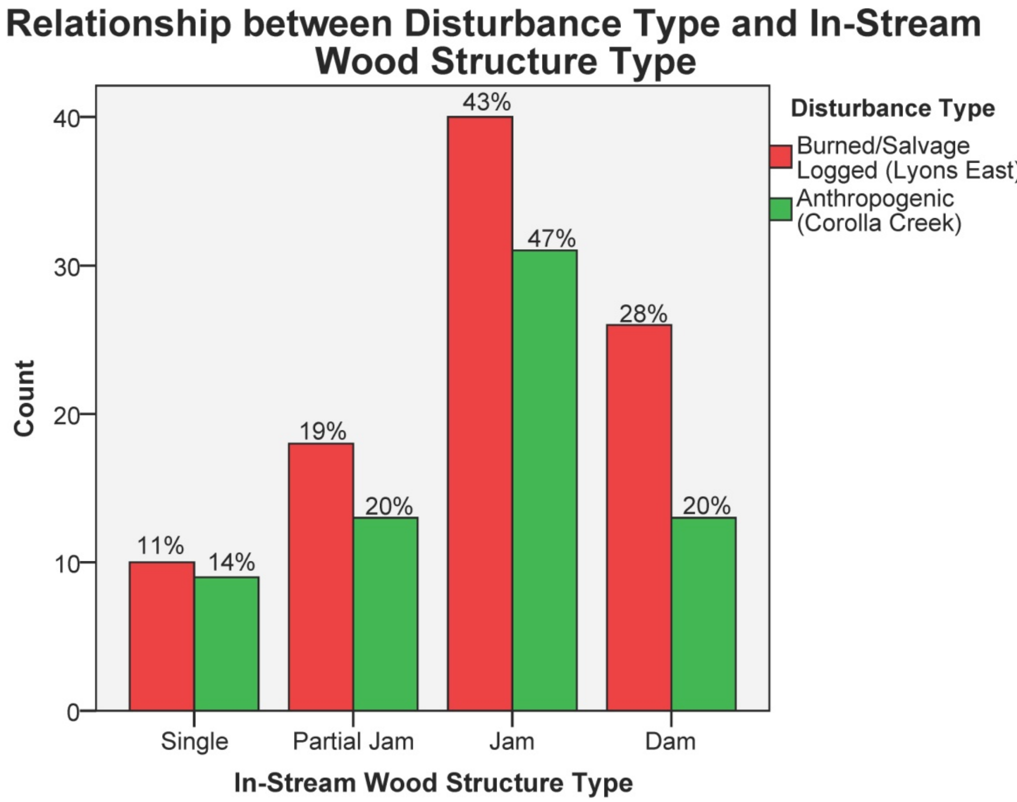


Figure 3-4: The number (and percentage) of in-stream wood structure types found in the two study watersheds.

When the in-stream wood structure types are represented as a percentage, the similarities and differences between watersheds can be compared (Figure 3-4). In-stream wood structure types are similar between the two watersheds with single structures being the least common (11% and 14%), and jam structures the most common (43% and 47%). The high number of jams, 40 jams (43%) in Lyons East and 31 jams (47%) in Corolla Creek includes a range in structural characteristics within the category. The selected jam definition included a number of different structure characteristics, examples of this diversity can be found in Figures E-9 and E-10 (Appendix E). In the two photographs in Figure E-9 the same structure characteristics are present within the structure, with two bridged logs accumulating loose wood on the upstream side. However, in Figure E-9B (Appendix E) the jam has accumulated more loose wood, making it a more complex structure as compared to Figure E-9A. The difference between the simple and more complex jams in Figure E-9 demonstrates the diversity of structures included within the jam definition. The primary difference between the two watersheds is the higher percentage of dams located within Lyons East (28%) as compared to Corolla Creek (20%) (Figure 3-4).

Data on the location and type of in-stream wood along the longitudinal profile is used to create a categorical spatial distribution and longitudinal profile of in-stream wood structure types for each watershed. The spatial distribution of in-stream wood classified by structure type is presented in Figures

3-5 and 3-6 for Lyons East and Corolla Creek, respectively. The figures show a slight trend towards partial jams (blue) clustering in the downstream section of both watersheds as compared to other structure types. In addition, other similar structure types generally appear to cluster together along the profile. However, the clustering of jams could be a visual representation of the higher proportion of sites categorized as a jam (43% for Lyons East and 47% for Corolla Creek). In order to better understand the relationship between land disturbance type and in-stream wood structures, the data were analyzed statistically.

3.1.1 Statistical results for in-stream wood distribution

Cross tabulation and chi-square statistics were used to determine relationships between variables. The first cross tabulation and chi-square test examined the independence between land disturbance type and in-stream wood structure type (Table 3-2). The chi-square test of independence was then completed for land disturbance type and each morphological variable (valley, bank stability, vegetation and pool and bar formations). The only test with enough observations to be statistically significant was channel shape and the results are presented in Table 3-2. In addition, statistical tests of independence between key member wood characteristics (position, orientation, rootwad presence and branch complexity) and landscape disturbance were examined. Only rootwad presence and branch complexity were found to have enough observations to be statistically significant and the results are recorded in Table 3-2.

Table 3-2: Chi-square tests for land disturbance type

	Asymp. Sig (2-sided)			
	In-stream wood structure type	**Channel shape**	**Rootwad presence**	**Branch complexity**
Land disturbance	0.687	0.982	0.000	0.101

A number of cross tabulations were tested for statistical significance using chi-square. However, due to an insufficient number of observations in some categories, which violated the assumptions of the statistical test and the relationship, significance could not be determined. The tests where significance could not be determined included the relationship between in-stream wood structure type and a number of variables, such as valley; downstream and upstream bank stability; vegetation on left and right banks; pool type; and bars along the banks and within the channel. With respect to the relationship between in-stream wood structure type and key member characteristics, no statistical significance could be calculated for orientation, presence of a rootwad or branch complexity. The two variables, channel shape and key member position, had enough observations to complete the statistical chi-square test of independence. Table 3-3 reports the results of the chi-square tests for both channel shape and key member position, in relation to the type of in-stream wood structure formed.

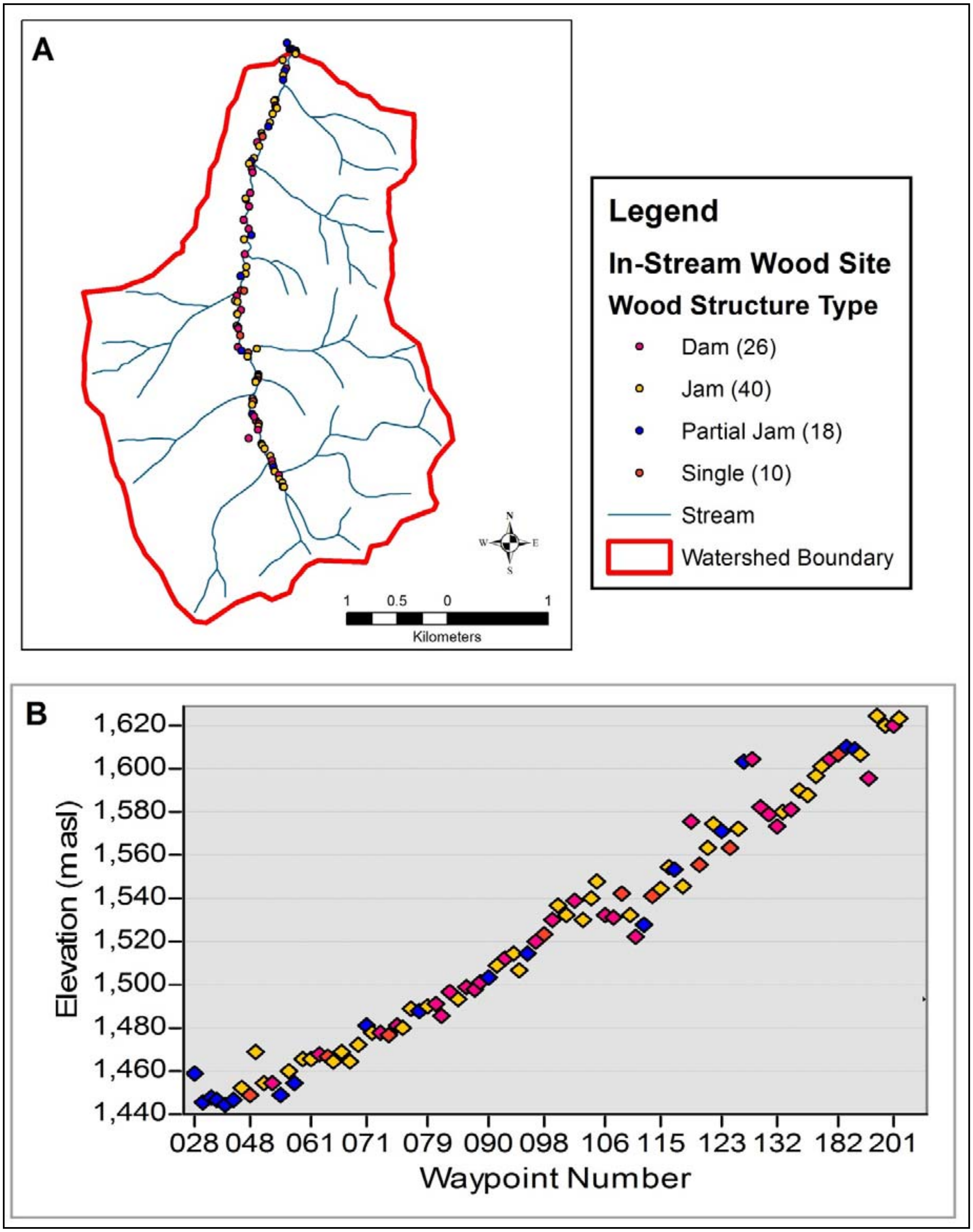


Figure 3-5: Spatial distribution of in-stream wood structure type along the planform (5A) and longitudinal profile (5B) for Lyons East

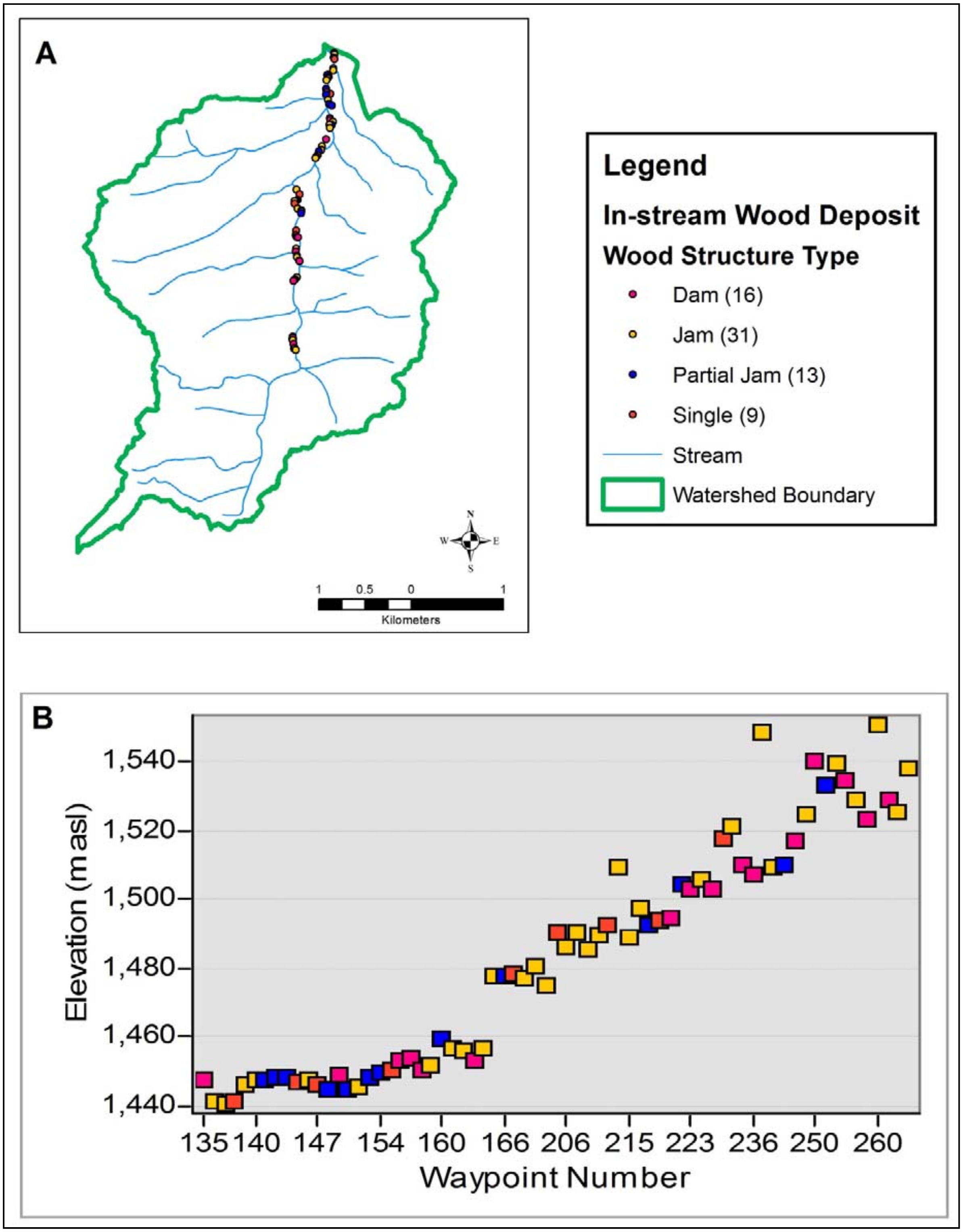


Figure 3-6: Spatial distribution of in-stream wood structure type along the planform (6A) and longitudinal profile (6B) for Corolla Creek

Table 3-3: Chi-square test results examining in-stream wood structure relationships

	Asymp. Sig (2-sided)	
	Channel shape	**Key member position**
In-Stream wood structure	0.013	0.001

3.2 Phase 2 – Reach scale analysis of channel characteristics for six selected in-stream wood sites

The morphological characteristics of in-stream wood structures were examined at three reaches in each of the two study watersheds. The selected sites are numbered based on their position in the initial longitudinal phase and include, Lyons East sites 10, 28 and 47 (LE10, LE28 and LE47) and Corolla Creek sites 3, 24 & 25 and 26 (CC3, CC24&25, CC26). The site CC24&25 was the only reach where two sites were combined due to the short distance between them. These locations, selected for the second phase of reach scale analysis, are labelled on the in-stream wood site graphs in Figures 3-2B and 3-3B in the previous section. The site locations within Corolla Creek are clustered more toward the downstream end of the profile due to accessibility limitations. Although the sites selected for Lyons East are more dispersed along the profile, they are generally located towards the lower half of the watershed due to accessibility restrictions. The GPS coordinates (latitude and longitude), elevation and measured plus/minus error for the selected sites are recorded in Table F-1 (Appendix F).

Planform maps for Lyons East (Figures 3-7 to 3-9) and Corolla Creek (Figures 3-10 to 3-12) provide information on the stream shape and general channel characteristics such as width upstream from, at and downstream of the in-stream wood structure. The location of the cross sections used to determine the channel parameters are illustrated on each of the six figures (Figures 3-7 to 3-12). Since the survey of the in-stream wood structure could not fully express its complexity, a photo was added to each planform map to illustrate the type of in-stream wood present. More detailed photographs showing the view looking towards the woody deposit site from both the upstream and downstream perspective are found in Appendix F. These photographs show the structural form of the woody deposit at each site location as well as the local channel characteristics. The figures within Appendix F follow the same order as the planform maps; LE10, LE28, LE47, CC3, CC24&25, and CC26.

The location of the in-stream wood structures are shown in the planform maps with sites LE10 and LE47 occurring at distinct meander curves, sites LE28, CC3 and CC25 situated at positions of a channel shift or more abrupt bend and sites CC24 and CC26 located along a straight channel. Channel morphometric characteristics for each of the six study reaches are listed in Table 3-4. The Lyons East sites have a higher sinuosity than Corolla Creek; however, within each watershed sinuosity has little variation. In Lyons East, sinuosity ranged from 1.20 to 1.53 with two of the reaches having a sinuosity of 1.53 (LE10 and LE47). In Corolla Creek, sinuosity ranged from 1.09 to 1.15 (Table 3-4). The stream length, sinuosity and channel shape provide information on the general channel reach characteristics; however information collected at cross sections provide details of changes in channel characteristics upstream from, at and downstream of the wood structures.

Table 3-4: Study site characteristics for Lyons East and Corolla Creek

Stream/Site	Stream length (m)	Valley length (m)	Sinuosity	Radius of curvature	Reach slope (%)
Lyons East					
Site 10	122	80	1.53	5.23	2.49
Site 28	101	84	1.20	3.72	2.15
Site 47	90	59	1.53	2.19/3.85	2.11
Corolla Creek					
Site 3	103	89	1.15	3.75	1.90
Site 24&25	87	78	1.09	5.32	2.42
Site 26	93	84	1.11	19.73	2.67

The cross sectional data can provide information into the channel forms and processes occurring upstream from, at and downstream of the in-stream wood structures for each study reach. Figures 3-7 to 3-12 show that the channel narrows just before the in-stream wood structure for sites LE28, LE47, CC3, CC25 and CC26. At site LE10, the channel appears to widen directly upstream of the structure and site CC24 changes little in channel width. To determine the actual changes in channel dimensions the width, depth, wetted perimeter and hydraulic radius at each cross section was calculated. A summary of the averages for upstream and downstream of the in-stream wood deposit can be found in Table 3-5 for Lyons East and Table 3-6 for Corolla Creek. More detailed cross sectional data for each reach is located in Appendix G. Table 3-5 summarizes the data for Lyons East and has italic values in the floodprone width and entrenchment ratio columns. These italic values have a different number of observations (n) due to the inability to obtain floodprone width for those particular cross sections using GIS. The channel parameters presented in Tables 3-5 and 3-6 include active channel width (W_{AC}), bankfull width (W_{BF}) floodprone width (W_{FP}), thalweg depth (D_{Thal}), mean active channel depth (D_{AC}), bankfull depth (D_{BF}), wetted perimeter (P_{AC}), bankfull width:depth ratio (W:D), entrenchment ratio (ER) and hydraulic radius (R_h). The values in Tables 3-5 and 3-6 are the averages for each of the channel parameters with the standard deviation located in brackets underneath.

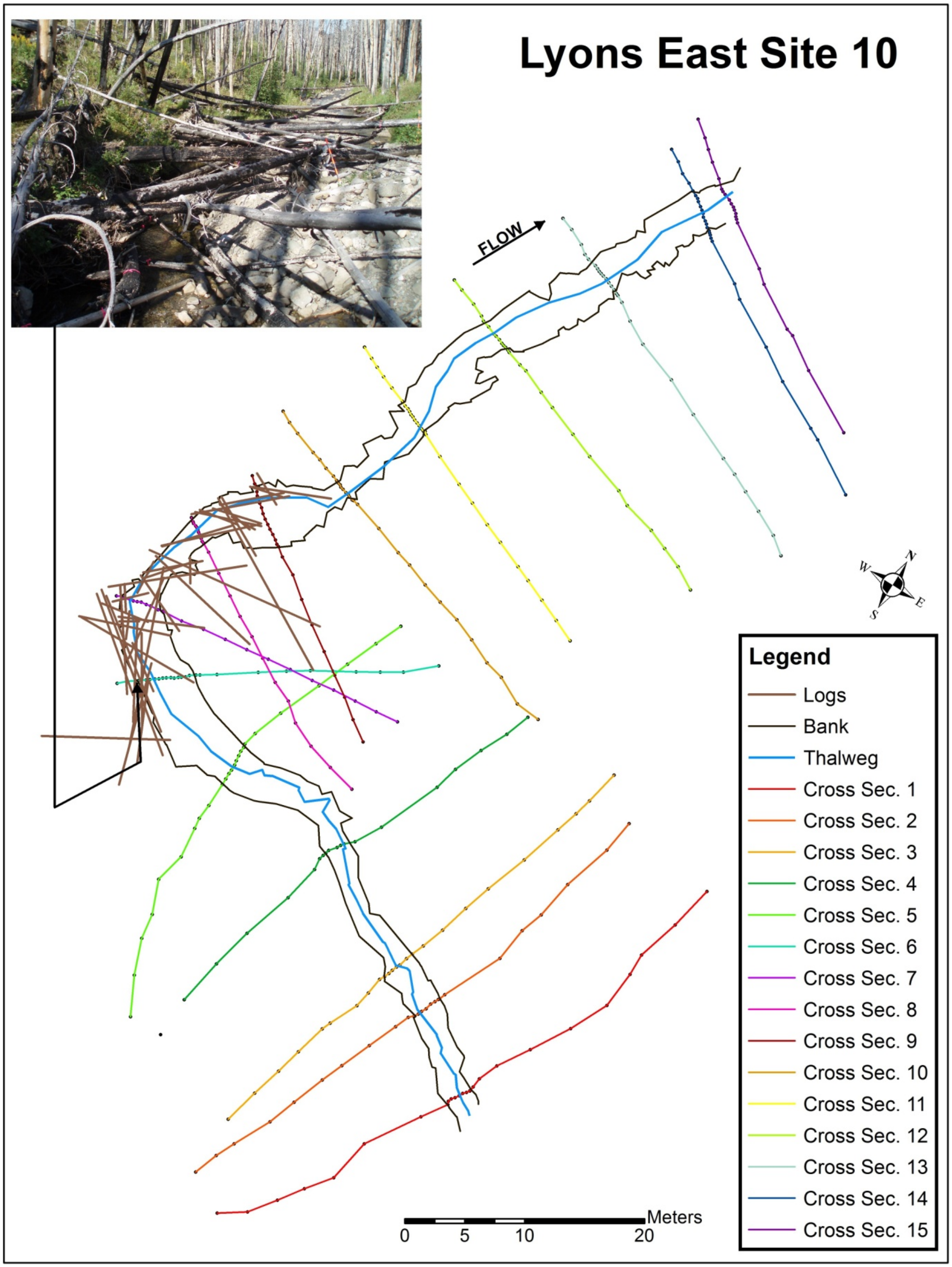


Figure 3-7: Cross sections and in-stream wood structure for site 10 in Lyons East

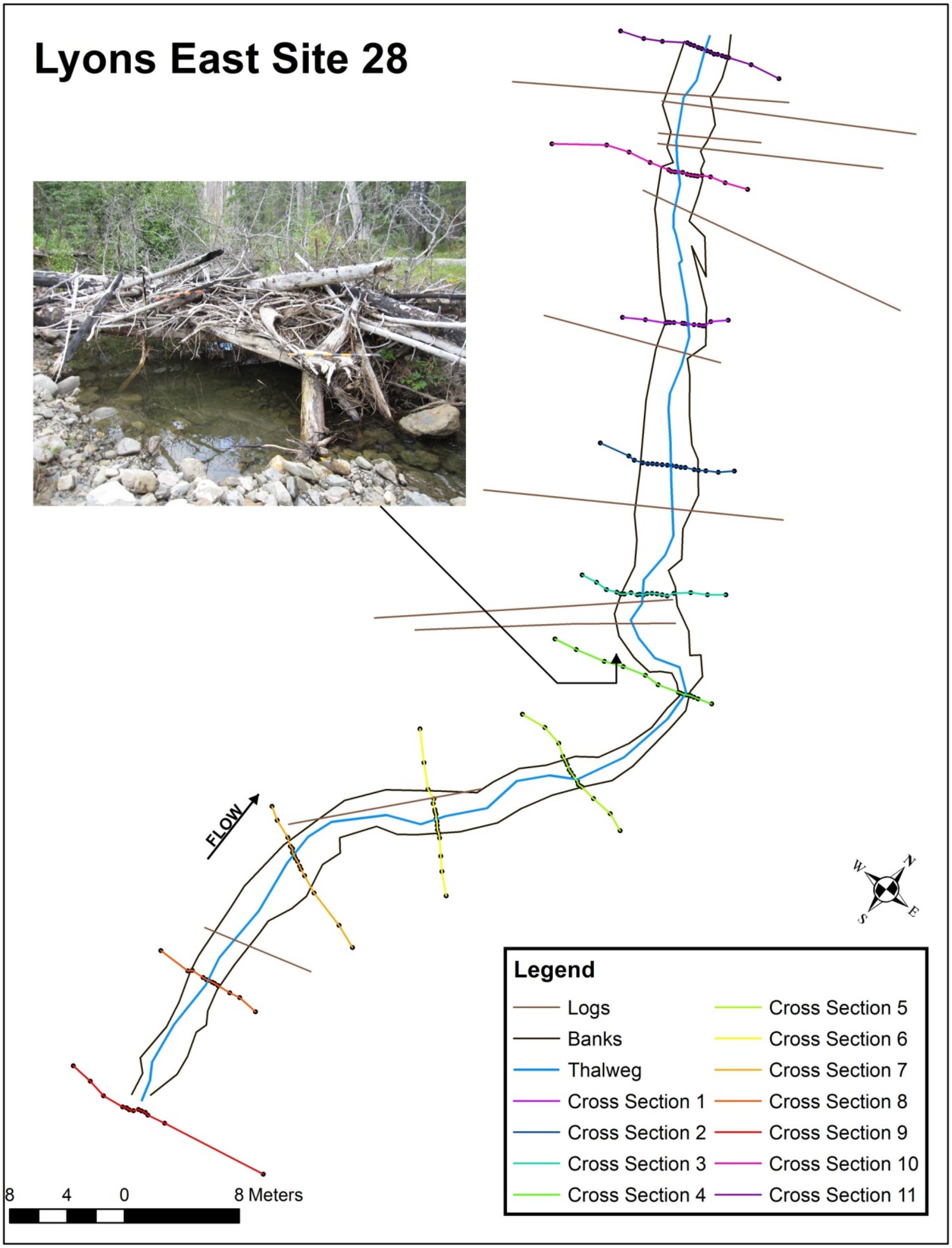


Figure 3-8: Cross sections and in-stream wood structure for site 28 in Lyons East

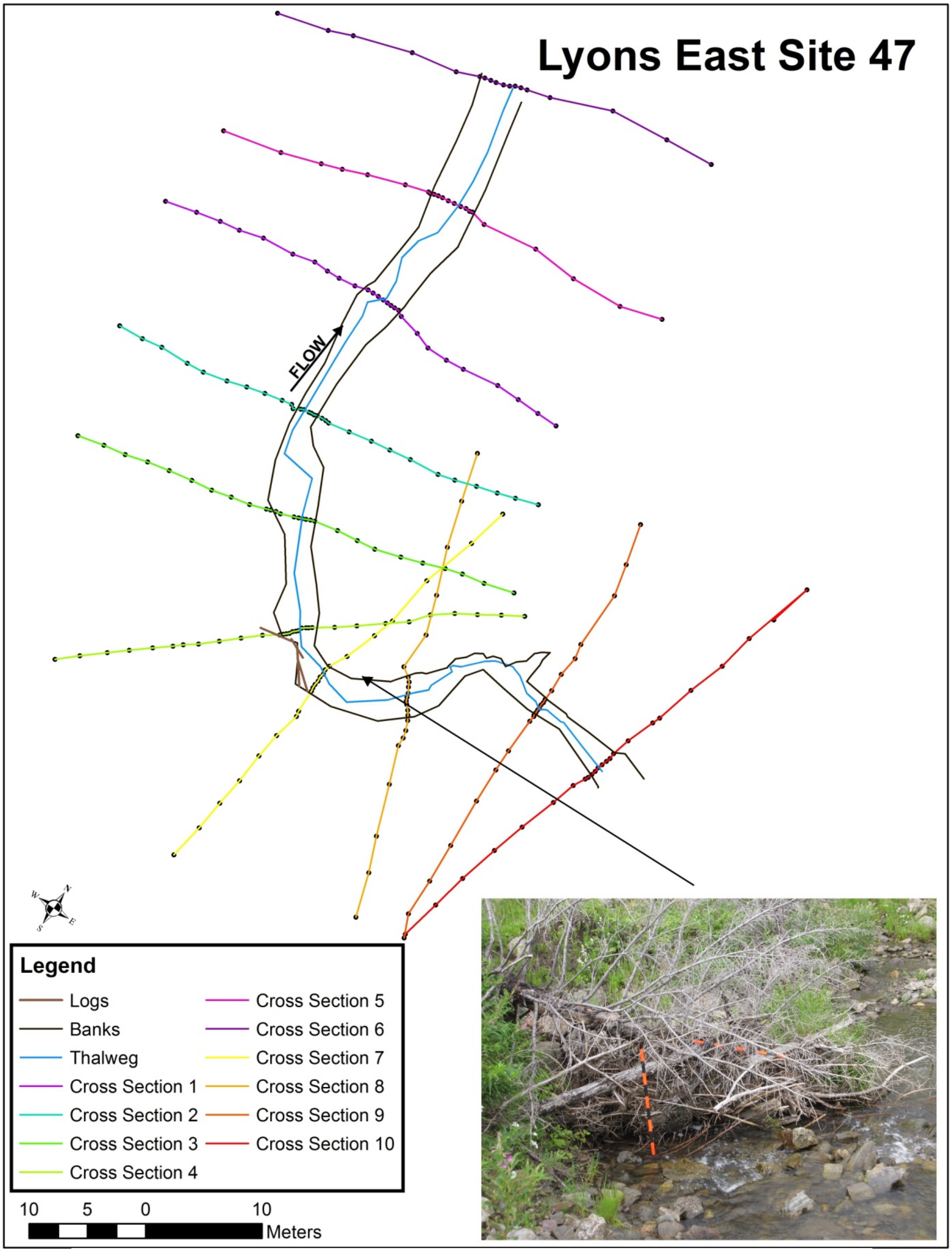


Figure 3-9: Cross sections and in-stream wood structure for site 47 in Lyons East

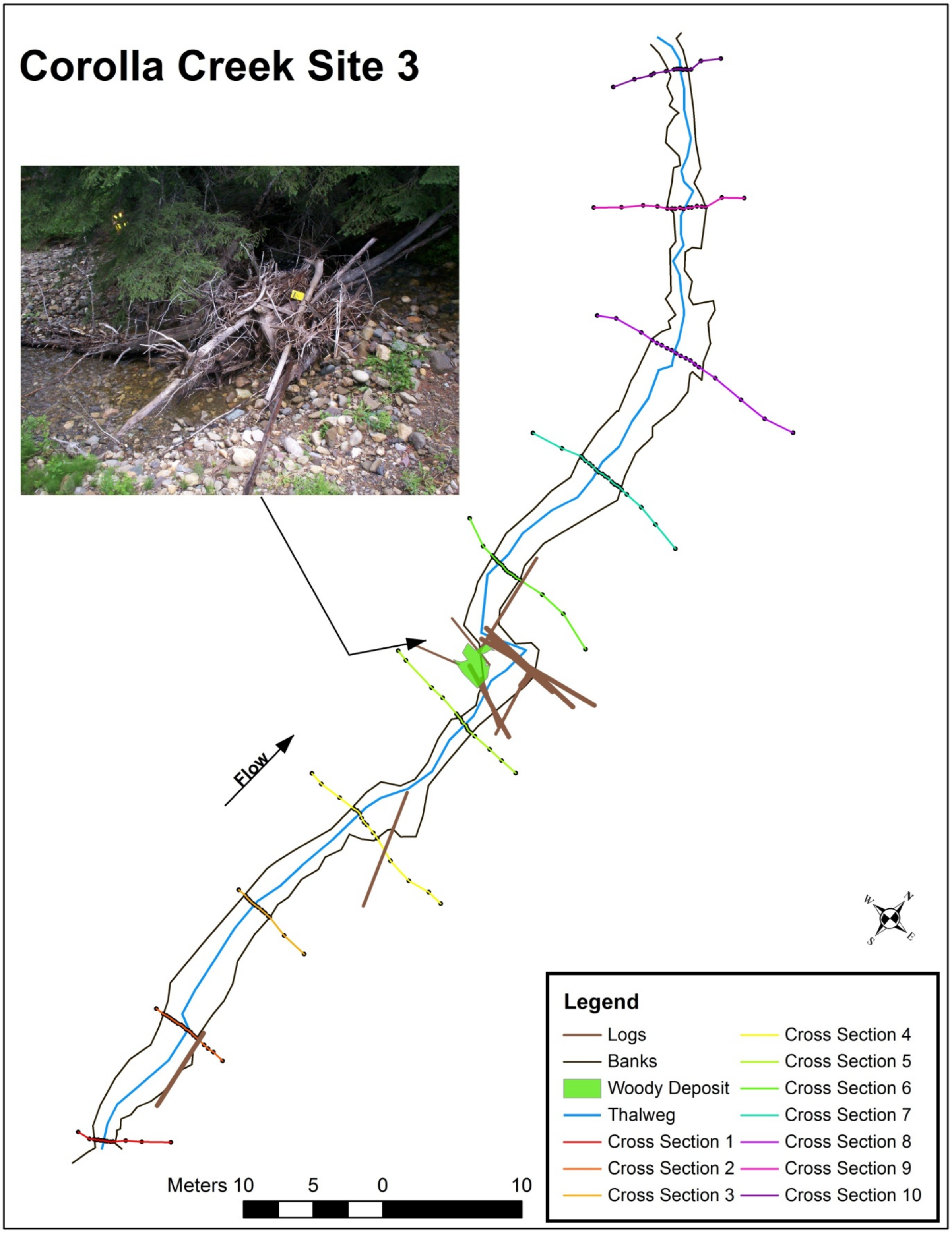


Figure 3-10: Cross Section and in-stream wood structure for site 3 in Corolla Creek

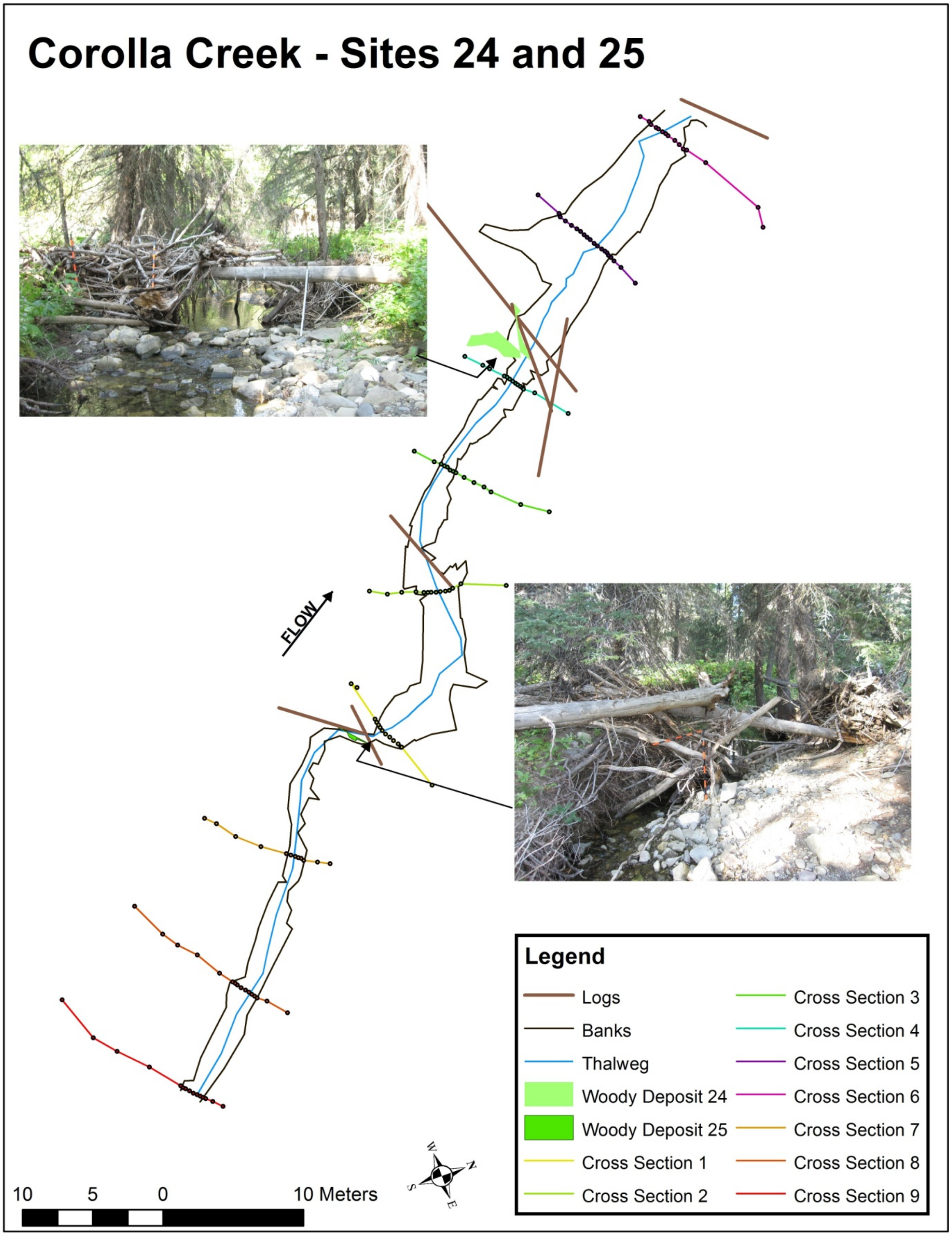


Figure 3-11: Cross sections and in-stream wood structure for sites 24 and 25 in Corolla Creek

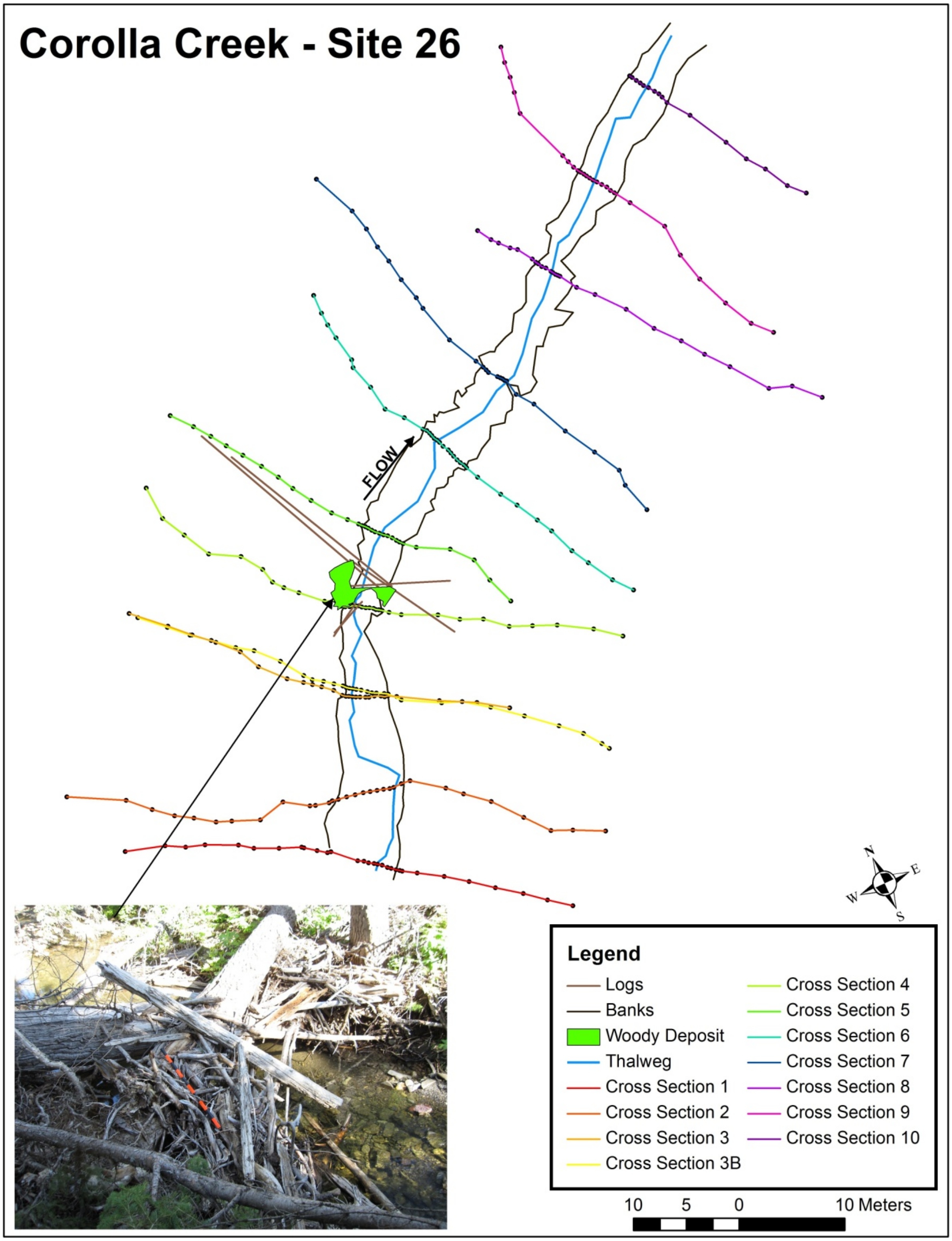


Figure 3-12: Cross sections and in-stream wood structure for site 26 in Corolla Creek

Table 3-5: Summary table of channel morphology characteristics for Lyons East

Site	n	W_{AC} (m)	D_{Thal} (m)	D_{AC} (m)	P_{AC} (m)	W_{BF} (m)	D_{BF} (m)	W:D	W_{FP} (m)	ER	R_h (m)
LE10 Upstream	5 *(4)*	3.08 (0.49)	0.27 (0.03)	0.17 (0.03)	3.81 (0.43)	10.57 (1.60)	0.26 (0.06)	41.80 (6.14)	*42* *(20.2)*	*4* *(1.5)*	0.29 (0.06)
LE10 Within	4 *(3)*	3.83 (1.54)	0.28 (0.04)	0.17 (0.04)	3.99 (1.59)	13.43 (2.01)	0.58 (0.15)	23.95 (4.00)	*50* *(4.3)*	*4* *(0.2)*	0.56 (0.15)
LE10 Downstream	6	3.12 (0.52)	0.23 (0.07)	0.12 (0.03)	3.22 (0.47)	15.28 (1.59)	0.83 (0.12)	18.82 (3.22)	58 (5.9)	4 (0.3)	0.79 (0.09)
LE10	**15** ***(13)***	**3.30** **(0.89)**	**0.26** **(0.05)**	**0.15** **(0.04)**	**3.62** **(0.89)**	**13.22** **(2.62)**	**1.17** **(0.53)**	**27.85** **(11.26)**	***51*** ***(13.1)***	***4*** ***(0.8)***	**0.56** **(0.24)**
LE28 Upstream	6	2.08 (0.55)	0.15 (0.03)	0.09 (0.03)	2.16 (0.55)	10.51 (2.10)	0.52 (0.08)	21.09 (6.32)	57 (19.7)	6 (1.6)	0.50 (0.07)
LE28 Downstream	5	3.15 (0.65)	0.15 (0.10)	0.08 (0.05)	3.22 (0.68)	9.89 (2.52)	0.50 (0.28)	23.31 (8.65)	39 (27.7)	4 (2.0)	0.48 (0.27)
LE28	**11**	**2.56** **(0.80)**	**0.15** **(0.67)**	**0.09** **(0.03)**	**2.64** **(0.81)**	**10.23** **(2.20)**	**0.51** **(0.19)**	**22.10** **(7.16)**	**49** **(24.2)**	**5** **(2.0)**	**0.49** **(0.18)**
LE47 Upstream	4 *(2)*	2.78 (0.82)	0.19 (0.02)	0.11 (0.03)	2.86 (0.79)	12.13 (3.47)	0.39 (0.21)	38.64 (19.79)	*43* *(45.7)*	*4* *(4.0)*	0.38 (0.21)
LE47 Downstream	6	3.71 (0.55)	0.29 (0.14)	0.18 (0.09)	3.70 (0.57)	13.57 (2.22)	0.75 (0.20)	19.59 (7.72)	60 (12.0)	5 (1.2)	0.72 (0.18)
LE47	**10** ***(8)***	**3.34** **(0.79)**	**0.25** **(0.12)**	**0.15** **(0.08)**	**3.37** **(0.76)**	**12.99** **(2.70)**	**0.61** **(0.27)**	**27.21** **(16.14)**	***56*** ***(21.5)***	***5*** ***(1.8)***	**0.59** **(0.25)**

Note: *The "n" values italicized in brackets correspond to the values in italics within the chart, where data was not available for all cross section*

Table 3-6: Summary table of channel morphology characteristics for Corolla Creek

Site	n	W_{AC} (m)	D_{Thal} (m)	D_{AC} (m)	P_{AC} (m)	W_{BF} (m)	D_{BF} (m)	W:D	W_{FP} (m)	ER	R_h (m)
CC3 Upstream	5	2.20 (0.66)	0.17 (0.08)	0.09 (0.05)	2.28 (0.68)	10.45 (3.63)	0.39 (0.28)	35.47 (23.88)	29 (24.2)	3 (1.1)	0.39 (0.27)
CC3 Downstream	5	2.81 (1.18)	0.19 (0.13)	0.10 (0.06)	2.88 (1.20)	14.90 (3.04)	0.37 (0.21)	49.64 (21.87)	68 (50.0)	4 (2.4)	0.36 (0.21)
CC3	**10**	**2.50 (0.96)**	**0.18 (0.10)**	**0.10 (0.05)**	**2.58 (0.97)**	**12.67 (3.93)**	**0.38 (0.24)**	**42.55 (22.85)**	**49 (42.4)**	**4 (2.0)**	**0.38 (0.23)**
CC24&25 Upstream	3	1.81 (0.42)	0.08 (0.02)	0.05 (0.02)	1.84 (0.42)	13.47 (2.10)	0.32 (0.10)	44.90 (15.46)	69 (23.0)	5 (2.2)	0.32 (0.10)
CC24&25 Between	4	2.03 (0.81)	0.18 (0.18)	0.12 (0.13)	2.12 (0.90)	11.98 (2.26)	0.33 (0.13)	38.23 (6.17)	77 (21.8)	7 (1.7)	0.33 (0.13)
CC24&25 Downstream	2	3.99 (0.89)	0.30 (0.16)	0.15 (0.08)	4.09 (0.84)	14.09 (4.55)	0.19 (0.04)	74.64 (8.83)	44 (7.2)	3 (1.6)	0.19 (0.04)
CC24&25	**9**	**2.39 (1.10)**	**0.17 (0.15)**	**0.10 (0.09)**	**2.47 (1.14)**	**12.95 (2.55)**	**0.30 (0.11)**	**48.55 (17.67)**	**67 (22.4)**	**5 (2.0)**	**0.29 (0.11)**
CC26 Upstream	4	5.33 (1.39)	0.32 (0.18)	0.15 (0.07)	5.46 (1.42)	14.14 (3.00)	0.76 (0.15)	18.70 (3.01)	68 (3.7)	5 (1.1)	0.74 (0.15)
CC26 Downstream	6	3.89 (1.06)	0.29 (0.13)	0.15 (0.07)	3.98 (1.08)	15.13 (1.43)	0.80 (0.08)	19.05 (2.01)	54 (1.8)	4 (0.4)	0.77 (0.07)
CC26	**10**	**4.47 (1.35)**	**0.30 (0.15)**	**0.15 (0.07)**	**4.57 (1.38)**	**14.73 (2.10)**	**0.78 (0.11)**	**18.91 (2.30)**	**59 (7.8)**	**4 (1.0)**	**0.76 (0.10)**

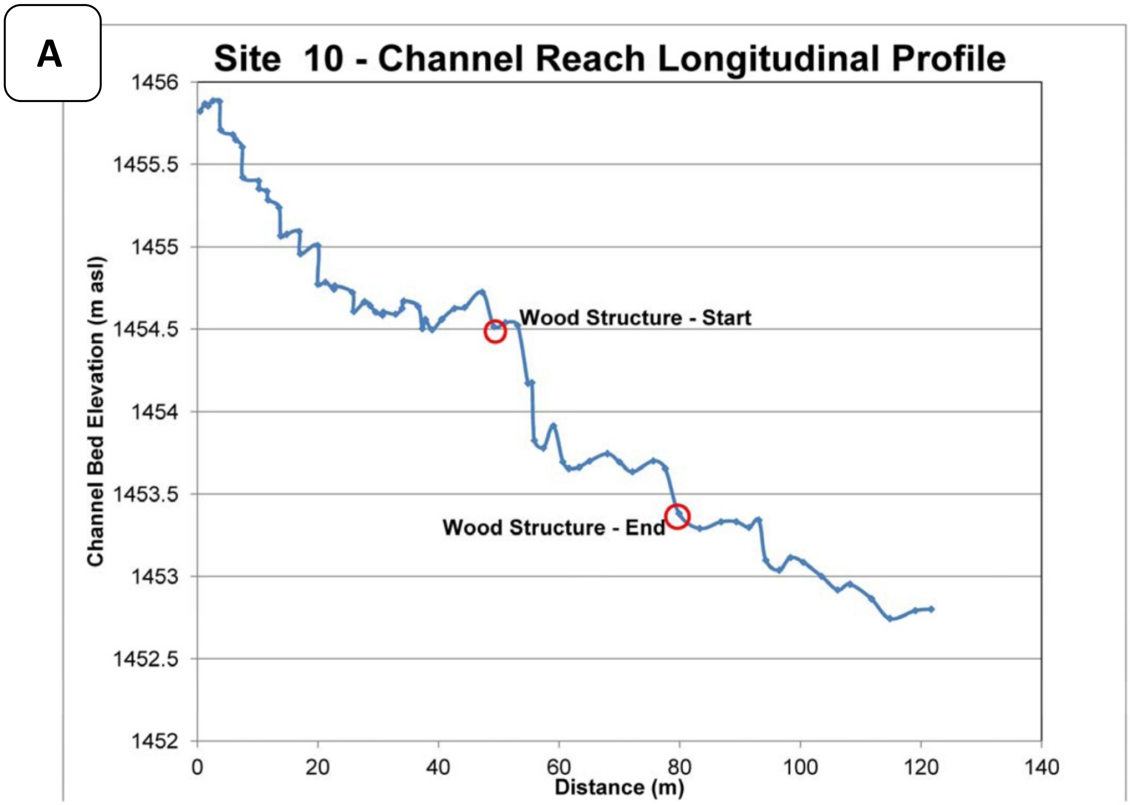
Some general trends in channel morphology for the study sites are evident in Tables 3-5 and 3-6. The active channel widths for all sites, except CC26, are wider downstream of the woody deposit than upstream. Taking into account the "within" and "between" measurements, the widest part of the channel for LE10 is within the wood structure. The majority of reaches had a similar trend for the upstream and downstream depth for both the thalweg and channel average depth. For most sites, the depth downstream of the woody deposit is greater for both the thalweg and average cross sectional channel depth. However, LE28 is deeper upstream of the wood deposit for both bankfull and active channel depth measurements. In site LE10 the thalweg depth is deeper within the wood deposit as compared to upstream or downstream reaches. However, the average channel depth is the greatest above the wood deposit when compared to within the wood structure or the downstream reach. At site CC26, the thalweg depth is greater upstream of the wood deposit and the average active channel depth is greater downstream of the wood deposit. The mean active channel depth was greater downstream of the wood structure for all sites in Corolla Creek, whereas this occurred at only one site (LE47) in Lyons East. Both LE10 and LE28 had a greater average active channel depth above the woody deposit than below.

