Downstream characteristics of in-stream wood in Wigwam Creek, Alberta

by

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Abstract

In this study I examined downstream patterns of wood characteristics and stand dynamics in a small basin in the Upper Foothills of Alberta. Fourteen study reaches were surveyed for wood size, orientation, position, origin and function, channel parameters including bankfull width, depth, slope and bed surface texture, and tree diameter, density and species composition of the adjacent riparian forest using the point centred quarter method. Based on geomorphic process domains, total stream power estimations and critical thresholds of change among wood attributes, I determined that wood movement began between 7-10km^2 drainage area. Upstream of this point wood had relatively little geomorphic function and decay was the main output process.

Wood characteristics responded strongly to the downstream increase in transport capacity. Wood loads ceased to resemble adjacent forests near the colluvial-fluvial boundary as wood began to be affected by transport. Total wood load decreased, and wood orientation changed from perpendicular to parallel as transport capacity increased downstream. Decay classes 1, 2 and 5 were more abundant in transport-limited reaches while decay class 3 was more abundant downstream. Log positions within the channel varied with transport capacity, with fewer bridges and more loose and braced wood found downstream of the valley step. Partial bridges and anchored wood occurred in the same amounts throughout the stream network. Wood distribution changed from segregated in transport-limited reaches to aggregated in transporting reaches. Most logs had been dead for less than 40 years, but some had persisted for over 125 years in transport-limited reaches. The mean age of woody debris did not change downstream since riparian stands were similar along the stream network. These findings have implications for forest management and aquatic systems in the Upper Foothills region.

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Chapter 1

Introduction

Fallen dead trees and branches can significantly influence the geomorphic and ecological development of streams (Harmon et al., 1986; Naiman and Bilby, 1998). Woody debris is any piece of wood from a tree trunk, branch or rootball of sufficient size that has fallen into or across a stream channel. Because it can exert considerable control over channel size, morphology and ecology, woody debris has become the focus of riparian forest and in-stream management and restoration efforts around the world (Gurnell et al., 2002). In order to effectively manage woody debris, managers must understand wood dynamics in riparian forests and streams.

Woody debris acts a primary link between terrestrial and in-stream ecology in forested watersheds (Richardson et al., 2005). The importance of woody debris to channel structure is proportional to its size, abundance and persistence in-stream (Montgomery et al., 2003). Stored wood has been found to locally increase stream width, and increase the diversity of channel morphology, size and bed surface texture (Hogan et al., 1998). The presence of wood promotes the development of log steps and log jams, thereby increasing channel roughness and complexity (Montgomery et al., 1995; Buffington and Montgomery, 1999). Woody debris can reduce flow velocity and create obstacles to sediment transport, effectively trapping it upstream over years to decades (Buffington and Montgomery, 1999; May and Gresswell, 2003). This is a particularly important process in coastal headwater streams, where alluvial deposits may accumulate only due to the presence of wood (May and Gresswell, 2003; Benda et al., 2005). Sediment accumulated by wood is then released more episodically, during peak flow events, wood mobilization or log jam destruction. The structure and flow resistance provided by wood can protect channel bed and banks from scouring thereby increasing channel stability (Montgomery et al., 1995). Elsewhere, it may promote local scouring by redirecting flow around wood pieces (Richmond and Fausch, 1995). Over longer time scales, wood changes the timing and magnitude of sediment pulses moving through the stream network by storing sediment until high flow events cause large episodic releases of sediment accumulations. These influences on channels have implications for biological processes within the stream.

Woody debris promotes ecological productivity by providing habitat or food to fish, amphibians and invertebrates (Plafkin et al., 1989). The structural complexity promoted by woody debris increases the heterogeneity and abundance of habitat. Pools, logjams and individual logs provide a variety of refugia for invertebrates, amphibians and fish. These structures are used in the short term, to rest, to shelter from the sun and hide from predators, and in the long term for over-wintering (Benda and Sias, 2003; McIlroy et al., 2008). Woody debris may also provide most of the available food to many upland streams (Bilby, 2003). Log jams can comprise the majority of all particulate organic matter in small streams, thus contributing significantly to the nutrient budget (Bisson and Bilby, 1998). In addition to being directly consumed, wood retains nutrients upstream by trapping fine twigs and leaves (Bilby, 2003; McIlroy et al., 2008) and regulates the propagation of forest-derived nutrients through watersheds. Mobile wood is transported to higher-order streams where it may be significant to downstream nutrient supplies (Richardson et al., 2005).

The effects of wood on stream morphology and ecology are controlled by its size and its position in relation to the channel (Hassan et al., 2005; Jones et al., 2010), as well as by its abundance. Both the size of the channel and the processes that input and export wood change down stream networks, which changes the types of functions that woody debris perform as well. In order to manage streams to maintain wood function it is very important to understand the nature and drivers of these changes in different parts of the watershed.

1.1 Wood dynamics

To examine wood dynamics in stream networks, I will be using wood budgets as a framework. Wood budgeting is an effective way to model wood dynamics in different parts of the watershed. A wood budget is a quantitative mass balance that accounts for the sources and sinks of wood within a defined system, which is usually a stream reach (Benda and Sias, 2003). Budgets describe the amount of wood in storage reservoirs and the rates at which wood is transferred between them. The basic formula for a wood budget is as follows:

$$I = \Delta S + O \tag{1.1}$$

where I (m^3) is the volume of wood input to the channel, ΔS (m^3) is change in the volume of wood stored and O (m^3) is output, or the volume of wood that was depleted from the reach. These components can be further broken down into separate contributing processes (Benda and Sias, 2003). A conceptual model of a wood budget describing the primary pathways of wood movement between hill slopes, riparian forests and stream channels in forested watersheds is shown in Figure 1.1. Headwater streams are supplied with wood from riparian forests and hill slopes, while high-order channels are supplied with wood from riparian forests and headwater streams. Within the channel, wood may proceed through several functional stages before being depleted by an output process. Input and output processes differ among reaches, watersheds and landscapes. Each process affects the abundance and characteristics of woody debris, and each process occurs over different periods of time. Separate budgets can be linked to create a budget for an entire watershed. Most studies of woody debris focus on a subset of input or output processes, usually examining one part of the wood budget in detail (Hassan et al., 2005). These studies have identified the major processes affecting woody debris inputs, storage and outputs, and their importance in wood budgets. The major processes that occur in temperate streams are summarized in the following section.

1.1.1 Wood recruitment (inputs)

Woody debris is derived from the branches and trunks of trees in the riparian forest or farther upslope. The movement of wood from these sources to the stream is caused by a variety of mechanisms. Chronic inputs of wood include stand dynamics and stream bank erosion. Episodic inputs include tree throw, forest fires, insect and disease epidemics and mass wasting. The dominance of these different processes depends on the geomorphic, hydrological and climatic conditions among locations in the channel network (Hassan et al., 2005).

A primary source of wood in forested streams is chronic tree mortality by senescence and competition, particularly in mature forests (Bormann and Likens, 1979; Benda and Sias, 2003; Powell et al., 2009). Recruitment can occur during, shortly after or many years after tree death. Snags can remain standing for over 140 years in the Alberta Foothills (Jones, 2009). The likelihood that a dying tree will enter the stream increases with valley slope, since steep banks and valley walls tend to make trees fall toward the stream (Murphy and Koski, 1989). The likelihood of wood recruitment to streams is also a function of source distance. Source distances have been calculated in several studies (e.g., McCleary, 2005; Dahlstrom and Nilsson, 2006); in general, wood recruited from fine-scale mortality is equivalent to the average or maximum tree height. Wood entering streams by fine-scale mortality tends to be randomly distributed, reflecting the irregular spacing of trees in natural forests (Kraft and Warren, 2003).

Bank erosion can also be a dominant chronic recruitment process and can recruit wood in three ways. Erosion can destabilize living trees, causing them to topple into the stream and die. Previously fallen terrestrial woody debris can enter streams when banks are undercut by stream erosion. Finally, bank erosion can exhume relict wood pieces long buried in the flood plain, although exhumation is rarely a significant part of the overall wood budget (Benda et al., 2003). Wood input from stream bank erosion can account for a large proportion of total wood recruitment in $>3^{rd}$ order reaches, particularly in migrating channels. For example, input rates of 1-6 and 1-16m^3 of wood per year have been documented by Martin and Benda (2001) and Benda et al. (2002) in their wide study streams. Hassan et al. (2005) pointed out that few studies have measured the volume of wood recruited by erosion in small streams. However, bank erosion is generally less important in small streams because they have less erosive power and are often confined and incapable of significant lateral migration (Nakamura and Swanson, 1993). For example, Benda et al. (2002) found input rates from bank erosion on the order of 0.01 m^3/yr in a small stream. In high-gradient headwater streams with bedrock channels, recruitment by erosion is virtually absent (Keller and Swanson, 1979; Nakamura and Swanson, 1993).