With the exception of LE28, the bankfull width for almost all sites in both watersheds is greater downstream of the woody structure than upstream. The bankfull depth is more varied between the study reaches. Half of the sites have a deeper bankfull depth downstream of the wood structure than upstream (sites LE10, LE47 and CC26). For the other three sites, two (LE28 and CC3) have deeper bankfull depths upstream of the structure, whereas site CC24&25 has the greatest value for bankfull depth between the two wood structures (CC24 and CC25). In Lyons East, the bankfull width and depth have the same order for all three sites; however the width:depth ratio is reversed (Table 3-5). In Lyons East, the bankfull width and depth is greater downstream of the wood structure for sites LE10 and LE 47, whereas the width:depth ratio is greater upstream for the same sites (LE10 and LE47). The reverse occurs in site LE28, where the bankfull width and depth is lower downstream of the wood structure and the width:depth ratio is lower upstream of the structure. For Corolla Creek (Table 3-6) the bankfull width, depth and width:depth ratio share the same order for CC3 and CC26. There is a difference with site CC24&25 which has an order of "downstream, upstream, between" for bankfull width and width:depth ratio, but "between, upstream, downstream" for bankfull depth, in rank order from highest to lowest value.

The reach slope was determined for each of the six study sites and presented in Table 3-4 and illustrated in Figures 3-13 to 3-15 for Lyons East and Figures 3-16 to 3-18 for Corolla Creek. In

Figures 3-16 to 3-18, the top graph (A) illustrates the longitudinal profile of the channel bed for each of the reaches. The bottom figure (B) illustrates the channel bed in relation to the water surface elevation, which was determined at the cross sections for each site. The gradients range from 1.90% to 2.49% for all study reaches (Table 3-4). The steepest gradient (2.67%) and most gradual gradient (1.90%) both occur in Corolla Creek at sites CC26 and CC3, respectively (Table 3-4). For Corolla Creek, the slopes decrease in the downstream direction. However, in Lyons East the most downstream site (LE10) has the highest channel slope (2.49%) and the slope decreases in the upstream direction.

The change in stream gradient along the longitudinal profile for each selected study reach are is presented in Figures 3-13 to 3-15 for Lyons East and Figures 3-16 to 3-18 for Corolla Creek. Site LE10 in Lyons East has a lower gradient upstream and downstream of the in-stream wood structure than the gradient measured within the structure (Figure 3-13A). The other five selected study reaches (Figures 3-14 to 3-18) generally show a similar gradient upstream and downstream of the in-stream wood structure. The second longitudinal profile, labelled "B," is based on cross sectional data and is missing some channel information due to the spacing of the cross sections, but it provides a general impression of the channel bed and water surface characteristics in the study reaches (Figures 3-13B to 3-18B). The longitudinal profiles based on the cross sectional data (Figures 3-13B to 3-18B) show some of the pools found in each of the study reaches, as the data includes the water surface. These profiles do not include all pools due to the spacing of cross sections along the reach.



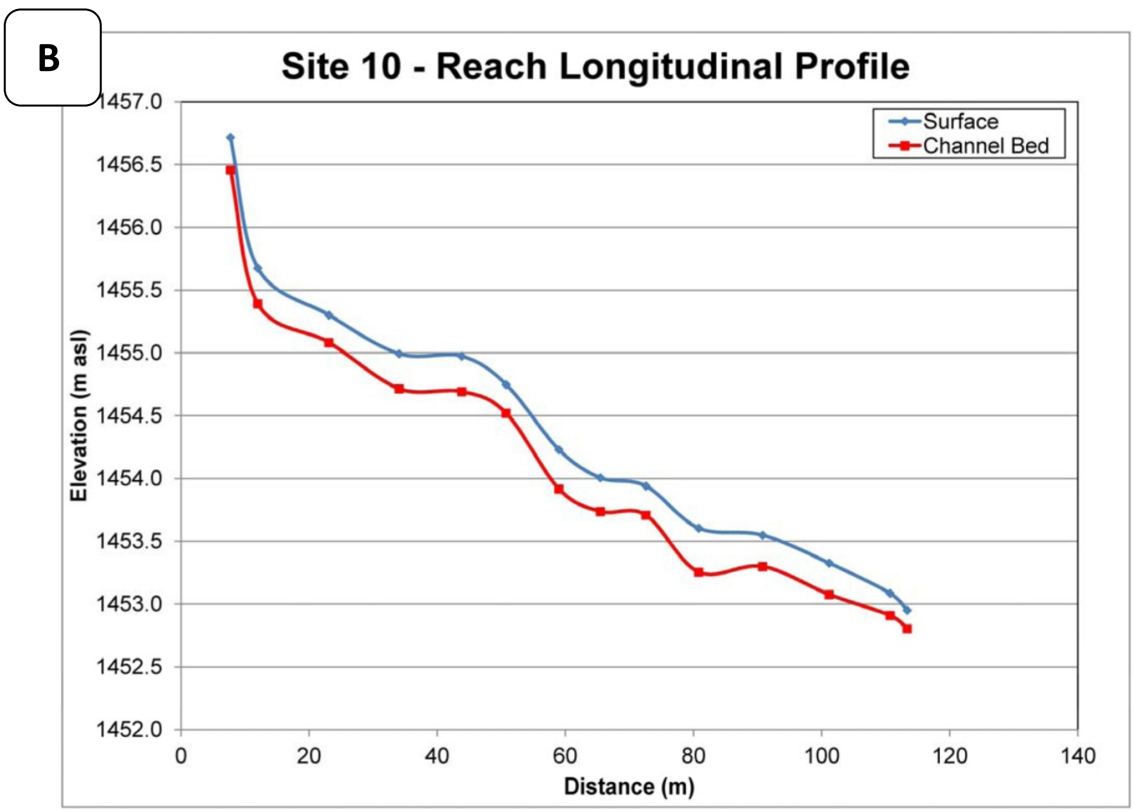
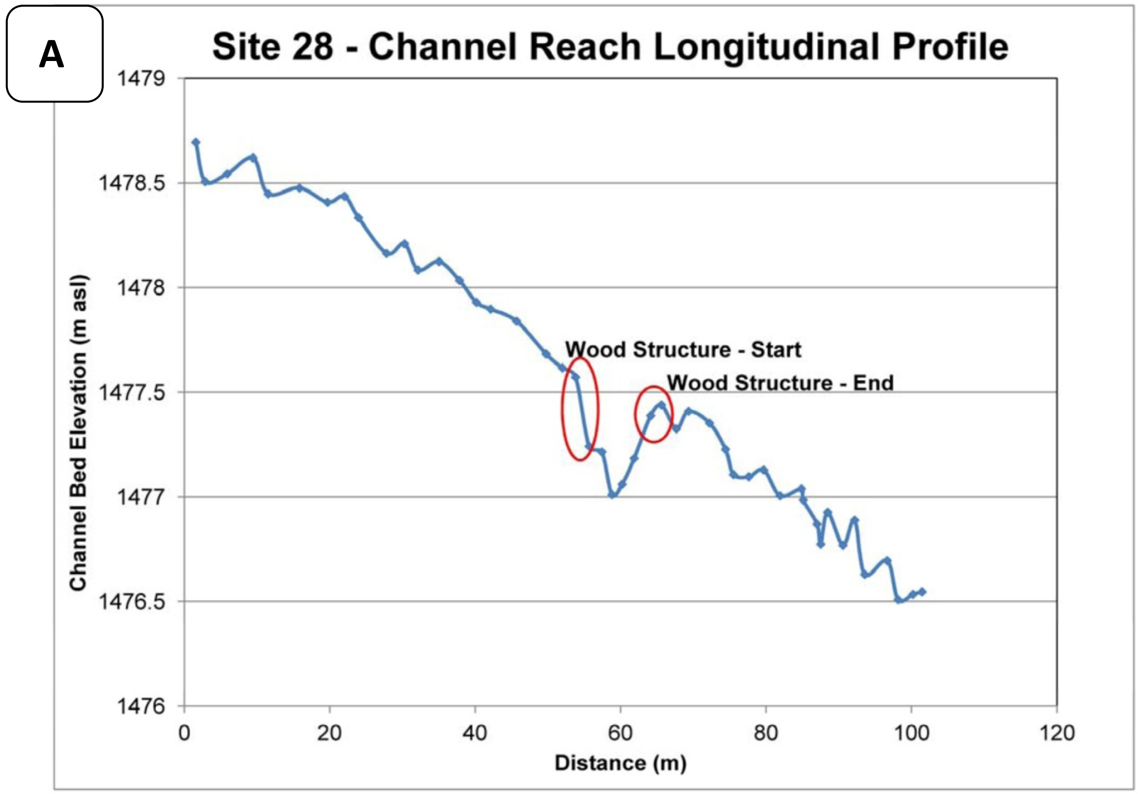


Figure 3-13: Longitudinal profile of channel bed for Lyons East site 10 with a vertical exaggeration of 26.7x (A). Water surface profile for Lyons East site 10 with a vertical exaggeration of 27.1x (B).



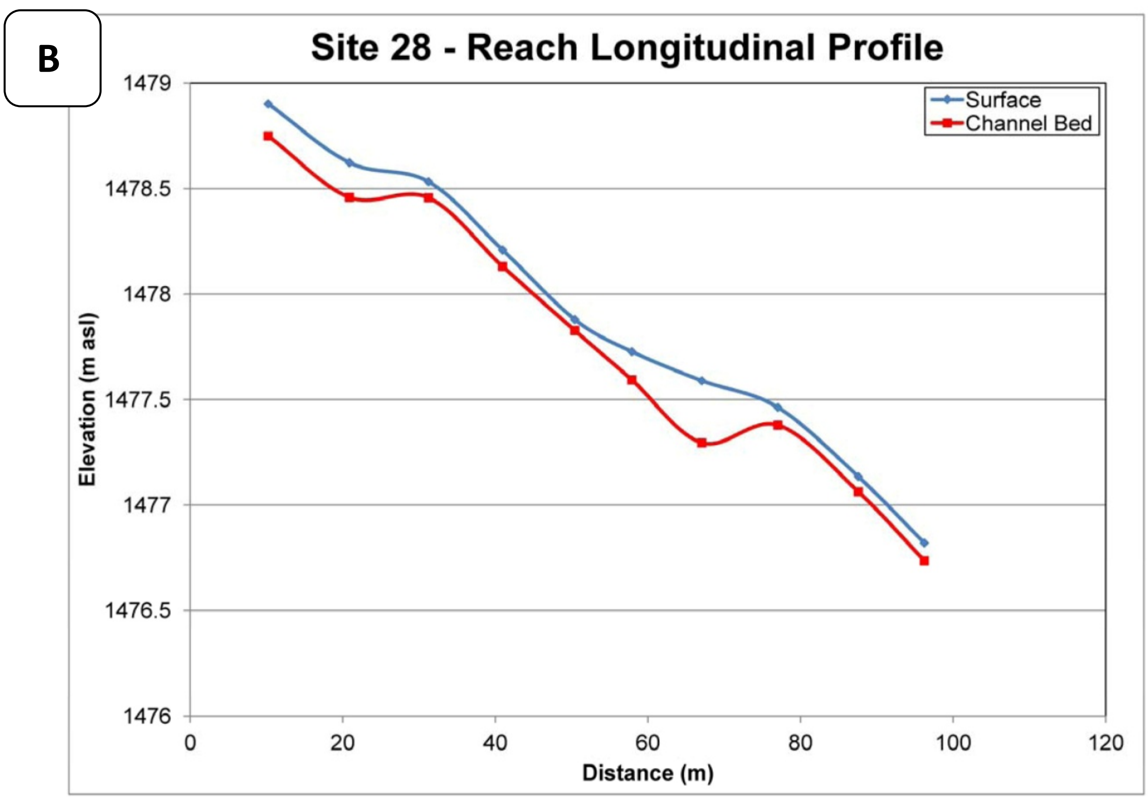
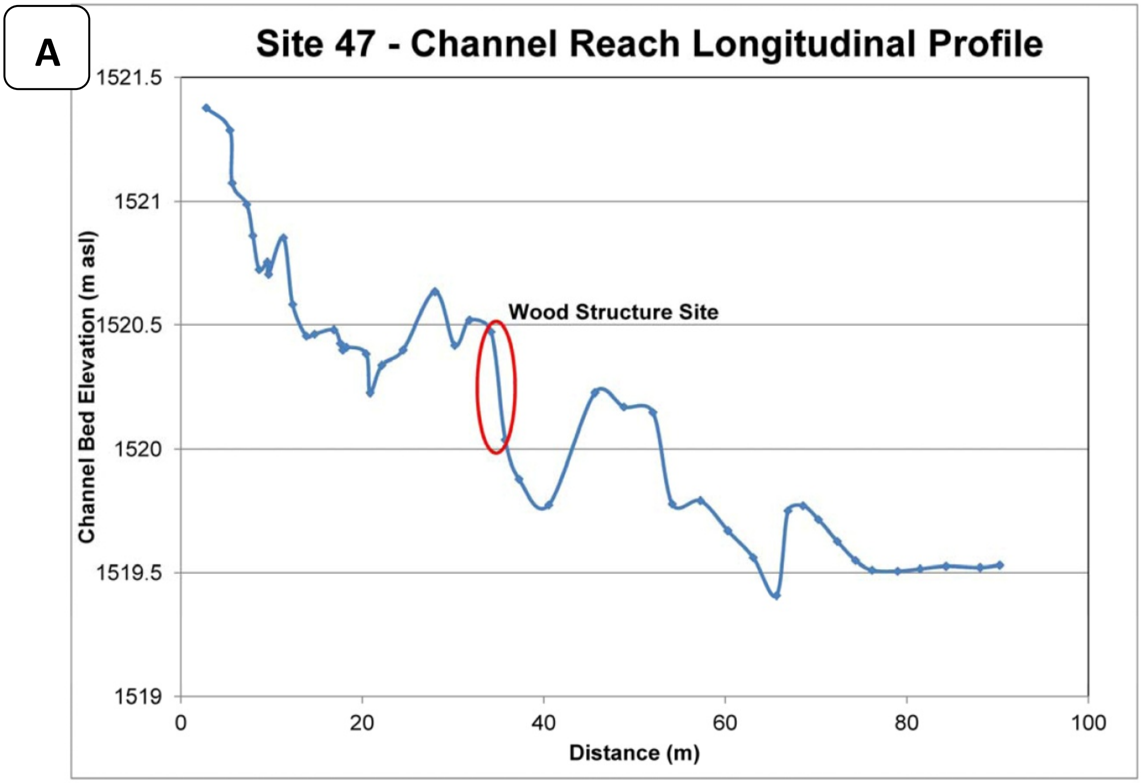


Figure 3-14: Longitudinal profile of channel bed for Lyons East site 28 with a vertical exaggeration of 29.2x (A). Water surface profile for Lyons East site 28 with a vertical exaggeration of 27.5x (B).



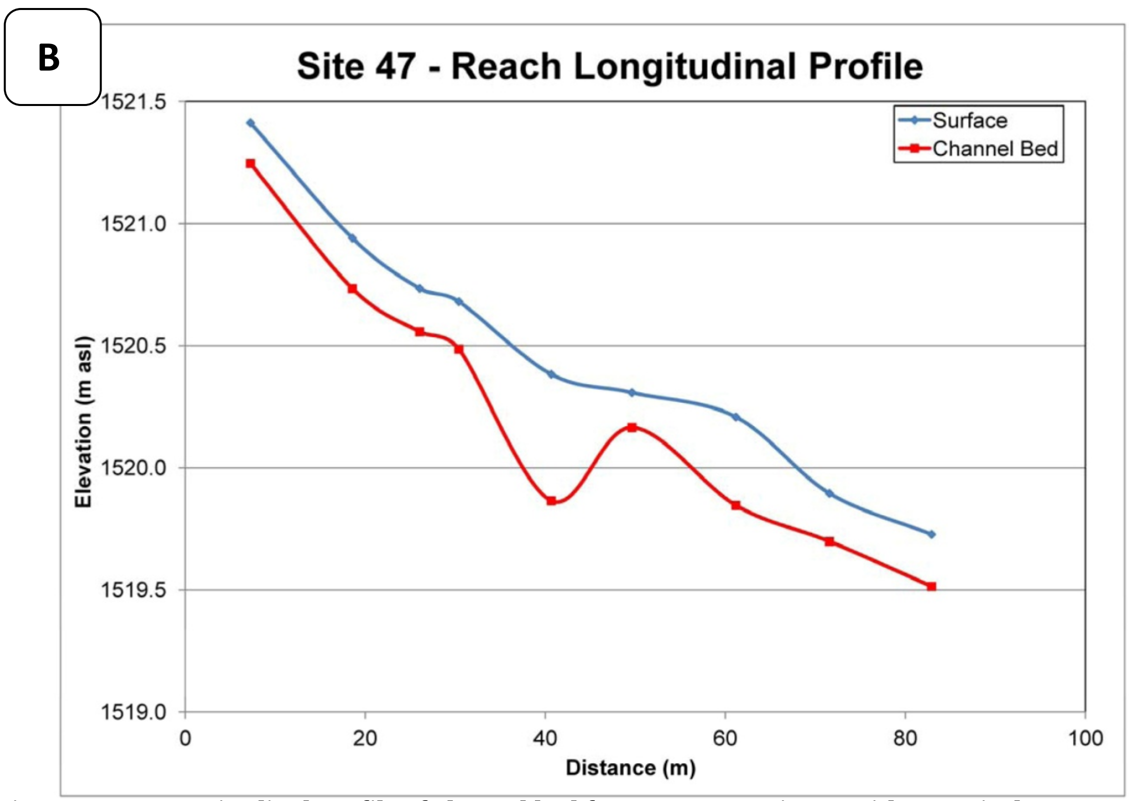


Figure 3-15: Longitudinal profile of channel bed for Lyons East site 47 with a vertical exaggeration of 27x (A). Water surface profile for Lyons East site 47 with a vertical exaggeration of 27x (B).

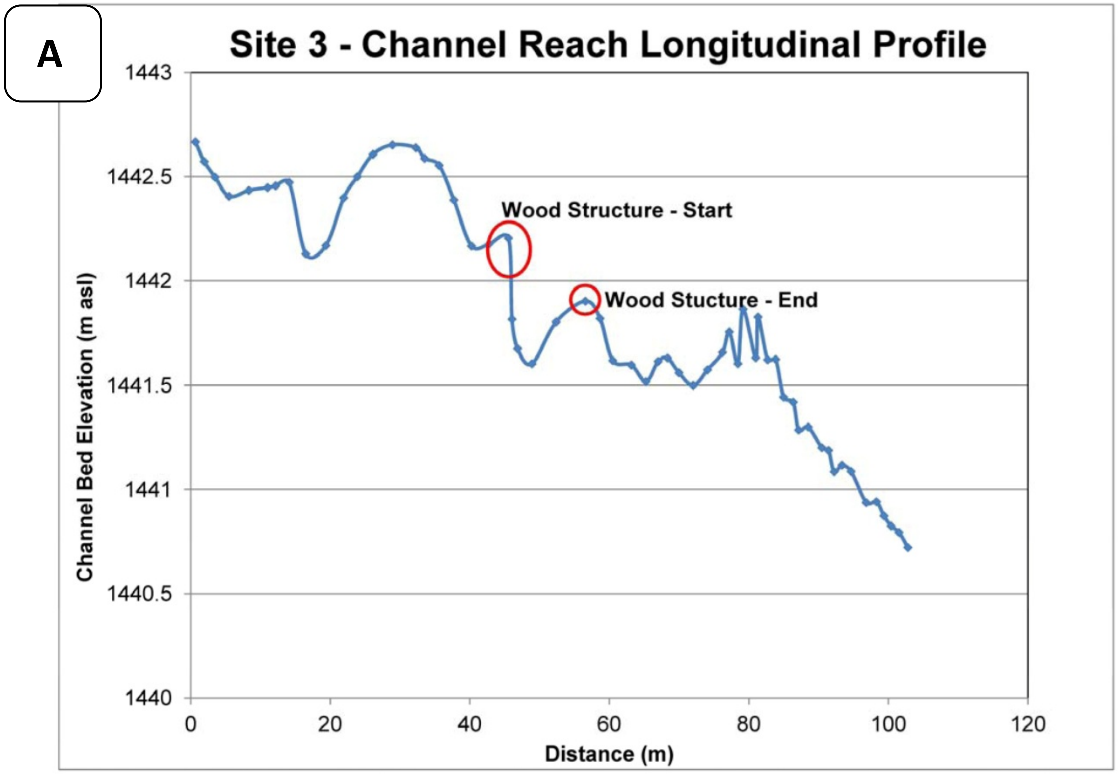
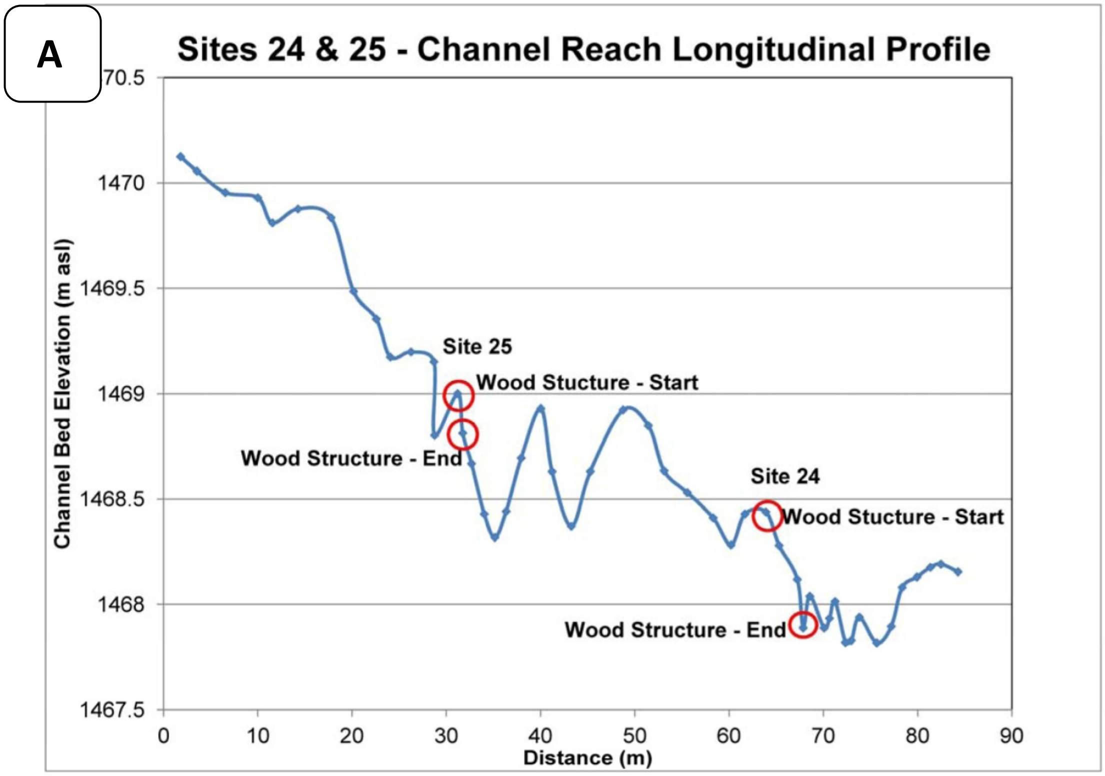


Figure 3-16: Longitudinal Profile of channel bed for Corolla Creek site 3 with a vertical exaggeration 29.7x (A). Water surface profile for Corolla Creek site 3 with a vertical exaggeration 30.1x (B).



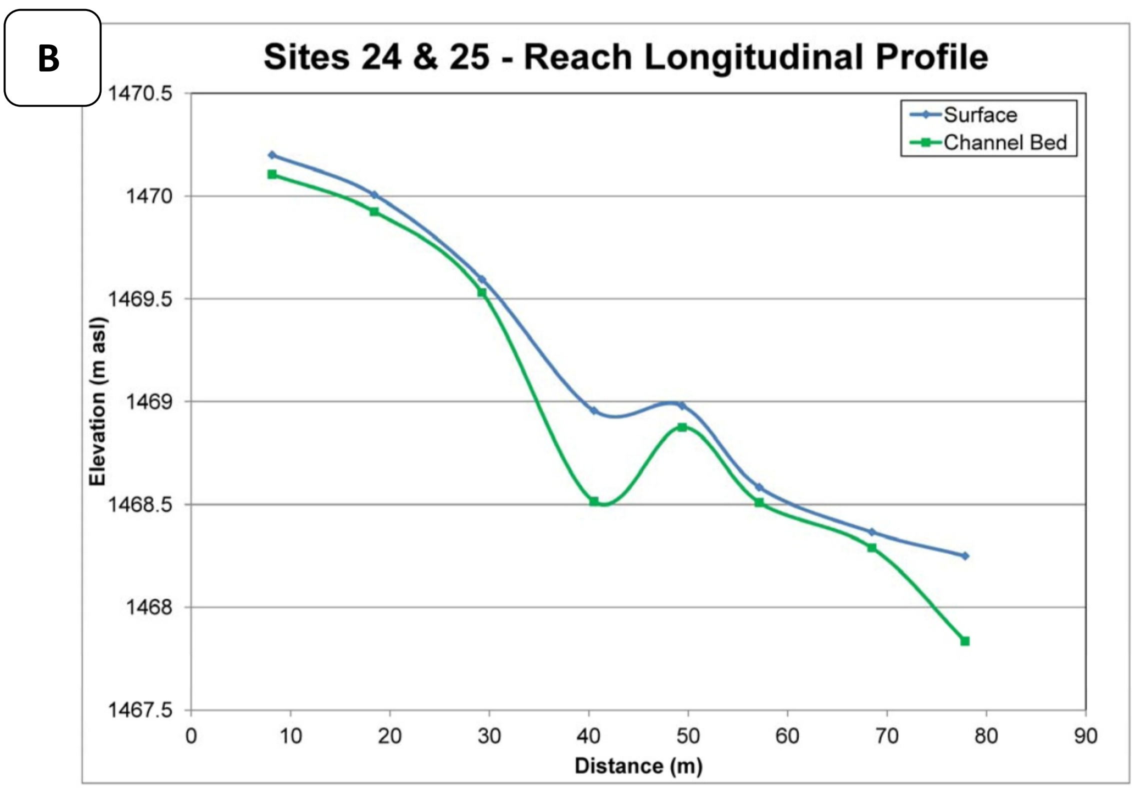
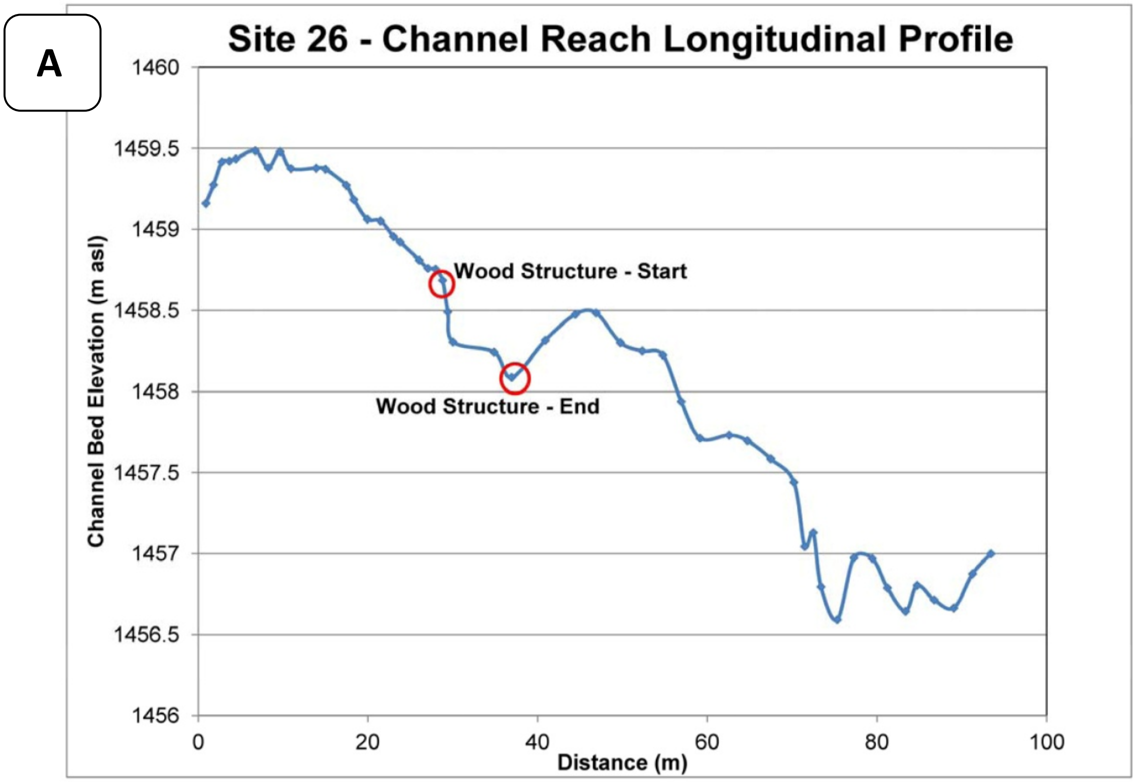


Figure 3-17: Longitudinal profile of channel bed for Corolla Creek sites 24 & 25 with a vertical exaggeration of 21.9x (A). Water surface profile for Corolla Creek sites 24 & 25 with a vertical exaggeration of 20.0x (B).



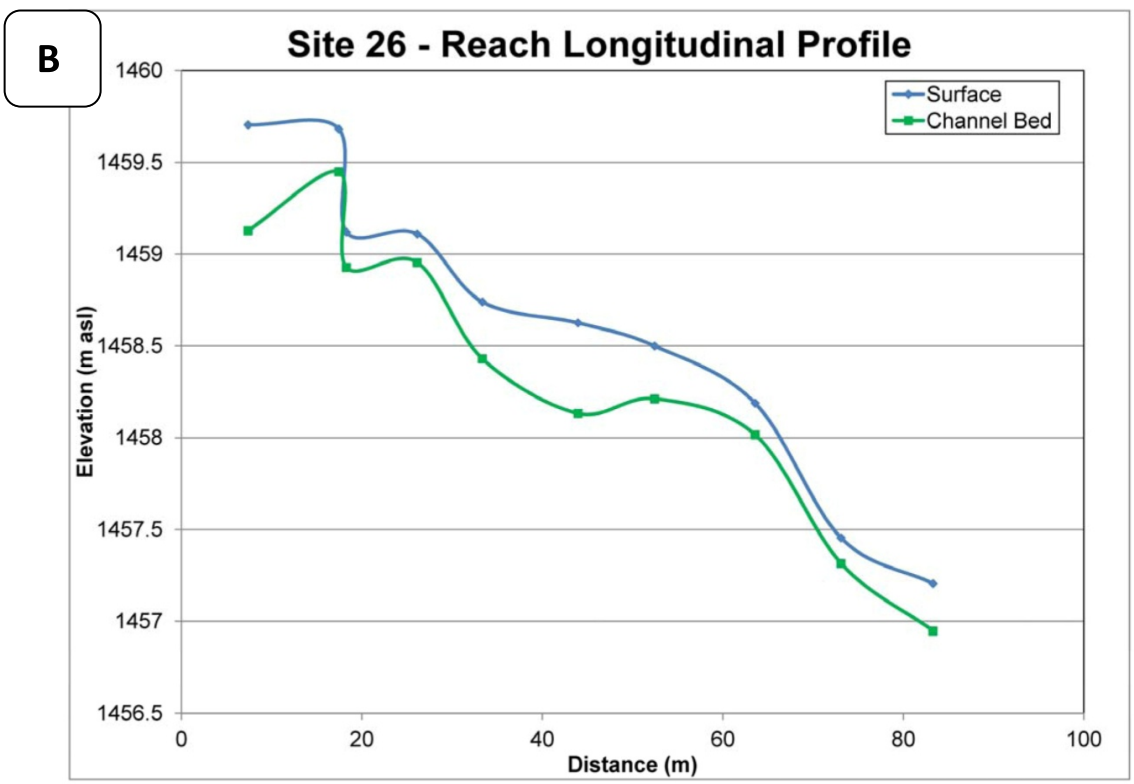


Figure 3-18: Longitudinal profile of channel bed for Corolla Creek site 26 with a vertical exaggeration of 18.9x (A). Water surface profile for Corolla Creek site 26 with a vertical exaggeration of 20.5x (B).

The scour and depositional features for each of the selected study reaches are presented in Figures 3-19 to 3-24. They show the planform view of the channel and illustrate the location of bar and pool formations. To gain an understanding of channel substrate, the clast size is represented as a percentage for each bar. All in-stream wood structures have a bar formation touching the structure, with the exception of site CC26. In general, Corolla Creek appears to have larger clast sizes within the bars compared to Lyons East. Field observations indicate the presence of overflow channels for the most downstream reaches in both Lyons East (LE10) and Corolla Creek (CC3). In Lyons East, the overflow channel is located above the deposit site and in Corolla it is located downstream. Both overflow channels contain cobble-sized clasts.

The bar formations differ slightly between the two watersheds. Lyons East reaches tend to have smaller and narrower bars found along the edge of the channels, such as those shown in the upper sections of sites LE 10 and LE47 (Figures 3-19 and 3-21, respectively). These bar formations are also found both upstream and downstream of the wood structure in site LE28 (Figure 3-20). Corolla Creek tends to have longer bar formations extending along the banks of the channel. These longer bar formations extend for approximately a third of the reach length and are illustrated in Figures 3-22 and 3-23 for sites CC3 and CC24&25, respectively. The upper Corolla Creek site had smaller bars along the edge of the channel; however the channel contains boulders and large cobbles projecting from the channel bed throughout the reach (Figure 3-24). The larger substrate of boulders and large cobbles projecting out of the water was not found in the other two study reaches in Corolla Creek. Site CC3 and site CC26 both have sections of bedrock located within the reach. For site CC3 bedrock is in the upper most section of the reach, whereas at site CC26 the bedrock is at the downstream end.

The relationship of the stream pools relative to the in-stream wood structures and cohesive sediment stored within the pools is shown in Figures 3-19 to 3-24. All in-stream wood structures at the study sites are associated with a pool, except for site CC24. The planform views of the study reaches (Figures 3-19 to 3-24) show the location and dimensions of the pools and the storage of cohesive sediment within the residual pools. The characteristics of both the pools and cohesive sediment will be discussed further in Section 3.4 with the results from the detailed pool analysis. These figures (Figures 3-19 to 3-24) provide the foundation for the detailed pool analysis.

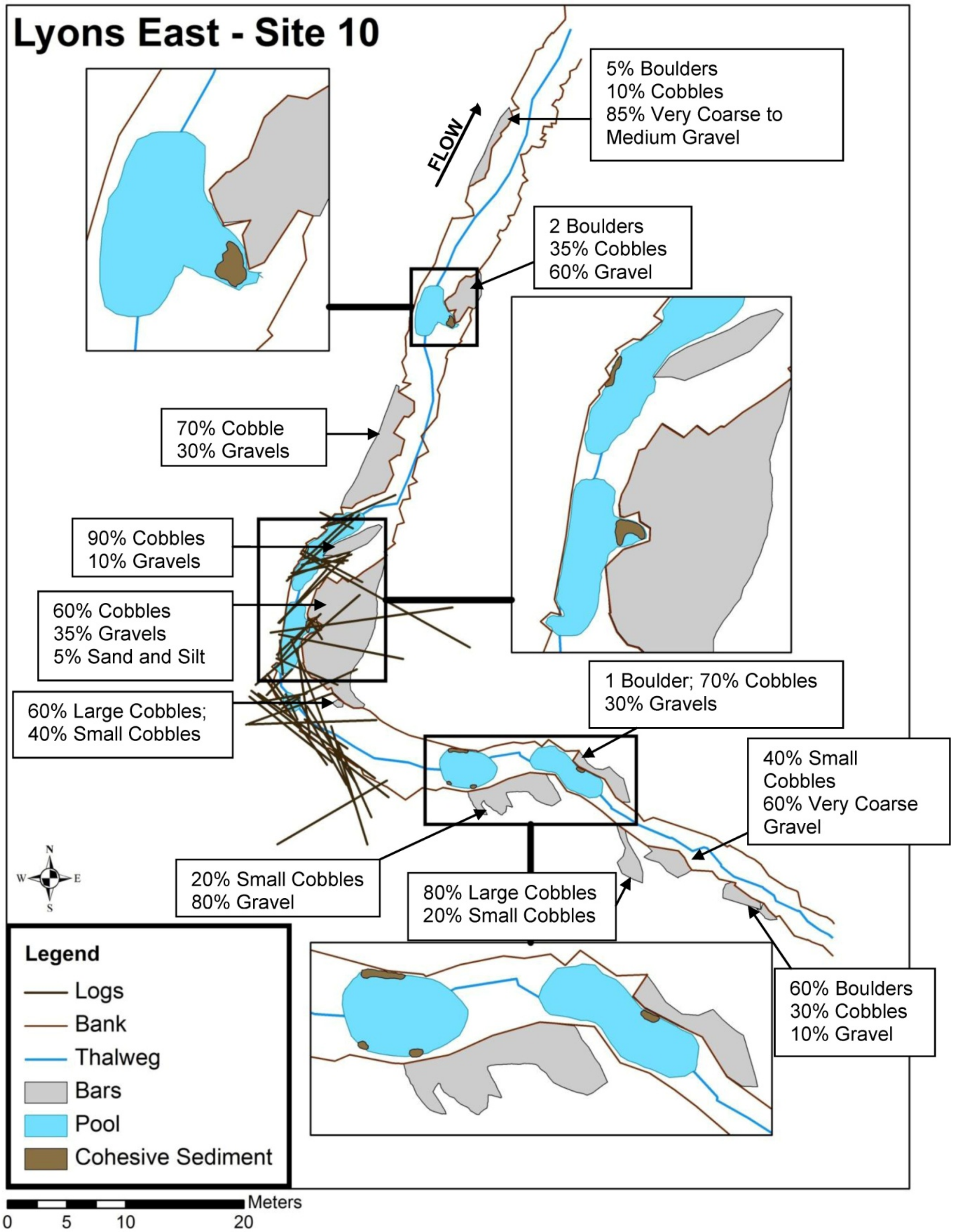


Figure 3-19: Stream reach morphology characteristics, in particular bar and pool formations in relation to in-stream wood deposit for Lyons East site 10

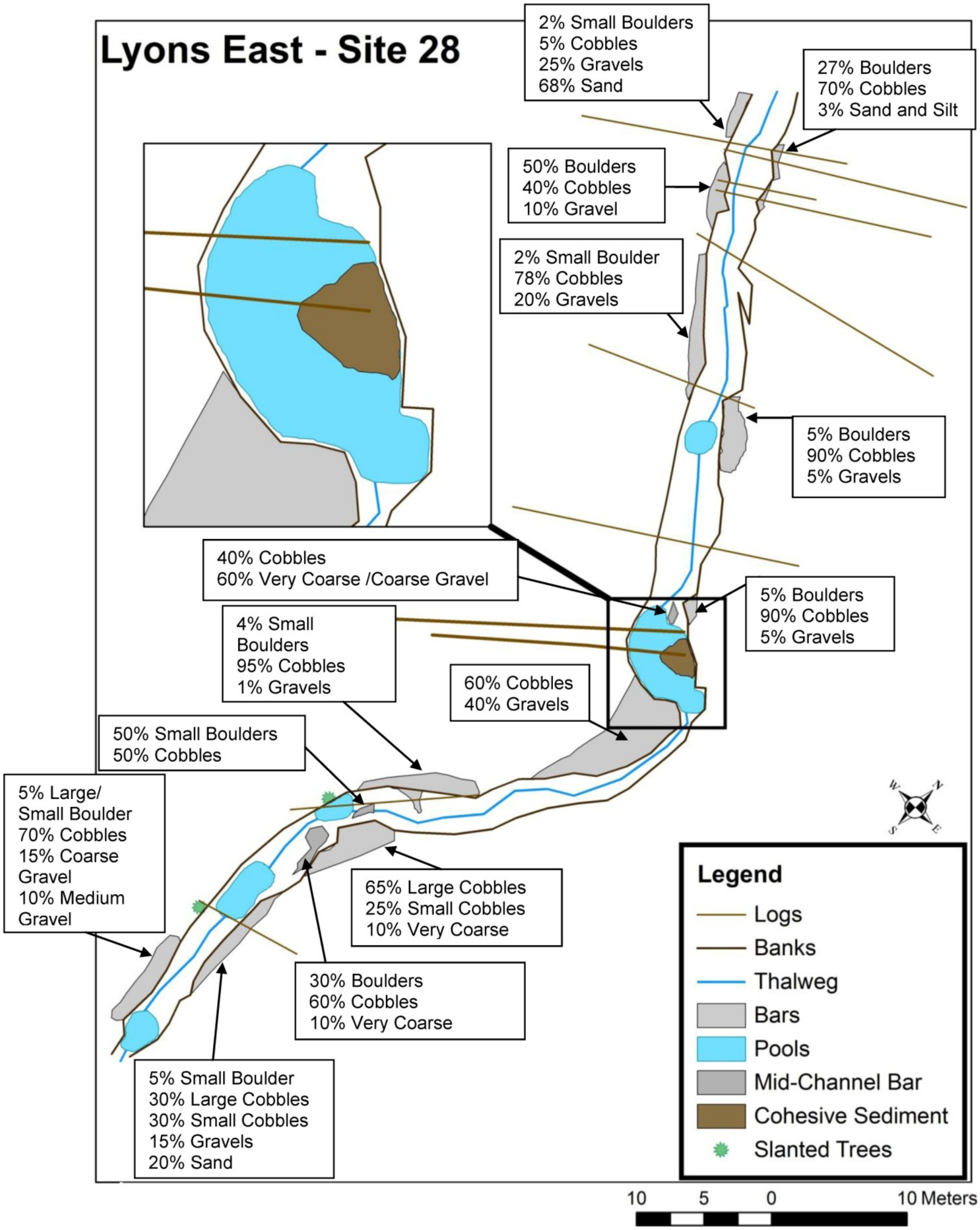


Figure 3-20: Stream reach morphology characteristics, in particular bar and pool formations in relation to in-stream wood deposit for Lyons East site 28

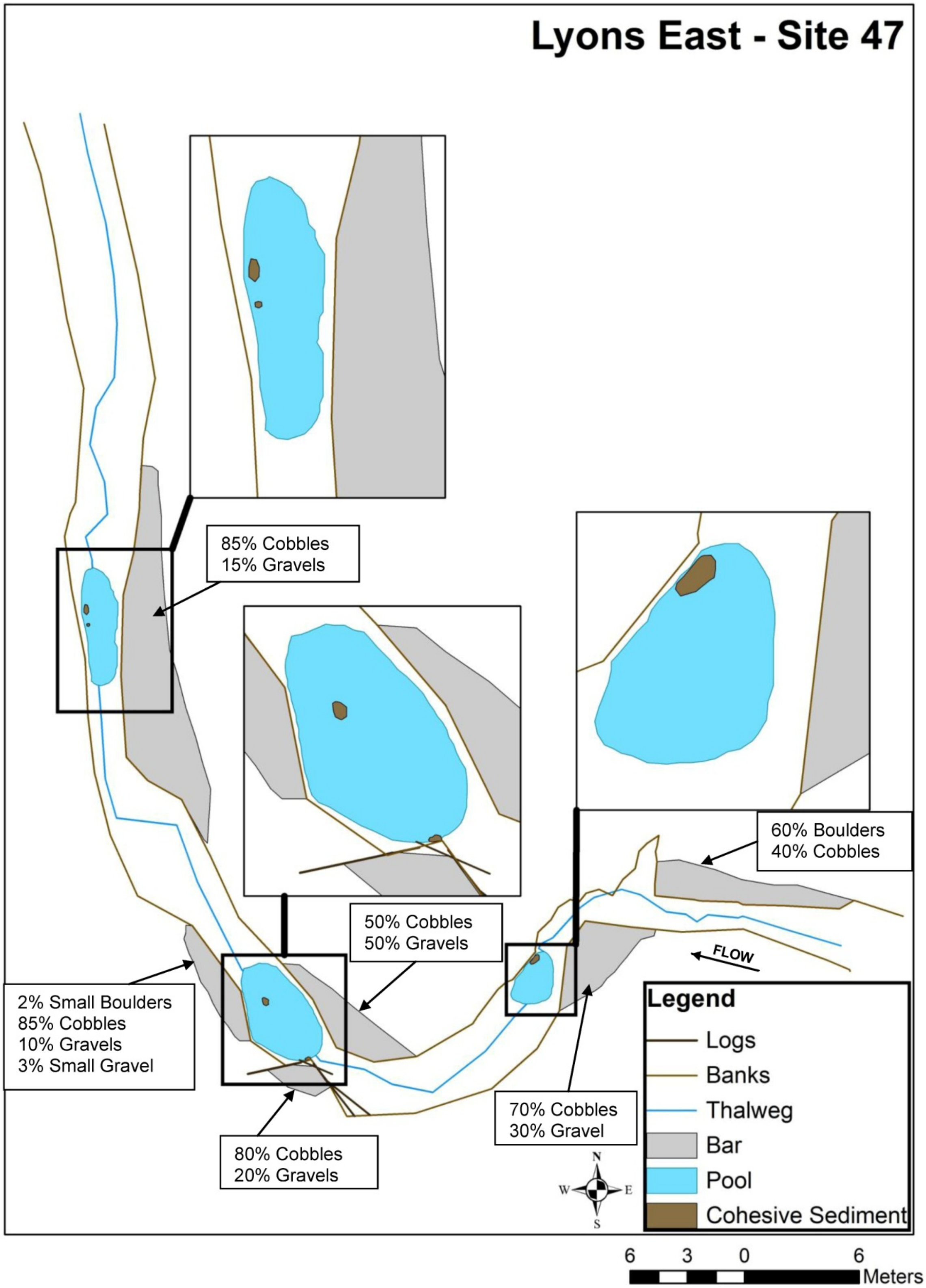


Figure 3-21: Stream reach morphology characteristics, in particular bar and pool formations in relation to in-stream wood deposit for Lyons East site 47

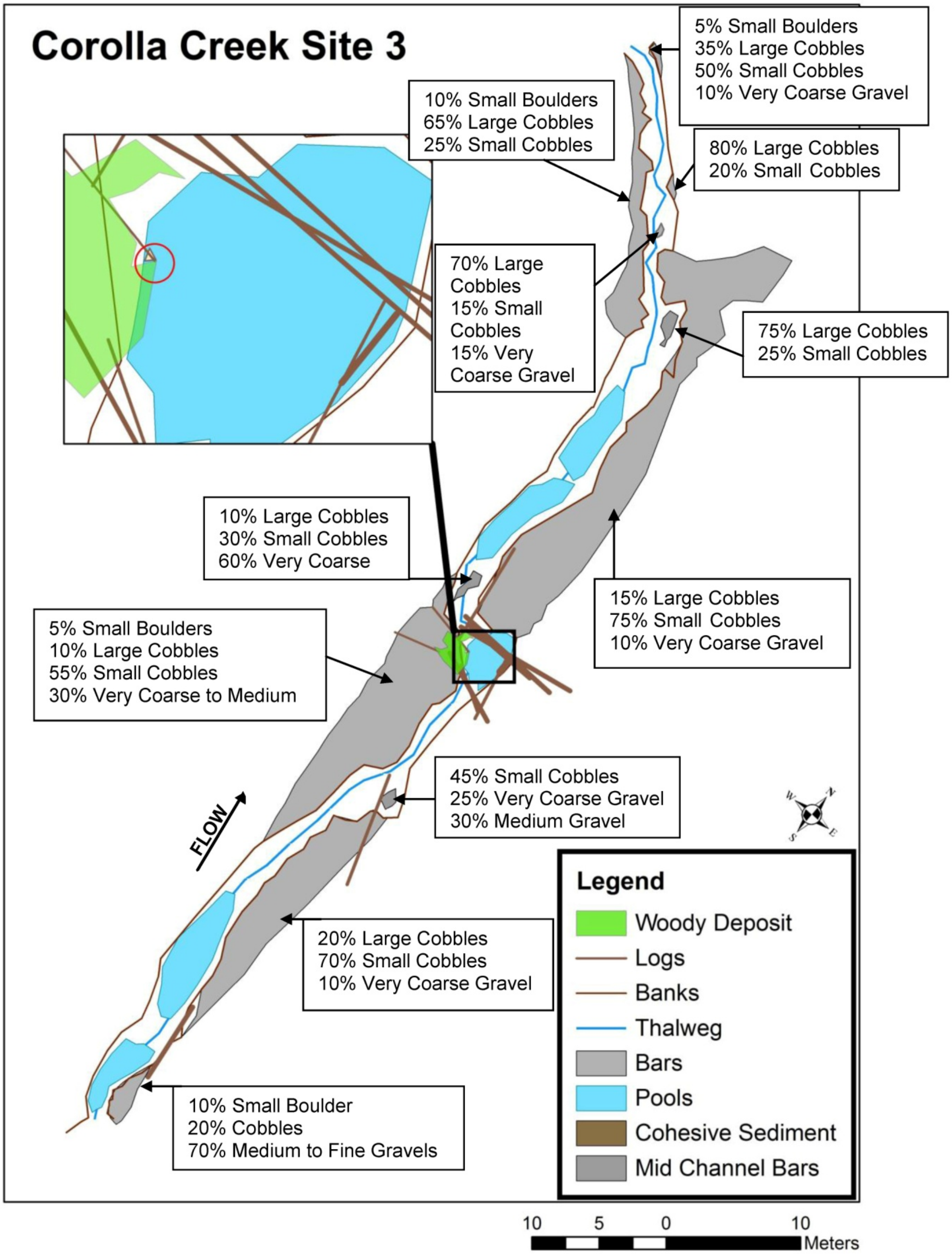


Figure 3-22: Stream reach morphology characteristics, in particular bar and pool formations in relation to in-stream wood deposit for Corolla Creek site 3

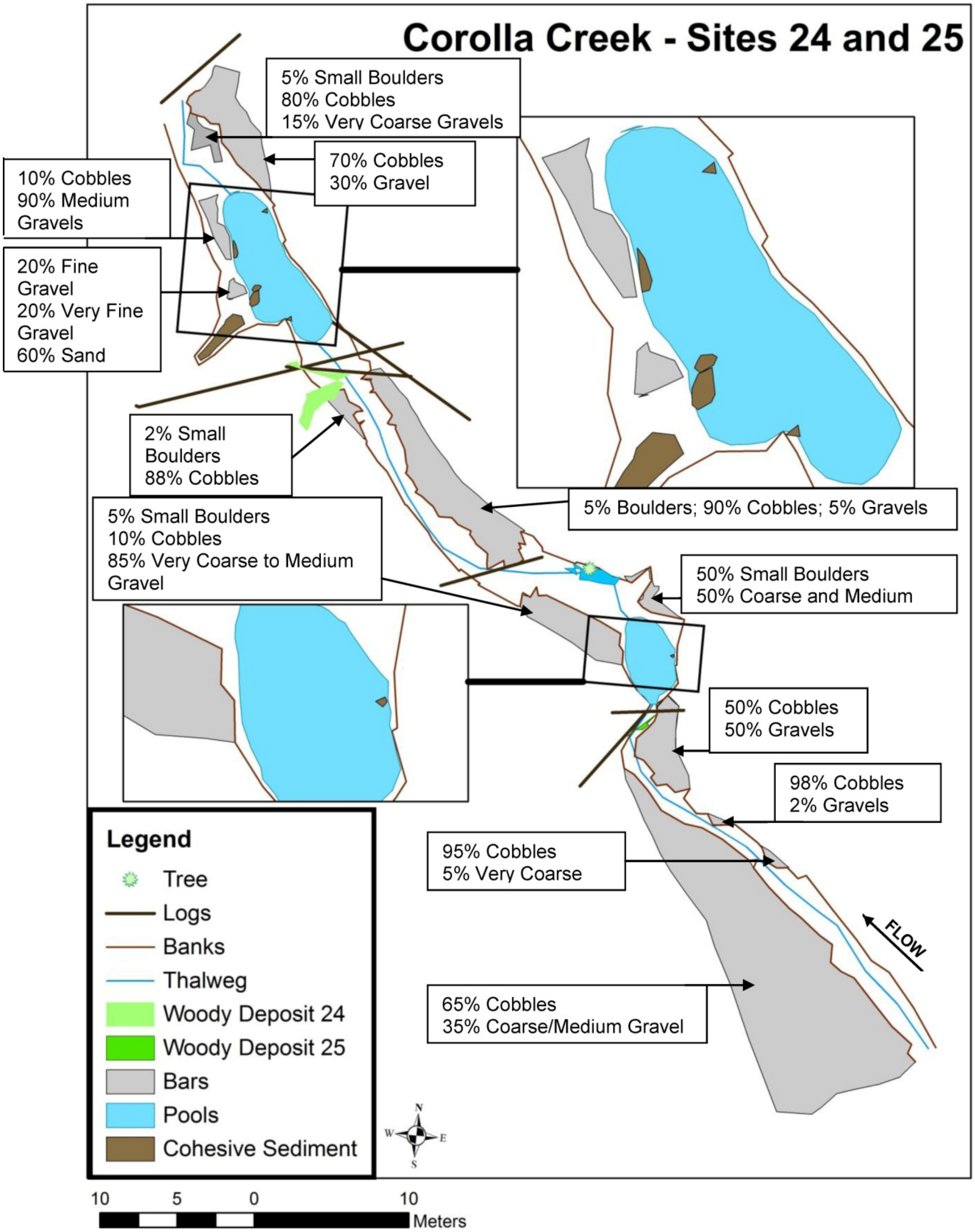


Figure 3-23: Stream reach morphology characteristics, in particular bar and pool formations in relation to in-stream wood deposit for Corolla Creek sites 24 & 25

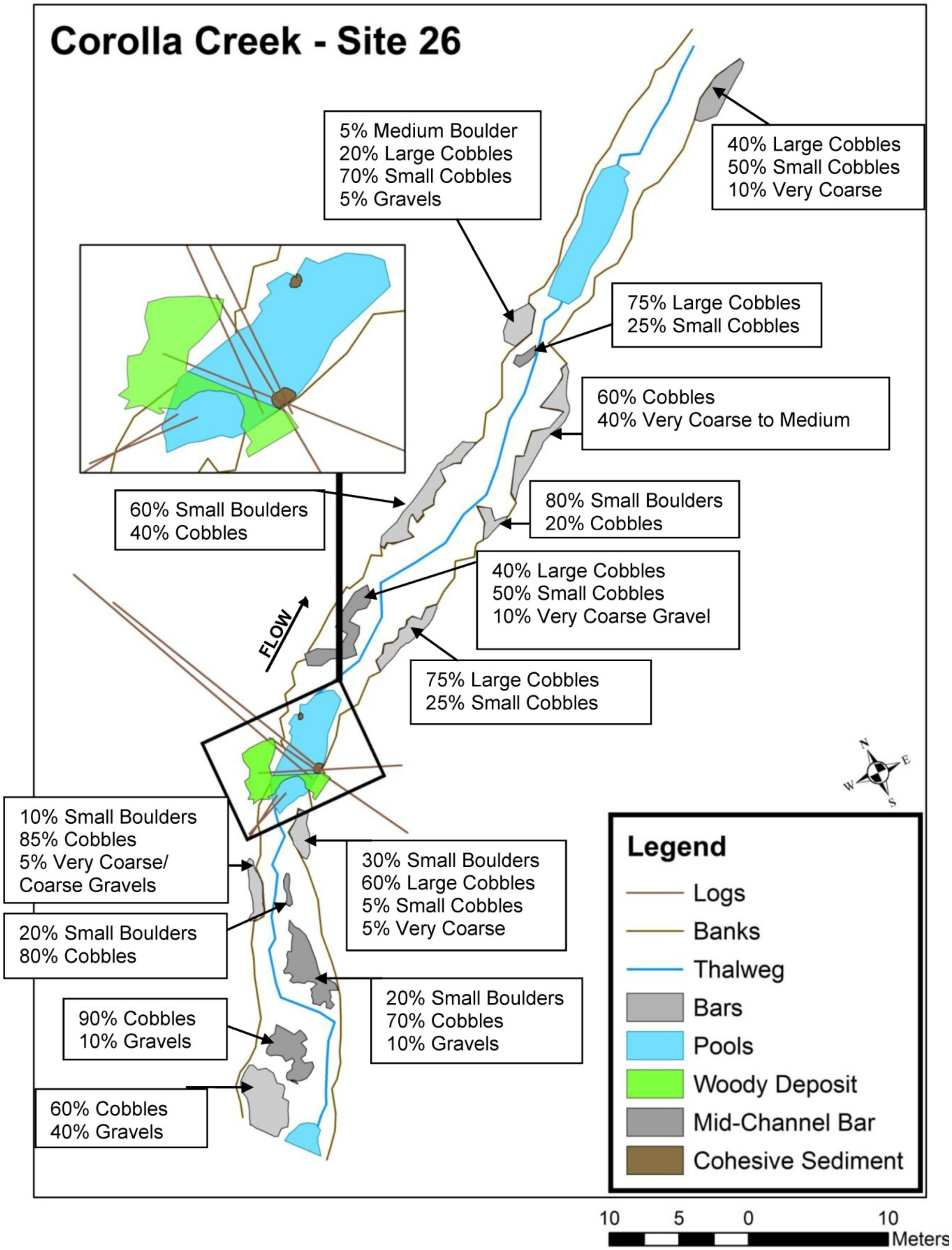


Figure 3-24: Stream reach morphology characteristics, in particular bar and pool formations in relation to in-stream wood deposit for Corolla Creek site 26

3.3 Channel classification

Geomorphic data collected for each of the six study sites was used to classify the channel morphology according to the methods of Montgomery and Buffington (1997). The results of the classification are presented in Table 3-7. The classification scheme requires data on bed material, bedform pattern, sediment storage and dominant roughness element and sediment source, along with the pool spacing and confinement of the channel. Using these seven parameters, the reaches were defined as either pool-riffle or step-pool streams. Four of the sites were found to be forced pool-riffle morphology because of the in-stream wood's influence on channel form and processes. The forced pool-riffle morphology was found at sites LE10, LE47 (downstream end), CC3 and CC24&25. The remaining sites, LE28, LE47 (upstream end) and CC26 were classified as step-pool morphology.

Lyons East showed an even distribution between the two types of channel reach morphology, with the lower site (LE10) being a forced pool-riffle, the middle site (LE28) was a step-pool and the upper site (LE47) was a combination of the two classifications. The lower sites of Corolla Creek (CC3 and CC24&25) were classified as forced pool-riffle morphology, while the upper reach was classified as step-pool. Based on field observations, Corolla Creek had a number of abandoned channels located within the floodplain, which provides evidence of lateral shifting in the floodplain. This process of lateral shift is characteristic of pool-riffle morphology, which was the dominant classification observed in Corolla Creek. Lyons East was found to have a more confined valley in the upper reaches of the watershed, which supports the shift in morphology from pool-riffle to step-pool classification.

The addition of in-stream wood structures can cause a change in flow as the obstruction can force a shift in channel reach morphology, this shift is referred to as forced. Montgomery and Buffington's (1997) classification includes forced morphologies, which are often associated with in-stream wood structures in forested mountain watersheds. Field observations indicate some reaches shifted between channel morphologies over a short distance, producing a forced morphology classification. For example, site CC3 is bedrock dominant in the upper reaches and resembles pool-riffle morphology downstream. This shift in channel reach morphology changes the channel reach to a forced pool-riffle classification (Table 3-7). Corolla Creek site CC26 is primarily a step-pool morphology, however it transitions to a bedrock channel in the downstream section of the reach. Another characteristic of a forced channel reach morphology is a shortened pool spacing, which is evident in sites LE10, LE47, CC3 and CC24&25 (Table 3-7). These watersheds are influenced by in-stream wood deposits, which can force channel morphology to shift over a short reach length. Therefore the classification results presented in Table 3-7 represent the most dominant channel morphology found in each selected study reach.

Table 3-7: Channel reach morphology of study sties according to the scheme of Montgomery and Buffington (1997)

	Lyons East 10	Lyons East 28	Lyons East 47		Corolla Creek 3	Corolla Creek 24 & 25	Corolla Creek 26
Typical bed material	Cobbles - Gravels	Cobbles and Boulders	Cobbles with some Gravel		Bedrock Gravels-Cobbles	Gravels - Cobbles	Boulders - Cobbles
Bedform pattern	Primarily Laterally oscillatory	Vertically and Laterally oscillatory	Vertically and Laterally oscillatory		Laterally oscillatory	Laterally oscillatory	Random and Vertically oscillatory
Dominant roughness elements	Bedform (bars), Grains sinuosity, Wood	Bedform (steps and bars), Grains, banks, Wood	Bedform (steps and bars), Grains, banks, sinuosity		Bedform (Bars), Grains, Wood	Banks, Grains, Bedform (Bars)	Grains, Banks, Bedform
Dominant sediment sources	Bank failure, Hillslope, and Fluvial	Bank failure, and Fluvial	Bank failure, and Fluvial		Fluvial and Bank failure	Bank failure, and Fluvial	Bank failure, and Fluvial
Sediment storage elements	Bedform, Overbank/ Overflow channel	Bedform	Overbank, Bedforms		Bedform	Overbank, Bedforms	Bedform, Stoss-lee sides of larger clasts
Typical confinement	Unconfined	Confined	Unconfined		Unconfined	Confined (Incised)	Confined (Incised)
Typical pool spacing	1.5	2	2 – 2.5		1.5 – 2	~2	~2
Stream type classification	**Forced Pool-Riffle**	**Step-Pool**	**Step-Pool to Forced Pool-Riffle downstream of debris**		**Forced Pool-Riffle**	**Forced Pool-Riffle**	**Step-Pool**

3.4 Pool characteristics

Pool morphology is discussed in this section. For comparison purposes the length of each pool formed by in-stream wood is converted to a percentage and presented with measured values in Table 3-8. In Lyons East, site LE10's in-stream wood structure has the largest percentage of the reach associated with wood-affected pools (16%) when compared to the other two sites (LE28 and LE47). Site LE47 had the lowest percentage of pool length formed by in-stream wood in Lyons East (6%), which corresponds to the lowest amount of in-stream wood measured in the active channel. In Table 3-8, the percentage of total pool length and percentage of pool length impacted by wood occur in the same order for the three sites. Site LE10 has the highest percentage of reach length found in pools (30%) and the highest percentage of wood-affected pool length (16%). Corolla Creek does not show the same trend (Table 3-8). Site CC3 in Corolla Creek has the largest percentage of reach length found in pools (42%), but the lowest percentage of wood-affected pool length (5%). In general the percentages of the reach found within wood-affected pools are smaller for Corolla Creek than Lyons East.

Table 3-8: Pool length and spacing for the selected study reaches

Stream/ Site	Reach length (m)	Total pool length (m)	Wood affected pool length (m)	Total pool length (%)	Wood affected pool length (%)	Pool spacing (m)	Channel width per pool
Lyons East							
Site 10	122	37	20	30	16	20	1.53
Site 28	101	25	10	24	9	20	1.97
Site 47	90	13	5	14	6	30	2.31
Corolla Creek							
Site 3	103	43	5	42	5	21	1.63
Site 24&25	87	11	6	12	7	29	2.24
Site 26	93	17	8	19	8	31	2.10

In addition to the percentage of the reach length found in pools, the spacing between pools was calculated. The pool spacing ranged from 1.53 channel widths to 2.31 channel widths (Table 3-8). The reaches with the highest and lowest pool spacing are both located in Lyons East. The pool spacing decreases as the percentage of pool length and in-stream wood pool length increases. The pool spacing for Corolla Creek shows an increasing trend as the percentage of reach pool length decreases (Table 3-8). The inverse relationship that is found between percentages of pool length associated with in-stream wood structures in Lyons East does not appear to occur in Corolla Creek

(Table 3-8). The data provide information on the average spacing of pools within the selected study reaches and provide context for the individual pool analysis classification.

The types of pools within each study reach were determined based on the formation mechanism as either self forming (free) or forced and the channel processes of scouring or damming (Hawkins et al., 1993; Montgomery et al., 1995). Using this information and the channel position, the pool classification is presented in Table 3-9. The information in Table 3-9 includes the stream, site and pool number, along with the location of each pool in relation to the in-stream wood structure. Pools were located either upstream (US), at the wood deposit (at wood) or downstream (DS). Over half of the pools (14 out of 25) were formed by a forced process while 11 of 25 were formed through free mechanisms. All wood-affected pools were considered forced pools, as the in-stream wood alters channel processes forming a pool. The majority of pools found in both watersheds were scour pools (24 of 25) and only 1 dammed pool was observed.

The pool classification shows there are similarities and differences between the two watersheds with respect to wood-affected pools. The types of non-wood-affected and wood-affected pools are presented in Table 3-9. Pool types found in Lyons East not associated with in-stream wood tend to be lateral scour, mid-channel and plunge pools. The plunge pools not formed by in-stream wood in Lyons East are related to the presence of boulders in the active channel. The plunge pools found at LE28 were located in a step-pool morphology reach; whereas lateral scour pools were located in pool-riffle morphology reaches. The wood-affected pools in Lyons East are plunge (20%), deflector (40%) and underflow (40%) pools.

In Corolla Creek, half the non-wood-affected pools were trench pools. These pools were generally located in the upper reach of CC3 and the downstream end of CC26, which are related to bedrock controls within these sections. The other types of pools formed were primarily mid-channel pools (25%), lateral scour (12.5%) and deflector pools (12.5%). The mid-channel and lateral scour pools were formed in the reaches with a pool-riffle morphology. The deflector pool was formed in the upper reach where larger substrate (boulders and large cobbles) deflects water along the substrate causing a scour pool to form on the upstream side. The wood-affected pools were different for each of the impacted pools (dam, deflector and underflow). The only dammed pool is located in site CC3 and is wood-affected. The deflector and underflow pools associated with the in-stream wood structures in Corolla Creek were similar to the wood-affected pools found in Lyons East (Table 3-9).

Table 3-9: Pool location and classification for each of the six selected reach scale study sites

Stream/ Site Pool	Location	Free/ Forced	Scour/ Dammed	Pool classification	Other details
LE10					
Pool 1	US	Free	Scour	Lateral scour	Undercut bank with leaning tree
Pool 2	US	Free	Scour	Mid-channel	
Pool 3	At wood	Forced	Scour	Plunge	Wood step
Pool 4	At wood	Forced	Scour	Deflector	Woody deposit on the outside meander bend
Pool 5	At wood	Forced	Scour	Underflow	Wood accumulation in the middle of the pool – deeper pool upstream
Pool 6	DS	Forced	Scour	Plunge	Boulder forming step
LE28					
Pool 1	US	Free	Scour	Plunge	Cascade with small plunge
Pool 2	US	Free	Scour	Mid-channel	
Pool 3	US	Forced	Scour	Lateral scour	
Pool 4	At wood	Forced	Scour	Deflector	Wood influence
Pool 5	DS	Forced	Scour	Plunge	Boulders within stream
LE47					
Pool 1	US	Free	Scour	Lateral scour	Leaning tree on the outside meander bend
Pool 2	At wood	Forced	Scour	Underflow	Wood influence
Pool 3	DS	Forced	Scour	Lateral scour	Stream bank projection and leaning tree
CC3					
Pool 1	US	Free	Scour	Trench	
Pool 2	US	Free	Scour	Trench	
Pool 3	At wood	Forced	Dammed	Dam	Leaning tree and woody accumulation
Pool 4	DS	Free	Scour	Mid-channel	
Pool 5	DS	Free	Scour	Trench	No bedrock but large substrate
CC24&25					
Pool 1	At wood	Forced	Scour	Underflow	Wood influenced
Pool 2	Between	Free	Scour	Lateral scour	Leaning tree on the outside meander bend
Pool 3	DS	Free	Scour	Mid-channel	
CC26					
Pool 1	US	Forced	Scour	Deflector	Large substrate and possible wood influence upstream
Pool 2	At wood	Forced	Scour	Deflector	Wood influence
Pool 3	DS	Forced	Scour	Trench	Bedrock outcrop

3.4.1 Pool dimensions

The length and average depth of each pool located in the six study reaches are presented in Table 3-10. There does not appear to be a relationship between either length or average water depth and the presence of in-stream wood. In half of the study reaches, wood-affected pool(s) had the highest average depth (LE28, CC3 and CC26). For the remaining study reaches, the average pool depth for wood-affected pools was generally within the middle range of pool depths for the reach. However, at site LE10 one of the wood-affected pools was the shallowest in the reach (Table 3-10). Pool length also varies among the study reaches. For example, site LE10 had both the longest and shortest pool in the reach associated with in-stream wood (Table 3-10). The results in Table 3-10 show half the sites (LE47, CC24&25 and CC26) had the wood-affected pools in the middle range for pool length in comparison to the non-wood-affected pools. Site CC3 is the only site where the wood-affected pool was the shortest.

The comparisons of pool type to length and depth dimensions are presented in Table 3-10. With respect to pool type, plunge pools are typically the shortest pools. The length of deflector pools ranged from 7.0m to 9.6m, with the exception of the much shorter Pool 1 in site CC26. In Corolla Creek, trench pools are generally the longest and most shallow pools in the watershed. There are no strong trends between pool types and the pool dimensions of length and average depth (Table 3-10).

A summary of channel width, average channel depth and average sediment thickness for each pool transect is found in Appendix H. During analysis information was supplemented with cross sectional graphs, which illustrate the channel shape at each transect and the location and shape of the cohesive sediment depositions. These cross sectional graphs were used in the classification of pool types and to visually represent the pool dimensions (depth and width). This allowed for each transect to be used when analyzing the pool instead of averages, which provided a more accurate comparison between pools. In particular these cross sections illustrate the impact of in-stream wood on both pool shape and cohesive sediment storage.

The dimensions of the channel were used to calculate the residual pool volume at low flow for the six study reaches, those resulting calculations can be seen in Table 3-11. The volume contained in wood-affected pools ranged from the lowest to the highest pool volume observed in a reach. In half the reaches (LE28, LE47 and CC26), the highest pool volume corresponded to pools formed at in-stream wood structures. In site LE10, one of the three pools associated with in-stream wood contained the highest volume of water in comparison to the other pools in the reach. However, site LE10 also had the lowest pool volume associated with the in-stream wood structure. Corolla Creek sites CC3 and CC24&25 did not have the highest or lowest pool volume associated with in-stream wood. The results in Table 3-11 show no trend between the type of pool and volume of water.

Table 3-10: Summary table of pool dimensions for six study reaches

Stream/ Site/ Pool number	Location	Pool type	Pool length (m)	Average water depth (m)	Average sediment thickness (m)
LE10					
Pool 1	Upstream	Lateral scour	7.0	0.161	< 0.001
Pool 2	Upstream	Mid-channel	5.5	0.195	0.001
Pool 3	At wood	Plunge	2.5	0.112	No sediment
Pool 4	At wood	Deflector	7.0	0.173	0.003
Pool 5	At wood	Underflow	10.0	0.164	0.001
Pool 6	Downstream	Plunge	4.5	0.177	0.002
LE28					
Pool 1	Upstream	Plunge	3.1	0.133	No sediment
Pool 2	Upstream	Mid-channel	5.8	0.112	No sediment
Pool 3	Upstream	Lateral scour	2.8	0.113	No sediment
Pool 4	At wood	Deflector	9.5	0.210	0.007
Pool 5	Downstream	Plunge	3.4	0.107	No sediment
LE47					
Pool 1	Upstream	Lateral scour	5.2	0.306	0.003
Pool 2	At wood	Underflow	5.3	0.294	0.005
Pool 3	Downstream	Lateral scour	2.5	0.231	0.001
CC3					
Pool 1	Upstream	Trench	8.0	0.151	No sediment
Pool 2	Upstream	Trench	10.5	0.237	No sediment
Pool 3	At wood	Dam	4.6	0.245	< 0.001
Pool 4	Downstream	Mid-channel	8.7	0.211	No sediment
Pool 5	Downstream	Trench	11.3	0.187	No sediment
CC24 & 25					
Pool 1	At wood	Underflow	6.0	0.249	0.001
Pool 2	Between	Lateral scour	4.5	0.177	No sediment
Pool 3	Downstream	Mid-channel	11.0	0.276	0.003
P3 Inlet	Downstream		3.8	0.061	0.037
CC26					
Pool 1	Upstream	Deflector	2.0	0.260	No sediment
Pool 2	At wood	Deflector	7.6	0.345	0.001
Pool 3	Downstream	Trench	10.6	0.247	No sediment

Table 3-11: Residual pool and cohesive sediment volume for six study reaches

Stream/ Site/ Pool number	Location	Pool type	Residual pool volume (m^3)	Residual cohesive sediment volume (m^3)	V*
LE10					
Pool 1	US	Lateral scour	1.094	0.002	0.001
Pool 2	US	Mid-channel	1.291	0.004	0.003
Pool 3	At wood	Plunge	0.490	No sediment	
Pool 4	At wood	Deflector	1.699	0.016	0.010
Pool 5	At wood	Underflow	1.361	0.006	0.004
Pool 6	DS	Plunge	1.294	0.006	0.005
LE28					
Pool 1	US	Plunge	0.472	No sediment	
Pool 2	US	Mid-channel	0.754	No sediment	
Pool 3	US	Lateral scour	0.466	No sediment	
Pool 4	At wood	Deflector	4.430	0.379	0.085
Pool 5	DS	Plunge	0.239	No sediment	
LE47					
Pool 1	US	Lateral scour	1.241	0.042	0.033
Pool 2	At wood	Underflow	3.100	0.049	0.016
Pool 3	DS	Lateral scour	0.588	0.002	0.004
CC3					
Pool 1	US	Trench	1.413	No sediment	
Pool 2	US	Trench	3.542	No sediment	
Pool 3	At wood	Dam	1.844	No sediment	
Pool 4	DS	Mid-channel	3.171	No sediment	
Pool 5	DS	Trench	4.785	No sediment	
CC24&25					
Pool 1	At wood	Underflow	3.729	0.017	0.004
Pool 2	Between	Lateral scour	1.229	No sediment	
Pool 3	DS	Mid-channel	5.063	0.154	0.030
CC26					
Pool 1	US	Deflector	0.014	No sediment	
Pool 2	At wood	Deflector	6.213	0.011	0.002
Pool 3	DS	Trench	5.730	No sediment	

NOTE: V* is a ratio of cohesive sediment volume to pool water volume plus cohesive sediment volume; US – Upstream; DS – Downstream

The pool length and volume were converted into a percentage in order to compare wood-affected and non-wood-affected pools within the study reaches (Tables 3-12 and 3-13) When comparing the two watersheds, the percentage of pool volume associated with in-stream wood was higher for Lyons East than for Corolla Creek. The wood-affected pool volume for Lyons East was approximately 50% to 70% of the total pool volume for a study reach. In contrast, the wood-affected pool volume for Corolla Creek ranged from 12.5% to 52%. The actual percentage values for each of the selected study reaches are presented in Tables 3-12 and 3-13 for Lyons East and Corolla Creek respectively.

3.4.2 Cohesive sediment storage

The average thickness of cohesive sediment stored within and alongside the study reach pools is presented in Table 3-10. For half the study reaches (LE28, C3 and CC26), cohesive sediment storage was observed only in wood-affected pools. When comparing cohesive sediment stored in both wood-affected and non-wood-affected pools there appears to be no association between the presence of in-stream wood and sediment thickness. The thickest deposit of cohesive sediment was located in CC24&25 at the inlet of pool 3. The next thickest cohesive sediment deposits were found in the middle and upper reaches of Lyons East (sites LE28 and LE47). In Corolla Creek, two of the three reaches only had sediment stored in the wood-affected pools (sites CC3 and CC26). However, in site CC24&25, the lowest sediment thickness was found stored in the wood-affected pool (Table 3-10). These results show the majority (5 out of 8) of wood-affected pools were able to store thicker cohesive sediment deposits than non-wood-affected pools.

The volume of stored sediment in each pool is presented in Tables 3-11, 3-12 and 3-13. The residual sediment calculations determine only the sediment stored within the residual pool. The sediment measured in pool 3 at site CC3 is not included in the volume of cohesive sediment as it is not located within a residual pool. In Lyons East, the wood-affected pools that stored sediment have the highest volume of cohesive sediment storage when compared to other pools in the reach. For the pools in Corolla Creek with stored cohesive sediment, the wood-affected pool volumes are similar between the two reaches, CC24&25 has $0.017 m^3$ and CC26 stores $0.011 m^3$ (Table 3-11).

Channel processes determine the type of pool formed and the pool's ability to store cohesive sediment. The results of cohesive sediment storage as it relates to pool type are shown in Table 3-11. Cohesive sediment storage in wood-affected pools was found predominately in scour pools. Two wood-affected pools did not store cohesive sediment, one is a dammed pool (CC3) and the other is a plunge pool (LE10). Turbulence in the plunge pool does not provide conditions for sediment storage. In one of four plunge pools, cohesive sediment was stored. In this plunge pool the storage occurred in an eddy formed behind a boulder. The field observations found all underflow pools had some cohesive sediment storage; whereas none of the trench pools had stored sediment.

Table 3-12: Pool characteristics expressed as measurements and percentage for the three selected study reaches in Lyons East

Stream Site/ Pool No.	Location	Pool length (m)	Pool length (%)	Residual pool volume (m^3)	Residual pool volume (%)	Residual cohesive sediment volume (m^3)	Residual cohesive sediment volume (%)
LE10							
Pool 1	US	7.0	19	1.094	15	0.002	6
Pool 2	US	5.5	15	1.291	18	0.004	12
Pool 3	At wood	2.5	7	0.490	7	No sediment	0
Pool 4	At wood	7.0	19	1.699	24	0.016	47
Pool 5	At wood	10.0	27	1.361	19	0.006	18
Pool 6	DS	4.5	12	1.294	18	0.006	18
	Total	*36.5*	*99***	*6.229*	*101***	*0.034*	*101***
Total - Wood		**19.5**	**53**	**3.55**	**50**	**0.022**	**65**
LE28							
Pool 1	US	3.1	13	0.472	7	No sediment	0
Pool 2	US	5.8	24	0.754	12	No sediment	0
Pool 3	US	2.8	11	0.466	7	No sediment	0
Pool 4	At wood	9.5	39	4.430	70	0.379	100
Pool 5	DS	3.4	14	0.239	4	No sediment	0
	Total	*24.6*	*101***	*6.361*	*100*	*0.379*	*100*
Total – Wood		**9.5**	**39**	**4.430**	**70**	**0.379**	**100**
LE47							
Pool 1	US	5.2	40	1.241	25	0.042	45
Pool 2	At wood	5.3	41	3.100	63	0.049	53
Pool 3	DS	2.5	19	0.588	12	0.002	2
	Total	*13*	*100*	*4.929*	*100*	*0.093*	*100*
Total – Wood		**5.3**	**40**	**3.100**	**63**	**0.049**	**53**

** Percentages may not total 100% due to rounding error

Table 3-13: Pool characteristics expressed as measurements and percentage for the three selected study reaches in Corolla Creek

Stream Site/ Pool No.	Location	Pool length (m)	Pool length (%)	Residual pool volume (m^3)	Residual pool volume (%)	Residual cohesive sediment volume (m^3)	Residual cohesive sediment volume (%)
CC3							
Pool 1	US	8.0	19	1.413	10	No sediment	
Pool 2	US	10.5	24	3.542	24	No sediment	
Pool 3	At wood	4.6	11	1.844	13	No sediment	
Pool 4	DS	8.7	20	3.171	22	No sediment	
Pool 5	DS	11.3	26	4.785	32	No sediment	
	Total	*43.1*	*100*	*14.755*	*101***	*No sediment*	*No sediment*
Total – Wood		**4.6**	**11**	**1.844**	**13**	**No sediment**	**No sediment**
CC24&25							
Pool 1	At wood	6.0	28	3.729	37	0.017	10
Pool 2	Between	4.5	21	1.229	12	No sediment	0
Pool 3	DS	11	51	5.063	51	0.154	90
	Total	*21.5*	*100*	*10.021*	*100*	*0.171*	*100*
Total – Wood		**6.0**	**28**	**3.729**	**37**	**0.017**	**10**
CC26							
Pool 1	US	2.0	10	0.014	0.1	No sediment	0
Pool 2	At wood	7.6	38	6.213	52.0	0.011	100
Pool 3	DS	10.6	53	5.730	47.9	No sediment	0
	Total	*20.2*	*101***	*11.957*	*100*	*0.011*	*100*
Total – Wood		**7.6**	**38**	**6.213**	**52.0**	**0.011**	**100**

** Percentages may not total 100% due to rounding error

Another factor contributing to cohesive sediment storage is the presence of in-stream wood. The cohesive sediment stored within the residual pool was converted to a percentage for each pool and then totalled for sediment stored in wood-affected pools (Tables 3-12 and 3-13). The data ranged from 10 % to 100% of sediment found in pools influenced by in-stream wood. The percentage of cohesive sediment found in Lyons East was higher for wood-affected pools as compared to non-wood-affected pools in the three reaches. The percentage of cohesive sediment volume stored was 65% for LE10, 100% for LE28 and 53% for LE47. In Corolla Creek the percentages tended to be lower, with two sites (CC3 and CC24&25) having less than10% of cohesive sediment stored in wood-affected pools. The results show only one reach in Corolla Creek where in-stream wood had control in the storage of sediment. This site was CC26, which had 100% of the stored sediment locate in the wood-affected pool.

The residual pool volume and residual cohesive sediment volume are positively related. The values presented within Tables 3-11, 3-12 and 3-13 show that as the residual pool volume increases, the stored sediment increases, assuming cohesive sediment is present. V* is expressed as the ratio of cohesive sediment volume to pool water volume plus cohesive sediment volume (Hilton & Lisle, 1993). The results of the V* calculation for each pool are recorded in Table 3-11. The V* values are generally higher in wood-affected pools except for at site LE47, where pool 1 (non-wood-affected) has a higher ratio. Wood-affected pools have a V* ranging from 0.002 in CC26 to 0.085 in LE28. The V* value provides information on the amount of sediment stored in individual pools.

In order to provide information on the overall fraction of scoured pool volume occupied by cohesive sediment the weighted average was calculated using Hilton and Lisle's (1993) formula (see section 2.5). The weighted average of V* (V^*_w) provides information on the overall storage of cohesive sediment for each study reach. The V^*_w results for Lyons East and Corolla Creek are presented in Table 3-14 and Figure 3-25**.** The results indicate that the number of pools within a reach is not a determining factor in the storage of cohesive sediment, as the reach with the highest number of pools does not have the highest V^*_w value. The largest number of pools occurred in Lyons East site 10 (6 pools), however it has the smallest V^*_w value (0.005) in the watershed. There is no clear relationship between the V^*_w value and number of pools, as half the reaches have 3 pools and differ in their V^*_w values; and the highest and lowest V^*_w values share the same number of pools.

Table 3-14: Weighted average of V* for selected study reaches

Stream/Site	V^*_w	Number of pools
Lyons East		
Site 10	0.005	6
Site 28	0.056	5
Site 47	0.019	3
Corolla Creek		
Site 3	0	5
Site 24&25	0.017	3
Site 26	0.001	3

Although the V^*_w values do not appear related to the number of pools in a reach, land-use disturbance does appear to have an effect. The V^*_w values are higher in Lyons East than Corolla Creek (Table 3-14). This difference can be seen in Figure 3-25, which shows that all the V^*_w values for Lyons East sites are larger than the V^*_w values for Corolla Creek sites. All reaches studied in Lyons East have some level of cohesive sediment storage within pools; whereas Corolla Creek has one site (CC3) which does not contain any stored cohesive sediment in the residual pools studied.

The graph in Figure 3-25 and the data in Table 3-14 illustrate a difference not only between the individual reaches but between the two studied watersheds.

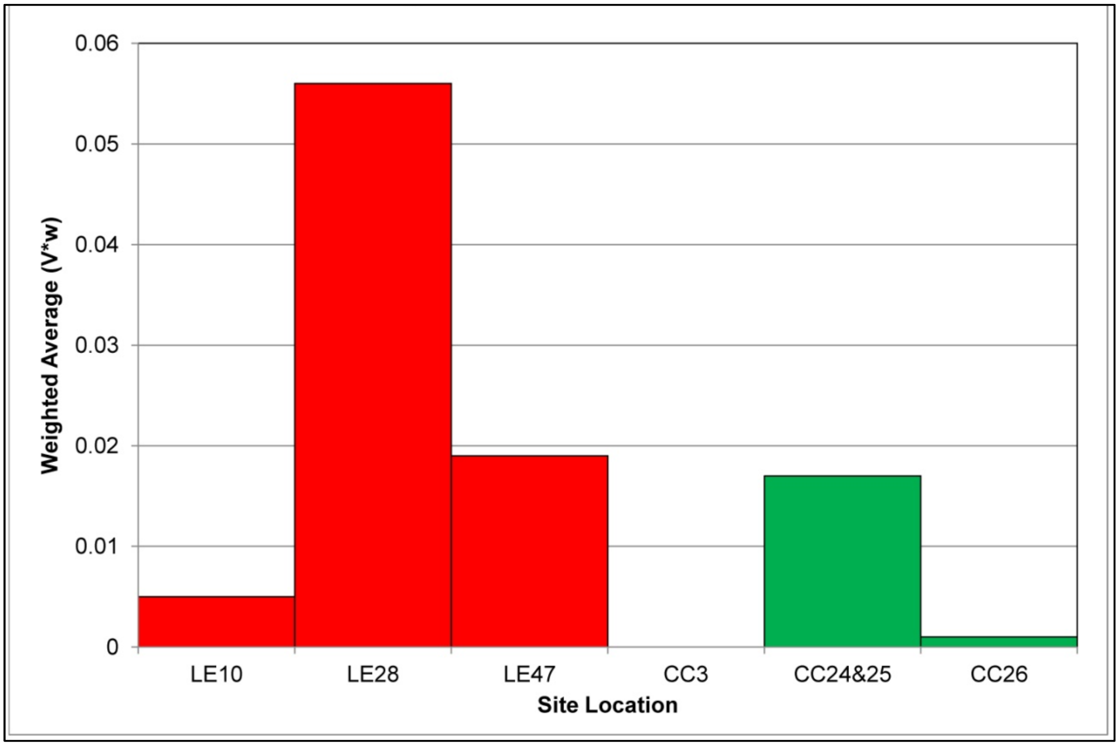


Figure 3-25: Weighted averages of V* for the six selected study reaches

Chapter 4
Discussion

4.1 Introduction

The presence of in-stream wood can alter the flow and sediment regime of a stream and strongly influence channel morphology (Montgomery et al., 2003). The current research project examined the spatial distribution of in-stream wood along the main stem of two headwater streams which represented different land-use disturbances (burned and unburned). The number of in-stream wood sites per 100m was comparable to previous work conducted in the Colorado Front Range and Wyoming Absaroka Range of the Rocky Mountains (Wohl & Jaeger, 2009; Zelt & Wohl, 2004). The following discussion examines possible explanations for the minimal difference in the frequency of in-stream wood structure types observed between the burned and unburned watersheds. In addition the wood characteristics and morphology variables used to understand the spatial distribution of in-stream wood formations will be discussed. These results and the following discussion provide a regional-scale description of in-stream wood characteristics in headwater streams of the Oldman River Basin.

In the second phase of the research project, a reach-scale level of analysis was conducted to examine the impacts of in-stream wood on channel morphology. The results indicate that reaches were forced towards a pool-riffle morphology by the presence of in-steam wood, which increased the number of pools formed. It was noted that pools stored more cohesive sediment when formed by in-stream wood. In particular, it was observed that pools stored more cohesive sediment when in-stream wood was recruited simultaneously with sediment during bank failure. This observation led to the creation of a conceptual model, which can be used to predict the location of stored cohesive sediment. Planning and management implications of impacts on water quality due to sediment-associated nutrients are discussed in this chapter.

4.2 Spatial distribution of in-stream wood deposits

A number of previous studies have examined the impact of in-stream wood on stream hydrology, geomorphology and ecology. These studies have been conducted in different geographical locations and on various stream types including; sand-bed streams in Australia (Webb & Erskin, 2005), gravel bed streams in Alaska (Gomi et al., 2001) and neotropical streams in Costa Rica (Wohl et al., 2009). The studies found that environments respond to disturbances and the input of wood differently due to climate, riparian forest structure and stream types. After completing a study in Bighorn National Forest (Wyoming, USA), Nowakowski and Wohl (2008) recommended more wood loading datasets be developed for the Rocky Mountains to better understand regional-scale controls. The current research project addressed this recommendation by examining the spatial distribution of in-stream wood located along the eastern slopes of the Canadian Rocky Mountains.

The number of in-stream wood sites for the two studied watersheds averaged out to 1.49 deposits per 100m. The research compiled in Table 4-1 illustrates the frequency of in-stream wood accumulations per 100 metres for a number of published studies. The terminology used for each study (jams, dams and accumulations) has been included in Table 4-1 due to the present inconsistencies throughout in-stream wood literature. These wording inconsistencies of structure types and their associated definitions make comparisons difficult, as some studies examine the frequency of jams or dams, where others simply examine accumulations (Table 4-1). Without a consistent definition among studies, it was a challenge to know if comparable structures were included in the listed studies.