Episodic natural disturbances including catastrophic windthrow, mass wasting, stand-replacing fires and large insect infestations recruit wood to streams (Hogan et al., 1998; Benda and Sias, 2003; Hassan et al., 2008; Jones and Daniels, 2008). Major episodic processes recruit wood in non-random, aggregated distributions. Windthrow may recruit wood on small to large scales, and is a moderately important form of wood recruitment in both small and large streams (e.g., Harmon et al., 1986; Nakamura and Swanson, 1993; May and Gresswell, 2003). Windthrow chronically recruits dead branches, topples individual trees and snags, or episodically destroys entire stands depending on the intensity of the wind and the stability or condition of trees. Large windstorms can create clusters of new wood recruits oriented perpendicularly to the stream or parallel with the wind direction (Seo et al., 2010). In addition to climate variables which determine the characteristic wind direction and speed, wind throw can be a function of topography. Small upland reaches experience more frequent and intense windstorms than downstream reaches due to their location near ridge tops or in confined valleys that funnel wind (May and Gresswell, 2003). In general less wood is recruited by wind throw than by bank erosion in $>3^{rd}$ order reaches (Reeves and Burnett, 2003).

Stand-replacing forest fires promote wood recruitment by reducing bank stability and causing tree mortality (Young, 1994; Berg et al., 1998). These processes contribute a pulse of dead wood to streams over the course of several years (Jones and Daniels, 2008). The intensity of a fire event and return interval or frequency of fire controls how much wood is contributed this way (Agee, 1993). Fire frequency varies with elevation, season, proximity to oceans and climatic cycles such as the PDO and El Niño, and may be reduced by fire suppression (Daniels et al., 2011). In general, inland watersheds are more prone to fire than coastal basins. In some regions, fire affects headwater streams more often than large streams in valley bottoms because hillslopes are generally drier and more susceptible to fire that burns upslope (Agee, 1993).

Insect and disease outbreaks occur periodically and can cause episodes of extensive tree death in riparian forests. The likelihood of disease and insect infestation is not inherently different between upper and lower parts of the drainage network unless forest composition differs with elevation or soil moisture. However, drier forests in montane or inland areas tend to be more susceptible to these disturbances in western Canada (Scherer, 2009). Severe insect and disease outbreaks generate the residual dead wood but the pulse of wood recruitment can be delayed (Young, 1994). For instance, interior forests in western Canada have been dramatically affected by mountain pine beetle outbreaks in recent years; however, the proportion of wood recruits from affected forests may be small. Hassan et al. (2005) reported that the amount of wood recruited after a mountain pine beetle outbreak fell within the natural range of variability of recruitment rates for small streams in the interior of British Columbia.

In many streams, mass wasting is a significant form of episodic wood recruitment. However, recruitment from mass wasting is highly variable over time and space. Of the types of mass wasting that can affect streams, one of the most influential and best documented types are debris flows. Debris flows are likely to propagate on slopes of >15 degrees (Hassan et al., 2005) and in humid environments (Gomi et al., 2002). In steep headwater streams, debris flows can account for the majority of wood recruitment (May and Gresswell, 2003; Reeves and Burnett, 2003). For instance, Reeves and Burnett (2003) found that 46% of in-stream wood volume had been derived from upslope sources in a small creek in coastal Oregon.

In low-gradient and large streams, mass wasting can have negligible effects on wood recruitment. Episodic mass wasting processes are absent in some low-gradient landscapes where hill slopes are less prone to failure. In high-gradient landscapes, large streams are often buffered from hill slopes affected by mass wasting by floodplains. As well, debris flows can be retained upstream by stable wood structures and other obstacles (Swanson et al., 1976). For instance, very few debris jams were found in wide segments of the Queets River in Washington state (Abbe and Montgomery, 2003) or in Game Creek in Alaska (Martin and Benda, 2001), although both watersheds were steep and upper reaches were prone to debris flows. Benda and Dunne (1987) estimated that, in general, debris flows are not significant downstream of 1 km^2 drainage area in high-gradient watersheds and this approximate boundary has been confirmed in subsequent studies (Montgomery and Foufoula-Georgiou, 1993; May and Gresswell, 2004; Comiti et al., 2006).

Mass wasting increases the interconnectivity of different parts of watersheds in two ways. Landslides and debris flows couple streams with hill slopes, increasing the area from which wood is derived to encompass both riparian forests and upper hill slopes (Gomi et al., 2002; Brardinoni and Hassan, 2006). Secondly, debris flows force the downstream transport of wood in small reaches where fluvial transport is negligible, thus creating a major control on sediment and wood routing from upper to lower sections of drainage networks (Gomi et al., 2002). Wood transported by debris flows tends to create large, chaotic debris jams composed of all size classes which lack and characteristic orientation (Abbe and Montgomery, 2003; Hogan, 1989).

1.1.2 Wood storage

The total volume of wood in storage in a stream reach is called the wood load. The amount of wood in storage is one of the most frequently measured parts of the wood budget (See Jones et al., 2010, Table II), and it has been used to make inferences about other parts of the wood budget, such as recruitment rates and sources.

The residence time of wood within a reach depends on the depletion processes acting on the log, which, in turn, vary with climate and location in the stream network. Persistence in storage has been measured using tree ring data, carbon isotope dating, modelling decay and transport rates and by annual surveying. Residence time has been shown to be highly variable (Powell et al., 2009; Hyatt and Naiman, 2001). Individual pieces of wood are commonly stored for over 100 years in small temperate streams, and have been found to persist for up to 1400 years (Swanson et al., 1976; Hyatt and Naiman, 2001). Storage occurs during periods of low flow, or in places where there are obstacles that trap wood. Such features include boulders, meander bends, wood bridges and log jams, or at slope breaks such as confluences. While wood remains in storage, its distribution reflects recruitment conditions and may be random or aggregated.

The amount of wood in storage has been measured using inconsistent methods among studies because there are no universally accepted size criteria for woody debris. Hassan et al. (2005) and Wohl et al. (2010) call for the standardization of terminology in order to produce comparable woody debris datasets. The most commonly used minimum piece size is 0.1 m in diameter by 1.0 m long (see Jones et al., 2010, Table II). This definition originated in studies conducted on the west coast of North America, where trees and woody debris are large. It is also based on the assumption that larger wood pieces are more important to stream functioning than small pieces and, therefore, are the priority for measurement. However, definitions and size criteria based on absolute piece size may not be reasonable to apply to all streams since woody debris varies in size and can be small, as it is in many inland watersheds. Absolute size definitions have the additional disadvantage of not accounting for stream size.When using absolute size criteria, only a fraction of the total wood load is measured. Small pieces of wood that may have geomorphic and ecological functions are not measured. This can be a serious oversight when trying to understand wood dynamics in small headwater streams (McCleary, 2005). A small number of studies have used more inclusive size definitions when either the study streams or the debris-forming trees were small (e.g., diameter = 5 cm or length = 0.5 m, see Jones et al., 2010, Table II). Recognizing the problem of scale, Martin and Benda (2001) used two size definitions to accommodate the large range of stream widths included in their study. Several authors have proposed that woody debris size criteria and terminology would be most appropriately determined by scaling wood to stream size, particularly in downstream studies (e.g., Gurnell et al., 2002; Hassan et al., 2005; Ewan, 2010; Wohl et al., 2010).

1.1.3 Wood outputs

Wood is removed from storage by decay and fluvial transport. Of the three components of wood budgets, output processes have been the least studied (Hassan et al., 2005). In general, wood output is difficult to quantify because output processes occur over long periods of time, and can be difficult to determine. Several previous studies incorporated all output processes into a single, total output rate sometimes referred to as depletion (e.g., Scherer, 2004; Harmon et al., 1986; McHenry et al., 1998). Other studies have assumed that depletion rates were equivalent to input rates (Hyatt and Naiman, 2001) or that depletion rates were constant over time (Murphy and Koski, 1989).

Wood pieces decay over time via fragmentation, abrasion, leaching, collapse, seasoning and respiration (Harmon et al., 1986). The rate of decay depends on the tree species, temperature, degree of submergence and burial (Harmon et al., 1986). Coniferous wood is more resistant to decay than deciduous wood (Harmon et al., 1986). Decay tends to occur more slowly in streams than terrestrially due to lower temperatures and relatively anoxic conditions underwater or under sediment (Guyette et al., 2002; Hyatt and Naiman, 2001), all of which limit microbial activity (Harmon et al., 1986). As well, woody debris may decay more quickly in warm subtropical streams than in boreal or temperate climates (Wohl and Jaeger, 2009). The complex processes that contribute to decay require more study, as variation in decay rates and controls remain insufficiently quantified (Scherer, 2004; Hassan et al., 2005). Although rates of decay vary, in general the size of wood pieces declines and in-stream functions change as decay progresses (Jones et al., 2010). Wood decay is more likely to be a major wood output in small streams that cannot mobilize wood (Hassan et al., 2005).