Table 4-1: The number of in-stream wood sites per 100m reported in the literature

Location	Jam/Dam Frequency	Reference
Rocky Mountains (Alberta, Canada)	1.49 deposits/100m	Current Study
Wyoming Absaroka Range (USA) in Bighorn National Forest	1.5 debris jams/100m (unburned) 1.6 debris jams/100m (burned)	(Zelt & Wohl, 2004)
Colorado Front Range (USA)	< 2 jams/100m	(Wohl & Jaeger, 2009)
Oregon (USA)	0.55 jams/100m	(Thom et al., 2001).
New Mexico (USA)	0-10 dams/100m (Aspen) 50 dams/100m (Coniferous)	(Trotter, 1990)
San Antonio River (Texas, USA)	0.1 jams/100m (2003) 0.21 jams/100m (2007)	(Curran, 2010)
Boreal Shield Forest (Ontario, Canada)	2.4 dams/100m	(Kreutzweiser et al., 2005)
Hubbard Brook Experimental Forest (New Hampshire, USA)	14 dams/100m	(Warren et al., 2007)
New Hampshire (USA)	34 dams/100m (1st order) 14 dams/100m (2nd order) 3 dams/100m (3rd order)	(Bilby & Likens, 1980)
Italian Dolomites (Italy)	0.71 jams/100m to 3.06 jams/100m	(Comiti et al., 2006).
Hampshire, UK (UK)	0-6 dams/100m	(Gregory et al., 1993)
Hampshire, UK (UK)	4 dams/100m	(Gregory et al., 1985)
Valdivian Coastal Reserve, (Chile)	1.3 accumulations/100m	(Iroume et al., 2010)
La Selva (Costa Rica)	0.47 jams/100m	(Cadol et al., 2009).
Tierra del Fuego (Argentina)	6.1 jams/100m	(Mao et al., 2008).
Trés Arroyos (Chilean Andes)	5.1 jams/100m 1.7 log-steps/100m	(Andreoli et al., 2007)

A wide range of in-stream wood sites have been reported for different watersheds (Table 4-1). These results show that similar environments can have different spatial distribution of in-stream wood deposits. For example, the five managed streams in the Italian Dolomites ranged from 0.71jams/100m to 3.06 jams/100m (Comiti et al., 2006). The observed complexity of spatial distribution for in-stream wood within similar environments was further complicated when considering comparisons in a range of differing geological and eco-hydrological settings. The studies have shown that climate and riparian forest characteristics influence the formation and distribution of in-stream wood structure. For example, when comparing the frequency of in-stream wood deposits in the Rocky Mountains and La Selva in Costa Rica, the difference in wood loading is attributed to variations in the local climate. Cadol et al. (2009) reported that a drier climate in the Rockies contributed to smaller tree size and lower decay rates. Lower frequencies of in-stream wood in alpine channels are likely due to the limited availability of large logs in these systems (Comiti et al., 2008). Similarly, lower frequencies of large logs are found in New Zealand, making the frequency of in-stream wood there comparable to streams in Colorado subalpine forests (Baillie & Davies, 2002).

Natural vegetation influences the formation and distribution of in-stream wood and the presence of in-stream wood is related to the type and abundance of riparian vegetation. Similar geographic regions typically have similar climate and vegetation, which reduces influential variables when comparing studies. The work completed in both Colorado and Wyoming is likely the most relevant to the current project in terms of forest structure and climate. The spatial distributions of in-stream wood accumulations per 100m are comparable between the Colorado study and the current project (Table 4-1) at fewer than 2 jams/100m and 1.49 deposits per 100m respectively. The results from Wyoming are even more similar with 1.5 debris jams/100m for the unburned watershed and 1.6 debris jams/100m for the burned watershed (Zelt & Wohl, 2004). Slightly less in-stream wood deposit sites were found in the current study, which may be due to differences in permitted land-use practices, such as recreational activities, ATV trails, livestock grazing, mineral exploration and salvage logging.

Generally, a change in land-use practices influences the distribution of in-stream wood because of the coupling between adjacent forested hillslopes and in-stream wood. It was hypothesized by the researcher that the different land-use practices in the two studied watersheds would cause a difference in spatial distributions of in-stream wood. However, the frequencies of in-stream wood deposits, for both Lyons East and Corolla Creek, were similar. In a comparable study, Zelt and Wohl (2004) examined both a burned catchment area and a reference catchment area in Wyoming. They found the frequencies of in-stream jams were similar for both streams (1.6 debris jams/100m and 1.5 debris jams/100m respectively). In addition, Zelt and Wohl (2004) reported little difference in the percentage of jams (including partial jams), between their study streams. These results are very close to the results in the current study, the similarities can be attributed to a similar method used to classify in-stream wood and environmental conditions.

Several differences have been reported in the definition of in-stream wood based on size and structure-type classification. Structure definition will determine the number of in-stream wood structures found per 100m. Accordingly, the diversity of definitions reported in published literature, for jams and dams, contributes to the range of values per 100m presented in Table 4-1. These definitions for in-stream wood structures, particularly jams and dams, are found in Tables C-2 and C-3 in Appendix C. Depending on the researcher, the definition of a jam could be two, three or five pieces of wood in contact with each other (for references refer to Table C-2). The difference in the number of pieces comprising a structure could alter the number of sites included within a particular studied watershed. In addition, if the definitions also include a size restriction on individual wood pieces located in a structure, it can further complicate comparisons between studies. The desire for cross-study comparison is part of the rationale behind the recent call for common metrics proposed by Wohl et al. (In Press). Comparable results would provide a solid foundation of in-stream wood characteristics, which could be used to develop a wood regime to be included in morphological classifications. This would allow for better predictions of channel responses following disturbance events in forested environments.

4.2.1 Land-use disturbance impacts

The spatial distribution of in-stream wood is governed by input and export processes within the channel. The type of riparian forest will determine the amount and type of wood available for recruitment to the channel. Previous research indicates the amount of in-stream wood changes considerably through the regeneration process following a disturbance (Berg et al., 2002; Chen et al., 2005; Chen et al., 2006; Reeves et al., 2006). A study conducted by Warren et al. (2007) in Hubbard Brook Experimental Forest, found the rate of in-stream wood increased from 4 dams per 100m to between 8 and 14 dams per 100m after forest regeneration. Based on the Hubbard Brook results and other previously published studies, it was thought that a difference in spatial distribution between the two studied watersheds would be observed.

Previous research completed in wildfire impacted regions report increases in the volume of in-stream wood from tree fall due to wildfire (Chen et al., 2005). The lack of difference found between the numbers of in-stream wood structures for the current studied watersheds, may be related to when the research was conducted. Research by Minshall and Brook (1991) and Zelt and Wohl (2004) both found a decrease of in-stream wood in burned watersheds four to five years after a wildfire, with an increase in jams occurring about ten years post-fire (Minshall & Brock, 1991; Zelt & Wohl, 2004). The trend between the landscape disturbance and quantity of in-stream wood has been described as a "U" shaped curve – there is an initial increase, followed by a decrease and then a return to higher levels with regeneration (Gurnell et al., 1995). The riparian forest and the disturbance characteristics influence how a system responds to a disturbance. A study completed by Comiti et al. (2008) found the response to a wildfire disturbance is not immediate and can have a lag time of several decades.

The wildfire in Lyons East occurred in 2003 and was one of the most severe fires on record for the area. The field investigation was conducted in the summer of 2009, six years after the fire. There are a number of sites in Lyons East where hillslope failures and blowdown are evident, with very few burned trunks still standing. However, other sections adjacent to the channel still have large amounts of standing charred wood. For site LE11, it was evident that additional wood had been recruited to the stream through blowdown within about one and a half months after the site was initially observed. Consequently, additional charred wood adjacent to the stream has the potential to increase wood recruited to the channel through blowdown processes. Based on field observations the majority of the watershed still had a significant supply of standing burned trees yet to be recruited to the channel. Accordingly, in-stream wood recruitment had likely not peaked within the disturbed watershed (Lyons East) in 2009.

4.2.2 In-stream wood recruitment mechanisms

Based on field observations the recruitment of in-stream wood was classified as local recruitment (hillslope) or fluvial (in-stream) recruitment. A piece of in-stream wood was classified as locally recruited if the rooting location of the tree could be determined. If the local growing point could not be identified, the wood was classified as fluvial recruitment. The position and orientation of the in-stream wood piece also provided additional information on the recruitment mechanism. In Lyons East the local recruitment mechanisms observed were; toppling of unstable charred trees along the channel banks, sporadic blowdown, inputs from bank erosion and wood delivery due to hillslope failure. In Corolla Creek the local recruitment of wood occurred primarily due to bank erosion and some hillslope failures. Both watersheds also had evidence of fluvial recruitment of wood to an in-stream structure.

In Lyons East there was some evidence of blowdown recruitment, such as the single tree recruited to site LE11 during the 2009 field season. Previous research has found either a single uprooted tree or numerous uprooted trees further upslope can be knocked down due to wind (May & Gresswell, 2003a). It is predicted that the fire weakened the root structure of trees in Lyons East, making them susceptible to blowdown during wind storms. There were trees observed on hillslopes and floodplains that had fallen over with the surrounding area remaining undisturbed; it is predicted these trees were blown over and will be potentially be recruited to the stream in the future. Although there was some evidence of blowdown recruiting trees to the channel and floodplain, further study is required to better understand the processes involved and identify the amount of wood recruited through this process.

In-stream wood was recruited through bank erosion processes in both Lyons East and Corolla Creek. This type of recruitment is important as previous research has identified bank erosion as a key component in wood and sediment budgets (Benda et al., 2002). In addition in-stream wood recruited through bank erosion generally falls across the channel with the rootwad still attached forming a more stable structure (Benda et al., 2002; Fetherston et al. 1995; Gurnell et al., 2002; Wohl et al., In Press). In laterally migrating channel, bank erosion has been found to be the dominant type of recruitment of wood (Murphy and Koski, 1989). This lateral migration was observed in both watersheds; however it appeared to be more dominant in Corolla Creek. The evidence of lateral migration corresponds to the observation of bank failure as the most common recruitment mechanism of in-stream wood to Corolla Creek. The more confined channel in Lyons East was characterized by steeper slopes and experienced not only bank erosion processes, but hillslope failures as a recruitment mechanism for in-stream wood.

Hillslope failures on steeper slopes were found to recruit more wood to the channel. A possible explanation for this is that the rotational slump on a sloped hillside has the ability to recruit all available wood from the failed location simultaneously. Field observations in Lyons East suggest complex jam and dam structures are formed at the base of hillslope failures within the watershed. This would be considered episodic end member recruitment and generally creates a jam structure (Wohl et al., In Press). This type of recruitment was not observed as much in Corolla Creek; however that is likely due to the less confined channel. In Corolla Creek, steeper hillslopes were generally dominated by bedrock outcrops with little to no vegetation. It is predicted that the vegetation root strength provided additional hillslope stability in Corolla Creek reducing the number of mass wasting events observed.

4.2.3 Spatial distribution by wood piece count and volume

Comparisons of in-stream wood studies are difficult to make because of the wide range of definitions and methods used by researchers. Some studies count the number of pieces within a particular size range or calculate the volume of wood within the study area (Cadol et al., 2009; Young et al., 2006; Zelt & Wohl, 2004). In the current study, the number of in-stream wood deposits was counted instead of individual pieces or volume of wood. This different technique likely contributed to results that were different than that published in the literature. In particular, the expected differences between the two studied watersheds may have not been evident in the current project due to counting the deposits, rather than individual pieces or volume as reported in previous spatial distribution studies. Researchers in Wyoming (Zelt & Wohl, 2004) compared a burned catchment (1.6 debris jams/100m) and an unburned (1.5 debris jams/100m) catchment and found a minimal difference between the numbers of jams per 100m. When comparing the number of pieces (1042 pieces in the burned and 970 pieces in the unburned) again only a minimal difference was reported between the two watersheds (Zelt & Wohl, 2004).

The current project did not count individual pieces of wood. However, it is hypothesized that the number of pieces of in-stream wood located in Corolla Creek and Lyons East would be different, due to the land use practice in each basin. This hypothesis is based on field observation of the complexity of structures and the results showing a slightly higher percentage of multi-piece structures in Lyons East. In order to confirm this prediction, a more detailed field study would have to be conducted in which the number of pieces were counted and classified.

4.2.4 In-stream wood clustering

The distribution of in-stream wood is influenced by wood availability and streamflow. Factors that govern wood availability include the type, abundance and distribution of wood adjacent to the stream. The lack of an adjacent forest in sections of the stream and the presence of meadows or bedrock in a reach can limit local recruitment of wood to the channel (Wohl & Jaeger, 2009). No in-stream wood was present in Corolla Creek where bedrock controls were predominant as well as in parts of the longitudinal profile that lacked bank vegetation. Reaches with bedrock caused breaks in the spatial distribution of wood along the profile, which are illustrated in the planform and longitudinal profile presented in Chapter 3 (Section 3.1 Figure 3-3). Due to these external controls, the distribution of wood in Corolla Creek is more clustered along the stream profile. In comparison Lyons East, which did not have sections of bedrock, has a more consistent distribution of in-stream wood sites. The only sections of Lyons East which would have been considered supply-limited for available wood were sections where the trees had already been recruited to the stream.

River discharge, particularly bankfull flow, is a critical factor influencing wood transport and the formation of wood structures. Threshold discharge that occurs during spring freshet or storm events is sufficient in depth and force to transport wood. However, during periods of low flow the streams are transport limited. When the receding limb of the hydrograph occurs, the flow is not sufficient to transport larger pieces causing jams to form within the smaller channel (Gurnell et al., 2002). In both watersheds, jam forming processes occur through a feedback mechanism of flow transporting and depositing in-stream wood. In addition, the interaction between flow and transport could provide an explanation for the clustering of structures. As more structures are formed there would be a greater impact on flow, which could then reduce the water's ability to transport wood out of the reach, thus creating clusters of stable structures. Previous research indicates the decrease in wood mobility is correlated with jam formation (Gurnell & Sweet, 1998; Wohl & Goode, 2008), as observed in the current study.

4.3 Types of in-stream wood structures

In Lyons East and Corolla Creek the majority of in-stream wood accumulated in multi-piece structures. These formations had at least one key member stabilizing the structure and often contained two or three key pieces. In the current study, various multi-piece structures including partial jams, jams and dams were prevalent. In particular, transport structures with loose pieces racked on larger stable key members were evident in Corolla Creek. There was also evidence along the channel of deposited loose wood on top of banks and bars, likely transported during previous high flow events. These observations do not necessarily correspond with findings from previous studies, which indicate wood transport in small streams is limited (Abbe & Montgomery, 2003; Wohl & Jaeger, 2009). The ability for these systems to transport wood allows for more complex structures to form.

Manners and Doyle (2008) describe a wood jam evolution process that appears to explain the development of jam structures found in both Lyons East and Corolla Creek. The accumulation of smaller wood and foliage create a framework on the upstream side of a key member which is attached and stabilized on at least one bank (Manners & Doyle, 2008). As wood enters from lateral or upstream sources, it accumulates along the large, stable piece of wood creating a jam formation. Field observations show that key members trapped loose pieces of wood and formed multi-piece structures such as jams and dams. The high number of jams and dams (61 and 39 respectively) could be related to the stability of the bridge and ramp positions of key members and their ability to remain stable, trapping wood pieces and evolving into multi-piece structures. This is shown in the photographs illustrating jam formations in Appendix D (Figures D-4 & D-5) and Appendix E (Figures E-4 to E-6) for Lyons East and Corolla Creek respectively. The comparison of a simple and complex jam illustrated in Appendix E (Figure E-9), shows the process of smaller wood being obstructed from further downstream transport by larger wood pieces spanning at least part of the channel. The majority of jams, including partial jams, found in both watersheds had this evolutionary structure.

Since the research was conducted over one field season, it is uncertain whether the structures are stable and will remain in place for an extended period of time. Some studies report a range of life spans for in-stream wood structures of weeks to years (Raikow et al., 1995). This was observed in Corolla Creek where one of the original wood structures (CC1) selected for reach-scale analysis was destroyed before the end of the study period. To better understand the temporal aspects of jam formation, evolution and degradation, a long term study (>5 years) on a range of jam sites would be required. This long term study should provide field observations related to the theoretical jam evolution model and local transport mechanisms. Such information would further extend knowledge of jam creation and provide detailed information on their morphological and ecological impacts on the stream.

4.3.1 Spatial distribution based on structure type

The spatial distribution of structure types is important because jams affect channel hydraulics, sediment storage and channel pattern to a greater extent than single pieces of in-stream wood (Wohl & Jaeger, 2009). Therefore, a more comprehensive understanding of the spatial distribution of structure types would allow for better prediction of morphological impacts along a channel.

The goal of this project was to provide new insight regarding processes that govern the distribution of different types of wood structures along the longitudinal profile. Therefore, the project examined the type of structures found in the two studied watersheds, to allow for a comparison between in-stream wood characteristics. Andreoli et al. (2007) examined the distribution of log steps and valley jam structures in South American watersheds. They reported that a smaller proportion of in-stream wood was represented by log steps compared to jams. These results are similar to the current research where only 10% to 13% of in-stream wood structures were comprised of a single wood piece. The manner in which wood is recruited and transported within the watershed can control the type of structures found. For example, a large log recruited by bank erosion with an attached rootwad is likely to remain stable as a single piece structure. However, if fluvial processes transport loose pieces of wood downstream to the single piece structure, they could create a more complex multi-piece structure.

The results showed no clear relationship between structure type and the structure's position along the longitudinal profile. However, the distribution of partial jams tended to be towards the downstream end of the channel in both watersheds. One possible explanation for this is the increase in channel width makes it difficult for smaller pieces to span the entire channel (Gregory et al., 1993). In the current study partial jams were also located near the upstream end of each of the study reaches. Since detailed channel width measurements were not recorded during the initial longitudinal phase of the study, there is no way to determine if channel width, or the size of available wood were controlling factors in the distribution of partial jams. Another possible explanation for the observed distribution is that the partial jams are the remnants of jams that have been broken during a change in channel processes, such as high flows, which occurred outside of the field season.

Human activity closer to the roads may have also impacted the formation of in-stream structures, leading to a higher rate of partial jams. The increase in smaller pieces of wood available after logging provides wood that is not long enough to span the channel and that could create partial jams. The post-fire harvest of trees, which altered wood availability, adjacent to the channel in Lyons East was most predominant at the downstream end. The harvesting of trees at the downstream location was by individuals who obtained firewood permits based on the proximity to the road and the observed logging practices used. Due to the logging activity there were fewer large logs to be recruited to the stream than elsewhere in the watershed, and more loose pieces along the banks, which had the potential to form partial jams.

The occurrence of dams can decrease downstream due to wood being unable to span the entire channel width, which is necessary to create dams (Gregory et al., 1993). An increased number of dams were observed in the upper reaches, which could be related to a decreased channel width, providing the needed conditions for the creation of a full barrier. If a structure did not create a full barrier, it was classified as a jam.

The different structures classified as a jam could be a problem with cross study comparison, as the term includes a variety of formations. Considering the types of jam formations, channel width likely served as a stability control, as longer pieces touching both sides of the channel would be less prone to transport and accumulate other pieces of wood forming a jam. In the upper sections of a watershed the size of in-stream wood pieces is greater than channel width, making the stream transport limited. However, as the stream widens in downstream sections, the size of wood pieces becomes smaller than channel width, decreasing stability and transporting wood out of the system (Fremier et al., 2010; Martin & Benda, 2001; Nakamura & Swanson, 1993; Wohl & Jaeger, 2009).

4.4 Applicability of conceptual models to the southern Rockies context

Whol and Jaeger (2009) proposed a conceptual model (Section 1.2.3, Figure 1-2) to explain the formation and spatial distribution of in-stream wood, based on wood supply and changes in riparian forest. The model shows that as forest type changes from dense subalpine to montane it can affect the size of trees available for recruitment to the channel. The model describes the longitudinal distribution of wood loading and suggests that in the downstream direction, there is a decrease in wood load but an increase in the number of jams (Wohl & Jaeger, 2009). The longitudinal profiles in the current studied watersheds were along third order streams which, according to the model, should contain the maximum number of jams. Results for the current project do show a higher proportion of jams (LE – 43%, CC – 47%) compared to other in-stream wood structure types. This proportion of structures would be even higher if partial jams were also included (LE – 62%, CC – 67%). Based on the previous research by Wohl and Jaeger (2009), it is predicted that the high number of jams were reported because the research was conducted in the middle reaches (3^{rd} order streams) of the channel network.

The conceptual wood supply model is based on the concept that transport capacity of the stream, along with wood load and distribution, affect the recruitment rate and location of wood. When flow can transport wood downstream to sites comprised of stable wood, jams form. However, at the most downstream end of a channel, the transport capacity can increase past a threshold, causing wood to be removed from the channel at a rate greater than it is recruited (Wohl & Jaeger, 2009).

The current study focused primarily on smaller streams, where supply and transport were balanced, allowing for maximum jam formation. Fluvial transport of in-stream wood was evident based on the position of wood pieces and the structure of the jams. Thus transport was limited due to the relative size of the stream as compared to wood size, with larger wood pieces becoming trapped on banks and bars. This inability to transport wood out of the system created the high number of multi-piece structures observed.

4.5 Factors used towards understanding spatial distribution of in-stream wood formations

The initial phase of research characterized the channel morphology and riparian forest to evaluate possible linkages between a number of variables and in-stream wood formation. The morphological variables included: valley shape, vegetation, bank stability, channel shape, bar formations and pool formations. The in-stream wood structures were each characterized base on structure type. The variables for each in-stream wood structure were related to the key member(s) and included: the position, rootwad presence, branch complexity and orientation in the channel. Visual observations were completed at each in-stream wood site for all variables; however due to insufficient sample size, many were not significant for statistical analysis. The variables with insufficient sample size for analysis included valley type morphology, riparian forest vegetation and the characteristics of key member pieces in structures. The insufficient sample size does not allow for statistical relationships between key variables and in-stream wood structures to be determined with this data set.

The diversity in vegetation type adjacent to the stream was recorded during the longitudinal analysis of the watersheds; however, after coding there were not enough cases for statistical analysis. Based on visual observation, the difference in vegetation between Lyons East and Corolla Creek was the size and structure of trees. The dominant vegetation along Lyons East was charred trunks of similar sized trees. Along Corolla Creek, the unburned forest had an abundance of coniferous and deciduous trees, bushes and small plants adjacent to the channel. The difference in tree branch complexity (size, density, and arrangement) and range of vegetation size may have contributed to different structure shapes within Corolla Creek as compared to Lyons East. The actual shapes of jams were only visually analyzed to determine representative sites for the reach-scale phase analysis. To understand the relationship between riparian vegetation and in-stream wood, a more complete study of the forest adjacent to different depositional sites would be required.

4.5.1 Valley and channel variables

In southern England, stream characteristics such as valley form and channel morphology were found to have an impact on the number of jams per 100m. The researchers found that reaches with floodplains, higher sinuosity and lower bank height produce a significantly higher number of jams per 100m (Sear et al., 2010). Other researchers have come to the same conclusion, stating that there is an increase in wood deposits in channel sections with bars and higher sinuosity, which subsequently restricts further downstream transport of wood (Kraft & Warren, 2003). The current study collected information on the valley form, channel shape, bar formation characteristics and upstream and downstream bank stability. The statistical significance for valley form, bank stability and bar formations was not achieved with the data set collected. Because of the small sample size, qualitative observations were made to provide some insight into the differences and similarities between the two watersheds with respect to valley form and bar formations.

Geology and topography are important factors that determine the delivery of burned deadwood to the channel from hillslopes (Comiti et al., 2008). One of the observed differences between Lyons East and Corolla Creek was the number of hillslope failures (mass wasting) observed along the channel. There are more bank and hillslope failures in Lyons East than in Corolla Creek. These processes alter the rate, type of delivery and amount of wood recruited to the stream channel and floodplain, which in turn impacts the structure types formed (Meyer et al., 2001). This could provide insight into the greater percentage of dams found in Lyons East, as hillslope failures can recruit a large number of wood pieces to the channel simultaneously. With the sudden increase in wood volume and sediment entering the channel a higher stream flow is required to transport the wood downstream (Wohl et al., In Press). Since logs are recruited together, it can cause them to become intertwined and trap other pieces within the mass of recruited wood, restricting transport downstream. These stream and recruitment processes cause dams to form at the base of the hillslope failure. The increase in wood delivered through unstable hillslopes was examined by Wohl et al. (In Press). These researchers found when a larger volume of wood entered the channel it was more spatially sporadic and caused an increase in sediment associate with the wood deposit. Personal field observations and previous research found recruitment mechanisms have a strong influence on determining the stability of the wood in the receiving channel (Wohl et al., In Press).

During the longitudinal investigation, changes in the floodplain characteristics (morphology and vegetation) were observed. Corolla Creek was a less confined channel, with a floodplain often occurring on one side of the channel. Due to this characteristic, a difference in the amount of wood accumulated on the floodplain was observed between the two watersheds. In previous reports, researchers have discussed the process of rafting wood onto the floodplain during overbank flows (Sear et al., 2010). Overbank deposits were more prominent in Corolla Creek as compared to those observed in Lyons East. These floodplain deposits provide a recruitment source of smaller wood to the stream during subsequent overland flows. This mechanism could explain the observed differences in jam structures found in the study watersheds (Appendix D and E). The jams within Corolla Creek tended to have more rafting of loose pieces trapped on a larger key member piece of wood spanning the channel; whereas Lyons East tended to recruit wood pieces from the adjacent forest.

Using the chi-square test, there were no statistically significant differences found for banks and in-stream wood structures or bar formations and in-stream wood formations, due to an insufficient number of observations. Although coding for bank stability was changed to combine similar categorizes and thereby increase the number of observations there were still categories with too few observations to provide statistical significance (25% of cells for upstream bank stability and 33% of cells for downstream banks had less than expected results). The chi-square test was used to find a relationship between bar formations along the banks and in-stream wood, however there were too few observations to state a statistical significance (69% of the cells had less than expected observations). The same lack of observations occurred when testing a relationship between bar formations within the channel and in-stream wood, with 68% of cells having less than expected observations. Based on the number of observations and the distribution within the categories, the chi-square test was unable to provide statistical significance for relationships between in-stream wood structure types and either bank stability or bar formations.

Although the chi-square analysis was not able to show statistical significance, a qualitative analysis of the site photographs provided information on bank stability and bar formation characteristics. The photographs and written observations showed the majority of in-stream wood sites had at least one bar formation along the bank directly upstream, downstream or at the site. The presence of bars has been recorded in the literature as a mechanism of trapping wood, due to changes in flow depth and channel roughness at the bar locations (Nowakowski & Wohl, 2008). The relationship between depositional features and in-stream wood has been found in previous field research and tested in flume studies. A positive relationship has been observed between bar formation and wood deposition, this relationship is due to the increased frequency in contact between wood and the channel (Abbe & Montgomery, 1996; Braudrick & Grant, 2001; Nakamura & Swanson, 1994). This increased contact of wood with bar formations was also observed in the current field investigation.

A statistical analysis was completed examining the relationship between channel shape and in-stream wood structure type. The null hypothesis used for the chi-square test stated that the in-stream wood structure type was independent of the channel shape. Based on the results of the chi-square test, this null hypothesis of independence was rejected (asymptotic significance of 0.013). The single piece structures tended to occur more along straight sections of the stream (13 of 19 sites). This field observation is opposite to previous research that found straight reaches generally did not have in-stream wood, due to the high shear stress, deep flow and limited bar development in those stretches of water (Braudrick & Grant, 2001; Nakamura & Swanson, 1994). The higher percentage of single piece structures recorded in the current study could be a function of both the recruitment mechanism and the position of the wood within the channel. Wohl et al. (In Press) found single structures tend to be recruited from adjacent forests through mortality or bank erosion. Wood pieces recruited in this manner are generally positioned as a ramp or bridge, with one or both ends anchored on the banks (Wohl & Goode, 2008). Zelt and Wohl (2004) found the ramp and bridge position to be stable within the channel. Based on field observations in the current study, the single structures were stable bridged pieces, close to the channel bed. Since higher flows are required to transport wood, these single structures may not have been able to trap fluvial wood, remaining instead as single structures.

When analyzing all the in-stream wood structures in relation to channel shape, the majority of in-stream wood structures (103 of 160 observations) were found at meander bends (including coming into or out of a meander bend). This observation agrees with previous research, which concluded that in-stream wood is generally deposited along the outer banks of sinuous reaches (Abbe & Montgomery, 1996; Braudrick & Grant, 2001; Nakamura & Swanson, 1994). Abbe and Montgomery (2003) classified an accumulation of racked wood, buttressed by key members on the outer banks of meander bends, as meander jams. These jams are formed in sinuous reaches when straight logs cannot make it around the channel curve, propelling them forward and depositing them on the outer banks of the meander bend. This contact with the bank anchors the wood and allows the accumulation to develop a more complicated structure (Abbe & Montgomery, 2003). These types of jams were more prevalent in Corolla Creek than Lyons East. Based on field observations, the difference between the two studied watersheds may have been related to the adjacent vegetation providing bank stability in Corolla Creek. This increased bank stability allowed wood to accumulate, whereas the less stable banks in Lyons East were susceptible to erosion during the high flow necessary to transport wood.

4.5.2 Wood characteristics

The formation of in-stream wood structures relies on the ability of the piece(s) of wood to remain stable. Flume studies found the characteristics that affect key member stability include the angle to flow, rootwad presence, log density and log diameter (Braudrick & Grant, 2000). In the current study, angle to flow (orientation), rootwad presence and position were recorded for all 160 in-stream wood sites. Based on field observations and previously published material, it was hypothesized that rootwads act as anchors for wood pieces and provide the fundamental control necessary for stability (Braudrick & Grant, 2000; Gurnell et al., 2002; Montgomery et al., 2003). The statistical analysis using chi-square rejected the null hypothesis of independence between disturbance type and the presence of a rootwad (Asymp. Sig = 0). However, when the chi-square test was used to find a relationship between structure type and rootwad presence, there were too few observations to state a statistical significance (17% of cells had less than expected observations). The current research only recorded the presence of a rootwad on key member pieces. This limitation contributed to the low number of observations for the chi-square test. Therefore, to test this hypothesis, a more detailed analysis of individual wood pieces would be necessary for each in-stream wood structure.

The position of in-stream wood tends to dictate the stability of the structure, which impacts the structure's longevity and its associated impacts on stream morphology and ecology. Based on the results of the chi-square test, the null hypothesis of independence between key member position and in-stream wood structure type was rejected (Asymp. Sig = 0.001). The rejection of independence is similar to observations in previous research, which found key member position is a mechanism in jam formation and stability. Research completed in Colorado concluded that pieces positioned as bridges and ramps typically originate from riparian recruitment (Wohl & Goode, 2008). Since these two positions are stabilized along the bank, it allows jams to evolve as described by Manners and Doyle (2008). These two positions within the channel are the dominant key member pieces' position in all 160 recorded sites. The connection found by Wohl and Goode (2008) between position of in-stream wood and recruitment mechanism, suggests all the key member pieces found in the current study watersheds were recruited from the local riparian forest. The observation from Colorado illustrates the importance of protecting the adjacent forest through management techniques, such as riparian buffers, to ensure a supply of available wood is maintained for recruitment to the channel.

4.6 Reach scale channel characteristics for the six in-stream wood sites

Based on previous research conducted by Keller and Swanson (1979), which found that jams in small to moderate sized mountain streams can impact channel morphology and associated aquatic ecology, a more detailed analysis of in-stream wood structures was deemed necessary. Six representative study sites were selected to examine the reach-scale geomorphic impacts of in-stream wood. This analysis provides further insight into the relationships between in-stream wood structures and channel morphology. Fluvial geomorphologists now understand that the relationship between wood and channel properties is an important component of the sediment and water regimes and how they influence channel systems (Montgomery et al., 2003). This section will discuss the results of in-stream wood impacts on channel dimensions, morphology, pool formation and sediment storage for the six study reaches.

4.6.1 Channel dimensions

The in-stream wood structure type can impact channel dimensions, such as width, depth and the width:depth ratio. Interactions between the channel and in-stream wood can control the channel width upstream and downstream of the deposit. Research has found that in-stream wood can act as an accelerator for bank erosion or as armour for channel banks that can then cause a shift in channel width as wood accumulates (Montgomery et al., 2003). If the obstruction shifts the direction of flow towards the bank, it increases the erosive pressure, causing widening of the channel and contributing additional sediment to the channel (Beschta & Platts, 1986; Bilby, 1981; Hart, 2003). Only one site (LE10) of the reach scale analysis had a wider channel upstream of the in-stream wood structure compared to downstream. However, at this site (LE10), the width was largest within the jam structure, which extended the entire length of the meander curve. The deflection of flow toward the bank resulted in increased erosive pressure, which in turn decreased bank stability and increased undercutting. Obtaining accurate measurements during field investigation was difficult, as the undercutting extended into the hillside and was often obstructed by in-stream wood (Figure 4-1). This means that the channel was wider along parts of the meander curve than could be measured with the available equipment. This site (LE10) was the most complex reach site analyzed, containing over

40 identifiable pieces of wood. Faustini and Jones (2003) found that more complex structures tend to have wider channels upstream of the deposit. The upstream end of the structure had a simple formation; it was low to the channel bed and extended the channel width, having minimal impact on flow (Figure 4-2A). The downstream section of the jam was higher and partially spanned the channel, which deflected flow and constricted the channel width (Figure 4-2B). The complexity of this in-stream wood structure and its interaction with the channel were found to influence stream width.

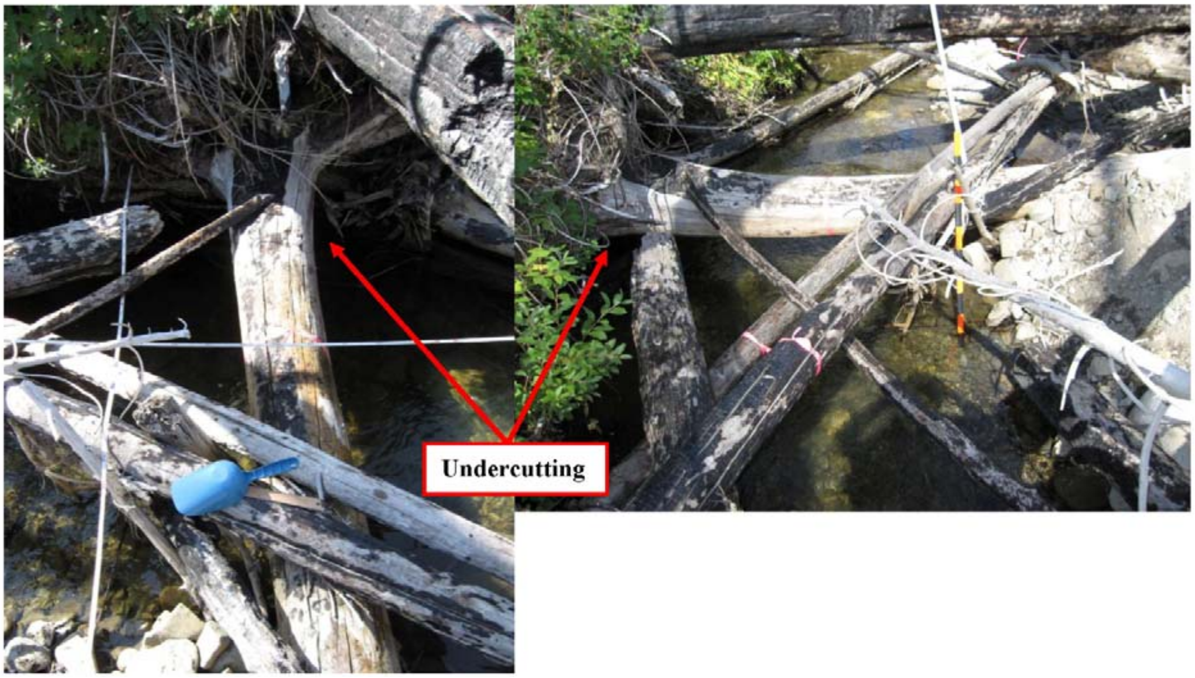


Figure 4-1: Undercutting at site LE10 in Lyons East. This particular location extended approximately 30cm to 40cm under the bank.

Figure 4-2: Channel width and in-stream wood clusters found at the upstream (A) and downstream (B) end of the jam structure at site LE10.

Field observations found five of the six sites were wider downstream of the in-stream wood structures, for both active channel and bankfull widths. The decrease in sediment transport supplied to downstream reaches is one possible reason for the widening downstream. The change in the sediment regime and channel form can enhance bank erosion, causing deep scour pools to form downstream of in-stream wood, which alters the cross sectional profile (Kail, 2003). The change in channel width upstream of the wood structure can be due to the structure lining the banks and reducing the channel width. In previous flume and field studies, meander bends have been found to trap wood along the outer bends of the channel during fluvial transport (Abbe & Montgomery, 1996; Braudrick & Grant, 2001; Nakamura & Swanson, 1994). This was evident in both site LE47 and site CC25, where the wood deflected flow away from, and armoured, the bank. In both of these sites, the narrowing upstream of the jam increased the force of the water and created a deep, wide pool on the downstream side. Abbe and Montgomery (1996) explained the association of large pools with these types of structures, as a shift in channel processes due to the wood compressing the radius of curvature and changing the orientation of flow. The change in channel width could be an indication of the channel evolving to a new stable state after changes in morphological processes due to in-stream wood (Downs & Simon, 2001).

Interactions with in-stream wood can impact channel depth both upstream and downstream of the deposit. Field observations found five of the six selected study reaches were shallower upstream of the wood structure compared to downstream, based on the average depth recorded for each transect. The only study reach that was not shallower upstream of the woody deposit was site LE10, which had the same depth (0.18m) both upstream and downstream. The minimal fluctuation in average channel depth along the reach (0.12m to 0.18m) is unique to site LE10, as no other selected reach exhibited this consistency. Based on these field observations the complex in-stream wood structure seems to have minimal impact on the depth of the channel. One possible explanation is the inability of this structure to impact localized scouring or damming processes in the channel necessary to deepen water levels (Hawkins et al., 1993). There may also be geological controls, such as channel substrate restricting the channel processes (scouring and storage of sediment) related to channel depth, as found in previous studies (Cadol et al., 2009; Massong & Montgomery, 2000).

The decreased stream depth upstream of wood deposits in the remaining five study reaches (LE28, LE47, CC3, CC24&25, CC26) is related to an accumulation of sediment on the upstream side of the obstruction. Previous research has noted the deposition of sediment, particularly gravels, on the upstream side of in-stream wood (Andreoli et al., 2007; Bilby & Ward, 1989; Fetherston et al., 1995; Webb & Erskine, 2003). This was observed in five of the six current study reaches, with gravels being the primary material accumulated. This accumulation is due to the decrease in stream velocity and the restriction to downstream transport (Gurnell & Sweet, 1998; Kreutzweiser et al., 2005). The barrier to transport causes sediment to settle out and accumulate on the upstream side of the wood obstruction. However, if water is still able to move through the porous structure, the water depth does not increase, creating a shallower cross section upstream of the structure. Numerous studies report the increased roughness and the dissipation of stream energy causes sediment and organic material to settle out on the upstream side of in-stream wood (Andreoli et al., 2007; Bilby & Ward, 1989; Curran & Wohl, 2003; Fetherston et al., 1995; Montgomery et al., 1996; Webb & Erskine, 2003).

The width:depth ratio expresses the interaction between the channel width and depth recorded at each transect measured in a study reach. There does not appear to be a consistent trend in the width:depth ratio upstream and downstream of the woody deposits for the six selected study reaches. Two sites have similar width:depth ratios on either side of the in-stream wood structure, site LE28 where the upstream and downstream ratios are 24.2 and 29.5 respectively, and site CC26 with a ratio of 26.3 upstream and 21.9 downstream. The low variability of width:depth ratio in a stream section with in-stream wood is likely due to the simultaneous increase of both width and depth as both banks and bed become eroded (Kail, 2003). The remaining four sites had more varied upstream and downstream width:depth ratios. Bed material can exert a geological control on stream morphology, allowing the channel banks to be impacted by in-stream wood more than the channel bed. In the current project, some reaches were dominated by bedrock or large cobbles along the channel bed, which would be resistant to erosion processes, thus causing change in width and depth to occur at different rates. This geological control was more predominant in Corolla Creek and could account for the differences reported between the two watersheds.

4.6.2 Channel gradient

The overall reach slope (gradient) and channel bed gradient upstream and downstream of the in-stream wood structures were examined. The overall gradients were similar for all six selected reaches and were generally low gradient reaches (ranging from 1.9% to 2.7%). Previous studies report channels with lower gradient can provide stability for sediment accumulation to occur (Gurnell & Sweet, 1998). Andreoli et al. (2007) reported that the initial loss of channel bed elevation corresponds to the dissipation of potential energy, which contributes to sediment storage and further impacts bed elevation. Similar results were observed in both Lyons East (ranging from 2.1% to 2.5%) and Corolla Creek (1.9% to 2.7%). One of the six reaches maintained a steady gradient throughout the reach despite the presence of in-stream wood. Site LE28 had minimal difference between the overall channel gradient (2.2%) and the gradients calculated upstream (2.7%) and downstream (2.3%) of the in-stream wood structure. These results show that the in-stream wood at site LE28 had minimal impact on the channel bed gradient.

The overall gradients did not differ between channel reaches, however when gradients were calculated for upstream and downstream of the in-stream wood structure, variations were reported. In sites LE10, LE47, CC3, CC24&25 and CC26 there were differences in the calculated upstream and downstream gradient, which were not represented in the overall gradient. For site LE47, a large decrease in the gradient occurred downstream of the wood structure (4.1% above, 0.9% below), which could be related to a shift in morphology. Based on field observations and the channel reach morphology classification of Montgomery and Buffington (1997), site LE47 appeared to shift toward a plane bed morphology downstream of the in-stream wood structure. A similar observation in channel gradient was also recorded in site CC24&25, which shifted from 3.8% upstream to 0.2% downstream of the in-stream wood structures. The channel gradient between the structures was calculated to be 1.6%, showing a decrease in channel gradient in the downstream direction. The difference between site CC24&25 and site LE47 was the inclusion of a second in-stream wood structure in the Corolla Creek reach. Shifts in channel morphology were previously reported by Massong and Montgomery (2000) who found that in-stream wood can change bed slope, thus shifting channel morphology.

Two of the investigated sites (LE10 and CC26) experienced a change in channel bed gradient within the structure rather than upstream or downstream. At these sites, a large difference was found in the overall, upstream, downstream and within structure channel gradient. In site LE10 the overall gradient was 2.5%, whereas the upstream, downstream and within structure gradients were 2.5%, 1.4% and 4.0% respectively. A similar trend was observed at site CC26 with the overall gradient being 2.7%, whereas the upstream, downstream and within structure gradients were 2.8%, 1.9% and 7.3% respectively. Since the channel gradient was higher within the wood structure for both sites, this illustrates a change in the step profile. This change in gradient could be an indicator of the channel adjusting toward a more stable stream bed position, based on the sharp gradient increase in relation to these structures (Nakamura & Swanson, 1993). An abundance of in-stream wood can cause local variability in channel gradient, particularly if there is a large amount of sediment stored upstream or within the structure. This change in sediment storage has previously been found to alter the channel bed elevation (Faustini & Jones, 2003; Lancaster & Grant, 2006).

4.6.3 Channel form

The channel form has been found to shift in response to wood obstructions. For example, in some cases a single channel can split into multiple channels, thus creating an anastomosing system. When this occurs, the active channel width is reduced and the number of channels is increased (Montgomery et al., 2003). There were few sites within the studied watershed where a single channel split into multiple channels due to in-stream wood. In unconfined channels the in-stream wood obstruction can divert water from the defined channel and onto the floodplain. If this occurs, the water can cut new channels within the floodplain. Sear et al. (2010) refer to the process of water moving over the floodplain and creating channels as floodplain branching. As the water moves over the floodplain it erodes sediment, including soil, cutting new defined channels. When water encounters roots it cannot erode, the sediment is removed around them and a root step is formed (Sear et al., 2010). This process was evident between sites LE10 and LE11 where two branches formed over the floodplain, eroding sediment and creating root steps (Figure 4-3, bottom). Figure 4-3 illustrates the channel branching downstream of site LE11 and shows the newly formed channels cutting through the floodplain vegetation. The process of creating floodplain channels provides a new source of sediment, causing the water to become sediment laden (Sear et al., 2010). Through this process more sediment is transported downstream towards the complex jam at site LE10. This additional source of sediment may have contributed to the higher amount of stored sediment found in the LE10 pools. This concept of stored cohesive sediment will be discussed in more detail in Section 4.9.6 - Sediment.

In-stream wood can also cause the channel to shift laterally within the floodplain. The process of lateral shifting in meandering streams provides an opportunity for wood to be recruited to the stream through undercutting of the banks. In Corolla Creek there were a number of abandoned channels observed, providing evidence of lateral shifting. Some of the abandoned channels had accumulations of wood structures; however, it could not be determined if the structures occurred prior to the channel becoming abandoned. Keller and Swanson (1979) found that a channel could shift up to two channel widths as a result of a single fallen tree, through the process of local bank erosion. At site CC26, abandon channels were found on either side of the active channel in the surrounding valley, demonstrating the potential for lateral shifting. Understanding this natural or forced movement of the channel would be important for land-use management decisions, as it indicates the importance of buffer zones for logging or other activities. Any management decision should take into consideration the potential amount a channel could move, in order to ensure a supply of wood is available for recruitment regardless of lateral shifting.

4.7 Channel classification

Previous research found that a change in scour and depositional patterns linked to in-stream wood can force a shift in channel shape and morphology classification (Cherry & Beschta, 1989; Kail, 2003). In reaches with larger wood deposits the channel is more likely to be altered in response to the obstruction. Thus the introduction of wood to a channel can create a "forced" morphology. Montgomery and Buffington (1997) define a forced pool-riffle morphology as a channel reach where pools are formed by obstructions, such as in-stream wood, instead of the natural alternating pool-bar sequence. All the pool-riffle reaches were classified as forced morphology (LE10, LE47-DS, CC3 and CC24&25). The step-pool channels (LE28, LE47-US and CC26) did not experience the same force of control over the morphological processes from in-stream wood.

Research on in-stream wood conducted in Park County, Wyoming found most of the studied stream reaches were pool-riffle morphology. Few of these pool-riffle reaches were formed freely; most were classified as forced pool-riffle morphology (Montgomery et al., 1995; Zelt & Wohl, 2004). This is similar to the channel classifications found in the current research, where all the pool-riffle reaches in both Lyons East and Corolla Creek came under the forced pool-riffle classification. A forced morphology means the morphology is found beyond the normal range of conditions, such as a lower/higher sediment supply rate (Faustini & Jones, 2003). The input of wood caused a shift in the scouring and deposition of the channel bed shortening the sequence between pools and riffles. In-stream wood traps sediment and channel material into bar formations and scours upstream and downstream of the deposit, which alters the channel type. This process, in addition to the lateral shifting of a channel, forces a shift in morphology.

Figure 4-3: Branching of the channel just downstream of site LE11 in Lyons East (top). The floodplain channels further downstream from the first photograph, illustrating the erosion and creation of root steps as the water cuts a channel (bottom). The circle highlights the research assistant's legs for scale.

Montgomery et al. (2003) found a fining of sediment due to the dissipation of energy can create an alluvial channel otherwise dominated by bedrock. Sites CC3 and CC26 both have sections of the reach controlled by bedrock. In site CC3 the upper end of the reach is dominated by bedrock and there is evidence of a former plane bed morphology downstream of the wood deposit. However, the reach was found to be forced pool-riffle morphology due to the presence of in-stream wood. This shift from a naturally occurring bedrock reach to a forced alluvial channel has been previously recorded for mountain streams in Washington (Montgomery et al. 1995; Montgomery et al. 1995). The shift in channel morphology from bedrock to alluvial is important as the latter morphology can provide diverse habitat and support a range of aquatic life (Montgomery et al., 1996). The addition of in-steam wood at site CC3 has created a deeper pool with cover, which provides habitat necessary for aquatic organisms.

In a step-pool channel, the introduction of in-stream wood can serve as a step, causing water to flow over it. Curran and Wohl (2003) found the diameter of in-stream wood that formed steps were generally larger than the size of clasts that created steps. The larger diameter of wood has a greater elevation change, which causes water to have higher energy as it cascades over the log, impacting the downstream morphology. A forced step-pool morphology is typically described as one where the majority of steps are formed by in-stream wood (Curran & Wohl, 2003). However, the field observations of Curran and Wohl (2003) found in-stream wood could control the location of steps, causing a mixture of forced and hydraulically arranged steps. The change in channel processes due to the presence of in-stream wood could be enough to shift a channel towards step-pool morphology, without the majority of steps being formed by the in-stream wood. This is the process in Lyons East and Corolla Creek, as the channel reaches classified as a step-pool morphology (LE28 and CC26), are formed through channel processes not the formation of wood steps. This change in channel processes can alter flow and stabilize large clast deposits forming steps and associated pools.

4.8 Depositional features – Bar formations

Stable in-stream wood allows for the gradual fill of coarser sediment (gravel, pebbles and cobbles) behind the structure (Wallace et al., 1995). The imprication of deposited sediment creates an armour layer on the streambed, further impacting the movement of water and sediment (Gurnell et al., 2002). This process can generate irregularities in streambed topography, such as non-regularly spaced bars (Kraft & Warren, 2003). However, the observed morphology had some regularity of bar patterns formed within each reach. In Lyons East, (sites LE10 and LE28) small bars formed along the banks when sediment entered the stream through bank erosion and finer material was transported downstream. The difference with Corolla Creek was the large bar formations found at sites CC3 and CC24&25, where significant storage of larger clasts, primarily cobbles, occurs.

Stream characteristics are altered due to woody deposits influencing the retention and sorting of bed material within gravel-bed streams (Gurnell & Sweet, 1998). In the current project the majority of the sites had bar formations touching the in-stream wood, either at the deposit or extending directly upstream or downstream from the wood. The only channel reach that did not have a bar formation touching the structure was site CC26. The bar formed directly downstream of the LE10 jam was a deposit along the bank and was sorted from smaller to larger clasts in the downstream direction. This type of clast sorting was unique to this single bar formation. At the downstream end of the LE10 jam there were two logs extending diagonally from the bank and slightly above the low flow channel. It is predicted the bar was formed during higher flow events, when water transported sediment into the space between the wood and the bank. As water flowed into the space, the velocity would decrease due to a change in bed roughness, creating an eddy and depositing sediment. Since the decreased velocity would cause deposition of the larger material on the downstream side of the bar, the smaller sediment would become trapped, causing it to deposit on the upstream side of the bar as water receded.

Another type of bar formation related to in-stream wood is the build-up of sediment in a deposited rootwad. As trees are transported downstream they can become snagged on bars with their rootwad upstream (Gurnell et al., 2005). This creates a cascading effect over time, allowing more wood and sediment to be trapped in the rootwad, which then forms a complex structure and larger bar (Gurnell et al., 2005). This process was found at site CC3, where a bar formed along the right bank of the channel upstream of a deposited rootwad. The stream flow was diverted towards the left, eroding the bank and contributing more wood to the channel. There was an accumulation of sediment along the length of the log in the active channel forming a gravel mid-channel bar under the log that extended directly downstream. Gurnell et al. (2005) report that this type of jam often creates an island formation, with established pioneer vegetation. The accumulation of fine sediment and growth of vegetation did not occur at site CC3. It is predicted that there was a lack of available fine sediment in the stream, thus not enough sediment would be deposited to support vegetative growth. The island building process described by Gurnell et al. (2005) generally occurs in larger, wider channels, which is another possible explanation for it not occurring in Corolla Creek. During high flow, the water can spread out in a wider channel, maintaining a shallower depth and decreasing the force exerted on young vegetation. This process of protection would allow vegetation to become established. In Corolla Creek (site CC3) the constrained channel can cause deeper water levels during high flows, which could hinder the ability for vegetation to survive.

4.9 The effect of in-stream wood on the formation of pools and storage of sediment

4.9.1 Pool spacing

One of the most influential impacts of in-stream wood on channel morphology is the formation of pools (Kreutzweiser et al., 2005). Research has found a direct correlation between wood loading and pool spacing in plane bed, pool-riffle and forced pool-riffle channels in Alaska and Washington (Abbe & Montgomery, 1996; Montgomery et al., 1995). As the amount of wood increases, so does the frequency of pools, which in turn decreases the spacing between them. Leopold et al. (1964) found pools are spaced an average of five to seven channel widths apart in a typical free-formed pool-riffle stream. In typical step-pool channels the pool spacing is one to four channel widths (Montgomery & Buffington, 1997). In the current study, the pool spacing is less than expected for pool-riffle and at the lower end for step-pool morphology. The reach with the highest wood load is site LE10, which corresponds to the highest number of pools and the lowest pool spacing compared to the other selected study reaches. Within the jam at LE10, in-stream wood caused scouring to occur and formed three pools. The reach with the lowest wood loading, in terms of pieces measured within the active channel, was site LE47, which had the highest pool spacing (2.31 channel width). The results from the current study provide additional support to the mountain stream research conducted by Abbe and Montgomery (1996) and Montgomery et al. (1995) which found that as wood load increases, pool spacing decreases.

An inverse relationship between mean pool spacing and wood frequency has been reported in a number of studies (Beechie & Sibley, 1997; Montgomery et al., 1995; Montgomery et al., 2003). However, the actual location of pools varies within the channel reach. In the current project, there is little difference between the calculated pool spacing for the six study reaches (1.5 to 2.5 channel widths). The planform view shows the actual spacing is not a consistent distance apart; some pools were formed closer together, while others were further apart. For example, site LE47 has more evenly spaced pools, while site LE10 has a cluster of pools within the woody deposit. The planform map for LE10 (Figure 3-19) illustrates the clustering of pools associated with in-stream wood, which causes the average pool spacing to decrease for the reach. Nakamura and Swanson (1993) report the decrease in pool spacing is due to the increased roughness of wood, which provides zones of high turbulence that aide in pool formation. This is similar to the results found in the current study; the stream sections with wood generally have pool formations (Figures 3-19 to 3-24 in Section 3.2).

A comparison of previously conducted studies found reduced pool spacing occurs in a variety of streams. As previously mentioned, the average spacing between pools is decreased because in-stream wood forms additional pools (Buffington et al., 2002; Gurnell et al., 2002; Montgomery et al., 1995). Zelt and Wohl (2004) found pool spacing ranged from 2.5 to 4.5 channel widths in Wyoming streams impacted by in-stream wood. In an Australian study, pool spacing was lower at 0.8 channel widths (Webb & Erskine, 2003). Montgomery et al. (1995) found pool spacing ranging from 0.2 to 13 channel widths in forested mountain channels. However, pool spacing in channels with the highest wood loading generally had a range of 0.2 to 3 channel widths (Montgomery et al., 1995). The research in the two studied watersheds found a pool spacing of 1.53 to 2.31 channel widths. These values are similar to previously recorded in-stream wood influenced pool spacing, for mountain forested streams in Alaska and Washington. Although there was minimal difference in pool spacing between the two studied watersheds (Table 3-8, Section 3.4) there was one noticeable difference. The lowest pool spacing in Lyons East was related to the most complex in-stream wood structure (LE10). However, in Corolla Creek the three sites had comparable jam complexity, but the pool spacing ranged from 1.63 to 2.24 channel widths.

The impact of in-stream wood on step-pool morphology can be similar to that reported for pool-riffle reaches, in that an increase in wood causes a decrease in pool spacing. Step pool channels without in-stream wood have a pool spacing ranging from one to four channel widths. However, when wood enters the channel it has been found to reduce pool spacing to 0.6 to 1.3 channel widths (Montgomery et al., 1995). In the current study, the two reaches classified as step-pool morphology had a pool spacing of 1.97 for Lyons East (LE28) and 2.10 for Corolla Creek (CC26). These values are closer to the non-wood-affected pool spacing. It is hypothesized that the in-stream wood at these sites (LE28 and CC26), impacted flow depth and velocity more than creating additional steps. This change to the channel bed would not create additional steps between hydraulically controlled ones within the reach, limiting the in-stream wood impact on pool spacing.

4.9.2 Pool formation

Pools within the current study reaches were classified as free or forced depending on their formation process. There is a near even division between the two types of processes for the studied watersheds, with slightly more pools being classified as forced. Gurnell and Sweet (1998) found a fairly even division between forced and free pools within their study watershed, which they defined as being transitional between pool-riffle and forced pool-riffle morphology. The transition between the two types of morphologies is also relevant in the current studied watersheds as discussed in Section 4.7. One of the main factors in creating forced pools was the presence of in-stream wood, which modified the channel processes.

With respect to the types of pools formed by in-stream wood, Mao et al. (2008) reported that scour pools form downstream of jams. The majority of pools associated with in-stream wood are scour pools, with only one of the 25 pools analyzed classified as a dammed pool. The scouring associated with pools is typically downstream of wood structures. Some pools were found within or beneath the wood structure (LE10 – Pools 3 and 4, LE28, CC3, and CC26). In two of the sites where pools formed beneath the wood structure (LE28 and CC26), the pool formed just downstream of the first wood piece in contact with the active channel and extended beneath the structure. Scour pools associated with in-stream wood for sites LE10 – Pool 5, LE47 and CC25 were all located directly downstream of the obstruction. At site LE10 there were clusters of wood within the larger jam structure. Due to this complexity, it was difficult to determine with certainty which individual wood pieces were influencing scour processes and forming pools. Based on field observations it appears two of the three wood-affected pools in site LE10 occurred downstream of the influential wood pieces.

Generally, the impact of a wood structure on channel processes and morphology increases as the number of in-stream wood pieces increase. Mao et al. (2008) found single wood pieces had less impact on pool formation than a jam of wood pieces. The complexity of the structure determines the impact on channel shaping processes, because there is generally a larger volume of wood interacting with the active channel. This is one of the difficulties with inconsistent definitions in literature for in-stream wood structures. The definition of jams can include a minimum of two, three or five pieces of wood (see Table C-2 in Appendix C for references). The selected definition can involve different structure complexities; for example a structure with two pieces of wood would generally be simpler than a structure with five pieces of wood. Also, the structures defined as jams within a study can differ. Although a definition for a multi-piece structure (jam or dam) typically includes a minimum number of pieces and the amount of channel obstructed, the types of structure formations varies. These differences in multi-piece classifications can make it difficult to predict morphological impacts such as pool formations based only on structure type. For example, Lyons East sites LE10 and LE47 were both classified as jams; however their formation and impact on channel morphology differ. Site LE10 is complex with 40 identified wood pieces and three pools within the length of the structure, while site LE47 has three identified wood pieces and a large underflow pool on the downstream side. This illustrates the importance of knowing both the formation and structure type when studying the relationship between in-stream wood and associated impacts on pool formations.

4.9.3 Pool types

The relationship between in-stream wood and pool formation has been examined in a number of studies listed in Table 4-2. Research conducted in the Pacific Northwest reported that ranges of 48% to 73% of pool formations were influenced by in-stream wood, whereas in Colorado the average was 75% (Andrus et al., 1988; Beechie & Sibley, 1997; Montgomery et al., 1995; Richmond & Fausch, 1995). In the current study the percentage of wood-affected pools (20% to 50%) was generally lower than that reported in previously conducted studies. The difference in the percentage of pools found for each of the studies may be related to factors such as geology and climate. These factors can control the characteristics of wood, stream hydrology and channel morphology. Researchers must acknowledge the geologic and climatic factors when determining the relationship between in-stream wood and pool formation, as these factors may exert more control over pool formation than in-stream wood.

Geological controls can influence the ability of wood to form pools. Sediment retention on the upstream side of the deposit and scouring of bed material on the downstream side are the primary processes involved in forming wood-affected pools (Kreutzweiser et al., 2005). When scour processes are the primary pool forming mechanism and the bed material is dominated by boulders, larger substrate (e.g. cobbles), or bedrock, the ability to form pools is restricted by the geology. Therefore when geology exerts greater control over pool formation, the relationship between pools and in-stream wood is typically not shown (Kreutzweiser et al., 2005). The lower percentage of wood-affected pools in Corolla Creek may be due to the increase in larger bed material and bedrock (seen at sites CC3 and CC26), compared to Lyons East and the previously conducted research.

Table 4-2: The percentage of wood-affected pools found in current and previous research

Location	Wood affected Pools (%)	Reference
Alberta, Canada	33% to 50% Lyons East 20% to 33% Corolla Creek	Current research project
Washington State (USA)	8% to 84% (The average was 48%)	(Beechie & Sibley, 1997)
Washington State (USA)	78% in forced pool riffle 63% in pool-riffle	(Montgomery et al., 1995)
Colorado (USA)	76% in old-growth 32% in disturbed	(Richmond & Fausch, 1995)
Oregon (USA) small coastal watershed	70% wood influenced	(Andrus et al., 1988)
Oregon (USA) – Cascades	90% wood influenced	(Keller & Swanson, 1979)
Alaska (USA)	87% in forced pool-riffle 78% in pool-riffle	(Montgomery et al., 1995)
Southeast Alaska (USA)	76% wood or rootwad influenced	(Robison & Beschta, 1990)
Boreal Forest, Ontario Canada	15% wood influenced	(Kreutzweiser et al., 2005)
Indiana and North Carolina (USA)	50% wood influenced	(Keller & Swanson, 1979)
Argentina	30% wood influenced	(Mao et al., 2008)
Australia	82% wood affected	(Webb & Erskine, 2003)
New Zealand	43% in native stream 54% in plantations	(Baillie & Davies, 2002)

In addition to geological controls, the frequency of threshold discharge (bankfull) can also determine the types of pools formed. Montgomery and Buffington (1997) found channel morphology was related to reach average bankfull shear stress, which drives sediment transport. For a pool to form through scour processes, the shear stress must be enough to move channel bed sediment, which deepens the channel. In gravel streams, Lisle (1979) found most scouring occurred at approximately bankfull stage. Therefore, the types of pools formed will generally be influenced by the frequency of bankfull discharge. When comparing wood-affected pools from different streams, bankfull discharge must be considered as a controlling channel-forming process. Bankfull discharge is partially related to climatic variability, as precipitation and temperature are driving forces in contributing water to the channel.

Climatic variability can make it difficult to compare in-stream wood studies. To decrease these different influences, researchers can compare their work to previous studies completed in similar environments. For this project, the similar environments (climate and forest type) generally occur in Washington and Colorado. In Washington, Beechie and Sibley (1997) studied 46 reaches and reported a range of 8% to 84% of pools that were associated with in-stream wood. The research conducted in Colorado found a higher percentage of pools were affected by wood in an old-growth forest compared to a disturbed forest (Richmond & Fausch, 1995). In the current project, the percentages of wood-affected pools, for both watersheds, were similar to the percentage of wood-affected pools found in the disturbed Colorado watershed (Table 4-2). Lyons East is a disturbed watershed, impacted by forest fire and salvage logging, which would correspond to the type of disturbance found in Colorado. Although Corolla Creek had not been influenced by a natural disaster, the density of trails discussed in Section 2.2 (Table 2-2) has created an anthropogenic disturbance in the watershed. The natural and anthropogenic disturbances in the current watersheds may have had similar impacts on the percentage of wood-affected pools. This prediction is based on the percentage of wood-affected pools found in the disturbed catchment in the Colorado study (Table 4-2).

Pool diversity in a stream is important, as pools provide habitat for aquatic life throughout their lifecycles, allowing aquatic biodiversity to thrive. Research has found in-stream wood impacts the spacing of pools (discussed in Section 4.9.1); however only one previous study has compared the type of pools created by in-stream wood and natural channel processes. The results from the previous study (Richmond & Fausch, 1995) and from the current research are presented in Table 4-3. The types of pools are categorized as wood-affected or non-wood affected. For comparison the pools are presented as a percentage formed within each category (Table 4-3). Both studies were located in the Rocky Mountains. The previous study occurred in Colorado, USA and the current study in Alberta, Canada. The two studies used a slightly different pool type classification, but have enough commonality to allow for trend comparisons. In the previous study, Richmond and Fausch (1995) found the most common in-stream wood-affected pools were plunge (57%) and dammed pools (23%), with a higher rate of plunge pools in disturbed catchments. In the current project a similar trend was not observed with fewer wood-affected plunge (12.5%) and dammed (12.5%) pools recorded for both watersheds combined.

Table 4-3: Percentage of wood-affected and non-wood-affected pools based on type classification

Location	**Type of pools Wood-affected**	**Types of pools Non-wood-affected**	**Reference**
Rocky Mountains Alberta, CA	Plunge (20%) Deflector (40%) Underflow (40%)	Plunge (33%) Lateral scour (22%) Mid-channel (44%)	Current study Lyons East
Rocky Mountains Alberta, CA	Dammed (33%) Deflector (33%) Underflow (33%)	Lateral scour (12.5%) Mid-channel (25%) Trench (50%) Deflector (12.5%)	Current study Corolla Creek
Rocky Mountains Alberta, CA	Plunge (12.5%) Dammed (12.5%) Deflector (37.5%) Underflow (37.5%)	Plunge (18%) Lateral scour (24%) Trench (29%) Mid-channel (24%) Deflector (6%)	Current study (Both watersheds)
Rocky Mountains North Central Colorado, USA	Plunge (57%) Dammed (23%) Scour pools (16%) Trench pools (3%)	Plunge (35%) Lateral scour (29%) Trench (3%)	(Richmond & Fausch, 1995)

The difference in pool types observed between the Colorado and Alberta studies could be related to the structure types formed within the respective watersheds. In the current study, the low percentage of wood-affected plunge pools was related to the position of in-stream wood. For a plunge pool to form, a wood piece (key member) needs to be in contact with the channel bed and have water flowing over top to increase turbulence downstream (Curran & Wohl, 2003; Wilcox & Wohl, 2006). In the current study, key members were generally suspended over the channel trapping additional wood pieces, creating more complex structures (CC24, CC26, part of LE10, LE28). These in-stream wood structures are not conducive to the formation of plunge pools. Instead of water simply flowing over in-stream wood, the complexity of the structures forced scouring to occur underneath the jams, forming underflow pools. The difference between plunge pools and underflow pools is where the scouring occurs. Underflow pools, scour the channel bed underneath the wood creating a jet stream of water whereas plunge pools create the jet by dropping from a height over the wood obstruction (Bisson et al., 1982; Hawkins et al., 1993; Montgomery et al., 2003; Robison & Beschta, 1990; Webb & Erskine, 2005). However, if the jam accumulation was greater along one side of the channel, the impact appeared to be similar to that reported for a partial spanning diagonal log, forming either a lateral pool or a deflector pool (Gurnell & Sweet, 1998; Robison & Beschta, 1990). In addition to the differing types of in-stream wood structures between the Colorado and Alberta watersheds, the differences in pool types found could be related to the channel morphology and associated channel processes.

Different watersheds typically have variations in channel processes and morphology. Therefore, to understand the morphology of the Colorado and Alberta channels, the percentage of pools formed through channel processes (non-wood-affected) were also compared. The results of non-wood affected pool types for the two studies are presented in Table 4-3. Richmond and Fausch (1995) found non-wood-affected pools included plunge (35%), lateral scour (29%) and trench pools (3%). In the current project, fewer plunge pools and more trench pools were observed within the selected reaches. The lower percentage of plunge pools observed is likely related to variations in channel characteristics between the two studies. Richmond and Fausch (1995) reported a higher number of plunge pools in the steeper reaches compared to gentler slopes. It is likely the gradient and morphology of the study streams differ, causing different pool-forming processes to dominate. The higher number of trench pools found in the current watersheds could be an indication of stronger geological controls, such as bedrock, on pool forming processes.

4.9.4 Pool dimensions

Although wood can influence pool types and formations in a reach, these wood-channel interactions can also impact the length, width and depth of the pools. Since wood alters the channel roughness it can influence scouring mechanisms. Therefore, the position, size and stability of wood strongly influence pool characteristics (Zelt & Wohl, 2004). Due to the diversity of structure formations within Lyons East and Corolla Creek, the dimensions of pools also differed. In Lyons East only length was found to be related to in-stream wood, with the longest pools generally being wood-affected. There were no major differences found between the length and depth of wood-affected and non-wood-affected pools for Corolla Creek. This suggests stream characteristics such as gradient and geology have a greater influence over pool formation processes in the watersheds.

4.9.5 Pool volume

In-stream wood can impact channel flow near a pool, with higher energy causing scouring and lower energy causing sediment deposition. The change in scouring or deposition determines the pool volume. In the current research, half of the reaches had the highest residual pool volume contained within wood-affected pools. The pools within Lyons East tended to have a greater percentage of pool volume associated with in-stream wood, ranging from 49% to 70% of the total pool volume. In comparison, Corolla Creek was more variable ranging from 12.5% to 52% of pool volume being wood-affected. At site CC3, the dammed pool was reported as the lowest pool volume, which was likely due to its smaller size and incomplete barrier. Although the pool was considered a dammed pool, a small slow leak of flow was found on the downstream side of the structure. It is predicted that as leaves and sediment accumulate, the small gap could become sealed. This prediction is based on previous observations, which found that as leaves and sediment increase upstream of a structure a more complete barrier forms (Wallace et al., 1995). Therefore, as more small material accumulates and works to close the gap, there should be an increase in water depth and pool volume. In addition, there are geological controls of bedrock observed within the reach, which limits the scouring potential and pool volume.

A positive correlation has previously been found between pool volume and in-stream wood abundance (Beschta & Platts, 1986; Bilby & Ward, 1989; Bisson et al., 1987; Keller & Swanson, 1979). The results from the current study are inconclusive regarding the relationship between wood abundance and pool volume. The most complex wood structure in Lyons East (LE10) was only responsible for 49% of the pool volume, which was the lowest in the watershed. In contrast, in Corolla Creek one of the more abundant woody deposits (CC26) had the largest wood-affected pool volume. With the low number of reaches studied, it is difficult to state conclusively whether a correlation exists between pool volume and in-stream wood abundance for either of the investigated watersheds.

4.9.6 Sediment

Previous research conducted in Wyoming by Zelt and Wohl (2004) reported a need for further investigation into the association between in-stream wood and fine-grained sediment deposits in different stream types and geographic areas. For their study, fine-grained sediment included clast sizes ranging from fine gravels to clay (Zelt & Wohl, 2004). The final component of the project was based on this recommendation and investigated the storage of sediment in wood-affected and non-wood-affected pools in the six selected study reaches. However, the current project focused on the storage of cohesive sediment within pools in forced pool-riffle and step-pool reaches.

Previous research has investigated the storage of fine-grained sediment (Andreoli et al., 2007; Cadol et al., 2009; Zelt & Wohl, 2004); however, no study has specifically examined the impact of in-stream wood on cohesive sediment storage. The focus on cohesive sediment storage is useful due to its importance for nutrient retention and impacts on water quality (Gurnell et al., 1995; Stone & Droppo, 1994). Cohesive sediment is defined as sediment less than 63μm and is the most important fraction for contaminant adsorption and transport due to its large surface area (Owens et al., 2005; Stone & Droppo, 1994). The storage of cohesive sediment is significant, as the deposition can alter the nutrient cycling within a stream, which impacts nutrient availability downstream (Newbold et al., 1981; Valett et al. 2002; Walling, 1999). Sediment storage can also influence habitat in the aquatic system, by smothering the riverbed, killing aquatic flora and clogging the substrate which is important for spawning. In addition, the changes to the channel bed can reduce habitat for benthic organisms (Wood & Armitage, 1997). Accumulation, storage and potential remobilization of sediment related to land use changes, or the removal of an obstruction, have consequences on the complete stream system. If these changes occur in the headwater systems of the Oldman River Basin, where the two studied watersheds are located, it could impact the entire basin, due to the connection of the stream network. The Oldman River Basin is important for fishing, tourism and drinking water for downstream communities (Oldman Watershed Council, 2010). Therefore, the relationship between in-stream wood and cohesive sediment storage is relevant for planning and management applications to ensure water quality is maintained.

4.9.6.1 Sediment thickness

Sediment impact on a stream reach depends on the amount of sediment stored on the channel bed. The sediment thickness in residual pools was used to determine the impact of in-stream wood on sediment storage. The thickness of fine-grained sediment deposits in disturbed creeks is greater on average than in reference streams (Zelt & Wohl, 2004). In the current research, the average thickness of sediment in Lyons East (burned) is larger than Corolla Creek. The average sediment thickness in pools for Lyons East ranged from <0.1cm to 0.7cm and for Corolla Creek ranged from <0.1cm to 0.3cm. The thicker stored sediment in Lyons East may be partially due to an increase in sediment supply to the channel, where hillslope failure and vegetation loss from the effects of wildfire were observed. Previous research on in-stream wood and fine-grained sediment storage reported thicker but less frequent deposits within disturbed watersheds (Zelt & Wohl, 2004). Thicker and more frequent sediment deposits were reported in the disturbed watershed (LE). More pools in Lyons East (64%) were found to store cohesive sediment compared to Corolla Creek (36%).

In steep mountain streams jams can promote sediment storage by creating changes in flow. In fact, the storage of sediment due to in-stream wood, may account for a larger portion of total stored sediment (Keller & Swanson, 1979). In Lyons East, cohesive sediment storage was generally greater in wood-affected pools than in non-wood-affected pools. This may have been related to an increase in local sediment supply from bank failures. At site LE28, 100% of the sediment stored in the reach was located in the wood-affected pool. At this particular site the key member log was recruited through bank erosion with the rootwad attached and it is predicted the sediment entered the channel at the same time. The in-stream wood provides protection for the cohesive sediment from being transported downstream, allowing the sediment to remain in storage along the left bank of the pool. It is predicted that this method of sediment recruitment could allow for a greater sediment storage potential in pools formed by in-stream wood.

In-stream wood forms a barrier to sediment transport and can also impact the roughness of the channel bed. Low shear stress can occur at in-stream wood deposits, which influences the storage of sediment and particulate organic matter in the channel network (Fetherston et al., 1995). A positive relationship has been found between the loading of in-stream wood and the storage of sediment (Comiti et al., 2008; Mao et al., 2008). Mao et al. (2008) reported a significant correlation (R-0.54; $p<0.01$) between stored sediment and jam wood volume in sub-Antarctic mountain streams. Research has found 87% of sediment stored in a New Hampshire channel bed was related to in-stream wood (Bilby, 1981), compared to 47% in small Idaho streams (Fetherston et al., 1995). In an Australian catchment almost half the total sediment stored was associated with in-stream wood deposits (Webb & Erskine, 2003). In the current research project, the percentage of cohesive sediment stored in wood-affected pools ranged from 10% to 100% of the total stored sediment in the reach. These results show a large range in the percentage of cohesive sediment storage and are inconclusive regarding the relationship between wood and sediment storage in the studied watersheds.

The formation of an in-stream wood structure, in particular the porosity of a jam, influences the amount of water and sediment retained by it (Manners & Doyle, 2008). For example, if a jam has a high porosity, a minimal interruption to the flow pattern occurs (see Figure E-9 in Appendix E); however, a low porosity jam impacts the flow and changes the potential for sediment storage (Manners & Doyle, 2008). The more complex site in the study, LE10, had a higher volume of cohesive sediment storage compared to the simpler structure at site LE47. Research has found the more channel width occupied by the in-stream wood, the more influence it has on sediment accumulation processes (Gurnell et al., 2002). Although site CC24&25 contains two jams, it is estimated that less of the channel was impacted compared to site CC26, which had more stored sediment. However, in the equally complex site CC3, there was no cohesive sediment stored in the wood-affected pool. The lack of relationship between in-stream wood complexity and sediment storage for Corolla Creek could be related to the geological controls and limited sediment supply within the study reaches.

The type of obstruction formed by in-stream wood influences not only the type of pool formed but the sediment stored. The obstruction to sediment transport and flow is highest with dam structures, as they form a more complete barrier compared to other wood structures. Generally, a dam structure forms a pool upstream. Previous research reported dammed pools tend to both accumulate and store more sediment than scour pools (Hawkins et al., 1993). This did not occur for the one dammed pool analyzed in the current study (site CC3). Accordingly, the results of the current research are related more to geology and sediment supply controls, rather than wood structure characteristics. Previous researchers mentioned the importance of understanding the sediment characteristics of the study reaches in order to determine if the lack of sediment storage was related to in-stream wood or sediment limitations of the stream (Berg et al., 1998; Cadol et al., 2009). It is predicted the lack of cohesive sediment stored in site CC3 was due to the sediment-limited nature of the study reach.

The spatial variation in cohesive sediment storage is partly related to sediment supply, basin geology and the transport capacity of streams (Massong & Montgomery, 2000). The large amount of bedrock observed in Corolla Creek limits the potential supply of sediment, particularly cohesive sediment. At site CC3, no cohesive sediment was found where the reach was dominated by bedrock upstream of the in-stream wood. In the cobble-dominated downstream reaches, cohesive sediment could potentially be stored in the pores of the coarse bed matrix. This prediction would require further investigation, as the current project only examined cohesive sediment stored on the channel bed within pools. At site CC26, 100% of sediment was stored in the wood-affected pool. It is important to recognize that the downstream pool at site CC26 is bedrock controlled. Due to the dominance of bedrock in the downstream reach it is unlikely sediment would be found in the pool. The geological controls were similar (bedrock) for the two reaches (CC3 and CC26); however they had opposite impacts on the percentage of sediment stored in wood-affected pools. It is predicted that this difference is related to the location of bedrock within the reach, as the bedrock was upstream of the woody deposit at site CC3 and downstream at site CC26.

In order to compare the overall storage of cohesive sediment within residual pools, the weighted average was calculated for each selected reach. This information allows for a comparison of reaches with different numbers of pools. Previous research conducted on the impact of in-stream wood on fine-grained sediment storage found the reach average of residual pool volume occupied by fine-grained sediment (V^*_w) was approximately 0.17 and 0.23 for reference and burned streams, respectively (Zelt & Wohl, 2004). In both studied watersheds a smaller V^*_w was reported, ranging from 0.005 to 0.056 for Lyons East (burned) and from 0 to 0.017 for Corolla Creek (unburned). The different values for V^*_w could correspond to the different definitions of fine-grained sediment in the two research areas. The previous study had a more inclusive definition of fine sediment (ranging from very fine gravels to clay); the current project only examined the cohesive sediment fraction $< 63\mu m$. Zelt and Wohl (2004) reported very fine gravel to coarse sand as the predominate sediment stored in mountain streams affected by in-stream wood. This observation provides support to the higher V^*_w value reported for reaches examined using the broader definition. It is predicted that if the same definition of fine-grained sediment used by Zelt and Wohl (2004) was used in Lyons East and Corolla Creek, similar results to the previous study would be observed.

4.9.6.2 Conceptual model

Patterns found during analysis of in-stream wood and the wood's impact on channel morphology, pool formations and sediment storage were used to create a conceptual model for the storage of cohesive sediment in wood-affected pools. Field observations found both local and fluvial recruitment of wood occurred primarily at meander bends. The local recruitment occurred where banks were undercut and failed, recruiting new wood to the stream; whereas fluvial wood could not be transported around meander curves and piled up on the outside bank of the bend. Wohl and Goode (2008) found the recruitment mechanism of wood determines its position in the stream. More recently the work of Wohl et al. (In Press) found episodic recruitment of wood, for example from landslides, provided large volumes of wood and sediment to the stream. The current research expanded on these previous observations and found that the simultaneous recruitment of wood and sediment was the determining factor in cohesive sediment storage in wood-affected pools. Figure 4-4 illustrates the conceptual model for cohesive sediment storage in wood-affected pools, based on patterns found in the headwater streams of the Oldman River Basin. This model illustrates that the recruitment mechanism of wood and sediment determines the position of both in-stream wood and cohesive sediment.

Field observations found that when wood and sediment are recruited simultaneously the cohesive sediment is stored in the pool along the bank. In addition, the current research found wood recruited from a local source (bank erosion, or hillslope failure) generally recruited sediment at the same time and that sediment was more likely to remain in storage (Figure 4-4). It appears that this simultaneous recruitment of wood and sediment to the channel provided conditions for sediment storage along the recruitment bank side of the channel. These locally recruited logs were often large logs with the rootwad still attached. A potential interpretation of this process is that the attached rootwad protected sediment from being transported downstream. In addition to protecting the sediment the rootwad anchors the log along the bank, which provides stability and allows for a thicker accumulation of sediment. These deposits were observed along the recruitment bank side of pools.

When the in-stream wood structure did not appear to be recruited from a local source, it was generally found to be formed through fluvial processes. This process allowed the in-stream wood to remain in storage by anchoring onto the banks or bars, creating a complex structure (jams and dams). However, despite these complex structures there was minimal or no cohesive sediment stored at these locations (Figure 4-4). It is predicted the high flows able to transport the in-stream wood were able to keep sediment in suspension and transport it downstream. A potential interpretation for these patterns is that sediment recruited at the same time as in-stream wood provides the sediment supply for storage in wood-affected pools. In areas where sediment is not recruited simultaneously with wood, there may be a lack of cohesive sediment available for storage in the stream. This conceptual model can be used to predict the storage of cohesive sediment in headwater streams located in the Oldman River Basin. This storage of cohesive sediment is important as it can potentially alter the physical and biological characteristics within the stream.

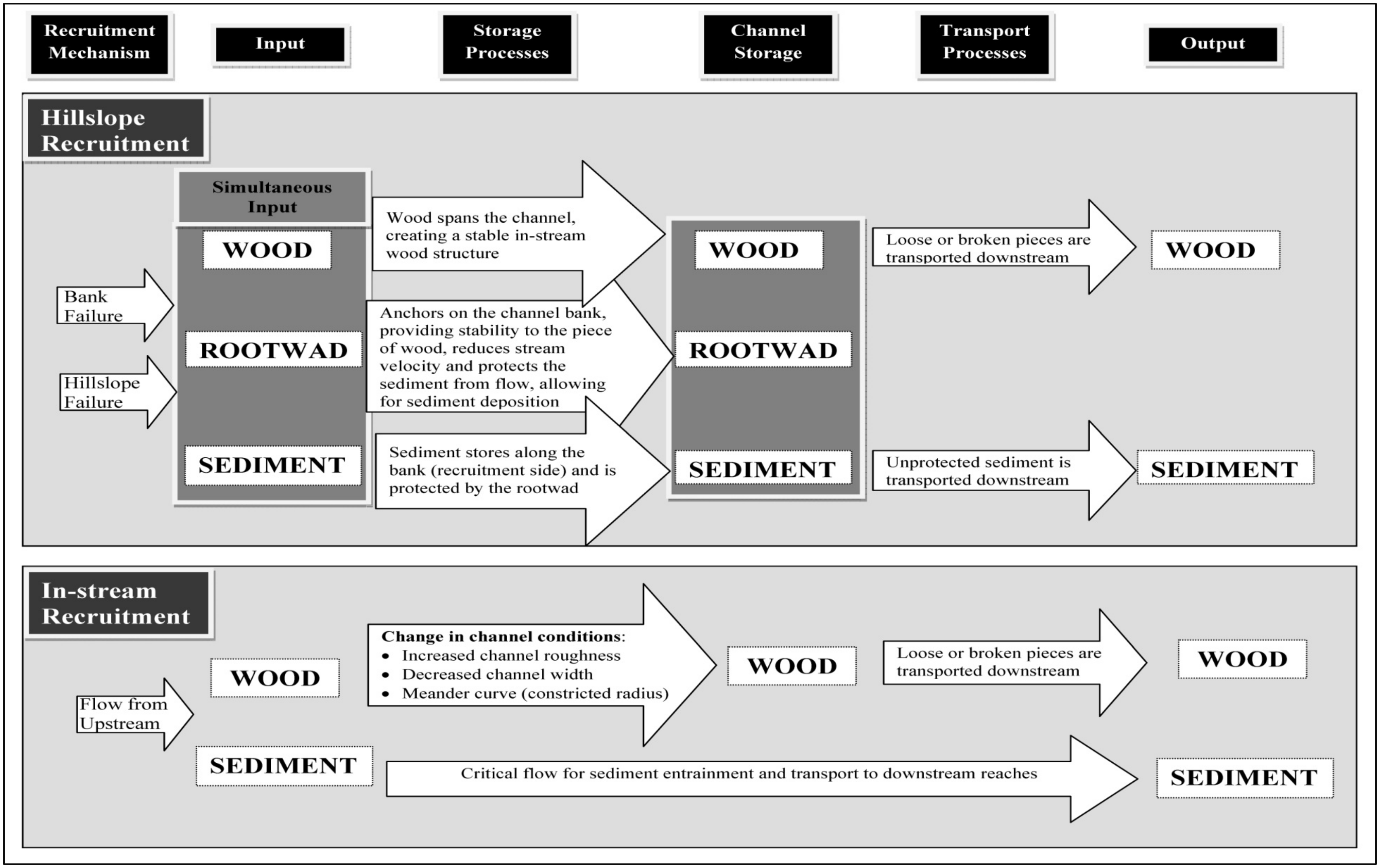


Figure 4-4: Conceptual model of in-stream wood as a mechanism for cohesive sediment storage based on recruitment mechanism of wood and sediment inputs. The size of the arrows represents the approximate proportion of input and output for each component.

4.9.6.3 Ecological implications of stored sediment

It is predicted that the storage of sediment in pools will have geomorphic and ecological implications. The storage of sediment has the ability to infill pools, which can reduce their volume and decrease pool diversity within a stream reach (Zelt & Wohl, 2004). It is predicted the accumulation of sediment will not only infill pools, but accumulate within the substrate along the channel bed. This prediction is based on previous research, which found increased fine-grained sediment smothered riverbeds and clogged pore spaces between substrate (Wood & Armitage, 1997). During the current field investigation, there was evidence of sand accumulating between cobbles at site LE47 (Pool 2). As sediment accumulates in pools and within channel bed substrate, it can decrease the diversity in aquatic habitat. In particular the clogging of pore space has been found to reduce habitat for benthic organisms, altering the food chain (Wood & Armitage, 1997). With the reduction of available habitat and the decrease in benthic invertebrates, it is predicted there will be a decline in the number of larger aquatic organisms. In addition to physically altering the channel, cohesive sediment storage can alter the biogeochemistry of a stream due to the nutrients and contaminants bound to its large surface area. This could further impact the aquatic ecosystem

Nutrients such as carbon, nitrogen and phosphorus are generally bound to cohesive sediment. Therefore, when sediment remains in storage it alters the biological processes in the stream by shortening the nutrient spiral. Previous research has reported the shortening of nutrient spiralling can cause an increase in nutrients at the storage location and a deficit downstream (Aumen et al., 1990; Raikow et al., 1995). The local increase in nutrients can increase the amount of bacteria, fungi and algae residing on the stream bed (Aumen et al., 1990). Algae blooms were observed at site LE10 during the field investigation. It is predicted that the algae represented an increase in local nutrients, which could have been impacting water quality. Dodds and Welch (2000) found increased nutrients and primary producers caused a build-up in organic carbon, which lowered the dissolved oxygen concentration and caused a higher pH in the water. The impacts from higher nutrient levels can cause a decrease in water quality in the stream (Dodds & Welch, 2000). Therefore, it is predicted that if nutrients bound to cohesive sediment remain stored in pools there will be an increase in algae growth and a decrease in oxygen levels. This process could result in a reduction in the number and diversity of aquatic organisms. These negative impacts on water quality and aquatic life make the study of cohesive sediment storage important for planning and management decisions.

4.10 Planning and management implications

Alberta has two government documents that include salvage logging guidelines. Currently a buffer of ten metres must be maintained around small permanent streams during harvesting (Alberta Sustainable Resource Development, 2006). An additional 25% of standing dead wood must be retained in salvage logged locations (Alberta Sustainable Resource Development, 2007). The height of trees and the lateral migration of the streams found in Lyons East and Corolla Creek provide evidence that a ten meter buffer is not sufficient to ensure a constant supply of in-stream wood. The input of wood from riparian areas typically occurs from within thirty metres of the channel (Benda et al., 2002; Murphy & Koski, 1989). The results of the thesis suggest a 30m buffer be implemented in areas where in-stream wood recruitment is a priority, but this set back (buffer width) should be flexible for headwater streams The fixed width method is easier to apply and monitor but requires no knowledge of basic ecological principles. Accordingly, the utilization of variable width riparian management will allow for the natural variation of the riparian zone to be accounted for in management decisions which are based on ecological and landscape principles (Phillips et al., 2000).

The width of a riparian management zone can be determined in two ways, the first is a standard width (fixed) and the second is a variable width based on specific site conditions. When determining the riparian buffer that should be maintained it is important to understand that riparian boundaries do not stop at an arbitrary, uniform distance from the channel, but varies in width and shape (Gregory, 1997 Ilhardt, 2000). The boundary of the riparian forest varies longitudinally and laterally throughout the channel network according to a variety of biophysical factors (Reeves et al., 2006). Due to the important ecological function associated with the riparian-stream connection, land-use management decisions should reflect the flexibility of the riparian zone. The variables that should be considered when establishing a flexible riparian management zone are: composition, age and condition of vegetation; site geomorphology, animal and place species, adjacent land use and sensitivity of the site to disturbance (Phillps et al., 2000).

Riparian management practices in the Pacific Northwest already have implemented flexible riparian buffers, which are modified for local conditions. The width of a buffer in the Pacific Northwest is determined based on the stand type, topography, channel or valley morphology and fish communities and is approached as a site-specific management strategy (Gregory, 1997). This consideration for the local landscape and the terrestrial-aquatic ecosystem connection allows for the best management decisions to be implemented for each watershed. This type of management effort should be employed in the headwater systems of the Oldman River Basin to ensure a continuous supply of available in-stream wood is maintained, as well as other ecological functions of the riparian forest for the stream channel. The implementation of the flexible boundaries in the Pacific Northwest provides support that this type of management is a viable alternative to set standard.

The long-term consequences of not maintaining available wood supply for recruitment to the channel include; (1) a decrease in production of salmonids, (2) reduction in biological productivity and (3) increased transfer of sediment from headwater to downstream reaches (Murphy & Koski, 1989; Swanson & Lienkaemper, 1978). Therefore, in areas where logging and recreational activities are permitted, it is recommended that streamside management be one of the highest priorities (Murphy & Koski, 1989). Alberta already has management guidelines established for logging in the study area. From field observations, the buffer zone widths were maintained in the salvage logged areas and other than fire breaks and cut lines, trees were preserved along either side of the channel. The only location where logging occurred close to the channel was in the most downstream section of Lyons East where firewood permit holders cut and remove trees. Firewood permit holders typically cut enough wood for personal use. Since permits required for wood cutting have no time restrictions, it is not reasonable to expect enforcement of the buffer zones. However, citizens should be encouraged through educational programs to avoid cutting trees or collecting wood near streams.

Improved knowledge regarding the link between the riparian forest and channel processes, will allow for an interdisciplinary approach to adaptive management for aquatic habitat in headwater streams (Buffington et al., 2002). The current study improves information regarding the diversity of habitat created by in-stream wood based on the different types of pools created and the importance of achieving a natural balance. Allowing in-stream wood structures to evolve naturally and securing wood for future recruitment will help to maintain healthy aquatic ecosystems, which is a primary goal of the *Water for Life Strategy*.

Another component of the *Water for Life Strategy* is to ensure that safe and clean drinking water is provided. Previous research has found that when an in-stream wood structure breaks, it causes a transfer of cohesive sediment and associated nutrients downstream (Bilby, 1981). In terms of drinking water, cohesive sediment can affect water quality, which can impact human health (pathogens and radionuclides) (Owens et al., 2005; Petticrew et al., 2007). Therefore, it might be useful for managers of water treatment facilities downstream to be able to predict these increases in cohesive sediment and nutrients. This would require improved knowledge of the stability of in-stream wood structures and the amount of stored sediment within the watershed. Since cohesive sediment is the primary vector of nutrient and contaminants in aquatic systems (Owens et al., 2005; Stone & Droppo, 1994), it would be useful for management to understand the stability of these storage sites. The ability to predict a sudden influx of cohesive sediment could allow water treatment experts to be better prepared to handle the corresponding increase in cohesive sediment and associated nutrients.

Chapter 5
Conclusion and Recommendations

5.1 Conclusion

The first goal of this research project was to evaluate the spatial distribution of in-stream wood deposits along the main stem of two headwater streams on the eastern slopes of the southern Rocky Mountains. The second goal was to determine the geomorphic impacts of in-stream wood at six representative stream reaches. The reach-scale study focused on the formation of pools by in-stream wood and their effect on cohesive sediment storage. This research provides a better understanding of the environmental impacts of disturbances and the importance of in-stream wood in maintaining a diverse and healthy aquatic ecosystem. Based upon the data analysis for the current project, the following conclusions are presented.

Spatial distribution of in-stream wood

1. The spatial distribution of in-stream wood between the two watersheds was similar. The number of in-stream wood structures along the longitudinal main stem was similar for the two watersheds (94 for Lyons East and 66 for Corolla Creek), at a frequency of 1.49 deposits per 100m for both watersheds. The percentage of deposits observed within each structure type category was also similar between the two watersheds. Single piece structures were the least common and jams were the most common structures. A slightly higher percentage of dams was observed in Lyons East.

2. There was some clustering of partial jams at the downstream end of both channels. More complex structures were found closer to the upper sections of the headwater channel, however due to the proportions of structures, particularly jams (43% in Lyons East and 47% in Corolla Creek) there was no clear trend in structure type. The only statistically significant variable in predicting the type of wood structure to form was channel shape.