Negative exponential decay models have been developed for streams in the Pacific Northwest in which 1-3% of wood was lost to decay per year (Harmon et al., 1986; Murphy and Koski, 1989; Hyatt and Naiman, 2001). Predicting future wood loads based on such decay rates should be done with caution, because wood load estimations are extremely sensitive to small differences in decay rates (Benda and Sias, 2003). In-situ decay curves have also been calculated by several researchers using dendrochronology and C^{14} dating. Powell et al. (2009) found that the half-life of coniferous wood pieces in small streams in the Alberta Foothills was 47 years. In a wide river in northern Quebec, Arsenault et al. (2007) found the average wood residence time was 150 years, and Hyatt and Naiman (2001) calculated a half-life of only 20 years in a large alluvial river in Washington. The least time-consuming approach to characterizing successive states of wood decay is to use decay classes. Decay classes are based on morphology and integrity of the wood and can be quickly assessed in the field (Maser et al., 1979; Jones and Daniels, 2008; Powell et al., 2009).

Several woody debris studies have quantified decay in particular stream types (e.g., Jones and Daniels, 2008; Powell et al., 2009; Guyette et al., 2002), but the only studies to my knowledge that have examined decay from a downstream perspective were Arsenault et al. (2007), Chen et al. (2006) and Seo et al. (2010). Arsenault et al. (2007) noted that the decay rate differed for buried and exposed logs. In their study, logs remained intact for much longer when they were buried in sediment, and more logs were buried downstream, so in general wood was less decayed downstream. In contrast, Chen et al. (2006) observed that highly decayed wood was more abundant in larger streams ($\geq$4 m wide). Based on a previous study by Seo et al. (2008), Seo et al. (2010) concluded that biological decomposition rates would decline from small to intermediate streams due to increased wood submergence, which reduces microbial activity, but that fragmentation from abrasion would simultaneously increase.

The second major method of wood depletion is fluvial transport. Fluvial transport is the main connection between wood budgets in up- and downstream reaches within basins, so understanding downstream change in transport is key to understanding wood dynamics at the landscape scale. Fluvial transport is virtually non-existent in small headwater streams, but can be a big component of wood recruitment and depletion in larger streams. Wood transport occurs much like sediment transport. After entering the channel, wood is entrained, transported downstream a certain distance via floating, rafting or rolling (Braudrick and Grant, 2000), and then deposited until it is re-entrained, buried or decayed (Gurnell et al., 2002). Transport can occur continuously or episodically over time, and this process may cause either input or output wood from a reach (Berg et al., 1998). Transport and decay occur simultaneously. Wood transport is further complicated by the asymmetric and highly variable morphology of logs (Berg et al., 1998), which have complex interactions with channel dimensions and morphology. As well, the presence of stable woody debris affects the transport capacity of streams, making log stability highly site-specific (Turcotte, 2004). The variability of these factors in natural channels makes realistic modelling of wood transport difficult (Merten et al., 2010).

The primary controls on wood transport have been determined based on a combination of flume and field studies. Using controlled flume experiments, Braudrick and Grant (2000) identified three main factors that determined the probability of transport: the ratio of piece length to stream width, the ratio of piece length to the radius of stream curvature and the area of stream in which stream depth exceeded the log's buoyant depth. However, their flume experiments did not include obstacles within the stream, so the conditions were not similar to those found in most streams in nature.

More studies of wood transport have been conducted in the field. These studies typically infer transport rates based on annual movements of tagged wood or annual changes in wood volume. For instance, Berg et al. (1998) found that 31% of woody debris was transported after a high-flow season but that very little wood was transported after a low-flow season in small to medium sized streams. Lienkaemper and Swanson (1987) found that 10% of wood recruited before their study and 24% of during-study recruits were transported over nine years in large, 10-20 m wide streams in Oregon. Young (1994) found that 18% of woody debris pieces were transported over the course of a single year in an undisturbed 7 m-wide stream, but that 58% of wood pieces were mobile in a recently burned stream in Wyoming.

Such field studies have found that the primary controls over wood transport are stream flow magnitude (Berg et al., 1998), degree of anchoring or burial (Berg et al., 1998), length of wood relative to channel width (Berg et al., 1998; Gurnell et al., 2002) and wood diameter (Berg et al., 1998;

Martin and Benda, 2001). In general, then, the larger the stream, the less stable wood will be. However, there is still an incomplete understanding of wood transport processes and rates, particularly between stream sizes (Hassan et al., 2005), and wood transport has not been very successfully modelled or predicted in the field (Turcotte, 2004). For instance, several researchers have reported being surprised by how mobile wood was in small and medium-sized reaches (Wohl and Jaeger, 2009; Young et al., 2006), and unintended transport of reintroduced wood is a common problem in stream restoration projects, despite best efforts to ensure wood stability (Shields, 2002). The difficulty in predicting wood mobility is partly because stability is controlled by numerous processes (Merten et al., 2010), and partly because episodic peak flows that cause most wood transport occur infrequently over time, requiring long term monitoring to accurately characterize maximum transport capacities.

1.2 Conceptual model of watershed scale wood dynamics

Because wood input and output processes differ spatially, wood dynamics vary among parts of the watersheds (Figure 1.1). To understand wood dynamics at the watershed scale, there is a need to examine the downstream patterns of wood inputs, outputs and storage in stream.

Several authors have noted that a landscape perspective is one of the major gaps in the state of knowledge of woody debris (Swanson, 2003; Hassan et al., 2005; Seo et al., 2010). In particular, our knowledge about basin-scale wood transport dynamics is limited (Hassan et al., 2005). Few conceptual models have been developed to describe the general downstream changes in wood (Wohl and Jaeger, 2009). Hassan et al. (2005) suggested a conceptual model depicting the connections between upstream and downstream wood source zones and wood transport processes based on Benda and Sias (2003), in which fluvial transport was only present in "higher order" areas. Based on field observations, Wohl and Goode (2008) described similar changes in wood transport and supply; they concluded that streams can be divided into transport-limited, transport-dominated and supply-limited zones, which were later outlined in Wohl and Jaeger (2009, Figure 7).

In a similar model, Marcus et al. (2003) proposed that watersheds could be divided by stream order into headwater, intermediate and large streams. They made these divisions based on the volume of wood they observed in reaches and the amount of wood transported before and after a storm. In their model, transport was insignificant in headwater streams (1^{st}-2^{nd} order), and was significant in intermediate streams (3^{rd}-4^{th} order), where wood moved in pulses during high flows, and in large streams (5^{th}-6^{th} order) where most wood moved during normal flows. However, their study defined transport-limited headwater streams as over 10 m wide, which is an unusually large definition for small streams.

Seo et al. (2008) also described wood transport among small (6-20 km^2 drainage area), intermediate (20-100 km^2) and large watersheds ($>$100 km^2) by examining the volume of wood exported from streams of different sizes into reservoirs across Japan. Unlike the other studies, they concluded that the rate of wood transport is moderate during high-flows in small streams, is highest in intermediate streams, and is low in large streams where most wood is stored on the floodplain. In a subsequent review of watershed-scale woody debris dynamics, (Seo et al., 2010) presented gradational transitions between watershed zones instead of proposing discrete boundaries, which, they argued, were imprecise.

Finally, Gurnell et al. (2002) also divided stream networks into three parts, in which the divisions were defined by scaled relationships between wood and stream size. In their model, wood transport was limited where most wood pieces were longer than stream width. In summary, each conceptual model of watershed-scale wood dynamics differentiated a transport-limited, upstream headwater zone from various forms of transporting, downstream zones.

Each of these models assumed that streams generally conform to the river continuum concept (Vannote et al., 1980), in which stream size and discharge increase gradually with drainage area and, thus, transport capacity increases downstream. However, not all rivers work this way, particularly in glaciated basins. Hanging valleys and glacial saddles cause local increases and decreases in slope and, therefore, in water velocity and transport capacity (Brardinoni and Hassan, 2006). Montgomery (1999) pointed out that stream morphology and ecology are actually shaped by a combination of basin-scale continuum processes and local patch-forming processes, which can be described collectively as process domains. Therefore, processes which disrupt continuum-like changes in rivers should be considered when examining woody debris on larger spatial scales. The conceptual models of wood transport outlined by Gurnell et al. (2002); Marcus et al. (2003); Wohl and Jaeger (2009); Seo et al. (2010) are, in theory, most applicable to rivers that display a continuum of changes, and are less controlled by local lithologies and topographic features that disrupt gradual downstream changes. Stream networks with low relief, simple geology and uniform climate are most likely to have continuum-like characteristics (Montgomery, 1999).