The effect of in-stream wood on geomorphic characteristics and classification

1. The presence of in-stream wood altered the width and depth of the channel. In the six study reaches examined, the channel was generally wider and deeper downstream of the deposit. The shift in channel dimensions was due to the accumulation of sediment upstream and the decrease in

sediment downstream of the in-stream wood. These results are comparable to those reported in previous studies.

2. In-stream wood deposits shifted channels toward a pool-riffle morphology, resulting in a forced classification. In two of the reaches examined, the portion of the stream near the woody deposit shifted from a bedrock-dominant morphology to a forced pool-riffle or step-pool morphology. The forced morphology resulted in a shortening of pool spacing in all reaches.

The impact of in-stream wood on pool formations and cohesive sediment storage

1. In-stream wood structures influenced pool type and sediment storage. The main wood-affected pools were classified as plunge, underflow and deflector pools. Only one in-stream wood structure blocked flow sufficiently enough to create a dammed pool (CC3 – Pool 3). Wood-affected pools were different types (plunge, underflow, deflector and dammed) compared to the non-wood-affected pools (lateral scour, mid-channel, trench), with the exception of two non-wood-affected plunge pools. Since there were often pieces of wood within the structure that did not come in contact with the channel bed, these pools also provided aquatic habitat and shade (cover) not present in non-wood-affected pools. The variety of pool types provide habitat for aquatic organisms throughout their lifecycles.

2. There was no relationship between pool volume and wood-affected pools. However, the two studied watersheds did contain a different percentage of pool volume in wood-affected pools. Lyons East had a greater percentage of pool volume (49% to 70%) compared to Corolla Creek (13% to 52%) in wood-affected pools. These results show that at minimum 49% of pool volume found in Lyons East was associated with in-stream wood structures, whereas the maximum was 52% in Corolla Creek. The in-stream wood did not have an observed impact on the physical dimensions of pools (volume). Therefore, the greater impact of in-stream wood in the two studied watersheds appears to be on pool type and aquatic habitat.

3. Cohesive sediment deposits were generally thicker and more prevalent in pools in Lyons East compared to Corolla Creek. The lack of sediment in Corolla Creek is related to the presence of bedrock in the channel, which limited the sediment supply. In Lyons East, the majority of wood-affected pools had a larger residual cohesive sediment volume compared to non-wood-affected pools. In Corolla Creek, too few pools (3 of 11 pools were wood-affected) were examined to develop a relationship between in-stream wood and cohesive sediment storage. The weighted V^*_w values were

generally higher in Lyons East, indicating an overall greater storage of cohesive sediment. These results indicate more cohesive sediment is stored in the burned watershed compared to the unburned watershed. The amount of stored cohesive sediment is important as it can cause water quality concerns, such as turbidity, eutrophication, pathogens and radionuclides, which can impact river ecology and human health (Owens et al., 2005; Petticrew et al., 2007).

Implications for planning and management

1. Buffers are the most commonly cited management strategy for protecting the natural terrestrial-aquatic interconnection (as mentioned in Section 1.2.10). The Alberta salvage logging guidelines currently require a riparian buffer width of 10m. Researchers in previous studies recommend a buffer of 30 meters to ensure that large tree recruitment is maintained to active stream channels, as the majority of tree recruitment occurs within this distance (Benda et al., 2002; Murphy & Koski, 1989). The field investigation provided evidence of lateral channel migration up to 30 metres from the current channel location in some sections and a confined channel with no migration in other sections. Therefore, a standard buffer for this channel is not the best management practice due to the variability of the riparian area. It is recommended a flexible riparian buffer be implemented based on land-use, valley type and hydrologic conditions. This flexibility in riparian buffer width will reflect the natural processes occurring within the watershed. The ability to enforce buffers along streams for individuals harvesting trees with a firewood permit is more difficult; therefore education is the best management technique available to maintain natural riparian vegetation.

2. The diversity of habitat provided by in-stream wood is important in developing and maintaining healthy aquatic ecosystems. Research and annual monitoring of in-stream wood should be completed for headwater streams in the Oldman River Basin, if funding allows. This monitoring would provide additional information and understanding on the natural processes such as recruitment and jam evolution, as well as the stability of in-stream wood structures. The data collected would be important in helping to preserve diverse habitats for aquatic organisms. It is recommended that in-stream wood structures be allowed to evolve naturally instead of being removed, as they provide diversity in aquatic habitat, which maintains a healthy aquatic ecosystem. The storage of cohesive sediment should be monitored due to its potential impact on the source, transport and storage of nutrients and contaminants, all of which can affect water quality. By maintaining this diverse habitat

and monitoring water quality, the primary goals of a healthy aquatic ecosystem, and safe drinking water required by Alberta's *Water for Life Strategy* will be achieved.

5.2 Recommendations for future research

The current study provides understanding of the in-stream wood structure types and their impact on channel morphology, pool formations and cohesive sediment storage for two headwater streams. However, in order to gain a more complete understanding of in-stream wood in the Oldman River Basin, further research is recommended. The current study occurred over one field season and along third order streams. In order to understand the spatial distribution of in-stream wood in the Canadian Rocky Mountains, it is recommend further research be conducted to include smaller (1^{st} order) and larger (5^{th} order) channels. This addition of other streams and reaches is necessary to gain a more complete data set of morphological channel responses to in-stream wood within the Oldman River Basin. This information would help determine if the conceptual model created by Wohl and Jaeger (2009) is appropriate for this basin. If the model were found to be appropriate, then it could be used to better predict the distribution of in-stream wood within the system. This information could then be used for planning and management initiatives.

Additional research should be conducted on the recruitment of wood to the channel as well as the stability of in-stream wood structures and their impact on channel morphology. In particular, the relationship between slope and wood recruitment would provide information on conditions that are necessary for the creation of different types of in-stream wood structure. Previous research has found that the primary contributor of wood in low gradient meandering streams is lateral migration; however wood is also recruited through processes of bank failure, windthrow, floatation and ice loading (Keller & Swanson, 1979). In steeper channels avalanches, debris flows, landslides and other mass movement are the primary recruitment mechanism of wood to stream channels (Comiti et al., 2006; Gurnell et al., 2002; Keller & Swanson, 1979). The study of wood recruitment along the longitudinal profile could provide information on the function of slope in wood recruitment within these headwater streams.

The dating of in-stream wood over time could be used to determine the age of recruited trees and possibly provide information on when the wood was recruited to the channel. This information would be particularly interesting for logs located in abandon channels, in order to determine if the wood was recruited prior to the channel becoming abandoned. Jones and Daniels (2009) discussed the use of dendrochronological techniques as a method of establishing the time since death of in-stream wood. Using this technique the researchers were able to determine if in-stream wood was killed and recruited as a result of the 2001 Dogrib fire (Jones & Daniels, 2009). The mortality of the tree is particularly interesting in burned catchments to determine if a tree was recruited prior to or following the forest fire. Dendrochronology could also allow a researcher to examine recruitment and stability of in-stream wood structures by dating trees over time.

The single field season provided minimal information on the stability of in-stream wood structures found in the study watersheds. Therefore, the formational processes of more complex structures and their stability should be examined in future research. The stability of a structure determines its impact on channel morphology and aquatic habitat. After observing site CC1 breaking during the 2009 field season, and wood being added to site LE11, it is apparent the system is constantly adjusting to the changes in wood load. A temporal study is recommended to test the theoretical jam evolution previously discussed (Section 1.2.6 and Figure 1-4) and understand the wood loading processes in terms of input and output. Additional studies of the in-stream wood transport process are necessary to further elucidate the formation mechanisms and stability of jams in the watershed. This research would provide additional information on the jam evolution occurring within these selected watersheds. This information will provide a more complete understanding of the possible morphological and ecological impacts on the stream.

The surficial geology of an area influences the type of material available for recruitment to the channel. It is therefore recommended that research be conducted to obtain information on the geologic properties in both watersheds. This information would allow researchers a better understanding the type of material available for recruitment to a channel. For example, if the watershed is dominated by a glacial till composed of a silty-clay matrix; it would provide fine-grained sediment to the channel during undercutting and hillslope failures. In addition, it is predicted that angular clasts could be recruited to the stream providing roughness necessary to trap in-stream wood and allow structures to form. This understanding of the geology would provide more information on the formation of in-stream wood structures and the storage of cohesive sediment, which would allow for further improvement of the conceptual model developed for the studied watersheds (Figure 4-4).

The presence of roads can impact the sediment delivered to a stream through runoff processes, causing an increase in fine-grained sediment loads (Jackson & Strum, 2002). There is an extensive trail network with a number of trail crossings in the Corolla Creek watershed. Prior to learning the extent of the trail network, a buffer zone was created to avoid the impact of ATV trails on the distribution of in-stream wood. However, it would be interesting to investigate the possible impacts the extensive trails have on in-stream wood distribution and the associated impacts on sediment storage. This additional research would provide information on these possible relationships and be useful in managing headwater streams, trail networks and determining the best location for bridge crossings in the larger basin.

Since the current research only examined cohesive sediment stored in residual pools, sediment stored in other areas of the channel such as the channel bed matrix or infill upstream of the in-stream wood obstruction was not measured. Previous research has found the accumulation of fine-grained sediment is generally more frequent on the upstream side of a woody obstruction (Faustini & Jones, 2003). Therefore, future research should examine the storage of cohesive sediment not confined to pools. This information would allow for a comparison of sediment stored upstream and downstream of the in-stream wood structure. Future research should also examine the cohesive sediment stored in the channel bed both in pools and along the reach. This would allow for a more complete understanding of the possible impacts in-stream wood has on the total storage of cohesive sediment in the streams.

During the field investigation cohesive sediment samples were collected. Analysis of these cohesive sediment samples would provide information on the nutrients (phosphorus, nitrogen and carbon) bound to the sediment and could provide further insight into differences between the two watersheds. In addition to the mentioned nutrients other chemical analysis could be completed to examine the sediment geochemistry in the two studied watersheds. This analysis would provide information on the storage of nutrients and contaminants bound to cohesive sediment and its relation to in-stream wood. The research could then compare the two watersheds and determine if there were changes in the type of nutrients and/or contaminants being stored in the watershed disturbed by wildfire. This could provide information into the length of time wildfire impacts remain in the streams, based on the storage of cohesive sediment. The results would provide a basis for understanding water quality issues, which could be used for watershed management.

In-stream wood is one of the most important components of fish habitat, because it creates diversity and provides cover for aquatic organisms (Berg et al., 1998). In-stream wood serves as a significant cover source for fish, particularly trout, as they require the cover for resting and predator avoidance (Berg et al., 1998). In addition, wood can contribute nutrients to the water through decomposition (Aumen et al., 1990; Harmon et al., 1986). The ecological component of wood-affected pools was not investigated in the current project; therefore to determine the impact of wood-affected pools on fish, an ecological study would need to be conducted. This study should include the location, type and number of fish and a detailed analysis of wood-affected and non-wood-affected pools. The analysis could then examine the effect of in-stream wood on fish populations.

Appendix A

In-stream wood definitions and Size classification

Table A- 1: Description of different in-stream wood definitions and size class requirements based on length and size within the current literature (emphasis added)

Wood	Definition	Length	Diameter	Reference
FWD	Woody debris less than 10cm in diameter	N/A	< 0.1m	(Aumen et al., 1990)
LWD	Woody debris (logs, limbs and rootwads) greater than 10cm in diameter	N/A	> 0.1m	(Aumen et al., 1990; Jefferies et al., 2003; Keller & Swanson, 1979)
LWD	All woody debris 10cm in diameter within stream reach *at low flow conditions*	N/A	> 0.1m	(Baillie & Davies, 2002)
Large wood	Any organic matter greater than 0.1m in diameter and located within the channel, including snags, logs, pieces of wood, large branches and coarse roots	N/A	> 0.1m	(Webb & Erskine, 2003, 2005)
CWD	Woody material greater than 0.1m in diameter *blocking the bankfull channel*	N/A	> 0.1m	(Hart, 2003)
Wood	Wooden objects larger than 25cm in length and 2.5cm in diameter	> 0.25m	> 0.025m	(Mutz, 2000)

Wood	Definition	Length	Diameter	Reference
WD	Wood with a minimum diameter of 0.05m and minimum length of 0.3m in *active channel and adjacent active floodplain*	> 0.3m	> 0.05m	(Comiti et al., 2006)
FWD	Wood with a diameter between 0.03m and 0.1m and minimum length of 0.5m	≥ 0.5m	0.03m - 0.1m	(Gomi et al., 2001)
LWD	Wood with a minimum diameter of 0.1m and minimum length of 0.5m	≥ 0.5m	≥ 0.1m	(Gomi et al., 2001)
LWD	Wood with a minimum diameter of 10cm and a minimum length of 50cm	> 0.5m	> 0.1m	(Jackson & Strum, 2002)
Wood	Wood with a minimum diameter of 0.05m and minimum length of 1.0m	≥ 1.0m	≥ 0.05m	(Nowakowski & Wohl, 2008; Wohl & Goode, 2008)
MW (medium)	Wood at least 0.08m in diameter and 1m in length	≥ 1.0m	≥ 0.08m	(Berg et al., 1998)
LWD	Wood with a length greater than or equal to 1m and a diameter of greater than or equal to 10cm	≥ 1.0m	≥ 0.1m	(Raikow et al., 1995; Richmond & Fausch, 1995; Wohl et al., 2011)
LWD	Downed logs that intersect the stream channel and exceeded 0.08m in diameter and 1m in length	> 1.0m	> 0.08m	(Jones & Daniels, 2008)

Wood	Definition	Length	Diameter	Reference
LWD	Logs with either a minimum diameter of 0.1m or a minimum length of 1m	> 1.0m	> 0.1m	(Curran, 2010)
LWD	*Isolated unbranched pieces* greater than 1m in length and 10cm in diameter	> 1.0m	> 0.1m	(Wyzga & Zawiejska, 2010)
LWD/ Trunks	Wood pieces with a minimum size criteria of 1 m long and 10 cm in diameter	> 1.0m	> 0.1m	(Abbe & Montgomery, 2003; Andreoli et al., 2007; Andrus et al., 1988; Chen et al., 2005; Chen et al., 2006; Comiti et al., 2006; Comiti et al., 2008; Curran & Wohl, 2003; Czarnomski et al., 2008; Kraft & Warren, 2003; Marcus et al., 2002; Morris et al., 2007; Murphy & Koski, 1989; Nakamura & Swanson, 1994; Piégay et al., 1999; Seo & Nakamura, 2009; Wohl & Cadol, 2011; Wohl & Jaeger, 2009; Wyzga & Zawiejska, 2005)
LWD	Trees, branches and other larger organic matter, with lengths greater than 1m and diameters greater than 0.1m	> 1.0m	> 0.1m	(Faustini & Jones, 2003; Wallerstein & Thorne, 2004)
LWD	Wood with a minimal length of 1m and a diameter at least 0.1m at the mid-point	> 1.0m	> 0.1m	(Kaczka, 2009)
LW	Wood with a minimum diameter of 0.1m and minimum length of 1.0m in the *active channel or adjacent active floodplain*	> 1.0m	> 0.1m	(Mao et al., 2008)

Wood	Definition	Length	Diameter	Reference
LWD	Wood pieces at least 1 m long and 10 cm in diameter *in or suspended across bankfull channel*	> 1.0m	> 0.1m	(Kreutzweiser et al., 2005)
LWD	Piece of wood at least 1m long and 10cm in diameter or at least 2m long and 5cm in diameter	> 1.0m O > 2.0m	> 0.1m R > 0.05m	(Cadol et al., 2009)
Wood	Wood with a minimum diameter of 0.1m and minimum length of 1.5m *in channels less than 5m*	> 1.5m	> 0.1m	(Martin & Benda, 2001)
LW	Wood with a minimum diameter of 0.2m and minimum length of 1.5m	> 1.5m	> 0.2m	(Robison & Beschta, 1990)
LW	Wood with a minimum diameter of 0.08m and minimum length of 1.8m	> 1.8m	> 0.08m	(Benda et al., 2002)
LWD	*Wood at least partially within or above the active channel* with a length greater than or equal to 2m and the small end diameter greater than or equal to 10 cm	≥ 2.0m	≥ 0.1m	(Zelt & Wohl, 2004)

Wood	Definition	Length	Diameter	Reference
Coarse Wood	Wood at least 2m long and <u>*one end*</u> at least 10 cm in diameter, with at least 0.1m of the length *in or suspended over the bankfull channel*	≥ 2.0m	≥ 0.1m	(Young et al., 2006)
LW	Wood with a minimum diameter of 0.1m and minimum length of 2.0m	> 2.0m	> 0.1m	(Bilby & Ward, 1989; Seo et al., 2010)
LWD pieces	Wood at least 10cm in mean diameter and 2m in length *at least partially within the bankfull channel*	> 2.0m	> 0.1m	(Beechie & Sibley, 1997)
Size class within Jam	<u>Small pieces</u> 10-20cm diameter and greater than 2m long <u>Medium pieces</u> 20-50cm diameter and greater than 3m long <u>Large pieces</u> greater than 50cm diameter and greater than 5m long	Sm. > 2.0m Med. > 3.0m Lg. > 5.0m	Sm. 0.01m - 0.02m Med. 0.02m - 0.05m Lg. > 0.05m	(Beechie & Sibley, 1997)
LW	Wood with a minimum diameter of 0.15m and minimum length of 2.0m	> 2.0m	> 0.15m	(Young, 1994)

Wood	Definition	Length	Diameter	Reference
Wood	Downed wood that exceeded 20cm in mean diameter and 2m in length and *in contact with bank-full channel*	> 2.0m	> 0.2m (mean)	(May & Gresswell, 2003)
LW (large)	Wood at least 0.3m in diameter and 3.0m in length	≥ 3.0m	≥ 0.3m	(Berg et al., 1998; Reeves et al., 2003)
LW	Wood with a minimum diameter of 0.1m and minimum length of 3.0m *in channels <u>wider than 5m</u>*	> 3.0m	> 0.1m	(Martin & Benda, 2001)
LWD	Minimum 30cm diameter and 5m length	> 5.0m	> 0.3m	(Hyatt & Naiman, 2001)
Key LWD	Minimum 60cm diameter and 5m length	>5.0m	> 0.6m	(Hyatt & Naiman, 2001)

Appendix B

In-stream wood formational characteristics

Table B-1: Description of definitions used within current literature for in-stream wood positions

Position	Description	Reference
Channel margin	Wood is located in the area adjacent to and higher than the bankfull channel (banks and terraces)	(Andreoli et al., 2007; Andrus et al., 1988; Comiti et al., 2008)
Bridge	Both ends rest on the banks above the reference level (bankfull channel)	(Andreoli et al., 2007; Cadol et al., 2009; Comiti et al., 2008; Wohl & Cadol, 2011; Wohl & Goode, 2008; Wohl & Jaeger, 2009; Wohl et al., 2009; Wohl et al., 2011; Zelt & Wohl, 2004)
	Wood is suspended across the stream channel	(Andrus et al., 1988; Baillie & Davies, 2002; Jones & Daniels, 2008)
Channel bridging	Wood spanning the channel at an elevation higher than bankfull stage	(Andreoli et al., 2007; Comiti et al., 2008)
Bankfull line	Wood corresponding to the bankfull stage	(Andreoli et al., 2007)
Ramp	One end rests on the bank above the reference level (bankfull channel)	(Cadol et al., 2009; Wohl & Cadol, 2011; Wohl & Goode, 2008; Wohl & Jaeger, 2009; Wohl et al., 2009; Wohl et al., 2011; Zelt & Wohl, 2004)
	Wood is partly suspended across the stream channel	(Baillie & Davies, 2002; Richmond & Fausch, 1995)
	Wood touching the left bank only; Wood touching the right bank only	(Richmond & Fausch, 1995)
Partial bridge	Log spanning the channel has broken in one or more places within the stream channel	(Jones & Daniels, 2008)
Pinned	Wedged beneath other wood either partially or wholly; or upstream of an obstacle such as a boulder or other wood	(Wohl & Cadol, 2011; Wohl et al., 2011)
Drift	Wood is resting on the channel floor (stream bed) in the active channel	(Andrus et al., 1988; Baillie & Davies, 2002; Zelt & Wohl, 2004)
In-channel	Wood elements lying at least partially at a lower elevation than bankfull height, excluding log steps	(Andreoli et al., 2007; Comiti et al., 2008)

Position	Description	Reference
Buried	Partially buried or partially in the stream bed alluvium	(Baillie & Davies, 2002; Jones & Daniels, 2008; Wohl & Cadol, 2011; Wohl & Goode, 2008; Wohl & Jaeger, 2009; Wohl et al., 2011)
Buried	Wood is contained in the active channel and is partially buried in bed sediment or pinned beneath another log	(Cadol et al., 2009; Wohl et al., 2009)
Buried	Wood is buried or partially buried in the substrate	(Baillie & Davies, 2002)
Buried	Log has become incorporated into the streambed or the sides of the stream bank with sediment stored upstream partially burying the log	(Jones & Daniels, 2008)
Unattached	Piece does not touch either bank above the reference level and is not buried within the bed or banks	(Cadol et al., 2009; Wohl & Cadol, 2011; Wohl & Goode, 2008; Wohl & Jaeger, 2009; Wohl et al., 2009; Wohl et al., 2011)
Loose	Log is no longer associated with the floodplain and is fully associated with the streambed where it is submerged during bankfull flow	(Jones & Daniels, 2008)
One	Wood is off to the side and only partially in the channel at bankfull flow	(Kreutzweiser et al., 2005)
One	Wood located on the bank	(Piégay et al., 1999)
Two	Wood is in the channel only at bankfull flow	(Kreutzweiser et al., 2005)
Two	Wood located in the main channel	(Piégay et al., 1999)
Three	Wood is partially in the channel at low flow	(Kreutzweiser et al., 2005)
Three	Wood located in the secondary channel	(Piégay et al., 1999)
Four	Wood is mid-channel at low flow	(Kreutzweiser et al., 2005; Richmond & Fausch, 1995)
Four	Wood located on the apex bar	(Piégay et al., 1999)
Five	Wood is in the channel and secured against the bank at low flow	(Kreutzweiser et al., 2005)
Five	Wood located on a bar (Boarder)	(Piégay et al., 1999)
Six	Wood located on head bar	(Piégay et al., 1999)

Table B-2: Description of definitions used within current literature for in-stream wood orientation

Orientation	Description	Reference
Degrees	Hand-held compass used to tell the orientation in degrees to the predominant direction of flow	(Gomi et al., 2001; Webb & Erskine, 2003, 2005; Wohl et al., 2011)
Perpendicular	Perpendicular or close to perpendicular to banks (60-120°/240-300°)	(Chen et al., 2006)
Orthogonal/ Class1/ Perpendicular	90° to stream flow	(Andreoli et al., 2007; Baillie & Davies, 2002; Comiti et al., 2008; Piégay et al., 1999; Richmond & Fausch, 1995)
Parallel	Parallel (0˚) or close (150-210°/30-330°) to stream flow	(Andreoli et al., 2007; Baillie & Davies, 2002; Chen et al., 2006; Comiti et al., 2008; Richmond & Fausch, 1995)
Small end downstream	Downstream as parallel to banks with smaller-diameter situated downstream (30-60°/210-240° or 120-150°/300-330°)	(Chen et al., 2006)
Roots downstream	Parallel with roots upstream	(Piégay et al., 1999)
Small end upstream	Upstream as parallel to banks with the smaller diameter situated upstream (30-60°/210-240° or 120-150°/300-330°)	(Chen et al., 2006)
Roots upstream	Parallel with roots downstream	(Piégay et al., 1999)
Angle One	45/225° to stream flow	(Baillie & Davies, 2002)
Angle Two	35/315° to stream flow	(Baillie & Davies, 2002)
Oblique/ Intermediate	An angle between perpendicular and parallel to flow	(Andreoli et al., 2007; Comiti et al., 2008; Piégay et al., 1999)
Angled	45° and 135° two diagonal orientations	(Richmond & Fausch, 1995)
Angle 0-60°	0-60° from the bank downstream from the piece	(Young, 1994)
Angle 61-119°	61-119° from the bank downstream from the piece	(Young, 1994)
Angle 120-180°	120-180° from the bank downstream from the piece	(Young, 1994)

Table B-3: Description of definitions used within current literature for in-stream wood decay classes

Decay Class	Description	Reference
Category 1 Fresh	Leaves or needles still attached to woody debris	(Wohl & Cadol, 2011; Wohl et al., 2011)
Class 1	Bark intact, limbs and twigs present	(Hyatt & Naiman, 2001; Murphy & Koski, 1989)
Class 1	Debris had intact bark or at least >50% remaining wood hard with original color, branches or twigs present	(Chen et al., 2005; Chen et al., 2006)
Class I	Wood has > 75% bark still intact, bark adheres tightly; braches have fine (third order) branchlets; sapwood is sound, log retains structural integrity	(Jones & Daniels, 2008)
Category 2 Partly Decay	At least some bark is still attached as well as small branches	(Wohl & Cadol, 2011; Wohl et al., 2011)
Class 2	Bark intact, limbs and twigs absent	(Hyatt & Naiman, 2001; Murphy & Koski, 1989)
Class 2	Debris had trace of bark <50% bark remaining, no twigs observed, wood had some surface abrasion	(Chen et al., 2005; Chen et al., 2006)
Class II	Wood has 25-75% bark intact which, in places, is loosely attached to the bole; first order branches have a solid connection to the bole; wood is solid with evidence of decay on some outer sections of sapwood only	(Jones & Daniels, 2008)
Category 3 Decay	Bark and branches gone, wood is partly soft to the touch	(Wohl & Cadol, 2011; Wohl et al., 2011)
Class 3	Debris had dark color, no bark and twigs observed, wood soft throughout with holes and openings	(Chen et al., 2005; Chen et al., 2006)
Class 3	Bark loose or 5% absent	(Hyatt & Naiman, 2001; Murphy & Koski, 1989)
Class III	Wood has 0-25% bark present, adhering loosely to the sapwood; first order branches and branch numbs are present and sit loosely in the bole; along some parts of the bole, wood shows significant signs of decay to depths, of 5-10cm	(Jones & Daniels, 2008)
Class 4	Bark 95% absent, surface firm	(Hyatt & Naiman, 2001; Murphy & Koski, 1989)

Decay Class	Description	Reference
Class IV	Bark is no longer attached; branch nubs only are present; along some parts of the bole, wood is soft, crumbly or fibrous, and decay can penetrate nearly through the sapwood	(Jones & Daniels, 2008)
Class 5	Surface deteriorating, center solid	(Hyatt & Naiman, 2001; Murphy & Koski, 1989)
Class 6	Surface deteriorating, center patchy	(Hyatt & Naiman, 2001; Murphy & Koski, 1989)
Class 7	Surface deteriorating, center solid rotten	(Hyatt & Naiman, 2001; Murphy & Koski, 1989)
Visual estimate	Low; Medium; High	(Andreoli et al., 2007)

Appendix C

Classification of in-stream wood structure types

Table C-1: Description of different single piece in-stream wood formations within the current literature

Single wood structure name	**Description**	**Reference**
Single	Single piece of wood	(Long, 1987)
Trunks	Isolated pieces of trees whose minimum size is 1m in length an 10cm in diameter	(Piégay et al., 1999)
Log steps	Channel-spanning bed-attached single pieces of LWD forming a natural wood drop-structure in the longitudinal profile	(Webb & Erskine, 2003)
Logs	Isolated, unbranched wood pieces greater than 1m in length and 10cm in diameter	(Wyzga & Zawiejska, 2005)

Table C- 2: Description of different formations of in-stream wood jam structure within the current literature

Jam name	**Description**	**Reference**
TWO PIECES		
Log jam	Accumulation of at least two elements	(Andreoli et al., 2007; Comiti et al., 2008; Wallerstein & Thorne, 2004)
Large-wood jams LWJ	Two or more pieces of large wood in contact with each other and extending into the bankfull channel	(Morris et al., 2007)
Logjams channel-spanning	Jams (2 or more pieces of wood touching) that elevate local water-surface elevation and create substantial backwater effects	(Wohl et al., 2011)
THREE PIECES		
1-tier	Single layer jam with more than 3 pieces	(Long, 1987)
2-tier	Multi-layer jam with more than 3 pieces	(Long, 1987)
Jams	Woody accumulations composed of at least three wood pieces having *dimensions greater than 10cm in diameter and 30cm long*	(Piégay et al., 1999)

Jam name	**Description**	**Reference**
Jam	Three or more pieces of wood are in *contact* with one another	(Montgomery & Abbe, 2006; Wohl & Cadol, 2011; Wohl & Goode, 2008; Wohl & Jaeger, 2009; Wohl et al., 2011)
FIVE PIECES		
Woody debris in jams	Five or more clustered pieces broken down into three size classes	(Beechie & Sibley, 1997)
CWD - jams	A structure with at least 5 key-CWD pieces	(Nakamura & Swanson, 1993)
KEY DEBRIS		
Underflow	Key debris elements span/straddle the channel at the bank top level allowing flow to pass unimpeded underneath, having minimal impact on the stream	(Downs & Simon, 2001; Wallerstein & Thorn, 1997; Wallerstein & Thorne, 2004)
Dam jam	Key debris elements lie in the channel but are similar in length to the channel width and completely block (impede) the flow	(Downs & Simon, 2001; Wallerstein & Thorn, 1997; Wallerstein & Thorne, 2004)
Deflector jam	Key debris elements are shorter than the channel width (partial) so that flow is deflected against one or both banks	(Downs & Simon, 2001; Wallerstein & Thorn, 1997; Wallerstein & Thorne, 2004)
Flow parallel/ Bar head jam	Channel width is significantly greater than key debris element length and debris is predominantly aligned parallel to the flow or deposited against incipient bars	(Downs & Simon, 2001; Wallerstein & Thorne, 2004)
ABBE AND MONTGOMERY CLASSIFICATION		
Autochthonous jam	Key wood elements not fluvially transported, thus coming from the bank or floodplain in the close proximity of the jam position	(Abbe & Montgomery, 2003; Mao et al., 2008)
Autochthonous jam – subcategory Bank-input debris	An autochthonous jam where the key members fallen directly in the channel – located in channel	(Abbe & Montgomery, 2003; Mao et al., 2008)
Autochthonous jam – subcategory Log steps	An autochthonous jam where the key member forms a step in the channel	(Abbe & Montgomery, 2003; Mao et al., 2008)
Allochthonous or Transported jam	Made of woody debris that has moved some distance downstream by fluvial processes	(Abbe & Montgomery, 2003; Mao et al., 2008)

Jam name	Description	Reference
Transported jam – subcategory Stable	5 types Debris flow/flood → chaotic LW accumulation lacking key member Bench → LW bench-like accumulation along channel edge Bar apex → one or more key members downstream of a jam, often associated with the development of bars/islands Meander → along the outer banks of meanders, key members buttressing accumulation of racked debris upstream Log raft → typically found in large low-gradient rivers, large stable accumulation plugging channel and causing backwater	(Abbe & Montgomery, 2003; Mao et al., 2008)
Transported jam – subcategory Unstable	Unstable accumulation composed of racked WD upon bars or pre-existing banks 3 types Bar top jam Bank edge Bank revetment → like mender or flow-deflection jam but lacking a key member	(Abbe & Montgomery, 2003; Mao et al., 2008)
Combination jam	Autochthonous key elements with racked transported pieces	(Abbe & Montgomery, 2003; Mao et al., 2008)
Combination jam – subcategory Valley jam	Accumulation is wider than the channel and influencing the long profile and valley bottom	(Abbe & Montgomery, 2003; Mao et al., 2008)
Combination jam – subcategory Flow-deflection jams	Partially spanning the channel width, key member is rotated and jam deflects channel course	(Abbe & Montgomery, 2003; Mao et al., 2008)
HETEROGENOUS COMPOSITION		
Debris jams	Heterogeneous mixture of logs, branches, root boles, and twigs as well as fine organic matter and inorganic sediment	(Manners & Doyle, 2008; Wyzga & Zawiejska, 2005; Wyzga & Zawiejska, 2010)

Table C-3: Description of different formations of in-stream wood dam structure within the current literature

Dam Name	Description	Reference
Debris dam	Jam that impounds or influences flow	(Long, 1987)
Organic Debris dam	Organic matter accumulations extending part way across the channel, forming a major impediment to water flow, creating a pool where fine sediment settles	(Bilby, 1981; Bilby & Liken, 1980)
Debris dam	A wedged accumulation of two or more pieces of large wood that span the active channel bed – consistent with active and complete debris dams	(Webb & Erskine, 2003, 2005)
Debris dam	Aggregates of two or more pieces of LWD that retain multiple small wood pieces and other particulate organic matter	(Kreutzweiser et al., 2005)
Debris dam	Composed of wood, boulders or a mixture of the two (i.e. wood-and-boulder jam)	(Lancaster & Grant, 2006)
Debris dam	Accumulation of wood and organic matter that spans the active channel and retains both fine and coarse particulate organic matter	(Morris et al., 2007)
LW dams	The ensemble of log steps and valley jams – 2 of these natural structures	(Comiti et al., 2008)
High water dam	Trees that have fallen across the channel but are suspended on the bank tops therefore only influence channel at near bankfull discharges	(Gregory et al., 1993; Sear et al., 2010)
THREE TYPE CLASSIFICATION		
Active dam	Completely spans the channel and create a distinct step in the channel profile. Forms a complete barrier to water and sediment	(Gregory et al., 1993; Gregory et al., 1985; Gurnell et al. 1995; Gurnell & Sweet, 1998; Sear et al., 2010; Webb & Erskine, 2003)
Complete dam	Completely spans the channel, but is sufficiently “leaky” to have no notable effect or step of the channel profile, even at low flow conditions	(Gregory et al., 1993; Gregory et al., 1985; Gurnell et al. 1995; Gurnell & Sweet, 1998; Sear et al., 2010; Webb & Erskine, 2003)
Passive dam	Partially blocking the channel, due to being incomplete or partly destroyed	(Gregory et al., 1993; Gregory et al., 1985; Gurnell et al. 1995; Gurnell & Sweet, 1998; Sear et al., 2010; Webb & Erskine, 2003)

Appendix D

Representative in-stream wood structures – Lyons East

Figure D-1: A photo looking upstream towards an example of a single log structure in Lyons East.

The left side of the photo shows water flowing over the log, creating a plunge pool downstream. The middle of the photo shows an accumulation of cobbles that have been scoured out, allowing water to flow under the log. The yellow “Rite in the Rain” field book provides scale.

Figure D-2: A photo looking upstream towards an example of a simple partial jam in Lyons East
This structure does not extend the width of the channel, but impacts the flow by diverting it along the log. The increased roughness and decreased velocity allows loose wood to accumulate along the key member. The yellow "Rite in the Rain" field book provides scale.

Figure D-3: A photo looking downstream towards a partial jam site in Lyons East.
This structure does not extend the width of the channel, but impacts flow by diverting water towards the channel bank causing erosion. The yellow "Rite in the Rain" field book provides scale.

Figure D-5: A photo looking downstream towards a jam site in Lyons East.

The logs were transported through fluvial processes and now divert flow around and along the obstruction. The yellow “Rite in the Rain” field book provides scale.

Figure D-4: A photo looking downstream towards a jam site in Lyons East.

The logs were transported through fluvial processes and are trapped on the bank recruited snags, creating an obstruction to flow. Scouring processes have created a pathway next to the boulder and formed a pool on the downstream side.

Figure D-7: A photo looking upstream towards a dam in Lyons East.
The accumulation of logs, twigs and organic matter has created a near complete barrier to flow. This process has formed a forced dammed pool on the upstream side of the wood structure. The yellow "Rite in the Rain" field book provides scale.

Figure D-6: A photo looking upstream towards a dam in Lyons East.
The logs are oriented diagonally along the channel and have caused scouring of the channel bed, which provides flow pathways for water. A person standing (5'8") provides scale in the photograph.

Figure D-8: A photo looking downstream towards a dam in Lyons East.
The logs have been recruited through erosional and fluvial processes, creating a complex structure. This structure has bar formations on the upstream side and a plunge pool underneath the wood structure. A person (5'8") in the middle of the photograph provides scale.

Appendix E

Representative in-stream wood structures – Corolla Creek

Figure E-1: A photo looking upstream towards an example of a single log site in Corolla Creek.
The flow of water is obstructed by the log, which spans the channel allowing minimal water to flow over the decaying log. The yellow "Rite in the Rain" field book provides scale.

Figure E-2: A photo looking upstream towards an example of a partial jam site with leaning tree influence in Corolla Creek.

This obstruction diverts flow away from the left bank, forming a pool on the downstream side. The yellow "Rite in the Rain" field book provides scale

Figure E-3: A photo looking upstream towards an example of a partial jam formed through fluvial processes in Corolla Creek

The flow is diverted towards the left bank due to the obstruction, undercutting the bank and depositing finer sediment upstream. The yellow "Rite in the Rain" field book provides scale.

Figure E-4: A photo looking upstream towards an example of a simple jam in Corolla Creek.
The larger log spans the channel diagonally, trapping additional wood pieces upstream primarily recruited through fluvial processes. The water flows underneath the large log due to channel bed scouring. The yellow "Rite in the Rain" field book provides scale.

Figure E-5: A photo looking downstream towards an example of a jam in Corolla Creek.
The jam is formed by a suspended bridge trapping loose wood on the upstream side. This structure causes water to be diverted to the middle of the channel, scouring the bed and forming a pool underneath. The height of wood shows the potential height of water levels transporting wood. The yellow "Rite in the Rain" field books provide scale.

Figure E-6: A photo looking across the meander bend towards an example of a jam in Corolla Creek.
This jam is formed as loose wood is transported downstream through fluvial processes and the wood becomes trapped along the outer meaner curve bank. The height of the jam provides evidence of potential water levels and rafting processes within the system. The circled “Rite in the Rain” field book provides scale

Figure E-7: A photo looking downstream towards an example of a dam in Corolla Creek.
This dam is formed through bank recruitment and fluvial processes and is found along a meander curve. The circled “Rite in the Rain” field book provides scale.

Figure E-8: A photo looking downstream towards an example of a dam in Corolla Creek.

This dam is formed as the channel narrows, constricting the transport of wood downstream. The two orange and black meter sticks showing 10cm intervals provide scale.

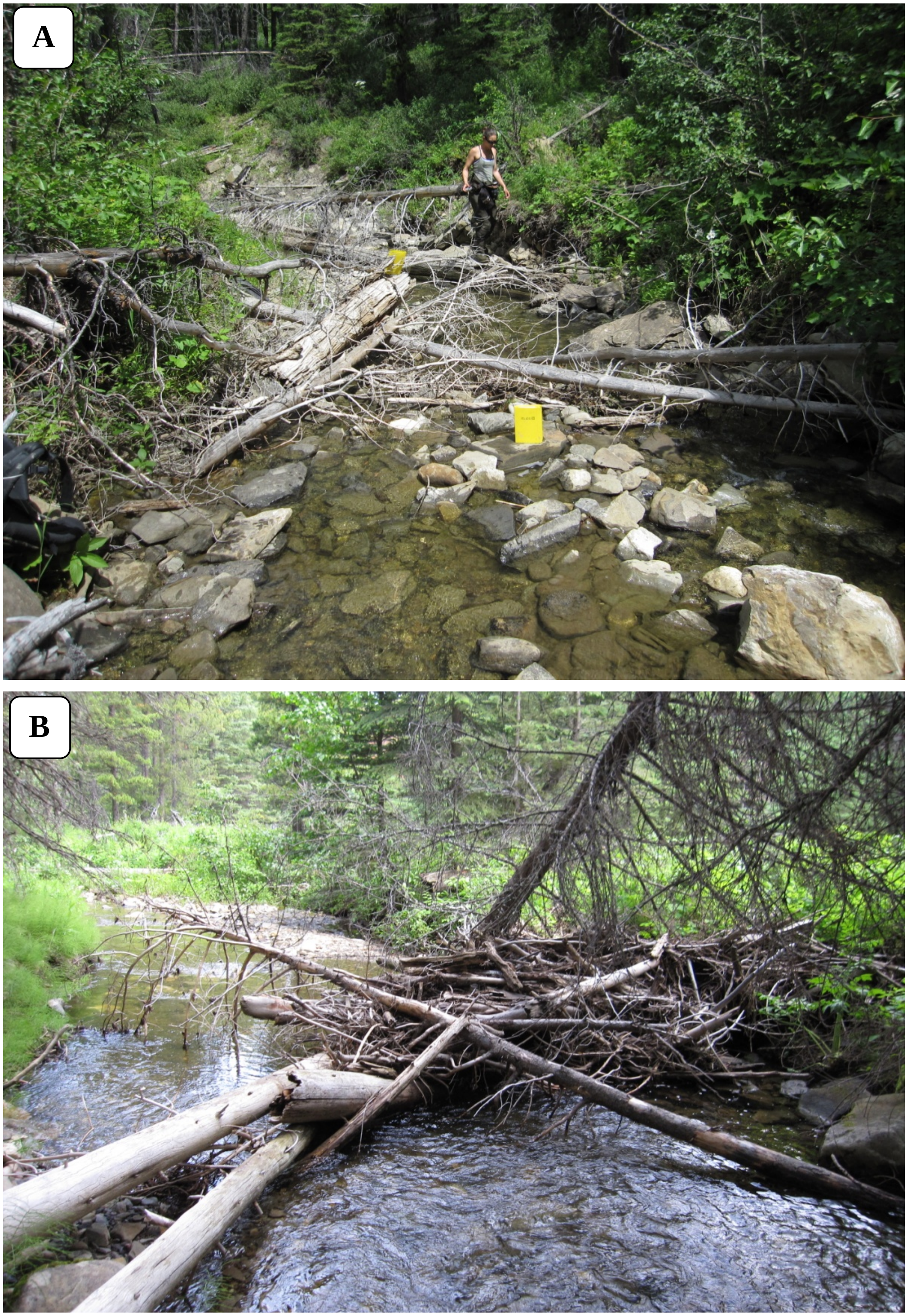


Figure E-9: Photos illustrating the variation in jam complexity found in Corolla Creek. This dam is formed as the channel narrows, constricting the transport of wood downstream. The two orange and black meter sticks showing 10cm intervals provide scale.

Figure E-10: Photos showing examples of simple jams within the lower reach (A) and upper reach (B) in Corolla Creek.
The upper reach logs lack branches, have softer wood and have established moss growth. The lower reach log still has simple branches and fewer signs of decay. The yellow "Rite in the Rain" field binder provides scale.

Appendix F

Selected reach scale in-stream wood structure sites – Coordinates and Photographs

Table F- 1: GPS Coordinates for the selected reach scale in-stream wood structure sites

Stream/ Site	Latitude	Longitude	Elevation (m)	Error (m)	Waypoint Number
Lyons East					
Site 10	49˚34’03.4” N 49˚34’03.3” N 49˚34’03.0” N	114˚27’21.3” W 114˚27’21.5” W 114˚27’21.7” W	1449 1451 1450	± 2 ± 2 ± 3	50 51 52
Site 28	49˚33’35.4” N 49˚33’35.4” N	114˚27’35.0” W 114˚27’34.9” W	1481 1480	± 2 ± 2	76 77
Site 47	49˚32’49.4” N	114˚27’46.4” W	1519	± 2	97
Corolla Creek					
Site 3	49˚25’26.5” N	114˚23’23.0” W	1441	± 3	137
Site 24 **Site 25**	49˚25’01.9” N 49˚24’55.2” N	114˚23’26.4” W 114˚23’27.8” W	1462 1463	± 3 ± 3	162 163
Site 26	49˚24’55.3” N	114˚23’30.9” W	1467	± 2	164

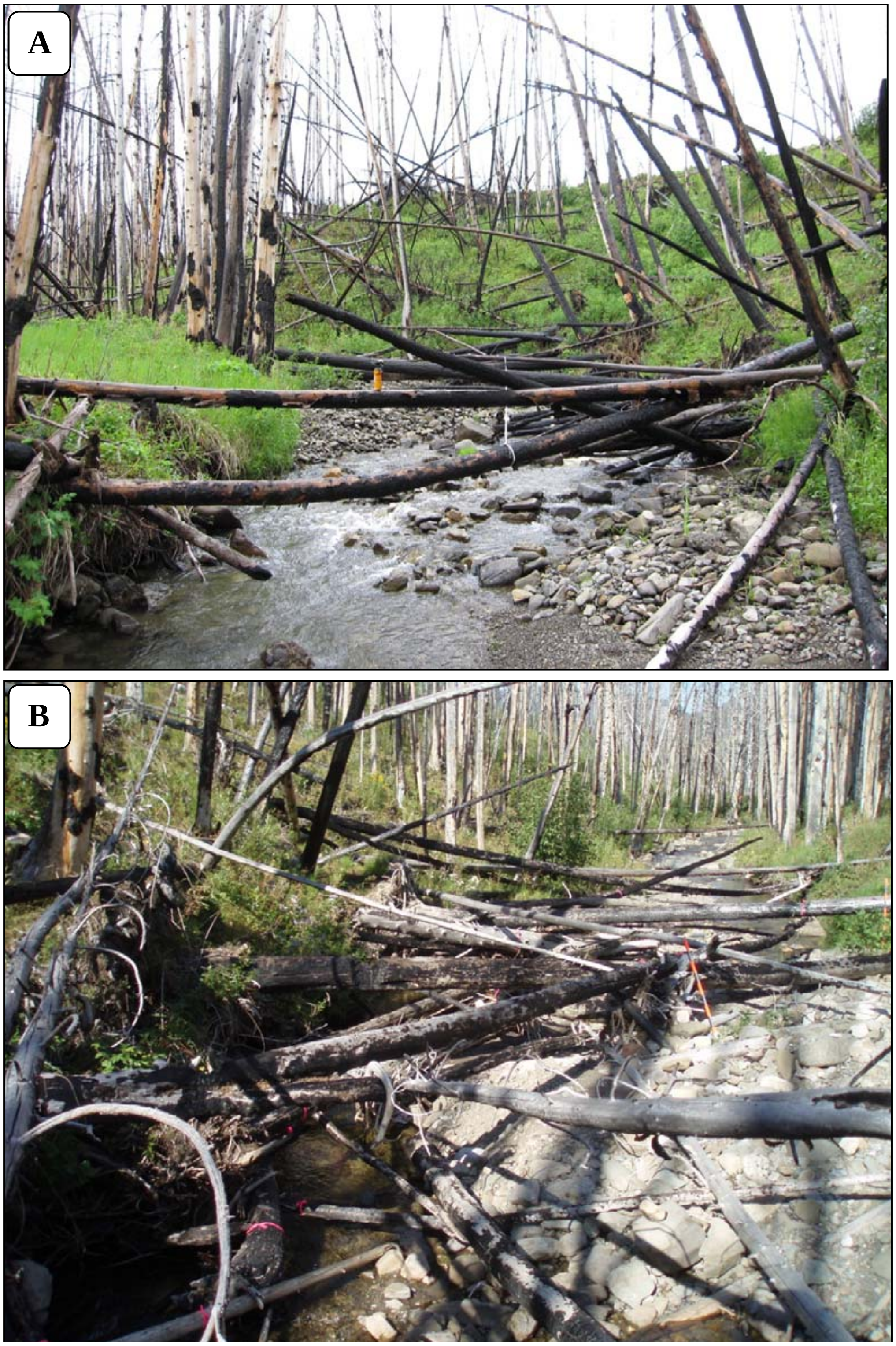


Figure F-1: Lyons East site 10 looking upstream (A) and downstream (B) towards the jam. These photos illustrate the jam structure, wood characteristics and geomorphic features. The bear spray provides scale (A) and the black and orange meter sticks are 10cm intervals for scale (B) provides scale.

Figure F-2: Lyons East site 28 looking upstream (A) and downstream (B) towards the jam. These photos illustrate the jam structure, wood characteristics and geomorphic features. The restriction of flow has created a pool to form under the structure, with cohesive sediment stored along the left bank. The black and orange meter sticks are10cm intervals for scale.

Figure F-3: Lyons East site 47 looking upstream (A) and downstream (B) towards the jam. These photographs illustrate the jam structure, wood characteristics and geomorphic features. The wood restricts flow, which has formed a pool downstream of the structure. The black and orange meter sticks are 10cm intervals for scale. The black and orange meter sticks are10cm intervals for scale.

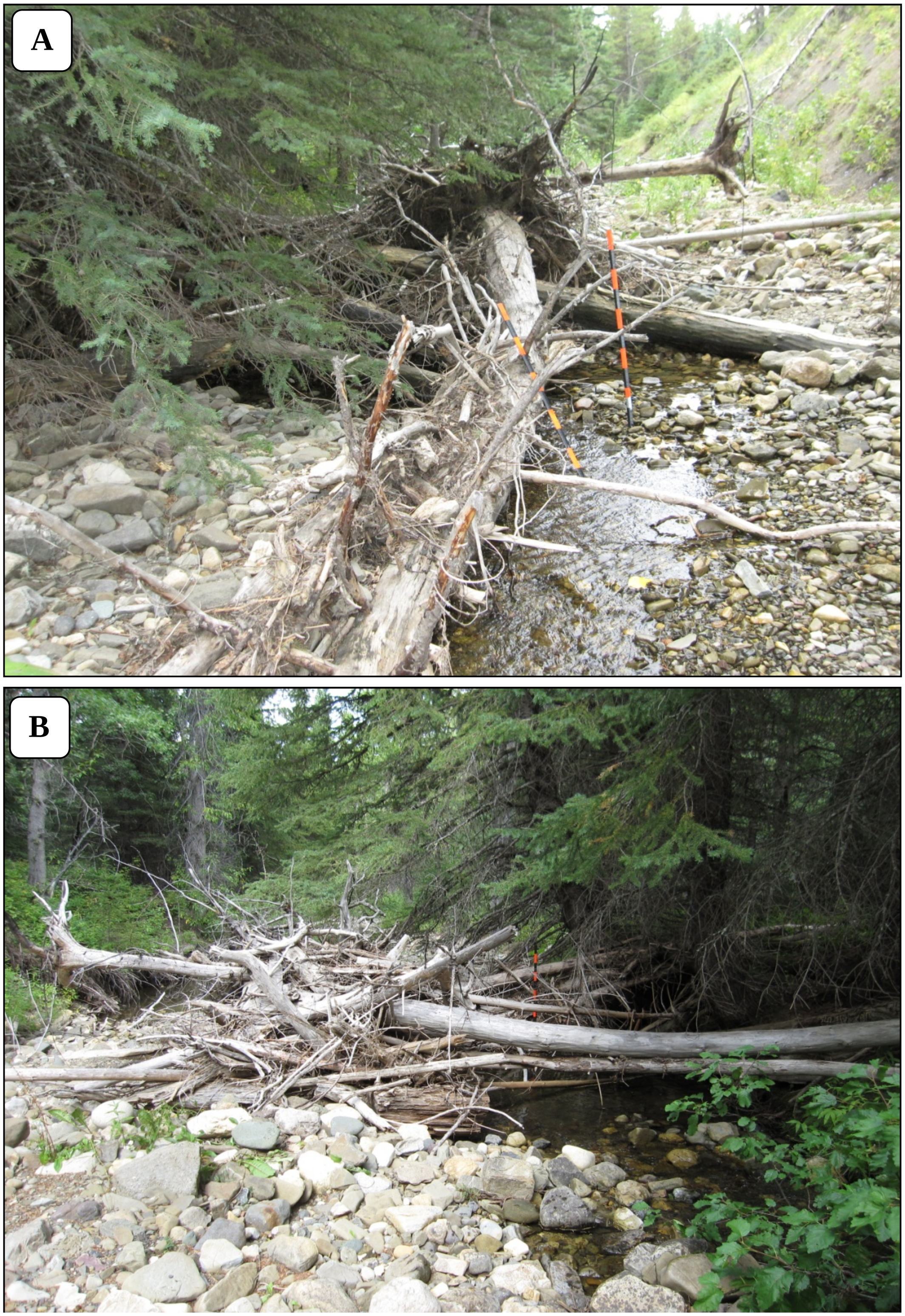


Figure F-4: Corolla Creek site 3 looking upstream (A) and downstream (B) towards the jam. These photographs illustrate the jam structure, wood characteristics and geomorphic features. The black and orange meter sticks are 10cm intervals for scale.

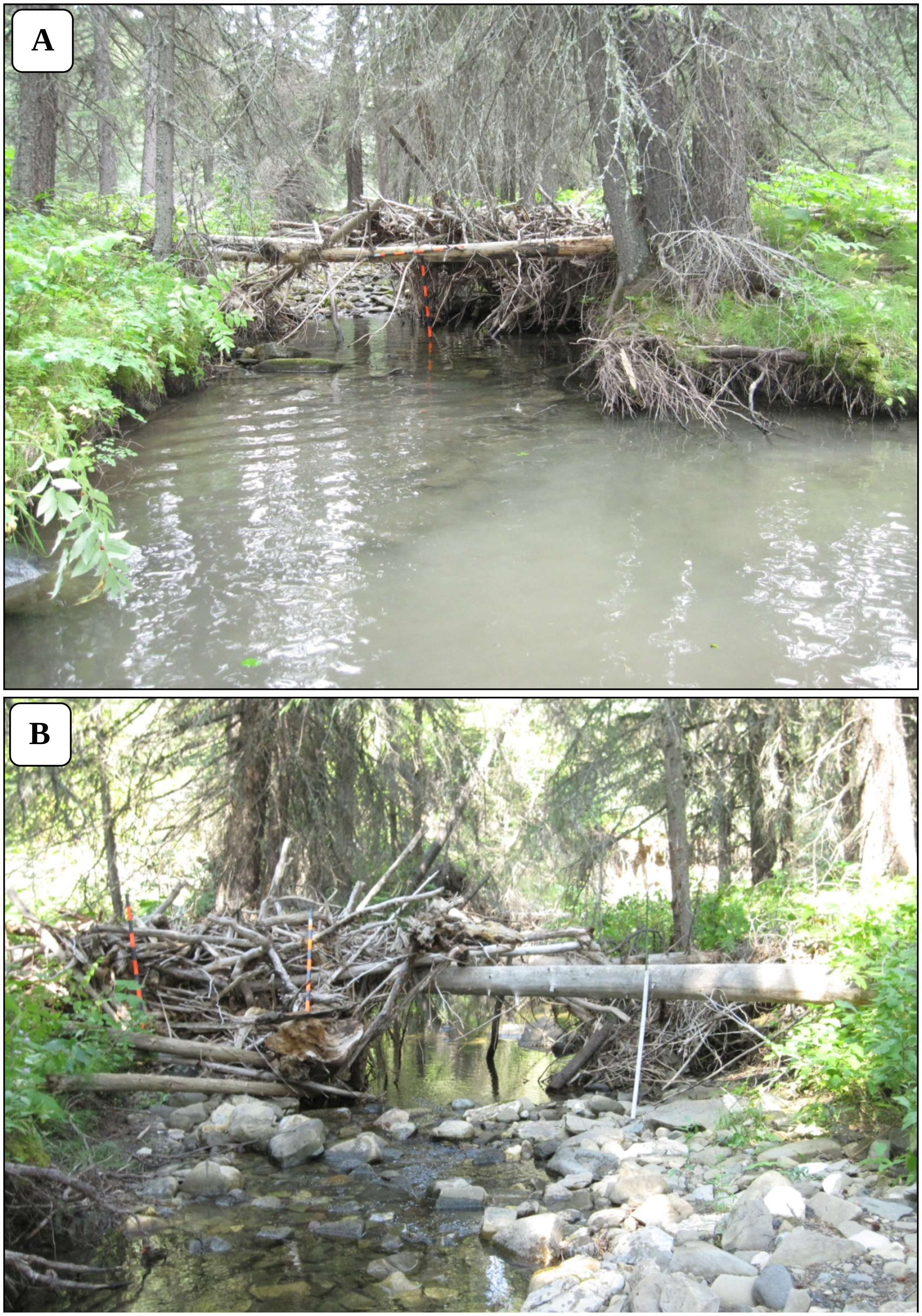


Figure F-5: Corolla Creek site 24 looking upstream (A) and downstream (B) towards the jam. These photographs illustrate jam structure, wood characteristics and geomorphic features. The murky water in "A" is due to suspended sediment from photographer's movement in the channel. The black and orange meter sticks are 10cm intervals for scale

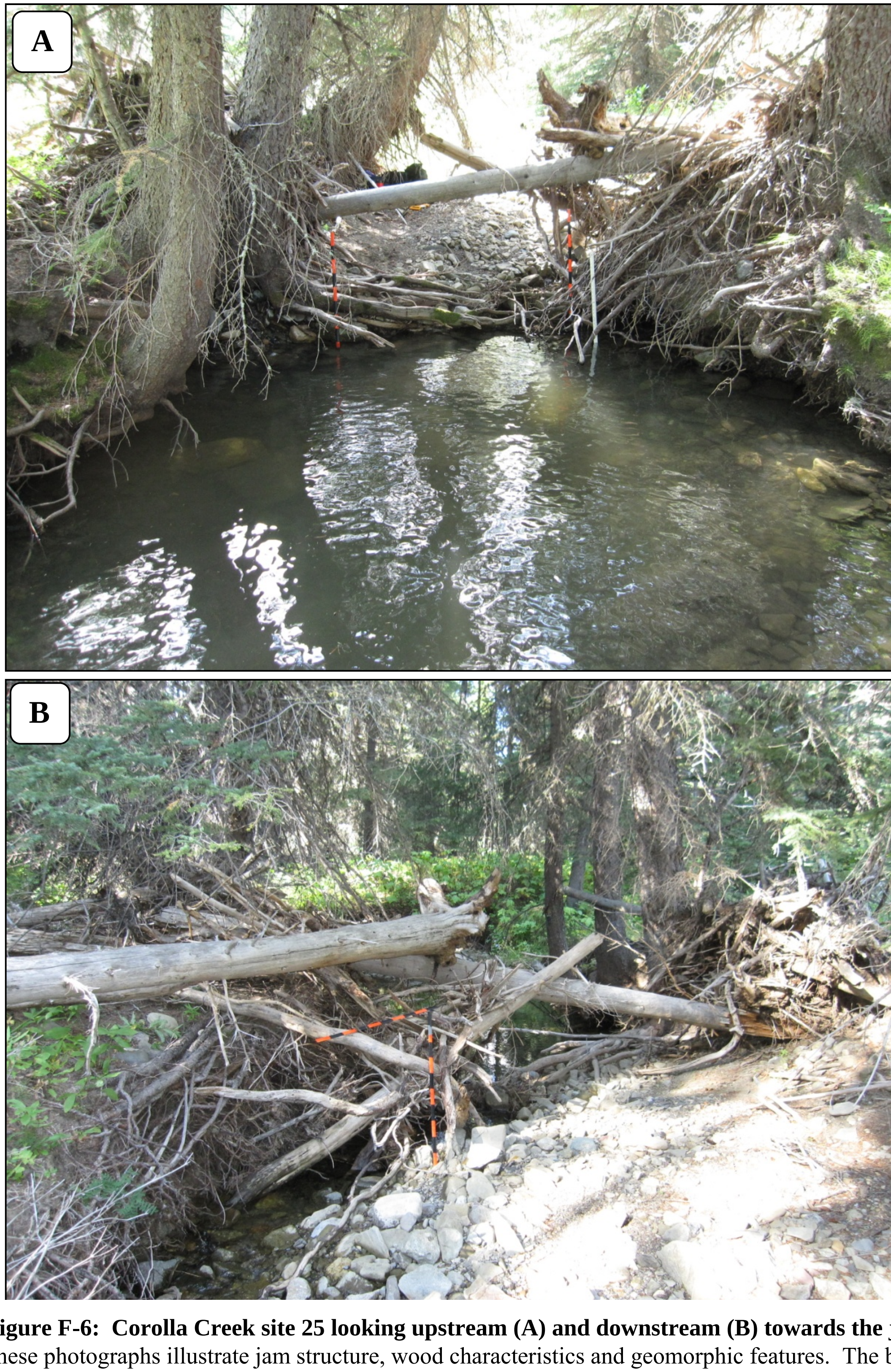


Figure F-6: Corolla Creek site 25 looking upstream (A) and downstream (B) towards the jam. These photographs illustrate jam structure, wood characteristics and geomorphic features. The black and orange meter sticks are 10cm intervals for scale.

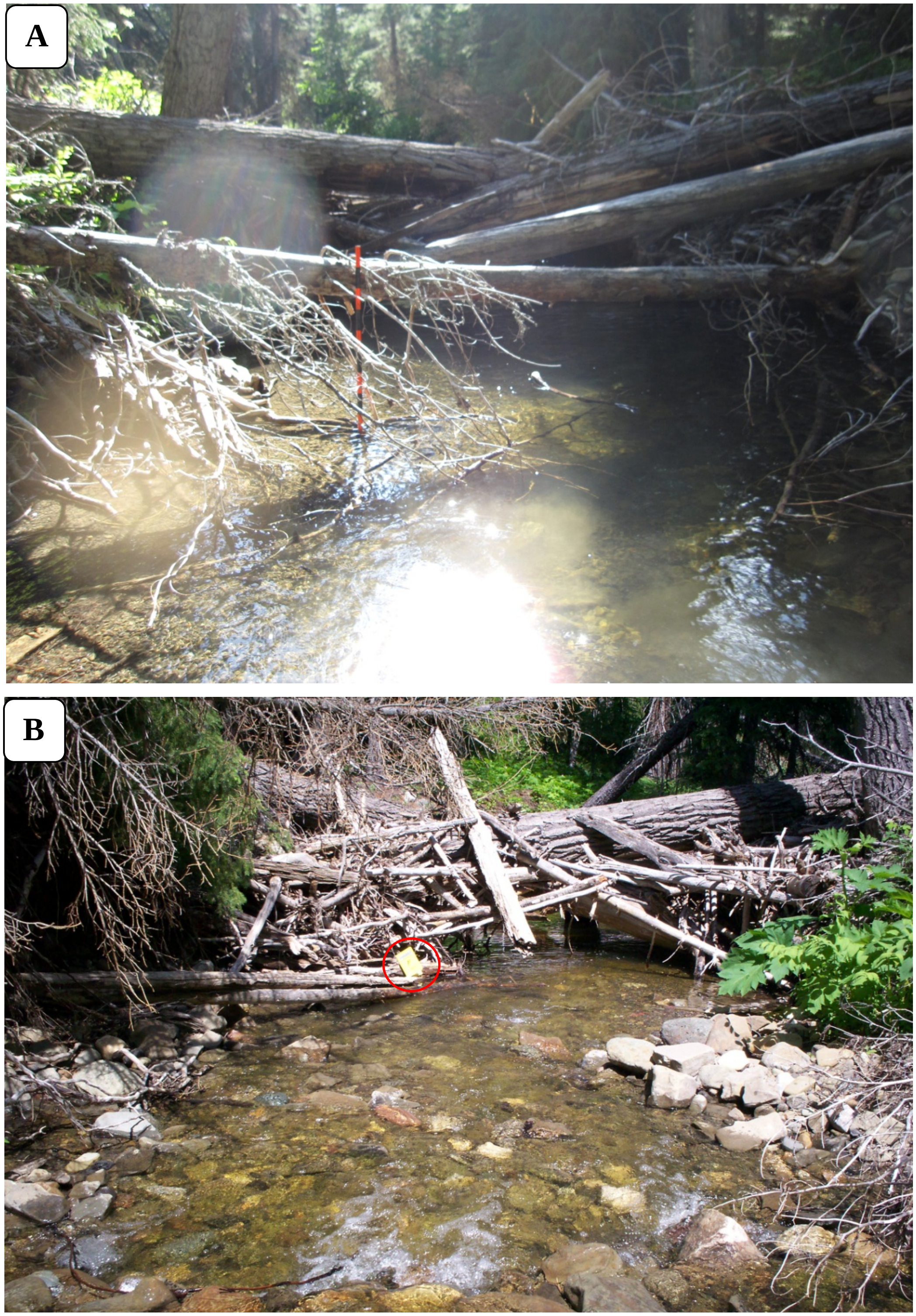


Figure F- 7: Corolla Creek site 26 looking upstream (A) and downstream (B) towards the jam. These photographs illustrate jam structure, wood characteristics and geomorphic features. The black and orange meter sticks are 10cm intervals for scale (A). The circled "Rite in the Rain" field book provides scale (B).

Appendix G

Cross sectional data for channel reach morphology analysis

Table G-1: Summary of channel reach morphology for the low flow conditions at Lyons East site 10

LYONS EAST - SITE 10							
Cross section - Number	**Active channel Width (m)**	**Active channel thalweg Depth (m)**	**Active channel mean Depth (m)**	**Cross sectional Area (m^2)**	**Wetted perimeter (m)**	**Width: depth Ratio**	**Hydraulic radius**
UPSTREAM (US)							
Cross section 1B	2.58	0.26	0.16	0.42	2.82	15.91	0.15
Cross section 2	2.54	0.29	0.21	0.53	2.66	12.18	0.20
Cross section 3	3.44	0.22	0.13	0.43	3.51	27.29	0.12
Cross section 4	3.27	0.28	0.19	0.60	3.39	17.70	0.18
Cross section 5	3.56	0.28	0.18	0.65	3.62	19.49	0.18
WITHIN							
Cross section 6	4.85	0.32	0.16	0.76	5.04	31.01	0.15
Cross section 7	3.44	0.31	0.21	0.71	3.51	16.73	0.20
Cross section 8	1.83	0.27	0.20	0.36	1.96	9.38	0.18
Cross section 9	5.21	0.23	0.12	0.61	5.46	44.78	0.11
DOWNSTREAM (DS)							
Cross section 10	2.20	0.35	0.18	0.40	2.41	12.00	0.17
Cross section 11	3.14	0.25	0.09	0.28	3.25	34.92	0.09
Cross section 12	3.38	0.25	0.14	0.46	3.43	24.86	0.13
Cross section 13	3.11	0.18	0.12	0.37	3.15	26.24	0.12
Cross section 14	3.78	0.15	0.11	0.41	3.86	34.84	0.11

Cross section - Number	Active channel Width (m)	Active channel thalweg Depth (m)	Active channel mean Depth (m)	Cross sectional Area (m^2)	Wetted perimeter (m)	Width: depth Ratio	Hydraulic radius
Cross section 15	3.11	0.21	0.10	0.31	3.22	31.35	0.10
AVG	**3.25**	**0.25**	**0.15**	**0.47**	**3.37**	**23.77**	**0.14**
St. Dev	**0.88**	**0.06**	**0.04**	**0.15**	**0.89**	**9.90**	**0.04**
US AVG	**2.99**	**0.25**	**0.16**	**0.49**	**3.10**	**19.02**	**0.16**
St. Dev (US)	**0.49**	**0.04**	**0.04**	**0.13**	**0.46**	**5.16**	**0.03**
WITHIN AVG	**3.83**	**0.28**	**0.17**	**0.61**	**3.99**	**25.47**	**0.16**
St. Dev (Within)	**1.54**	**0.04**	**0.04**	**0.18**	**1.59**	**15.69**	**0.04**
DS AVG	**3.12**	**0.23**	**0.12**	**0.37**	**3.22**	**27.37**	**0.12**
St. Dev (DS)	**0.52**	**0.07**	**0.03**	**0.07**	**0.47**	**8.63**	**0.03**

Table G-2: Characteristics of channel reach morphology for Lyons East site 10

LYONS EAST - SITE 10						
Cross section - Number	Bankfull width (m)	Avg. bankfull depth (m)	Flood-prone Width (m)	Width Depth Ratio	Entrenchment ratio	Hydraulic radius
UPSTREAM						
Cross section 1	10.75	0.21	46	50.22	4	0.21
Cross section 2	11.77	0.31		38.33		0.30
Cross section 3	7.80	0.19	25	41.04	3	0.36
Cross section 4	10.97	0.24	28	45.13	3	0.24
Cross section 5	11.56	0.34	69	34.30	6	0.33
WITHIN						
Cross section 6	10.56	0.37		28.79		0.36
Cross section 7	14.19	0.60	46	23.72	3	0.55
Cross section 8	15.24	0.63	55	24.27	4	0.61
Cross section 9	13.72	0.72	49	19.01	4	0.70
DOWNSTREAM						
Cross section 10	13.62	0.72	49	18.91	4	0.70
Cross section 11	16.83	0.92	58	18.37	4	0.89
Cross section 12	14.51	1.01	59	14.42	4	0.90
Cross section 13	13.79	0.84	55	16.39	4	0.81
Cross section 14	17.43	0.76	66	22.84	4	0.75
Cross section 15	15.51	0.71	62	22.01	4	0.69
AVERAGE	**13.22**	**0.57**	**51**	**27.85**	**4**	**0.56**
St. Dev	**2.62**	**0.27**	**13**	**11.26**	**0.8**	**0.24**
Upstream AVG	**10.57**	**0.26**	**42**	**41.80**	**4**	**0.29**
St. Dev (US)	**1.60**	**0.06**	**20**	**6.14**	**1.5**	**0.06**
WITHIN AVG	**13.43**	**0.58**	**50**	**23.95**	**4**	**0.56**
St. Dev (Within)	**2.01**	**0.15**	**4**	**4.00**	**0.2**	**0.15**
Downstream AVG	**15.28**	**0.83**	**58**	**18.82**	**4**	**0.79**
St. Dev (DS)	**1.59**	**0.12**	**6**	**3.22**	**0.3**	**0.09**

Table G-3: Summary of channel reach morphology for the low flow conditions at Lyons East site 28

LYONS EAST - SITE 28							
Cross section - Number	Active channel Width (m)	Active channel thalweg Depth (m)	Active channel mean Depth (m)	Cross sectional Area (m^2)	Wetted perimeter (m)	Width: depth Ratio	Hydraulic radius
UPSTREAM							
Cross section 9	1.85	0.16	0.08	0.15	1.99	22.28	0.08
Cross section 8	2.34	0.18	0.07	0.16	2.44	35.34	0.06
Cross section 7	2.28	0.14	0.10	0.24	2.34	22.06	0.10
Cross section 6	2.75	0.17	0.13	0.35	2.82	21.83	0.12
Cross section 5	2.10	0.09	0.06	0.13	2.17	33.33	0.06
Cross section 4	1.14	0.17	0.11	0.13	1.18	10.08	0.11
DOWNSTREAM							
Cross section 3	3.69	0.32	0.15	0.56	3.90	24.15	0.15
Cross section 2	3.92	0.09	0.04	0.16	3.94	93.90	0.04
Cross section 1	2.73	0.09	0.05	0.15	2.76	50.21	0.05
Cross section 10	2.35	0.09	0.06	0.14	2.41	41.07	0.06
Cross section 11	3.05	0.15	0.08	0.26	3.11	36.65	0.08
AVG	**2.56**	**0.15**	**0.09**	**0.22**	**2.64**	**35.54**	**0.08**
St. Dev	**0.80**	**0.07**	**0.03**	**0.13**	**0.81**	**22.32**	**0.03**
US AVG	**2.08**	**0.15**	**0.09**	**0.19**	**2.16**	**24.15**	**0.09**
St. Dev (US)	**0.55**	**0.03**	**0.03**	**0.09**	**0.55**	**9.17**	**0.03**
DS AVG	**3.15**	**0.15**	**0.08**	**0.25**	**3.22**	**49.20**	**0.08**
St. Dev (DS)	**0.65**	**0.10**	**0.04**	**0.18**	**0.68**	**26.70**	**0.04**

Table G-4: Characteristics of channel reach morphology for Lyons East site 28

LYONS EAST - SITE 28						
Cross section - Number	**Bankfull width (m)**	**Avg. bankfull depth (m)**	**Flood-prone Width (m)**	**Width Depth Ratio**	**Entrenchment ratio**	**Hydraulic radius**
UPSTREAM						
Cross section 9	7.69	0.53	55	14.43	7	0.51
Cross section 8	8.89	0.66	52	13.42	6	0.63
Cross section 7	9.56	0.49	43	19.39	5	0.48
Cross section 6	12.83	0.48	91	26.68	7	0.47
Cross section 5	11.55	0.41	64	28.31	6	0.40
Cross section 4	12.53	0.52	36	24.29	3	0.51
DOWNSTREAM						
Cross section 3	10.22	0.35	31	29.53	3	0.34
Cross section 2	8.15	0.29	17	28.01	2	0.29
Cross section 1	6.60	0.270	11	24.52	2	0.27
Cross section 10	10.49	0.70	61	14.96	6	0.67
Cross section 11	12.90	0.89	75	14.45	6	0.85
AVERAGE	**10.13**	**0.51**	**49**	**21.64**	**5**	**0.49**
St. Dev	**2.17**	**0.19**	**24**	**6.39**	**2.0**	**0.18**
ABOVE AVG	**10.51**	**0.52**	**57**	**21.09**	**6**	**0.50**
St. Dev (US)	**2.10**	**0.08**	**20**	**6.32**	**1.6**	**0.07**
BELOW AVG	**9.67**	**0.50**	**39**	**22.29**	**4**	**0.48**
St. Dev (DS)	**2.41**	**0.28**	**28**	**7.16**	**2.0**	**0.26**

Table G-5: Summary of channel reach morphology for the low flow conditions at Lyons East site 47

LYONS EAST - SITE 47							
Cross section - Number	**Active channel Width (m)**	**Active channel thalweg Depth (m)**	**Active channel mean Depth (m)**	**Cross sectional Area (m^2)**	**Wetted perimeter (m)**	**Width: depth Ratio**	**Hydraulic radius**
UPSTREAM							
Cross section 10	2.97	0.16	0.07	0.21	3.01	42.67	0.07
Cross section 9	1.76	0.21	0.13	0.23	1.88	13.51	0.12
Cross section 8	3.75	0.18	0.12	0.43	3.81	32.65	0.11
Cross section 7	2.63	0.19	0.12	0.31	2.75	22.03	0.11
DOWNSTREAM							
Cross section 4	2.86	0.52	0.31	0.90	3.17	9.09	0.28
Cross section 3	4.28	0.14	0.11	0.49	4.32	37.66	0.11
Cross section 2	3.29	0.36	0.26	0.86	3.43	12.57	0.25
Cross section 1	3.66	0.20	0.11	0.40	3.01	33.22	0.11
Cross section 5	3.95	0.21	0.12	0.48	4.01	32.89	0.12
Cross section 6	4.21	0.32	0.13	0.54	4.28	32.68	0.13
AVG	**3.34**	**0.25**	**0.15**	**0.49**	**3.37**	**26.90**	**0.14**
St. Dev	**0.79**	**0.12**	**0.07**	**0.24**	**0.76**	**11.70**	**0.07**
US AVG	**2.77**	**0.19**	**0.11**	**0.30**	**2.86**	**27.72**	**0.10**
St. Dev (US)	**0.82**	**0.02**	**0.03**	**0.10**	**0.79**	**12.68**	**0.02**
DS AVG	**3.71**	**0.29**	**0.18**	**0.61**	**3.70**	**26.35**	**0.17**
St. Dev (DS)	**0.55**	**0.14**	**0.09**	**0.21**	**0.57**	**12.21**	**0.08**

Table G-6: Characteristics of channel reach morphology for Lyons East site 47

LYONS EAST - SITE 47						
Cross section - Number	**Bankfull width (m)**	**Avg. bankfull depth (m)**	**Flood-prone Width (m)**	**Width Depth Ratio**	**Entrenchment ratio**	**Hydraulic radius**
UPSTREAM						
Cross section 10	13.84	0.40		34.26		0.40
Cross section 9	15.90	0.63		25.08		0.63
Cross section 8	10.79	0.39	76	27.47	7	0.39
Cross section 7	7.99	0.12	11	67.75	1	0.12
DOWNSTREAM						
Cross section 4	17.11	0.44	39	38.54	2	0.44
Cross section 3	16.44	0.83	66	19.76	4	0.81
Cross section 2	14.90	0.85	61	17.59	4	0.81
Cross section 1	15.41	0.82	66	18.91	4	0.79
Cross section 5	11.38	1.01	66	11.32	6	0.95
Cross section 6	14.93	0.73	70	20.50	5	0.72
AVERAGE	**13.87**	**0.62**	**57**	**28.12**	**4**	**0.60**
St. Dev	**2.91**	**0.27**	**21**	**16.10**	**1.8**	**0.26**
US AVG	**12.13**	**0.39**	**43**	**38.64**	**4**	**0.38**
St. Dev (US)	**3.47**	**0.21**	**46**	**19.79**	**4.0**	**0.21**
DS AVG	**15.03**	**0.78**	**61**	**21.10**	**4**	**0.75**
St. Dev (DS)	**1.99**	**0.19**	**11**	**9.15**	**1.1**	**0.17**

Table G-7: Summary of channel reach morphology for the low flow conditions at Corolla Creek site 3

COROLLA CREEK - SITE 3							
Cross section - Number	**Active channel Width (m)**	**Active channel thalweg Depth (m)**	**Active channel mean Depth (m)**	**Cross sectional Area (m^2)**	**Wetted perimeter (m)**	**Width: depth Ratio**	**Hydraulic radius**
UPSTREAM							
Cross section 1	1.39	0.17	0.09	0.13	1.47	15.45	0.09
Cross section 2	2.94	0.28	0.16	0.47	3.06	18.48	0.15
Cross section 3	2.34	0.21	0.14	0.33	2.43	16.77	0.13
Cross section 4	2.68	0.07	0.03	0.08	2.73	85.51	0.03
Cross section 5	1.65	0.11	0.05	0.08	1.69	34.70	0.05
DOWNSTREAM							
Cross section 6	2.64	0.27	0.18	0.47	2.71	14.82	0.17
Cross section 7	3.79	0.37	0.19	0.72	3.95	20.12	0.18
Cross section 8	3.89	0.10	0.06	0.24	3.92	63.57	0.06
Cross section 9	2.75	0.14	0.07	0.19	2.81	40.87	0.07
Cross section 10	0.96	0.08	0.05	0.05	1.01	19.88	0.05
AVG	**2.50**	**0.18**	**0.10**	**0.27**	**2.58**	**33.02**	**0.10**
St. Dev	**0.96**	**0.10**	**0.06**	**0.22**	**0.97**	**24.05**	**0.06**
US AVG	**2.20**	**0.17**	**0.09**	**0.22**	**2.28**	**34.18**	**0.09**
St. Dev (US)	**0.66**	**0.08**	**0.06**	**0.17**	**0.68**	**29.73**	**0.05**
DS AVG	**2.81**	**0.19**	**0.11**	**0.33**	**2.88**	**31.85**	**0.11**
St. Dev (DS)	**1.18**	**0.13**	**0.07**	**0.26**	**1.20**	**20.36**	**0.07**

Table G-8: Characteristics of channel reach morphology for Corolla Creek site 3

COROLLA CREEK - SITE 3						
Cross section - Number	**Bankfull width (m)**	**Avg. bankfull depth (m)**	**Flood-prone Width (m)**	**Width Depth Ratio**	**Entrenchment ratio**	**Hydraulic radius**
UPSTREAM						
Cross section 1	9.76	0.37	23	26.10	2	0.37
Cross section 2	8.12	0.25	20	33.14	3	0.24
Cross section 3	9.26	0.12	13	77.77	1	0.12
Cross section 4	12.97	0.46	25	28.12	2	0.45
Cross section 5	16.67	0.86	72	19.45	4	0.84
DOWNSTREAM						
Cross section 6	15.50	0.58	65	26.78	4	0.57
Cross section 7	21.22	0.63	156	33.68	7	0.62
Cross section 8	19.15	0.29	34	67.18	2	0.30
Cross section 9	15.92	0.24	48	67.45	3	0.24
Cross section 10	10.57	0.22	51	47.61	5	0.22
AVERAGE	**13.91**	**0.40**	**51**	**42.73**	**3**	**0.40**
St. Dev	**4.47**	**0.23**	**42**	**20.87**	**1.8**	**0.22**
US AVG	**11.35**	**0.41**	**31**	**36.92**	**3**	**0.40**
St. Dev (US)	**3.47**	**0.28**	**24**	**23.36**	**1.1**	**0.27**
DS AVG	**16.47**	**0.39**	**71**	**48.54**	**4**	**0.39**
St. Dev (DS)	**4.06**	**0.20**	**49**	**18.71**	**2.1**	**0.19**

Table G-9: Summary of channel reach morphology for the low flow conditions at Corolla Creek sites 24 & 25

COROLLA CREEK – SITES 24 & 25							
Cross section - Number	**Active channel Width (m)**	**Active channel thalweg Depth (m)**	**Active channel mean Depth (m)**	**Cross sectional Area (m^2)**	**Wetted perimeter (m)**	**Width: depth Ratio**	**Hydraulic radius**
UPSTREAM							
Cross section 9	2.00	0.09	0.06	0.12	2.04	32.66	0.06
Cross section 8	2.10	0.08	0.03	0.06	2.12	68.96	0.03
Cross section 7	1.33	0.06	0.05	0.07	1.35	26.06	0.05
BETWEEN							
Cross section 1	2.76	0.44	0.30	0.83	3.01	9.13	0.28
Cross section 2	2.70	0.11	0.06	0.15	2.78	48.85	0.05
Cross section 3	1.22	0.07	0.06	0.07	1.25	21.40	0.06
Cross section 4	1.45	0.08	0.05	0.07	1.46	31.81	0.05
DOWNSTREAM							
Cross section 5	4.61	0.41	0.20	0.93	4.69	22.95	0.20
Cross section 6	3.36	0.19	0.09	0.31	3.50	36.25	0.09
AVG	**2.39**	**0.17**	**0.10**	**0.29**	**2.47**	**33.12**	**0.10**
St. Dev	**1.10**	**0.15**	**0.09**	**0.35**	**1.14**	**17.36**	**0.08**
US AVG	**1.81**	**0.08**	**0.05**	**0.09**	**1.84**	**42.56**	**0.05**
St. Dev (US)	**0.42**	**0.02**	**0.02**	**0.03**	**0.42**	**23.10**	**0.02**
BETWEEN AVG	**2.03**	**0.17**	**0.12**	**0.28**	**2.12**	**27.80**	**0.11**
St. Dev (Between)	**0.81**	**0.18**	**0.13**	**0.37**	**0.90**	**16.82**	**0.11**
DS AVG	**3.99**	**0.30**	**0.15**	**0.62**	**4.09**	**29.60**	**0.14**
St. Dev (DS)	**0.89**	**0.16**	**0.08**	**0.44**	**0.84**	**9.40**	**0.08**

Table G-10: Characteristics of channel reach morphology for Corolla Creek sites 24 and 25

COROLLA CREEK - SITE 24 & 25						
Cross section - Number	**Bankfull width (m)**	**Avg. bankfull depth (m)**	**Flood-prone Width (m)**	**Width Depth Ratio**	**Entrenchment ratio**	**Hydraulic radius**
UPSTREAM						
Cross section 9	15.79	0.32	72	49.34	5	0.32
Cross section 8	18.06	0.28	51	63.61	3	0.30
Cross section 7	11.69	0.42	91	27.70	8	0.42
BETWEEN						
Cross section 1	10.37	0.26	45	40.04	4	0.26
Cross section 2	15.08	0.52	92	29.18	6	0.51
Cross section 3	12.25	0.29	88	42.98	7	0.28
Cross section 4	10.23	0.25	84	40.74	8	0.25
DOWNSTREAM						
Cross section 5	10.88	0.16	49	68.40	5	0.16
Cross section 6	18.67	0.24	41	77.14	2	0.26
AVERAGE	**13.67**	**0.30**	**68**	**48.79**	**5**	**0.31**
St. Dev	**3.30**	**0.11**	**21**	**17.37**	**2.2**	**0.10**
US AVG	**15.18**	**0.34**	**71**	**46.88**	**5**	**0.35**
St. Dev (US)	**3.23**	**0.07**	**20**	**18.08**	**2.5**	**0.06**
BETWEEN AVG	**11.98**	**0.33**	**77**	**38.23**	**7**	**0.33**
St. Dev (Between)	**2.26**	**0.13**	**22**	**6.17**	**1.7**	**0.13**
DS AVG	**14.77**	**0.20**	**45**	**72.77**	**3**	**0.21**
St. Dev (DS)	**5.51**	**0.060**	**6**	**6.18**	**1.7**	**0.07**

Table G-11: Summary of channel reach morphology for the low flow conditions at Corolla Creek site 26

COROLLA CREEK - SITE 26							
Cross section - Number	**Active channel Width (m)**	**Active channel thalweg Depth (m)**	**Active channel mean Depth (m)**	**Cross sectional Area (m^2)**	**Wetted perimeter (m)**	**Width: depth Ratio**	**Hydraulic radius**
UPSTREAM							
Cross section 1	6.75	0.58	0.25	1.67	6.96	27.24	0.24
Cross section 2	6.28	0.23	0.13	0.82	6.37	48.40	0.13
Cross section 3	4.33	0.19	0.10	0.41	4.44	45.66	0.09
Cross section 3B	4.35	0.16	0.08	0.36	4.41	52.24	0.08
Cross section 4	3.94	0.31	0.12	0.46	4.09	33.71	0.11
DOWNSTREAM							
Cross section 5	4.59	0.49	0.24	1.11	4.73	19.07	0.23
Cross section 6	5.14	0.29	0.11	0.57	5.24	46.20	0.11
Cross section 7	2.57	0.17	0.08	0.21	2.68	31.18	0.08
Cross section 8	2.64	0.14	0.07	0.17	2.67	40.82	0.06
Cross section 9	4.02	0.26	0.18	0.74	4.07	21.95	0.18
Cross section 10	4.35	0.40	0.21	0.93	4.47	20.33	0.21
AVG	**4.45**	**0.29**	**0.14**	**0.68**	**4.56**	**35.16**	**0.14**
St. Dev	**1.28**	**0.14**	**0.07**	**0.44**	**1.31**	**12.11**	**0.07**
US AVG	**5.13**	**0.29**	**0.14**	**0.74**	**5.25**	**41.45**	**0.13**
St. Dev (US)	**1.29**	**0.17**	**0.07**	**0.55**	**1.31**	**10.54**	**0.06**
DS AVG	**3.89**	**0.29**	**0.15**	**0.62**	**3.98**	**29.92**	**0.15**
St. Dev (DS)	**1.06**	**0.13**	**0.07**	**0.38**	**1.08**	**11.48**	**0.07**

Table G-12: Characteristics of channel reach morphology for Corolla Creek sites 26

COROLLA CREEK - SITE 26						
Cross section - Number	**Bankfull width (m)**	**Avg. bankfull depth (m)**	**Flood-prone Width (m)**	**Width Depth Ratio**	**Entrenchment ratio**	**Hydraulic radius**
UPSTREAM						
Cross section 1	16.09	0.87	71	18.56	4	0.85
Cross section 2	16.65	0.90	72	18.46	4	0.88
Cross section 3	9.83	0.59	65	16.64	7	0.57
Cross section 4	18.55	0.70	67	26.39	4	0.72
DOWNSTREAM						
Cross section 5	15.25	0.70	55	21.91	4	0.68
Cross section 6	14.89	0.78	56	19.14	4	0.76
Cross section 7	13.36	0.81	54	16.42	4	0.78
Cross section 8	13.92	0.79	51	17.63	4	0.76
Cross section 9	16.10	0.77	52	20.72	3	0.75
Cross section 10	17.27	0.94	54	18.47	3	0.91
AVERAGE	**15.19**	**0.79**	**60**	**19.43**	**4**	**0.77**
St. Dev	**2.43**	**0.10**	**8**	**2.96**	**1.0**	**0.10**
US AVG	**15.28**	**0.77**	**69**	**20.01**	**5**	**0.75**
St. Dev (US)	**3.78**	**0.15**	**3**	**4.34**	**1.3**	**0.14**
DS AVG	**15.13**	**0.80**	**54**	**19.05**	**4**	**0.77**
St. Dev (DS)	**1.43**	**0.08**	**2**	**2.01**	**0.4**	**0.07**

Appendix H

Pool characteristics for the six selected reach sites

Table H-1: Transect dimensions and sediment thickness for Lyons East site 10 - Pool 1

LYONS EAST - SITE 10 - POOL 1

Transect	Width	Average water depth (m)	Average sediment thickness (m)
1	2.24	0.194	0.000
2	2.37	0.150	0.000
3	2.53	0.178	0.000
4	1.57	0.176	0.000
5	3.19	0.140	0.001
6	3.08	0.128	<0.001
7	2.07	0.166	0.000
8	2.11	0.179	0.000
9	1.45	0.143	0.000
Avg.	**2.29**	**0.161**	**<0.001**

Table H-2: Transect dimensions and sediment thickness for Lyons East site 10 - Pool 2

LYONS EAST - SITE 10 - POOL 2

Transect	Width	Average water depth (m)	Average sediment thickness (m)
1	3.31	0.179	0.002
2	3.26	0.208	0.002
3	3.14	0.244	0.001
4	3.11	0.199	0.001
5	2.55	0.189	0.000
6	2.53	0.149	0.000
Avg.	**2.98**	**0.195**	**0.001**

Table H-3: Transect dimensions and sediment thickness for Lyons East site 10 - Pool 3

LYONS EAST - SITE 10 - POOL 3

Transect	Width	Average water depth (m)	Average sediment thickness (m)
1	3.40	0.097	0.000
2	3.80	0.107	0.000
3	3.59	0.133	0.000
Avg.	**3.60**	**0.112**	**0.000**

Table H-4: Transect dimensions and sediment thickness for Lyons East site 10 - Pool 4

LYONS EAST - SITE 10 - POOL 4

Transect	Width	Average water depth (m)	Average sediment thickness (m)
1	1.78	0.142	0.000
2	3.15	0.126	0.016
3	3.23	0.214	0.005
4	2.28	0.276	0.000
5	1.99	0.248	0.000
6	2.82	0.132	0.000
7	2.83	0.070	0.000
Avg.	**2.58**	**0.173**	**0.003**

Table H-5: Transect dimensions and sediment thickness for Lyons East site 10 - Pool 5

LYONS EAST - SITE 10 – POOL 5

Transect	Width	Average water depth (m)	Average sediment thickness (m)
1	2.19	0.069	0.000
2	2.32	0.113	0.000
3	1.60	0.156	0.000
4	0.78	0.110	0.000
5	1.78	0.260	0.000
6	1.52	0.330	0.001
7	1.50	0.166	0.011
8	2.03	0.103	0.000
9	1.60	0.160	0.000
10	1.46	0.173	0.000
Avg.	**1.68**	**0.164**	**0.001**

Table H-6: Transect dimensions and sediment thickness for Lyons East site 10 - Pool 6

LYONS EAST - SITE 10 - POOL 6			
Transect	**Width**	**Average water depth (m)**	**Average sediment thickness (m)**
1	2.20	0.131	0.000
2	2.36	0.173	0.000
3	4.96	0.222	0.003
4	4.64	0.196	0.008
5	1.66	0.162	0.000
Avg.	**3.16**	**0.177**	**0.002**

Table H-7: Transect dimensions and sediment thickness for Lyons East site 28 - Pool 1

LYONS EAST - SITE 28 - POOL 1

Transect	Width	Average water depth (m)	Average sediment thickness (m)
1	2.94	0.116	0.000
2	3.00	0.127	0.000
3	3.10	0.138	0.000
4	1.90	0.159	0.000
5	1.30	0.127	0.000
Avg.	**2.45**	**0.133**	**0.000**

Table H-8: Transect dimensions and sediment thickness for Lyons East site 28 - Pool 2

LYONS EAST - SITE 28 - POOL 2

Transect	Width	Average water depth (m)	Average sediment thickness (m)
1	2.90	0.141	0.000
2	3.10	0.110	0.000
3	1.98	0.136	0.000
4	2.37	0.124	0.000
5	3.46	0.105	0.000
6	3.80	0.059	0.000
Avg.	**2.94**	**0.112**	**0.000**

Table H-9: Transect dimensions and sediment thickness for Lyons East site 28 - Pool 3

LYONS EAST - SITE 28 - POOL 3

Transect	Width	Average water depth (m)	Average sediment thickness (m)
1	1.96	0.061	0.000
2	2.55	0.157	0.000
3	1.98	0.125	0.000
4	1.61	0.110	0.000
Avg.	**2.03**	**0.113**	**0.000**

Table H-10: Transect dimensions and sediment thickness for Lyons East site 28 - Pool 4

LYONS EAST - SITE 28 - POOL 4

Transect	Width	Average water depth (m)	Average sediment thickness (m)
1	2.52	0.073	0.000
2	3.35	0.091	0.000
3	3.57	0.208	0.011
4	4.98	0.289	0.046
5	3.92	0.446	0.015
6	3.36	0.329	0.002
7	2.00	0.195	0.000
8	1.00	0.120	0.000
9	1.85	0.231	0.000
10	2.58	0.115	0.000
Avg.	**2.91**	**0.210**	**0.007**

Table H-11: Transect dimensions and sediment thickness for Lyons East site 28 - Pool 5

LYONS EAST - SITE 28 - POOL 5

Transect	Width	Average water depth (m)	Average sediment thickness (m)
1	2.62	0.087	0.000
2	2.54	0.133	0.000
3	2.89	0.121	0.000
4	3.14	0.086	0.000
Avg.	**2.80**	**0.107**	**0.000**

Table H-12: Transect dimensions and sediment thickness for Lyons East site 47 - Pool 1

LYONS EAST - SITE 47 - POOL 1

Transect	Width	Average water depth (m)	Average sediment thickness (m)
1	3.00	0.187	0.000
2	2.50	0.369	0.002
3	2.31	0.437	0.014
4	1.92	0.401	0.003
5	1.88	0.244	0.000
6	2.20	0.201	0.000
Avg.	**2.30**	**0.306**	**0.003**

Table H-13: Transect dimensions and sediment thickness for Lyons East site 47 - Pool 2