We lack a quantitative understanding of where transport initiation begins within stream networks. Few studies have examined changes in wood characteristics and transport from upper to lower reaches. Instead most studies have focused on either small (e.g., Millard, 2001; McCleary, 2005) or large streams (Hyatt and Naiman, 2001; Lienkaemper and Swanson, 1987; Nakamura and Swanson, 1993). As well, few studies have examined riparian forest dynamics and how input rates are organized across landscapes. Understanding the nature and location of the transition from transport-limited to transport-dominated parts of the stream network is particularly important in headwater regions, where up to 80% of total stream length is comprised of 1^{st} and 2^{nd}-order streams, which implies that transport boundaries or transitions occur frequently throughout watersheds. Headwater streams are often difficult to access (Benda et al., 2005) and monitoring wood movement over time is expensive and slow (Kraft and Warren, 2003). Thus, it is also important to be able to efficiently interpret wood dynamics from wood characteristics observed in the field. Managers and researchers alike must continue to study wood at the watershed scale.

1.3 Objectives

Little research has considered downstream patterns of wood abundance or wood input and output characteristics, which are the links between woody debris, forest and hillslope dynamics. This study attempts to bridge these two gaps in knowledge. Therefore, the objectives of this study were (1) to document downstream patterns of wood characteristics in a low-gradient forested stream network and (2) to identify the transition from transport-limited to transport-influenced reaches within an undisturbed stream network to identify the point of transport initiation.

To meet these objectives I quantified downstream changes in eleven wood characteristics at 14 sites in a single stream network, and inferred which wood pieces had been transported from the observed attributes. Because the transport and turnover of wood loads occurs over long time scales, it was more effective to use this approach than it was to monitor wood piece movement directly. All observations were made within a single basin to avoid the confounding affects of geomorphic and forest variation among basins. As well, I selected a basin with similar forest stands throughout the riparian zone, which made reaches easier to compare. I hypothesized that wood abundance would decrease downstream, and that wood would differ from nearby trees and become increasingly large, loose, oriented parallel and aggregated downstream. As well, I expected wood would be less decayed, older, and more functional downstream. I hypothesized that the transition from transport-limited to transport-dominated wood regimes would occur at the boundary between colluvial and fluvial channels.

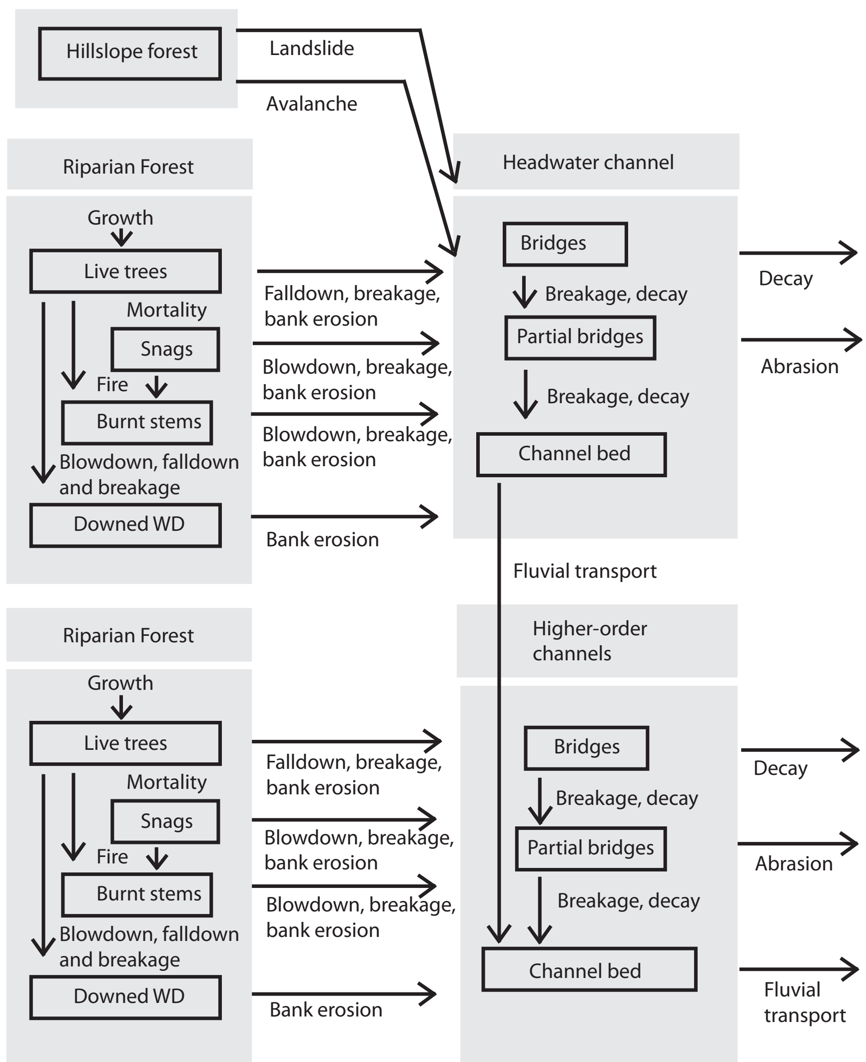

Figure 1.1: Conceptual model of a wood budget for a watershed. Boxes indicate wood storage sites and open text indicates processes affecting wood movement. Modified from Hassan et al. (2005) and McCleary (personal communication, 2011).

Chapter 2

Methods

2.1 Study area

This study was conducted in Wigwam Creek, a 90 km^2 sub-basin of the MacLeod River watershed in Alberta, Canada. Wigwam Creek is part of the Hinton Wood Products Forest Management Area (HWP FMA), which is a jointly managed research and industrial forest comprising the eastern portion of the Foothills Research Institute (FRI) land base. The HWP FMA is located on the eastern slopes of the Rocky Mountains in west-central Alberta (53°0'N 122°53'W) within the Upper and Lower Foothills Natural Subregions (Figure 2.1), and lies within the Athabasca and North Saskatchewan River watersheds.

Wigwam Creek was selected as a suitable study basin because much of its area was forested with undisturbed, mature stands over 80 years old, and the stream was affected by few road crossings yet remained accessible. Logging had occurred in many upland areas over 100 m away from the channel, but riparian forests were intact. A continuous survey of the stream network was not feasible, so I focused field work on the thorough investigation of 14 study reaches and adjacent forests along one stream. Study reaches were positioned to characterize downstream patterns of woody debris and riparian forest conditions (Figures 2.2, 2.3 and 2.4). Ten sites were located on the main channel, and four were located on 1^{st} and 2^{nd} order tributaries. Areas affected by beavers were avoided.

Surficial materials in this region are composed of thick layers of glacial till and colluvium overlying Paleozoic bedrock of sandstone and shale (Beckingham et al., 1996), creating a topography of rolling hills and plateaus. Soil types include grey luvisols and brunisols, which are associated with deciduous and coniferous forests in cool climates (Agriculture and Rural Development, 2010). In forested riparian zones, soil moisture regimes are mesic to subhydric (Alberta Sustainable Resource Development, 2005). The climate is characterized by long, cold winters and cool summers. The average annual temperature is 3°C, with a mean temperatures of -6°C in the winter and 11.5°C in the summer (Strong, 1992). Annual precipitation is approximately 540 mm, the majority of which is spring and summer rain resulting from frequent convective storms.

Stream hydrological regimes are snowmelt-dominated in the Upper Foothills. Annual peak flows occur in May during snowmelt, and secondary peaks occur in July in response to frequent rainstorms (Culp et al., 2005). No hydrological data have been recorded for the Wigwam basin. However, regional relations of peak flows with drainage area have been developed for the Upper Foothills which indicate that the two year flood discharge rates range from 1 to 10 m^3/s for streams spanning the range of drainage areas that I investigated (Table 2.1). Headwater streams comprised over 70% of total channel length in the Wigwam basin, resulting in a very high density of small streams (McCleary et al., 2003).

Riparian zones of the Upper Foothills are dominated by mature coniferous stands. The average age of riparian trees is 75 years in the Upper Foothills sub-region, and approximately one quarter of riparian stands established prior to 1850 (Andison and McCleary, 2002). The average density and height of riparian forests are 3,375 trees per hectare and 22 m respectively (Andison and McCleary, 2002; Alberta Sustainable Resource Development, 2005). Diameter distributions in riparian forests typically decline exponentially with increasing diameter, and maximum diameters rarely exceed 50 cm (Andison and McCleary, 2002). Riparian zones in Wigwam Creek were dominated by closed-canopy coniferous forests that consist of lodgepole pine (*Pinus contorta*), white spruce (*Picea glauca*), black spruce (*Picea mariana*), and alder (*Alnus incana*) (Beckingham et al., 1996). Lodgepole pine is typically found in uplands and recently burned areas, while black and white spruce are dominant in low-lying areas and late-successional forests (O'Leary et al., 2002).