LYONS EAST - SITE 47 - POOL 2

Transect	Width	Average water depth (m)	Average sediment thickness (m)
1	2.47	0.128	0.000
2	2.80	0.187	0.000
3	3.80	0.388	0.000
4	3.60	0.417	0.010
5	3.09	0.386	0.001
6	1.31	0.257	0.020
Avg.	**2.85**	**0.294**	**0.005**

Table H-14: Transect dimensions and sediment thickness for Lyons East site 47 - Pool 3

LYONS EAST - SITE 47 - POOL 3

Transect	Width	Average water depth (m)	Average sediment thickness (m)
1	3.42	0.220	0.003
2	2.49	0.269	0.002
3	1.62	0.291	0.000
4	1.68	0.145	0.000
Avg.	**2.30**	**0.231**	**0.001**

Table H-15: Transect dimensions and sediment thickness for Corolla Creek site 3 - Pool 1

COROLLA CREEK - SITE 3 - POOL 1

Transect	Width	Average water depth (m)	Average sediment thickness (m)
1	3.08	0.138	0.000
2	2.85	0.191	0.000
3	2.46	0.194	0.000
4	2.16	0.172	0.000
5	1.49	0.128	0.000
6	1.56	0.184	0.000
7	1.40	0.137	0.000
8	1.32	0.065	0.000
Avg.	**2.04**	**0.151**	**0.000**

Table H-16: Transect dimensions and sediment thickness for Corolla Creek site 3 - Pool 2

COROLLA CREEK - SITE 3 - POOL 2

Transect	Width	Average water depth (m)	Average sediment thickness (m)
1	1.92	0.146	0.000
2	2.20	0.140	0.000
3	2.31	0.188	0.000
4	2.30	0.188	0.000
5	2.58	0.285	0.000
6	3.24	0.323	0.000
7	3.41	0.311	0.000
8	3.63	0.317	0.000
9	3.63	0.286	0.000
10	3.22	0.228	0.000
11	2.73	0.195	0.000
Avg.	**2.83**	**0.237**	**0.000**

Table H-17: Transect dimensions and sediment thickness for Corolla Creek site 3 - Pool 3

COROLLA CREEK - SITE 3 - POOL 3

Transect	Width	Average water depth (m)	Average sediment thickness (m)
1	2.02	0.103	0.000
2	2.66	0.302	0.000
3	2.52	0.356	0.000
4	2.96	0.353	0.001
5	2.42	0.216	0.000
6	2.14	0.142	0.000
Avg.	**2.45**	**0.245**	**<0.001**

Table H-18: Transect dimensions and sediment thickness for Corolla Creek site 3 - Pool 4

COROLLA CREEK - SITE 3 - POOL 4

Transect	Width	Average water depth (m)	Average sediment thickness (m)
1	2.97	0.196	0.000
2	3.04	0.246	0.000
3	2.69	0.287	0.000
4	2.46	0.250	0.000
5	2.70	0.208	0.000
6	2.61	0.235	0.000
7	2.38	0.238	0.000
8	2.48	0.166	0.000
9	2.48	0.076	0.000
Avg.	**2.65**	**0.211**	**0.000**

Table H-19: Transect dimensions and sediment thickness for Corolla Creek site 3 - Pool 5

COROLLA CREEK - SITE 3 - POOL 5

Transect	Width	Average water depth (m)	Average sediment thickness (m)
1	3.29	0.055	0.000
2	3.46	0.098	0.000
3	3.73	0.129	0.000
4	3.60	0.185	0.000
5	3.20	0.220	0.000
6	3.05	0.252	0.000
7	2.94	0.273	0.000
8	3.05	0.250	0.000
9	3.10	0.252	0.000
10	3.49	0.212	0.000
11	3.32	0.183	0.000
12	2.64	0.137	0.000
Avg.	**3.24**	**0.187**	**0.000**

Table H-20: Transect dimensions and sediment thickness for Corolla Creek sites 24 & 25 - Pool 1

COROLLA CREEK - SITES 24 & 25 - POOL 1			
Transect	Width	Average water depth (m)	Average sediment thickness (m)
1	2.03	0.056	0.000
2	2.15	0.122	0.000
3	3.27	0.198	0.000
4	4.46	0.315	0.004
5	3.52	0.440	0.000
6	3.06	0.457	0.000
7	2.89	0.156	0.000
Avg.	**3.06**	**0.249**	**0.001**

Table H-21: Transect dimensions and sediment thickness for Corolla Creek sites 24 & 25 - Pool 2

COROLLA CREEK - SITES 24 & 25 - POOL 2			
Transect	Width	Average water depth (m)	Average sediment thickness (m)
6	2.67	0.111	0.000
1	2.35	0.175	0.000
2	2.76	0.234	0.000
3	2.81	0.248	0.000
4	2.76	0.185	0.000
5	3.60	0.112	0.000
Avg.	**2.83**	**0.177**	**0.000**

Table H-22: Transect dimensions and sediment thickness for Corolla Creek sites 24 & 25 - Pool 3 Inlet

COROLLA CREEK - SITES 24 & 25 - POOL 3 - INLET			
Transect	Width	Average water depth (m)	Average sediment thickness (m)
1	3.71	0.075	0.023
2	2.55	0.068	0.050
3	1.35	0.057	0.036
4	1.18	0.042	0.040
Avg.	**2.20**	**0.061**	**0.037**

Table H-23: Transect dimensions and sediment thickness for Corolla Creek sites 24 & 25 - Pool 3

COROLLA CREEK - SITES 24 & 25 - POOL 3

Transect	Width	Average water depth (m)	Average sediment thickness (m)
1	2.99	0.096	0.000
2	3.41	0.162	0.000
3	3.49	0.202	0.003
4	4.65	0.211	0.003
5	5.14	0.238	0.005
6	3.63	0.349	0.000
7	3.90	0.317	0.006
8	4.04	0.297	0.017
9	2.77	0.270	0.000
10	2.85	0.492	0.002
11	3.09	0.471	0.000
12	3.65	0.203	0.000
Avg.	**3.63**	**0.276**	**0.003**

Table H-24: Transect dimensions and sediment thickness for Corolla Creek site 26 - Pool 1

COROLLA CREEK - SITE 26 - POOL 1

Transect	Width	Average water depth (m)	Average sediment thickness (m)
1	3.40	0.153	0.000
2	2.17	0.289	0.000
3	3.70	0.337	0.000
Avg.	**3.09**	**0.260**	**0.000**

Table H-25: Transect dimensions and sediment thickness for Corolla Creek site 26 - Pool 2

COROLLA CREEK - SITE 26 - POOL 2

Transect	Width	Average water depth (m)	Average sediment thickness (m)
1	4.80	0.133	0.000
2	4.86	0.222	0.002
3	4.47	0.330	0.000
4	3.75	0.441	0.000
5	4.30	0.452	0.004
6	3.00	0.580	0.000
7	3.35	0.256	0.000
Avg.	**4.08**	**0.345**	**0.001**

Table H-26: Transect dimensions and sediment thickness for Corolla Creek site 26 - Pool 3

COROLLA CREEK - SITE 26 - POOL 3

Transect	Width	Average water depth (m)	Average sediment thickness (m)
1	3.80	0.286	0.000
2	3.95	0.354	0.000
3	4.12	0.317	0.000
4	4.34	0.162	0.000
5	4.45	0.181	0.000
6	3.70	0.150	0.000
7	3.50	0.267	0.000
8	2.65	0.297	0.000
9	2.65	0.366	0.000
10	2.85	0.090	0.000
Avg.	**3.60**	**0.247**	**0.000**

Bibliography

Abbe, T., & Montgomery, D. (1996). Large woody debris jams, channel hydraulics and habitat formation in large rivers. *Regulated Rivers: Research & Management,* 12(2-3), 201-221.

Abbe, T., & Montgomery, D. R. (2003). Patterns and processes of wood debris accumulation in the Queets river basin, Washington. *Geomorphology,* 51(1-3), 81-107.

Agee, J. K. (1998). The Landscape Ecology of Western Forest Fire Regimes. *Northwest Science,* 72(Special), 24-43.

Alberta Environment (2003, November). *Water for Life – Alberta's strategy for sustainability*. (ISBN No. 0-7785-3058-2), Edmonton AB. Retrieved on December 3, 2008 from: http://www.waterforlife.alberta.ca/documents/wfl-strategy_Nov2003.pdf

Alberta Sustainable Resource Development. (2006). *Alberta timber harvest planning and operating ground rules framework for renewal*. Edmonton, AB: Alberta Sustainable Resource Development - Forest Management; 100pp

Alberta Sustainable Resource Development. (2007). *Fire salvage planning and operations* (Directive No. 2007-01). Edmonton, AB: Alberta Sustainable Resource Development - Forest Management; 7pp.

Alberta Water Council (2008, January). *Water for Life – recommendations for renewal*. (Catalogue No. ENV-671-O/P). Retrieved on December 11th, 2008 from: http://www.albertawatercouncil.ca/Portals/0/pdfs/Renewal_Final_Report.pdf

Andreoli, A., Comiti, F., & Lenzi, M. A. (2007). Characteristics, distribution and geomorphic role of large woody debris in a mountain stream of the Chilean Andes. *Earth Surface Processes and Landforms,* 32(1675-1692).

Andrus, C. W., Long, B. A., & Froehlich, H. A. (1988). Woody debris and its contribution to pool formation in a coastal stream 50 years after logging. *Canadian Journal of Fisheries and Aquatic Sciences,* 45, 2080-2086.

Aumen, N. G., Hawkins, C. P., & Gregory, S. V. (1990). Influence of woody debris on nutrient retention in catastrophically disturbed streams. *Hydrobiologia,* 190, 183-192.

Baillie, B., & Davies, T. (2002). Influence of large woody debris on channel morphology in native forest and pine plantation streams in the Nelson region, New Zealand. *New Zealand Journal of Marine and Freshwater Research*, 36(4), 763-774.

Beechie, T. J., & Sibley, T. H. (1997). Relationships between channel characteristics, woody debris, and fish habitat in northwestern Washington streams. *Transactions of the American Fisheries Society,* 126, 217-229.

Benda, L. (2003). A quantitative framework for evaluating the mass balance of in-stream organic debris. *Forest Ecology and Management*, 172(1), 1-16.

Benda, L. E., Bigelow, P., & Worsley, T. M. (2002). Recruitment of wood to streams in old-growth and second-growth redwood forests , northern California , U.S.A . *Canadian Journal of Forest Research,* 32, 1460-1477.

Benda, L. E., & Sias, J. C. (2003). A quantitative framework for evaluating the mass balance of in-stream organic debris. *Forest Ecology and Management,* 172, 1-16.

Berg, N., Carlson, A., & Azuma, D. (1998). Function and dynamics of woody debris in stream reaches in the central Sierra Nevada, California. *Canadian Journal of Fisheries and Aquatic Sciences,* 55(8), 1807-1820.

Berg, N. H., Azuma, D., & Carlson, A. (2002). *Effects of wildfire on in-channel woody debris in the Eastern Sierra Nevada, California* (Gen. Tech. Rep. No. PSW-GTR-181). Albany, California: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station; 15 p.

Bergeron, Y., & Flannigan, M. D. (1995). Predicting the effects of climate change on fire frequency in the southeastern Canadian boreal forest. *Water, Air, & Soil Pollution,* 82(1-2), 437-444.

Beschta, R. L., & Platts, W. S. (1986). Morphological features of small streams: Significance and function. *JAWRA Journal of the American Water Resources Association*, 22(3), 369-379.

Beschta, R. L., Rhodes, J. J., Kauffman, J. B., Gresswell, R. E., Minshall, G. W., Karr, J. R., Perry, D. A., Hauer, F. R., & Fissell, C. A. (2004). Postfire management on forested public lands of the western United States. *Conservation Biology,* 18(4), 957-967.

Bilby, R. E. (1981). Role of organic debris dams in regulating the export of dissolved and particulate matter from a forested watershed. *Ecology,* 62(5), 1234-1243.

Bilby, R. E., & Likens, G. E. (1980). Importance of organic debris dams in the structure and function of stream ecosystems. *Ecology,* 61(5), 1107-1113.

Bilby, R. E., & Ward, J. W. (1989). Changes in characteristics and function of woody debris with increasing size of streams in western Washington. T*ransactions of the American Fisheries Society,* 118, 368-378.

Bilby, R. E., & Ward, J. W. (1991). Characteristics and function of large woody debris in streams draining old-growth, clear-cut, and second-growth forests in southwestern Washington. *Canadian Journal of Fisheries and Aquatic Sciences*, 48, 2499-2508.

Bisson, P. A., Bilby, R. E., Bryant, M. D., Dolloff, C. A., Grette, G. B., House, R. A., Murphy, M. L., Koski, K. V., Sedell, J. R. (1987). Large woody debris in forested streams in the Pacific northwest: Past, present and future. Pages 143-190 in E. O. Salo & T. W. Cundy (Eds.), *Streamside management: Forestry and fishery interactions*. Contribution no. 57, Institute of Forest Resources, University of Washington, Seattle

Bisson, P. A., Montgomery, D. R., & Buffington, J. M. (2006). Valley segments, stream reaches, and channel units. In F. R. Hauer & G. A. Lamberti (Eds.), *Methods in Stream Ecology 2nd Edition.* Boston: Academic Press.

Bisson, P. A., Nielsen, J. L., Palmason, R. A., & Grove, L. E. (1982). A system of naming habitat types in small streams, with examples of habitat utilization by salmonids during low streamflow. Pages 62-73 in N.B. Armantrout (ed.). *Acquisition and utilization of aquatic habitat inventory information.* American Fisheries Society, Western Division, Bethesda, Maryland.

Bladon, K. D., Silins, U., Wagner, M. J., Stone, M., Emelko, M. B., Mendoza, C. A., Devito, K.J & Boon, S. (2008). Wildfire impacts on nitrogen concentration and production from headwater streams in southern Alberta's Rocky Mountains. *Canadian Journal of Forest Research,* 38(9), 2359-2371.

Brady, N. C., & Weil, R. R. (2002). *The nature and properties of soils* (13th ed.). Upper Saddle River, NJ: Prentice Hall.

Bragg, D. C. (2000). Simulating catastrophic and individualistic large woody debris recruitment for a small riparian system. *Ecology,* 81(5), 1383-1394.

Braudrick, C. A., & Grant, G. E. (2000). When do logs move in rivers? *Water Resources Research,* 36(2), 571-583.

Braudrick, C. A., & Grant, G. E. (2001). Transport and deposition of large woody debris in streams: a flume experiment. *Geomorphology,* 41(4), 263-283.

Buffington, J. M., Lisle, T. E., Woodsmith, R. D., & Hilton, S. (2002). Controls on the size and occurrence of pools in coarse-grained forest rivers. *River Research and Applications,* 18, 507-531.

Buffington, J. M., & Montgomery, D. R. (1999). Effects of hydraulic roughness on surface textures of gravel-bed rivers. *Water Resources Research,* 35(11), 3507-3521.

Cadol, D., Wohl, E., Goode, J. R., & Jaeger, K. L. (2009). Wood distribution in neotropical forested headwater streams of La Selva, Costa Rica. *Earth Surface Processes and Landforms,* 34, 1198-1215.

Chen, X., Wei, X., & Scherer, R. (2005). Influence of wildfire and harvest on biomass, carbon pool, and decomposition of large woody debris in forested streams of southern interior British Columbia. *Forest Ecology and Management,* 208(1-3), 101-114.

Chen, X., Wei, X., Scherer, R., Luider, C., & Darlington, W. (2006). A watershed scale assessment of in-stream large woody debris patterns in the southern interior of British Columbia. *Forest Ecology and Management,* 229, 50-62.

Cherry, J., & Beschta, R. L. (1989). Coarse woody debris and channel morphology: A flume study. *Water Resources Bulletin,* 25(5), 1031-1036.

Comiti, F., Andreoli, A., Lenzi, M. A., & Mao, L. (2006). Spatial density and characteristics of woody debris in five mountain rivers of the Dolomites (Italian Alps). *Geomorphology,* 78, 44-63.

Comiti, F., Andreoli, A., Mao, L., & Lenzi, M. A. (2008). Wood storage in three mountain streams of the Southern Andes and its hydro-morphological effects. *Earth Surface Processes and Landforms,* 33, 244-262.

Curran, J. C. (2010). Mobility of large woody debris (LWD) jams in a low gradient channel. *Geomorphology,* 116(3-4), 320-329.

Curran, J. H., & Wohl, E. E. (2003). Large woody debris and flow resistance in step-pool channels, Cascade Range, Washington. *Geomorphology,* 51(1-3), 141-157.

Czarnomski, N. M., Dreher, D. M., Snyder, K. U., Jones, J. A., & Swanson, F. J. (2008). Dynamics of wood in stream networks of the western Cascades Range, Oregon. *Canadian Journal of Forest Research,* 38(8), 2236-2248.

DeBano, L. F., Neary, D. G., & Ffolliott, P. F. (1998). *Fire's effects on ecosystems.* New York, NY: John Wiley and Sons.

Dodds, W. K., & Welch, E. B. (2000). Establishing nutrient criteria in streams. *Journal of North American Benthological Society*, 19(1), 186-196.

Downs, P. W., & Simon, A. (2001). Fluvial geomorphological analysis of the recruitment of large woody debris in the Yalobusha River network, Central Mississippi, USA. *Geomorphology,* 37(1-2), 65-91.

Faustini, J. M., & Jones, J. A. (2003). Influence of large woody debris on channel morphology and dynamics in steep, boulder-rich mountain streams, western Cascades, Oregon. *Geomorphology,* 51(1-3), 187-205.

Fetherston, K. L., Naiman, R. J., & Bilby, R. E. (1995). Large woody debris, physical process, and riparian forest development in montane river networks of the Pacific Northwest. *Geomorphology,* 13, 133-144.

Flannigan, M. D., Stocks, B. J., & Wotton, B. M. (2000). Climate change and forest fires. *The Science of the Total Environment,* 262(3), 221-229.

Frelich, L. E. (2002). *Forest dynamics and disturbance regimes - Studies from temperate evergreen-deciduous forests.* Cambridge, UK: Cambridge University Press.

Fremier, A. K., Seo, J. I., & Nakamura, F. (2010). Watershed controls on the export of large wood from stream corridors. *Geomorphology*, 117(1-2), 33-43.

Furniss, M. J., Staab, B. P., Hazelhurst, S., Clifton, C. F., Roby, K. B., Ilhadrt, B. L., Larry, E. B., Todd, A. H., Reid, L. M., Hines, S. J., Bennett, K. A., Luce, C. H. & Edwards, P. J. (2010). *Water, climate change and forests: watershed stewardship for a changing climate* (Gen. Tech. Rep. PNW-GTR-812). Portland, OR: Department of Agriculture, Forest Service, Pacific Northwest Research Station; 75p.

Gomi, T., Sidle, R. C., Bryant, M. D., & Woodsmith, R. D. (2001). The characteristics of woody debris and sediment distribution in headwater streams, southeastern Alaska. *Canadian Journal of Forest Research,* 31(8), 1386-1399.

Government of Alberta. (2010). *C5 Forest Management Plan 2006-2026*. Government of Alberta. Edmonton, AB

Gregory, S. V. (1997). Riparian management in the 21st century. In K. A. Kohm, and J. F. Franklin (eds). *Creating a forestry for the 21st century: the science of ecosystem management*. Washington, D.C.: Island Press

Gregory, K., Davis, R., & Tooth, S. (1993). Spatial distribution of coarse woody debris dams in the Lymington Basin, Hampshire, UK. *Geomorphology,* 6(3), 207-224.

Gregory, K. J., Gurnell, A. M., & Hill, C. T. (1985). The permanence of debris dams related to river channel processes. *Hydrological Sciences,* 30(3), 371-381.

Gregory, K. J., Gurnell, A. M., Hill, C. T., & Tooth, S. (1994). Stability of the pool-riffle sequence in changing river channels. *Regulated Rivers: Research & Management*, 9(1), 35-43.

Gurnell, A. M., Gregory, K. J., & Petts, G. E. (1995). The role of coarse woody debris in forest aquatic habitats: Implications for management. *Aquatic Conservation: Marine and Freshwater Ecosystems,* 5, 143-166.

Gurnell, A. M., & Petts, G. E. (2002). Island-dominated landscapes of large floodplain rivers, a European perspective. *Freshwater Biology,* 47, 581-600.

Gurnell, A. M., Petts, G. E., Hannah, D. M., Smith, B. P. G., Edwards, P. J., Kollmann, J., Ward, J. V., & Tockner, K. (2001). Riparian vegetation and island formation along the gravel-bed Fiume Tagliamento, Italy. *Earth Surface Processes and Landforms,* 26 (1), 31-62.

Gurnell, A. M., Piégay, H., Swanson, F. J., & Gregory, S. V. (2002). Large wood and fluvial processes. *Freshwater Biology,* 47(4), 601-619.

Gurnell, A. M., & Sweet, R. (1998). The distribution of large woody debris accumulations and pools in relation to woodland stream management in a small, low-gradient stream. *Earth Surface Processes and Landforms*, 23(12), 1101-1121.

Gurnell, A. M., Tockner, K., Edwards, P. J., & Petts, G. (2005). Effects of deposited wood on biocomplexity of river corridors. *Frontiers in Ecology and the Environment,* 3, 377-382.

Harmon, M. E., Franklin, J. F., Swanson, F. J., Sollins, P., Gregory, J. D., Lattin, J. D., Anderson, N. H., Cline, S. P., Aumen, N. G., Sedell, J. R., Lienkaemper, G.W., Cromack Jr, K. & Cummins, K. W. (1986). Ecology of course woody debris in temperate ecosystems. *Advances in Ecological Research,* 15, 133-302.

Harrelson, C. C., Rawlins, C. L., & Potyondy, J. P. (1994). *Stream channel reference sites: an illustrated guide to field technique*. (Gen. Tech. Rep. RM-245). Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 61 p.

Hart, E. A. (2003). Dead wood: Geomorphic effects of coarse woody debris in headwater streams, Great Smoky Mountain. *Journal of the Tennessee Academy of Science*, 78(2), 50-54.

Hassan, M. A., Hogan, D. L., Bird, S. A., May, C. L., Gomi, T., & Campbell, D. (2005). Spatial and temporal dynamics of wood in headwater streams of the Pacific Northwest. *Geomorphology,* 41(4), 899-919.

Hauer, F. R., Stanford, J. A., & Lorang, M. S. (2007). Pattern and process in northern Rocky Mountain headwaters: Ecological linkages in the headwaters of the Crown of the Continent1. *JAWRA Journal of the American Water Resources Association,* 43(1), 104-117.

Hawkins, C. P., Kershner, J. L., Bisson, P. A., Bryant, M. D., Decker, L. M., Gregory, S. V., McCullough, D. A., Overton, C. K., Reeves, G. H., Steedman, R. J., & Young, M. K. (1993). A hierarchical approach to classifying stream habitat features. *Fisheries,* 18(6), 3-10.

Hessburg, P. F., & Agee, J., K. (2003). An environmental narrative of inland Northwest United States forests, 1800-2000. *Forest Ecology and Management*, 178, 23-59.

Hilton, S., & Lisle, T. E. (1993). *Measuring the fraction of pool volume filled with fine sediment* (Report No. PSW-RN-414). Albany, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 11 p.

Hyatt, T. L., & Naiman, R. J. (2001). The residence time of large woody debris in the Queets River, Washington, USA. *Ecological Applications,* 11(1), 191-202.

Ice, G. G., Neary, D. G., & Adams, P. W. (2004). Effects of wildfire on soils and watershed processes. *Journal of Forestry,* 102(6), 16-20.

Ilhardt, B.L., Verry, E.S., Palik, B.J. (2000). Defining riparian areas. In E.S. Verry, J.W. Hornbeck and C.A. Dolloff (eds.). *Riparian management in forests of the continental eastern United States.* Boca Raton, FL: Lewis Publishers, CRC Press

Iroume, A., Andreoli, A., Comiti, F., Ulloa, H., & Huber, A. (2010). Large wood abundance, distribution and mobilization in a third order coastal mountain range river system, southern Chile. *Forest Ecology and Management*, 260, 480-490.

Jackson, C. R., & Strum, C. A. (2002). Woody debris and channel morphology in first- and second-order forested channels in Washington's coast ranges. *Water Resources Research,* 38(9), 1-14.

Jeffries, R., Darby, S. E., & Sear, D. A. (2003). The influence of vegetation and organic debris on flood-plain sediment dynamics: case study of a low-order stream in the New Forest, England. *Geomorphology*, 51(1-3), 61-80.

Jones, T. A., & Daniels, L. D. (2008). Dynamics of large woody debris in small streams disturbed by the 2001 Dogrib fire in the Alberta foothills. *Forest Ecology and Management,* 256(10), 1751-1759.

Kaczka, R. (2009). *Dynamics of large woody debris and wood dams in mountain Kamienica Stream, Polish Carpathians.* Paper presented at the DENDROSYMPOSIUM 2008.

Kail, J. (2003). Influence of large woody debris on the morphology of six central European streams. *Geomorphology,* 51(1-3), 207-223.

Karr, J. R., Rhodes, J. J., Minshall, G. W., Hauer, F. R., Beschta, R. L., Frissell, C. A., & Perry, D.A. (2004). The effects of postfire salvage logging on aquatic ecosystems in the American West. *BioScience,* 54(11), 1029-1033.

Keller, E. A., & Swanson, F. J. (1979). Effects of large organic material on channel form and fluvial processes. *Earth Surface Processes and Landforms,* 4, 351-380.

Kraft, C. E., & Warren, D. R. (2003). Development of spatial pattern in large woody debris and debris dams in streams. *Geomorphology,* 51(1-3), 127-139.

Kreutzweiser, D. P., Good, K. P., & Sutton, T. M. (2005). Large woody debris characteristics and contributions to pool formation in forest streams of the boreal shield. *Canadian Journal of Forest Research,* 35, 1213-1223.

Lachance, S., & Dubé, M. (2004). A new tool for measuring sediment accumulation with minimal loss of fines. *North American Journal of Fisheries Management,* 24(1), 303-310.

Laiho, R., & Prescott, C. E. (1999). The contribution of coarse woody debris to carbon, nitrogen and phosphorus cycles in three Rocky Mountain coniferous forest. *Canadian Journal of Forest Research,* 29(10), 1592-1603.

Lancaster, S. T., & Grant, G. (2006). Debris dams and the relief of headwater streams. *Geomorphology,* 82(1-2), 84-97.

Lancaster, S. T., Hayes, S. K., & Grant, G. E. (2001). Modeling sediment and wood storage and dynamics in small mountainous watersheds. In J. M. Dorava, D. R. Montgomery, B. B. Palcsak & F. A. Fitzpatrick (Eds.), *Geomorphic Processes and Riverine Habitat* (pp. 85-102). Washington: American Geophysical Union.

Lane, E.W. (1955). The importance of fluvial morphology in hydraulic engineering. *American Society of Civil Engineering Proceedings Paper 81-745*, 1-17

Leopold, L. B., & Wolman, M. G. (1957). *River channel patterns: Braided, meandering and straight*. U.S. Geological Survey Professional Paper, 282-B, 39-85.

Leopold, L. B., Wolman, M. G., & Miller, J. P. (1964). *Fluvial processes in geomorphology.* San Francisco: W.H. Freeman and Company.

Lisle, T. (1979). A sorting mechanism for a riffle-pool sequence. *Geological Society of America Bulletin, Part 11*, 90, 1142-1157

Lisle, T. E. (1986). Stabilization of a gravel channel by large streamside obstructions and bedrock bends, Jacoby Creek, northwestern California. *Geological Society of America Bulletin,* 97, 999-1011.

Lisle, T. E. (1987). *Using "residual depths" to monitor pool depths independently of discharge* (Res. No. PSW-394). Berkley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, 4 p.

Lisle, T. E. (1995). Effects of coarse woody debris and its removal on a channel affected by the 1980 eruption of Mount St. Helens, Washington. *Water Resources Research,* 31(7), 1797-1808.

Lisle, T. E., & Hilton, S. (1992). The volume of fine sediment in pools: An index of sediment supply in gravel-bed streams. *Water Resources Bulletin,* 28(2), 371-383.

Lisle, T. E., & Hilton, S. (1999). Fine bed material in pools of natural gravel bed channels. *Water Resources Research,* 35(4), 1291-1304.

Long, B. A. (1987). *Recruitment and abundance of large woody debris in an Oregon coastal stream system*. Unpublished masters dissertation, Oregon State University, Corvallis, OR.

Malmon, D. V., Reneau, S. L., Katzman, D., Lavine, A., & Lyman, J. (2007). Suspended sediment transport in an ephemeral stream following wildfire. *Journal of Geophysical Research,* 112, 1-16.

Manners, R. B., & Doyle, M. W. (2008). A mechanistic model of woody debris jam evolution and its application to wood-based restoration and management. *River Research and Applications, 24,* 1104-1123.

Mao, L., Andreoli, A., Comiti, F., & Lenzi, M. A. (2008). Geomorphic effects of large wood jams on a sub-antarctic mountain stream. *River Research and Applications,* 24, 249-266.

Marcus, W. A., Marston, R. A., Colvard Jr., C. R., & Gray, R. D. (2002). Mapping the spatial and temporal distributions of woody debris in streams of the Greater Yellowstone Ecosystem, USA. *Geomorphology,* 44(3-4), 323-335.

Martin, D. J., & Benda, L. E. (2001). Patterns of instream wood recruitment and transport at the watershed scale. *Transactions of the American Fisheries Society,* 130, 940-958.

Massong, T. M., & Montgomery, D. R. (2000). Influence of sediment supply, lithology and wood debris on the distribution of bedrock and alluvial channels. Geological Society of America Bulletin, 112(5), 591-599.

May, C. L., & Gresswell, R. E. (2003a). Large wood recruitment and redistribution in headwater streams in the southern Oregon Coast. *Canadian Journal of Forest Research*, 33, 1352-1362.

May, C. L., & Gresswell, R. E. (2003b). Processes and rates of sediment and wood accumulation in headwater streams of the Oregon Coast Range, USA. *Earth Surface Processes and Landforms*, 28(4), 409-424.

McCain, M., Fuller, D., Decker, L. & Overton, K. 1990. *Stream habitat classification and inventory procedures for northern California*. FHR Currents, USDA Forest Service, Region 5, San Francisco, California. Fish Habitat Relationships Tech. Bull., 1, 1-15

McIver, J. D., & Ottmar, R. (2007). Fuel mass and stand structure after post-fire logging of a severely burned ponderosa pine forest in northeastern Oregon. *Forest Ecology and Management,* 238(1-3), 268-279.

McIver, J. D., & Starr, L. (tech. eds.) (2000). *Environmental effects of postfire logging: Literature review and annotated bibliography* (General Technical Report No. PNW-GTR-486). Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 72 p.

Meyer, G. A., Pierce, J. L., Wood, S. H., & Jull, A. J. T. (2001). Fire storms, and erosional events in the Idaho batholith. *Hydrological Processes,* 15, 3025-3038.

Meyer, G. A., & Wells, S. G. (1997). Fire-Related Sedimentation Events on Alluvial Fans, Yellowstone National Park, U.S.A. *Journal of Sedimentary Research,* 67(5), 776-791.

Minshall, G. W., & Brock, J. T. (1991). Observed and anticipated effects of forest fire on Yellowstone stream ecosystems. In R. B. Keiter & M. S. Boyce (Eds.), *The Greater Yellowstone Ecosystem: Redefining America's wilderness heritage* (pp. 123-135). Yale University Press, New Haven.

Montgomery, D. R., & Abbe, T. B. (2006). Influence of logjam-formed hard points on the formation of valley-bottom landforms in an old-growth forest valley, Queets River, Washington, USA. *Quaternary Research,* 65, 147-155.

Montgomery, D. R., Abbe, T. B., Buffington, J. M., Peterson, N. P., Schmidt, K. M., & Stock, J. D. (1996). Distribution of bedrock and alluvial channels in forested mountain drainage basins. *Nature,* 381, 587-589.

Montgomery, D. R., & Buffington, J. M. (1997). Channel-reach morphology in mountain drainage basins. *Geological Society of America Bulletin, 109*(5), 596-611.

Montgomery, D. R., Buffington, J. M., Smith, R. D., Schmidt, K. M., & Pess, G. (1995). Pool spacing in forest channels. *Water Resources Research,* 31(4), 1097-1105.

Montgomery, D. R., Collins, B. D., Buffington, J. M., & Abbe, T. B. (2003). Geomorphic effects of wood in rivers. *American Fisheries Society Symposium,* 1-27.

Montgomery, D. R., & Piégay, H. (2003). Wood in rivers: interactions with channel morphology and processes. *Geomorphology,* 51(1-3), 1-5.

Morris, A. E. L., Goebel, P. C., & Palik, B. J. (2007). Geomorphic and riparian forest influences on characteristics of large wood and large-wood jams in old-growth and second-growth forests in Northern Michigan, USA. *Earth Surface Processes and Landforms,* 32(8), 1131-1153.

Murphy, M. L., & Koski, K. V. (1989). Input and depletion of woody debris in Alaska streams and implications for streamside management. *North American Journal of Fisheries Management,* 9, 427-436.

Mutz, M. (2000). Influences of woody debris on flow patterns and channel morphology in a low energy, sand-bed stream reach. *International Review of Hydrobiology,* 85(1), 107-121.

Naiman, R. J., Balian, E. V., Bartz, K. K., Bilby, R. E., & Latterell, J. J. (2002). Dead wood dynamics in stream ecosystems. In: W.F. Laudenslayer Jr., P.J. Shea, B. Valentine, C.P., Weatherspoon, T.E., Lisle. *Proceedings of the Symposium on the Ecology and Management of Dead wood in western Forest.* General Technical Report PSW-GTR-181. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, California, pp. 23–48.

Nakamura, F., & Inahara, S. (2007). Fluvial geomorphic disturbances and life history traits of riparian tree species. In E. A. Johnson & K. Miyanishi (Eds.), *Plant Disturbance Ecology: The process and the response* (pp. 283-310). San Diego, California: Elsevier.

Nakamura, F., Shin, N., & Inahara, S. (2007). Shifting mosaic in maintaining diversity of floodplain tree species in the northern temperate zone of Japan. *Forest Ecology and Management,* 241(1-3), 28-38.

Nakamura, F., & Swanson, F. J. (1993). Effects of coarse woody debris on morphology and sediment storage of a mountains stream system in western Oregon. *Earth Surface Processes and Landforms,* 18, 43-61.

Nakamura, F., & Swanson, F. J. (1994). Distribution of coarse woody debris in a mountain stream, western Cascade Range, Oregon. *Canadian Journal of Forest Research*, 24, 2395-2403.

Nakamura, F., & Swanson, F. J. (2003). Dynamics of wood and rivers in the context of ecological disturbance. In S. V. Gregory, K. L. Boyer & A. M. Gurnell (Eds.), *The Ecology and Management of Wood in World Rivers* (pp. 279-297). Bethesda, MD: American Fisheries Society.

Nakamura, F., Swanson, F. J., & Wondzell, S. M. (2000). Disturbance regimes of stream and riparian systems - A disturbance-cascade perspective. *Hydrological Processes,* 14(16-17), 2849-2860.

Nanson, G. C., & Knighton, A. D. (1996). Anabranching rivers: their cause, character and classification. *Earth Surface Processes and Landforms,* 21, 217-239.

Newbold, J. D., Elwood, J. W., O'Neill, R. V., & Van Winkle, W. (1981). Measuring nutrient spiralling in streams. *Canadian Journal of Fisheries and Aquatic Sciences,* 38, 860-863.

Nowakowski, A. L., & Wohl, E. E. (2008). Influences on wood load in mountain streams of the Bighorn National Forest, Wyoming, USA. *Environmental Management,* 42(4), 557-571.

Oldman Watershed Council. (2010). *Oldman River State of the Watershed Report 2010*. Oldman Watershed Council, Lethbridge, Alberta: 284 pp.

Owens, P. N., Batalla, R. J., Collins, A. J., Gomez, B., Hicks, D. M., Horowitz, A. J., Kondolf, G. M., Marden, M., Page, M. J., Peacock, D. H., Petticrew, E. L., Salomons, W., Trustrum, N. A. (2005). Fine-grained sediment in river systems: environmental significance and management issues. *River Research and Applications,* 21(7), 693-717.

Petticrew, E. L., Krein, A., & Walling, D. E. (2007). Evaluating fine sediment mobilization and storage in a gravel-bed river using controlled reservoir releases. *Hydrological Processes,* 21, 198-210.

Phillips, M.J., Swift, L.W. & Blinn, C.R. (2000). Best management practices for riparian areas. In E.S. Verry, J.W. Hornbeck and C.A. Dolloff (eds.). *Riparian management in forests of the continental eastern United States.* Boca Raton, FL: Lewis Publishers, CRC Press

Piégay, H., & Gurnell, A. M. (1997). Large woody debris and river geomorphological pattern: Examples from SE France and S England. *Geomorphology,* 19, 99-116.

Piégay, H., & Marston, R. A. (1998). Distribution of large woody debris along the outer bend of meanders in the Ain River, France. *Physical Geography,* 19, 318-340.

Piégay, H., Thevenet, A., & Citterio, A. (1999). Input, storage and distribution of large woody debris along a mountain river continuum, the Drôme River, France. *Catena,* 35(1), 19-39.

Raikow, D. F., Grubbs, S. A., & Cummins, K. W. (1995). Debris dam dynamics and coarse particulate organic matter retention in an Appalachian mountain stream. *Journal of the North American Benthological Society*, 14(4), 535-546.

Reeves, G. H., Bisson, P. A., Rieman, B. E., & Benda, L. E. (2006). Postfire logging in riparian areas. Conservation *Biology,* 20(4), 994-1004.

Reeves, G. H., Burnett, K. M., & McGarry, E. V. (2003). Sources of large wood in the main stem of a fourth-order watershed in Coastal Oregon. *Canadian Journal of Forest Research,* 33, 1363-1370.

Richmond, A. D., & Fausch, K. D. (1995). Characteristics and function of large woody debris in subalpine Rocky Mountain streams in northern Colorado. *Canadian Journal of Fisheries and Aquatic Sciences,* 52(8), 1789-1802.

Robichaud, P. R., & Waldrop, T. A. (1994). A Comparison of Surface Runoff and Sediment Yields From Low- and High-Severity Site Preparation Burns. *Water Resources Bulletin,* 30(1), 27-34.

Robinson, C. T., Uehlinger, U., & Minshall, G. W. (2005). Functional characteristics of wilderness streams twenty years following wildfire. *Western North American Naturalist,* 65(1), 1-10.

Robison, E. G., & Beschta, R. L. (1990). Coarse woody debris and channel morphology interactions for undisturbed streams in southeast Alaska, USA. *Earth Surface Processes and Landforms,* 15(2), 149-156.

Schumm, S.A. (1977). *The fluvial system.* New York: Wiley-Interscience. 338pp.

Sear, D. A., Millington, C. E., Kitts, D. R., & Jeffries, R. (2010). Logjam controls on channel:floodplain interactions in wooded catchments and their role in the formation of multi-channel patterns. *Geomorphology,* 116(3-4), 305-319

Seo, J. I., & Nakamura, F. (2009). Scale-dependent controls upon the fluvial export of large wood from river catchments. *Earth Surface Processes and Landforms,* 34, 786-800.

Seo, J. I., Nakamura, F., & Chun, K. W. (2010). Dynamics of large wood at the watershed scale: A perspective on current research limits and future directions. *Landscape and Ecological Engineering,* 6(2), 271-287.

Shakesby, R. A., & Doerr, S. H. (2006). Wildfire as a hydrological and geomorphological agent. *Earth-Science Reviews,* 74(3-4), 269-307.

Shields, F. D., & Gippel, C. J. (1995). Prediction of effects of woody debris removal on flow resistance. *Journal of Hydraulic Engineering*, 121, 341-354.

Smith, D. G., & Smith, N. D. (1980). Sedimentation in anastomosed river systems: Examples from alluvial valleys near Banff, Alberta. *Journal of Sedimentary Petrology,* 50, 157-164.

Stone, M., & Droppo, I. G. (1994). In-channel surficial fine-grained sediment laminae. Part II: Chemical characteristics and implications for contaminant transport in fluvial systems. *Hydrological Processes,* 8, 113-124.

Strahler, A. N. (1952). Dynamic basis of geomorphology. *Geological Society of America Bulletin,* 63, 923-938.

Swanson, F. J. (1981). Fire and geomorphic processes In H.A. Mooney, T.M. Bonnicksen, N.L. Christensen, J.E. Lotan & W.A. Reiners (eds.). *Fire Regimes and Ecosystem Properties* (General Technical Report WO-GTR- 26). Washington, DC: U.S. Department of Agriculture, Forest Service. pp.401-420

Swanson, F. J. (2003). Wood in rivers: A landscape perspective. *American Fisheries Society Symposium,* 37, 299-313.

Swanson, F. J., & Lienkaemper, G. W. (1978). *Physical consequences of large organic debris in pacific northwest streams* (General Technical Report PNW-69). Portland, Oregon: U.S. Department of Agriculture, Forest Service; 12p.

Thom, B. A., Kavanagh, P. S., & Jones, K. K. (2001). *Reference site selection and survey results, 2000.* (Monitoring Program Report Number OPSW-ODFW-2001-6). Portland, OR: Oregon Department of Fish and Wildlife; 23p.

Thomas, A. D., Walsh, R. P. D., & Shakesby, R. A. (1999). Nutrient losses in eroded sediment after fire in eucalyptus and pine forests in the wet Mediterranean environment of northern Portugal. *Catena,* 36, 283-302.

Tinker, D. B., & Knight, D. H. (2000). Coarse woody debris following fire and logging in Wyoming Lodgepole pine forests. *Ecosystems,* 3, 472-483.

Trotter, E. H. (1990). Woody debris, forest-stream succession, and catchment geomorphology. *Journal of North American Benthological Society,* 9(2), 141-156.

Valett, H. M., Crenshaw, C. L., & Wagner, P. F. (2002). Nutrient uptake, forest succession and biogeochemical theory. *Ecology*, 83(10), 2888-2901.

Vannote, R. L., Minshall, G. W., Cummins, K. W., Sedell, J. R., & Cushing, C. E. (1980). The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences,* 37(1), 130-137.

Wallace, J. B., Webster, J. R., & Meyer, J. L. (1995). Influence of log additions on physical and biotic characteristics of a mountain stream. *Canadian Journal of Fisheries and Aquatic Sciences,* 52, 2120-2137.

Wallerstein, N., & Thorne, C. R. (1997). *Impacts of woody debris on fluvial processes and channel morphology in stable and unstable streams* (Project No. R&D 7897-EN-09). Nottingham, UK: University of Nottingham, Department of Geography

Wallerstein, N. P., & Thorne, C. R. (2004). Influence of large woody debris on morphological evolution of incised, sand-bed channels. *Geomorphology,* 57(1-2), 53-73.

Walling, D. E. (1999). Linking land use, erosion and sediment yields in river basins. *Hydrobiologia,* 410, 223-240.

Warren, D. R., Bernhart, E. S., Hall Jr., R. O., & Likens, G. E. (2007). Forest age, wood and nutrient dynamics in headwater streams of the Hubbard Brook Experimental Forest, NH. *Earth Surface Processes and Landforms,* 32(8), 1154-1163.

Warren, D. R., & Kraft, C. E. (2008). Dynamics of large wood in an eastern U.S. mountain stream. *Forest Ecology and Management,* 256, 808-814.

Webb, A. A., & Erskine, W. D. (2003). Distribution, recruitment, and geomorphic significance of large woody debris in an alluvial forest stream: Tonghi Creek, southeastern Australia. *Geomorphology,* 51, 109-126.

Webb, A. A., & Erskine, W. D. (2005). Natural variability in the distribution, loading and induced scour of large wood in sand-bed forest streams. *River Research and Applications*, 21, 169-185.

Wentworth, C. K. (1922). A scale of grade and class terms for clastic sediments. The Journal of *Geology,* 30(5), 377-392.

Wilcox, A. C., & Wohl, E. E. (2006). Flow resistance dynamics in step-pool stream channels: 1. Large woody debris and controls on total resistance. *Water Resources Research,* 42, W05418 - 05411-05416.

Wohl, E., Bolton, S., Cadol, D., Comiti, F., Goode, J. R., & Mao, L. (In Press). A two end-member model of wood dynamics in headwater neotropical rivers. *Journal of Hydrology.*

Wohl, E., & Cadol, D. (2011). Neighborhood matters: Patterns and controls on wood distribution in old-growth forest streams of the Colorado Front Range, USA. *Geomorphology,* 125, 132-146.

Wohl, E., Cenderelli, D. A., Dwire, K. A., Ryan-Burkett, S. E., Young, M. K., & Fausch, K. D. (2010). Large in-stream wood studies: A call for common metrics. *Earth Surface Processes and Landforms,* 35, 618-625.

Wohl, E., & Goode, J. R. (2008). Wood dynamics in headwater streams of the Colorado Rocky Mountains. *Water Resources Research,* 44, W09429, doi:09410.01029/02007WR006522.

Wohl, E., & Jaeger, K. (2009). A conceptual model for the longitudinal distribution of wood in mountain streams. *Earth Surface Processes and Landforms,* 34, 329-344.

Wohl, E., Ogden, F. L., & Goode, J. (2009). Episodic wood loading in a mountainous neotropical watershed. *Geomorphology,* 111, 149-159.

Wohl, E., Polvi, L. E., & Cadol, D. (2011). Wood distribution along streams draining old-growth floodplain forests in Congaree National Park, South Carolina, USA. *Geomorphology,* 126, 108-120.

Wood, P. J., & Armitage, P. D. (1997). Biological effects of fine sediment in the lotic environment. *Environmental Management,* 21(2), 203-217.

Wyzga, B., & Zawiejska, J. (2005). Wood storage in a wide mountain river: Case study of the Czarny Dunajec, Polish Carpathians. *Earth Surface Processes and Landforms,* 30(12), 1475-1494.

Wyzga, B., & Zawiejska, J. (2010). Large wood storage in channelized and unmanaged sections of the Czarny Dunajec River, Polish Carpathians: Implications for the restoration of mountain rivers. *Folia Geographica - Series Geographica-Physica,* 41, 5-34.

Young, M. K. (1994). Movement and characteristics of stream-borne coarse woody debris in adjacent burned and undisturbed watersheds in Wyoming. *Canadian Journal of Forest Research,* 24, 1933-1938.

Young, M. K., Mace, E. A., Ziegler, E. T., & Sutherland, E. K. (2006). Characterizing and contrasting instream and riparian coarse wood in western Montana basins. *Forest Ecology and Management,* 226(1-3), 26-40.

Zelt, R. B., & Wohl, E. E. (2004). Channel and woody debris characteristics in adjacent burned and unburned watersheds a decade after wildfire, Park County, Wyoming. *Geomorphology,* 57(3-4), 217-233.