Riparian stand distribution was patchy along Wigwam Creek, which is characteristic of the Upper Foothills natural subregion (McCleary et al., 2003). Riparian zones were white spruce-dominated along the eastern headwater reaches, and were black spruce-dominated along the main stem up to approximately 14 km^2 drainage area (Figure 2.3). Between 14-28 km^2 drainage area, forest density declined and forest stands were intermittent or absent. Downstream of 28 km^2 drainage area riparian zones were forested with spruce stands in which lodgepole pine was the secondary species.

Streams and riparian forests have been affected by both natural and anthropogenic processes in the Upper Foothills. Stand-replacing fires constitute the primary natural disturbance in the region, with a return period of 80-120 years in the Upper Foothills (Beckingham et al., 1996; Andison, 2000). Anthropogenic activities include logging, oil and gas extraction, and the construction of seismic lines and roads. Approximately 1% of the Hinton Wood Products Forest is harvested annually, and remaining stands have undergone over 50 years of fire suppression. The cumulative impact of human activities in the Foothills has caused fragmentation of forest cover and consequently has reduced the area of undisturbed in-stream and core forest habitat.

To identify the dominant processes that control the landscape I conducted a process domain analysis of slope-area relationships and channel classification. By relating breaks in slope with observations from the digital elevation model I identified the geomorphic features of each study reach (Figures 2.4 and 2.5). Basin characteristics (e.g., valley width and drainage area) and other channel variables (e.g., slope) were derived from 2 m-resolution LIDAR data using the geomorphic modelling program Netmap (Benda et al., 2007). Wetland locations were collected from the 2006 Alberta Vegetation Inventory database and from field observations. The main stem of Wigwam Creek flows through a low-gradient hanging valley formed by two ridges oriented northeast to southwest. First-order streams developed on slopes of 0.05-0.1 km^2 drainage area. Drainage area increased gradually along the main stem from 0.1-10 km^2 as it flowed through the hanging valley. At approximately 10-12 km^2 drainage area there was a subtle valley step of up to 0.07 m/m slope, where the hanging valley met the wider main valley. Downstream of the valley step channel sinuosity increased, slope declined

(0.01-0.02 m/m) and drainage area increased because several tributaries joined the main channel. This low-gradient zone was part of a large wetland that was unsuitable for sampling because of the lack of woody debris. First-order tributaries continued to join the main stem predominantly from the northern ridge.

Each study site was identified as fluvial or colluvial by applying the classification system of McCleary et al. (2009) to field observations of stream structure and sediment composition. Colluvial reaches differ from fluvial reaches because they lack sufficient stream power to transport their bed surface materials (Hassan et al., 2005). Study reaches were classified as colluvial if they possessed six or more of the following characteristics: the majority of sediment on the streambed surface is smaller than sand; boot sinks >10 cm into streambed; no pools present; no riffles created by mobile cobbles; undercut width exceeds stream width; organic bridges present; headcuts are present; the widest channel width >3x the narrowest width (McCleary et al., 2009). Based on this suite of characteristics, reaches with drainage area up to 3 km^2 were classified as colluvial (Figure 2.5). These process domains and the location of the boundary dividing them are typical of the Upper Foothills landscape but differ from mountainous coastal basins in British Columbia, Washington and Oregon (e.g., Benda et al., 2005).

Table 2.1: Estimated maximum discharge (m^3/s) in HWP FMA streams. Source: Hydroconsult (1997).

Drainage area (km^2)	Return period		
	2 yr	10 yr	100 yr
1	0.1	0.5	1.0
10	1.0	4.0	10.0
100	10.0	20.0	99.0

2.2 Data collection

2.2.1 Stream surveys

Surveys of each of the 14 study reaches were conducted to describe their dimensions, morphology and stream power. Study reaches were established by installing a marker post at an upstream benchmark and recording its UTM coordinates. To compare small to large streams, study reach lengths and sampling intervals for the stream survey were scaled to stream size represented by bankfull width. Bankfull is the highest stage that can be reached in a channel before water enters the floodplain (Radecki-Pawlik, 2002). I took bankfull measurements because they can be used to estimate the maximum competence and power of stream channels. I identified bankfull in each channel by noting changes in vegetation and bankslope (Dunne and Leopold, 1978). Reach length was $\geq$40x the average bankfull width (W_b) measured at the upstream benchmark. Cross sections were measured at intervals of 2 W_b along the reach (e.g. in a stream with a W_b of 1.5 m, the measurement interval was 3 m). A downstream benchmark was established at the end of the stream reach. The mean bankfull depth (W_d) and width of each study reach was calculated from survey measurements.

Stream depth, unit morphology and dominant size class of bed surface sediment were assessed at every cross section. Bankfull depths were recorded at three regular intervals across the channel bed. Units are short, structurally distinct channel segments (Hassan et al., 2005). Observed morphology types included step-pool, pool-riffle, forced step-pool and plane bed, which are described in Table 2.2 (Benda et al., 2005). For each cross section I noted whether woody debris or boulders forced the local morphology (McCleary et al., 2009). The dominant sediment size was visually estimated using the Wentworth (1922) grain-size scale.

Table 2.2: Unit morphologies of headwater streams. Modified from Hassan (2005)

Type	Description
Colluvial	Contain sediment derived from adjacent hillslopes which the streamflow is too weak to move. Often irregular in width, and can have sections that are buried.
Pool-riffle	Sequence in which an undulating streambed develops by scour and deposition in gravel-bed rivers.
Step-pool (forced/not)	Sudden drop in channel bed caused by an obstruction. Occurs in small streams with low sediment supply and large logs or boulders.
Plane bed	Featureless gravel beds without pools also known as rapids.

2.2.2 Tree-wood comparison

Riparian forest conditions

The point centered quarter method (Cottam and Curtis, 1956) was used to characterize the species composition and density of riparian forests and allow comparison to in-stream woody debris (Hyatt and Naiman, 2001; Mitchell, 2007). At every study reach, four sample points were established on either side of the stream (n = 8). Sample points were located 10 m from the stream, and points were spaced evenly between upstream and downstream benchmarks. The area surrounding each point was divided into four quadrants (N, S, E, W). In each quadrant (n = 4 trees per point) the distance to the closest living tree $\geq$5 cm in diameter was measured to the nearest 0.1 m, and the species and diameter at breast height were recorded. In total, 32 trees were surveyed per site.

Woody debris survey

In every study reach I surveyed all individual wood pieces of sufficient size. Woody debris was defined as any fallen or suspended part of a dead tree lying completely or partially within the bankfull channel. Broken or detached logs were counted as separate wood pieces even if they originated from the same tree (MacLean et al., 2003).

All pieces of wood $\geq$5 cm in diameter and $\geq$50 cm long were inventoried and assigned a unique identification number. Because wood pieces <10 cm diameter are important structural and functional components of 1^{st} order streams (Seo et al., 2010; Comiti et al., 2006; Jackson and Sturm, 2002), I used more inclusive criteria for log length and diameter than most woody debris surveys to accommodate the small streams included in this project. Log diameter was measured at the centre of the stream channel. The total piece length and the length between bankfull margins, called "in-stream wood," were measured to the nearest 0.1 cm.

2.2.3 Downstream change in wood attributes

Orientation, position, and decay

To observe downstream changes in the character of wood debris, the orientation, position and decay class of each log was recorded. Piece orientation was visually estimated and classified as perpendicular (~70-90°), diagonal (~20-70°) or parallel (~0-20°) to the thalweg (Figure 2.6). Each log was assigned to one of five position classes according to its location in the channel cross section (Figures 2.9, 2.8 and 2.7). Position classes describe both the vertical location in the channel and the degree of embeddedness in the stream banks or bed (see Table 2.3). The state of decay of each log was quantified using 5-category scheme adapted from Maser et al. (1979) and Jones and Daniels (2008) based on the integrity of the wood and the presence of needles and bark (Figure 2.10, Table 2.4).

Origin of wood pieces

I stratified woody debris into locally recruited and unknown origin categories. It is useful to distinguish between locally-recruited and non-local woody debris because their proportions indicate the influence of wood trans-

Table 2.3: Position classes

Position	Description
Bridge	Piece rests on stream banks suspended over the channel. Does not interact with stream flow except during floods.
Partial bridge	One end rests on the stream bank, and the other rests on the stream bed.
Anchored	Buried in stream bed or banks.
Loose	Unattached piece that may float, rest on a stream bank or lie on the stream bed. Position is changeable and easily entrained.
Braced	Loose wood held in place by other woody debris.

Source: McCleary, 2003.

port processes within a reach. Local origin was assessed by observing whether wood pieces were rooted to stream banks, were connected to the adjacent forest, or had broken from a stump or snag (Martin and Benda, 2001). All pieces with known origin had not been transported, and all unattached or deeply buried wood pieces were classified as unknown. Although some studies have assumed that logs without visible local origin were fluvially transported (Urabe and Nakano, 1998), I was conservative and called such pieces "unknown origin." Therefore, the number of locally-recruited wood pieces identified using this system were minimum estimates.

Geomorphic function

To complement the assessment of unit morphology forcing by wood, individual logs were assessed for the types of geomorphic and hydraulic functions they provided to the stream. Function classes describe types of wood influence on in-stream processes but not their magnitude, and function cat-

Table 2.4: Decay classes

Class	Description
1	Wood is hard. Red or green needles are usually present. All bark is still intact.
2	Wood is hard. Some needles may be present but bark has begun to fall off.
3	Wood is hard or slightly soft. No bark present. Often feels light or hollow.
4	Wood is substantially decayed and pieces easily slough off. Inner heartwood may be soft but is intact. Moss is often present on unsubmerged surfaces.
5	Wood is decayed throughout and collapses when kicked. Texture can be slimey. Extremely waterlogged and heavy. Moss is often present on unsubmerged surfaces.

Modified from: Jones and Daniels (2008)

egories were not ordered or hierarchical. Pieces could be assigned up to seven geomorphic function classes, which were identified by visual inspection (MacLean et al., 2003; Abbe and Montgomery, 2003; Martin and Benda, 2001). Wood pieces had to have a visible and direct influence on stream morphological features to be assigned to any function class. Two function classes described wood-forced unit morphologies, which included pool and log steps. Multiple pieces of wood could contribute to the same pool or step. Five function classes described how wood slows the transfer of in-stream materials. These included bank stabilizing, storing sediment, initiating log jams and storing fine (diameter $<$5 cm) or large wood (diameter $\geq$5 cm). Bank stabilizing wood was embedded in the stream bank and was usually parallel in orientation (MacLean et al., 2003). Logs that trapped sediment upstream or downstream in noticeable quantities were classified as storing sediment.

Jam-initiating pieces were those that held log jams in place.

2.2.4 Wood distribution

To assess the spatial distribution of logs within each reach, the location of each log was measured in relation to the upstream benchmark. Measurements were taken from the up- and downstream extent of the log within bankfull margins where wood intersected the stream bank. Measurements were made to the nearest 0.1 m using a measuring tape that extended above the stream parallel to the thalweg.

2.2.5 Wood year of death (YOD)

To compare woody debris year of death or age (time since death) along the stream network I randomly selected and extracted 25 log cross-sectional disks from five study sites. These sites were chosen to represent a range of stream sizes and transport capacities including small colluvial to large fluvial reaches (Sites 3, 5, 7, 10 and 13). Logs were selected for sampling using a random number table and were limited to logs with diameter $\geq$8 cm to ensure that ring series were long enough to successfully crossdate and logs that could be sampled safely. I sampled the most intact part of the stem to ensure that I was capturing the outer tree ring, which represented the best estimate of the year of death (Daniels et al., 1997). For most samples, cross-sectional disks were taken from parts of the log that were exposed and accessible to the chainsaw. I unearthed buried pieces, lifted submerged wood out of the water, stabilized cross-sectional disks with duct tape and used a bow saw to hand cut samples when pieces were too deep to use the chainsaw.

Samples were wrapped for transport and air-dried for several months.

2.3 Data analysis

2.3.1 Reach characteristics and transport capacity

Total and unit stream power of each reach was determined using estimated roughness coefficients and peak discharge calculations. I compared the field estimates of sediment size and the streamside vegetation conditions depicted in site photos with standard stream photos in Barnes (1967) and Hicks and Mason (1998) to estimate Manning roughness coefficients (n) for every reach. To calculate stream power from peak discharge, I had to determine the hydraulic radius and average velocity of each stream. Hydraulic radius (R) was calculated as follows:

$$R = \frac{\bar{A_b}}{2 \cdot \bar{D_b} + \bar{W_b}} \tag{2.1}$$

Where A_b is bankfull area calculated as bankfull width (W_b) multiplied by average reach depth. Average velocity (v) was calculated using the Manning equation (1891):

$$v = \frac{1}{n} \cdot R^{0.67} \cdot S^{0.5} \tag{2.2}$$

Where n is the Manning roughness coefficient (Manning, 1891) and S is stream gradient (m/m), derived from the Netmap reach data. Peak discharge (Q, m^3/s) was calculated using the bankfull measurements for each study reach and the calculated average velocity (v):

$$Q = \mathrm{v} \cdot \bar{\mathrm{W}}_{\mathrm{b}} \cdot \bar{\mathrm{D}}_{\mathrm{b}} \tag{2.3}$$

Total stream power (ω_{total}) was calculated as:

$$\omega_{\mathrm{total}} = \rho \mathrm{gQS} \tag{2.4}$$

where ρ is the density of water (1000 kg/m^3); g is gravity (9.8 m/s^2); Q is the peak discharge (m^3/s); and, S is stream gradient (m/m). Finally, unit stream power (ω_{unit}) was calculated as:

$$\omega_{\mathrm{unit}} = \rho \mathrm{gQS/w} \tag{2.5}$$

The relationships between drainage area and total stream power, bankfull width and bankfull depth were tested using semi-log regressions using the statistical package R (version 2.10.1).

2.3.2 Riparian forests

The total density (number/ha) of trees in each riparian forest was estimated using the mean distance between the sample points and trees as follows (Cottam and Curtis, 1956):

$$\mathrm{Density} = 10000/(\mathrm{dist\bar{a}nce})^2 \tag{2.6}$$

To estimate the total basal area (m^2/ha) of trees in each riparian forest, the basal areas of individual trees were calculated using equation 2.7 and summed.

$$\text{Basal area} = \pi \cdot \mathrm{r}_{\mathrm{i}}^{2} \tag{2.7}$$

Differences between riparian forests were examined in terms of size structure, composition and age. I used a Kruskal-Wallis test, the non-parametric version of a one-way ANOVA, to test for differences in tree diameters among riparian sites. Where significant differences ($\alpha = 0.05$) were detected, Mann-Whitney post-hoc tests were used to differentiate pairs of riparian sites. The alpha level for these and all other statistical tests was 0.05, unless otherwise specified.

2.3.3 Comparison of woody debris and riparian forests

To test the hypothesis that the size of woody debris and riparian trees were similar within sites, I compared the means and frequency distributions of live tree and woody debris diameters at each site. Since the data were not normally distributed, I plotted box plots and used the non-parametric Mann-Whitney test to compare means (Conquest and Ralph, 1998; Hyatt and Naiman, 2001). Diameter distributions were plotted as histograms and cumulative distribution curves of the tree and woody debris diameters were compared using the Kolmogorov-Smirnov test (Zar, 1984). Pairs of distribution curves within sites that were significantly different indicated a decoupling between the trees and in-stream wood. The drainage area of each site was noted and downstream patterns of tree-wood decoupling were identified visually.

2.3.4 Downstream change in wood characteristics

The following section explains how wood attribute variables were derived from the wood survey data and were tested to identify downstream trends. The hypotheses and tests performed are described in the following three sections, which are divided by the spatial scale of analysis: (1) individual pieces of wood (2) reach-scale wood load and (3) reach-scale wood attributes.

Individual wood pieces

The characteristics of individual pieces of wood were examined down the stream network using wood piece diameter, length, stability and volume. Diameter, in-stream and total length data were taken directly from the wood survey dataset. The volume of each wood piece was calculated using diameter and length measurements in the equation for a cylinder. This equation does not reflect the tapered shape of tree trunks and branches; however, it is a standard technique in the woody debris literature (Wohl et al., 2010) and was precise enough for my purposes. Both the total and in-stream volume was calculated for each log using the total and in-stream wood piece lengths.

The size of wood relative to the channel in which it is stored is an important determinant of its likelihood of movement, termed stability. I assessed the stability of individual wood pieces by scaling individual pieces of wood to channel dimensions. Two methods of scaling have been found to be effective indicators of stability; these are the ratio of wood diameter to stream depth (L_d:D_b) and the ratio of wood length to stream width (L_l:W_b)

(Braudrick and Grant, 2000; Gurnell et al., 2002). Therefore, I calculated these unitless ratios for each piece of wood (Equations 2.8, 2.9). To test the hypotheses that wood size increases and wood stability decreases downstream, I examined the relationships between the mean diameter, length, volume and the stability ratios (L_l:D_b and L_l:W_b) with drainage area using semi-log regressions. Since the distributions of all individual piece size variables were skewed, I used their geometric means in these analyses.

$$L_d : D_b = \text{diameter/mean bankfull depth} \tag{2.8}$$

$$L_l : W_b = \text{total length/mean bankfull width} \tag{2.9}$$

$$\text{Volume}_{total} = \pi(\text{diameter}/2)^2 \cdot \text{length}_{total} \tag{2.10}$$

$$\text{Volume}_{in-stream} = \pi(\text{diameter}/2)^2 \cdot \text{length}_{in-stream} \tag{2.11}$$

Reach-scale wood load

To test the hypothesis that more wood is stored in non-transporting upstream channels than in transporting downstream channels, I compared the number of pieces and the total volume of in-situ wood among reaches. To derive reach-scale wood loads, I counted the number of individual pieces and added their in-stream and total volumes. Because the study reaches varied in length, the frequency and total wood volumes were scaled to allow comparison among sites and with other studies (Jackson and Sturm, 2002; Chen et al., 2006; Scherer, 2009; Wohl and Jaeger, 2009). Wood piece frequencies and volumes were scaled to stream length (per 100 m stream) and surface area (per m^2 stream surface). The scaled frequency and volume wood data were plotted against drainage area and semi-log or linear regressions were used to test for downstream trends.

Reach-scale wood attributes

Wood attributes included classification of the orientation, position, decay, function and origin of individual pieces of wood. For each attribute, the proportion of wood in each class at each site was calculated. For the wood origin analysis, all anchored wood pieces were excluded because it was not possible to ascertain their origin due to their position buried in the streambed or bank (Benda et al., 2002). To test for downstream changes the resulting proportions were plotted against drainage area on scatter graphs, and semi-log regressions were conducted.

Three additional attributes were derived from the original wood and stream classifications: position types, wood-forced morphologies, and stability classes. Position classes were grouped by piece location relative to the bankfull margins. Two resulting position types were active logs that were wholly within the bankfull margins and included the loose, braced and anchored classes and inactive which were partially or fully outside the bankfull margins and included the bridge and partial bridge classes. Based on the stream surveys, the proportion of wood-forced pool and riffle unit morphologies were calculated. The scaled stability ratios were divided into categories according to the classification system proposed by Hassan et al. (2005). Values of 0.0-0.33 for either of the two ratios were low stability. Ratios of 0.33-0.66 were moderate stability and 0.66-1.0 or above were high stabliity. To test for downstream changes in these derived attributes, their proportions were plotted against drainage area on scatter graphs and semi-log regressions were conducted.

2.3.5 Wood distribution

To test the null hypothesis that wood distribution within study reaches was random, I employed a one-dimensional version of Ripley's K test (Kraft and Warren, 2003; Ripley, 1977) using R 2.10.1. This tool analyzes the spatial distribution of wood along a stream reach to classify it as random, aggregated or segregated. In this analysis, the stream reach was treated as a one-dimensional transect and each piece of wood was a point along the line. The distance from the upstream benchmark to the centre of each wood piece was calculated by averaging the upstream and downstream piece distances surveyed in the field. The Euclidean distance between all pairs of wood within each reach was calculated. To examine the size of wood aggregations, I performed the K(t) analysis on multiple scales (t) ranging from 1 to 20 m, after Kraft and Warren (2003) and Scherer (2009). For Site 14, I used larger scales because wood aggregations (log jams) exceeded 20 m in length. To assess the statistical significance of the calculated K statistics, I performed 10 000 Monte Carlo simulations using the equivalent number of wood pieces and reach length for each analysis and derived 95% confidence intervals. Only statistically significant distribution patterns were reported in the results.

The K(t) analysis was applied to all woody debris in each reach as well as on subsets of woody debris reflecting the transportability of wood pieces.

In the first subset, the distributions of large (diameter $\geq$ 10 cm) and small (5-10 cm diameter) wood pieces were compared. Based on the premise that fine wood is more easily transported and jammed than large wood, I hypothesized that fine wood would be aggregated farther upstream than large wood. Second, the distributions of wood in active and inactive position types were compared. I expected that active wood would be aggregated in downstream, wider streams and inactive wood would be segregated at all sites. Third, wood was subdivided according to L_d:D_b and L_l:W_b stability classes. I hypothesized that low stability wood pieces (<0.33 L_d:D_b and L_l:W_b) would be aggregated in all reaches because it is relatively small and may require little power to entrain, and because it is less likely to get caught on stream banks due to its shape. I expected that moderate and high stability wood would be segregated or random.

2.3.6 Year of death (YOD)

Once dry, wood samples were glued to enhance structural integrity and sanded to 600 grit until rings could be clearly identified under a microscope. On each cross-sectional disk I selected two intact radii extending from the pith to the bark or outer ring that were spaced, when possible, approximately 90° apart. To help ensure that the ring series I measured were the product of regional rather than local growth patterns, I selected radii with minimal distortion from releases, local suppression or from branches.

I used standard dendroecological techniques to crossdate and assign a calendar year to the outer ring of sampled cross-sectional disks. The species of the woody debris was determined based on the colour and shape of the wood cells and the concentration and size of resin ducts as viewed under a microscope. Ring-widths of both radii were measured to the nearest 0.001 mm using a Velmex measuring bench interfaced with the tree ring measurement program MeasureJ2X (VoorTech Consulting, 2004). Ring series were crossdated against regional species-specific chronologies (Powell et al., 2009) using the statistical software COFECHA (Grissino-Mayer, 2001) and TSAP-Win^{TM} (Rinn, 2003). Correlation analyses in COFECHA used 50-ring segments with a lag of 10 rings. Potential outer ring dates with corresponding R-square values >0.32 were generally considered acceptable; however, in some cases, R-square values were low but the ring-width patterns matched clearly when examined graphically using TSAP. After assigning an outer-ring date to each sample and calendar years to each ring, I used visual crossdating to confirm that narrow marker rings such as 1926 were properly located, which verified that the outer-ring date was correct. By combining these dating techniques, I was confident that I had precisely estimated the year of the outermost ring, which estimates the year of death (YOD) of woody debris. This method assumes that the outermost annual ring was formed the last year the tree was alive and that decay and abrasion of outer rings was limited.

For each site I plotted woody debris YOD distributions as histograms to visually interpret age cohorts among sites. A statistical comparison of YOD distributions in different parts of the stream network was performed using a Kolmogorov-Smirnov test. I hypothesized that YOD distributions differed significantly among sites. Significant differences could be caused by either (1) transport or (2) differences in the riparian forest.

To examine processes that may underlie differences in YOD due to transport, I grouped the YOD data from all sites and determined if there were differences in YOD among other wood attributes, which may be indicators of wood transport. Specifically, I tested for differences in YOD between orientation, position and decay classes and small (unstable), medium and large (stable) stability classes using Kruskal-Wallis and post-hoc Mann-Whitney tests. Because of low sample size, the single sample in decay class 5 was grouped with decay class 4. A Mann-Whitney test was used to differentiate YOD between active and non-active position classes, and between logs with and without functions.

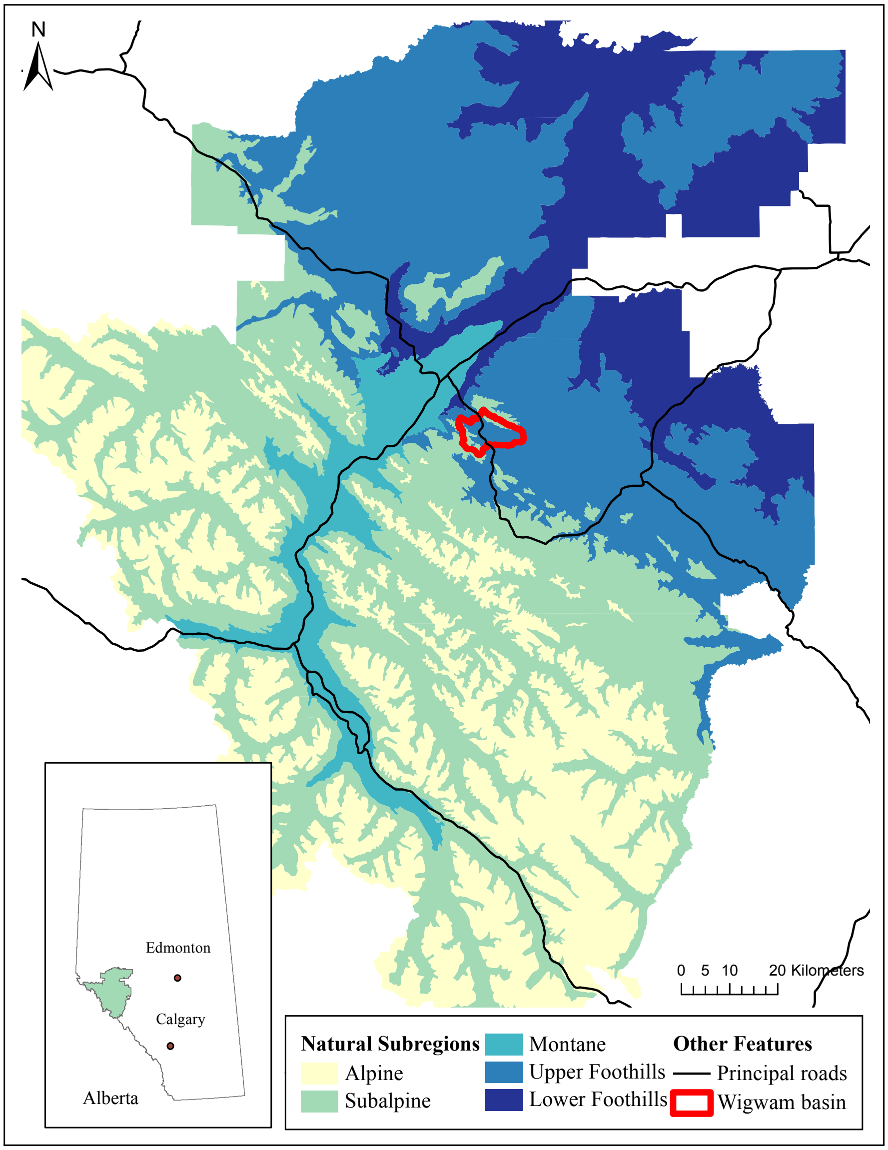

Figure 2.1: Natural subregions of the Foothills Research Institute land base, based on (Beckingham et al., 1996). The red outline indicates the location of Wigwam Creek. The location of the study area within the province of Alberta is inset.

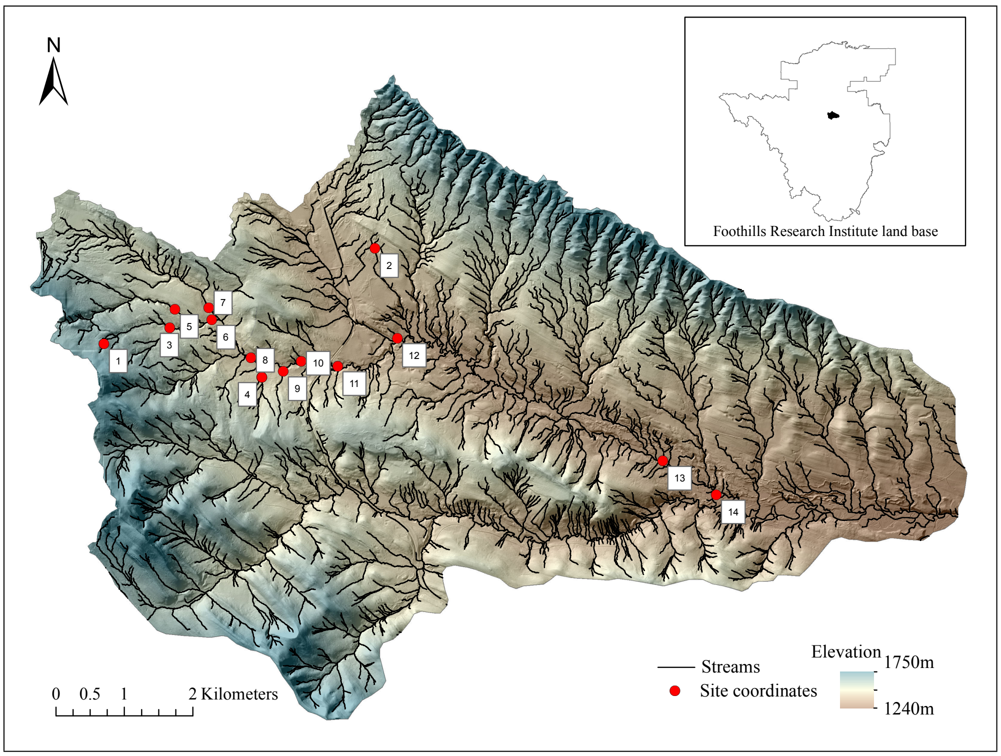

Figure 2.2: Location of study reaches in Wigwam Creek, and topography of the basin.

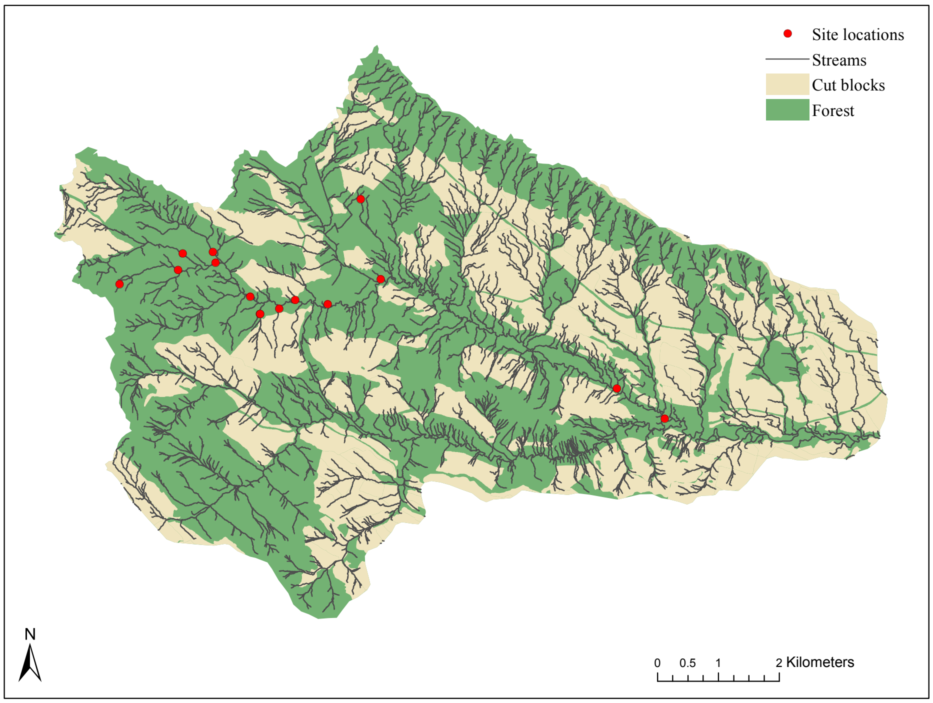

Figure 2.3: Map of intact forest and cutblocks in the Wigwam Creek basin. Logging occurred predominantly in upland areas between 1963-2002. Cutblocks frequently traverse 1^{st} and 2^{nd} order streams, but undisturbed forest was present along most of the main channel. All study sites were located in forested areas.

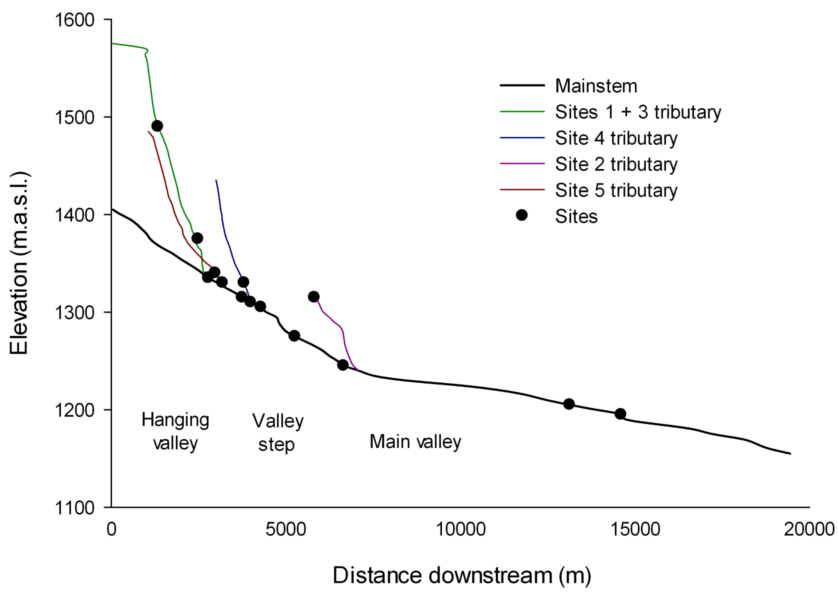

Figure 2.4: Longitudinal profile of Wigwam Creek and its tributaries. Black dots indicate the location of study reaches. The main stem flows east south-east. Sites 1, 3-5 are located in headwater tributary streams on the hillslopes of a hanging valley. Site 2 is located in a hillslope tributary in the main valley. Sites 9-10 are located on the valley step and Sites 11-14 are within the wide, low-gradient main valley.

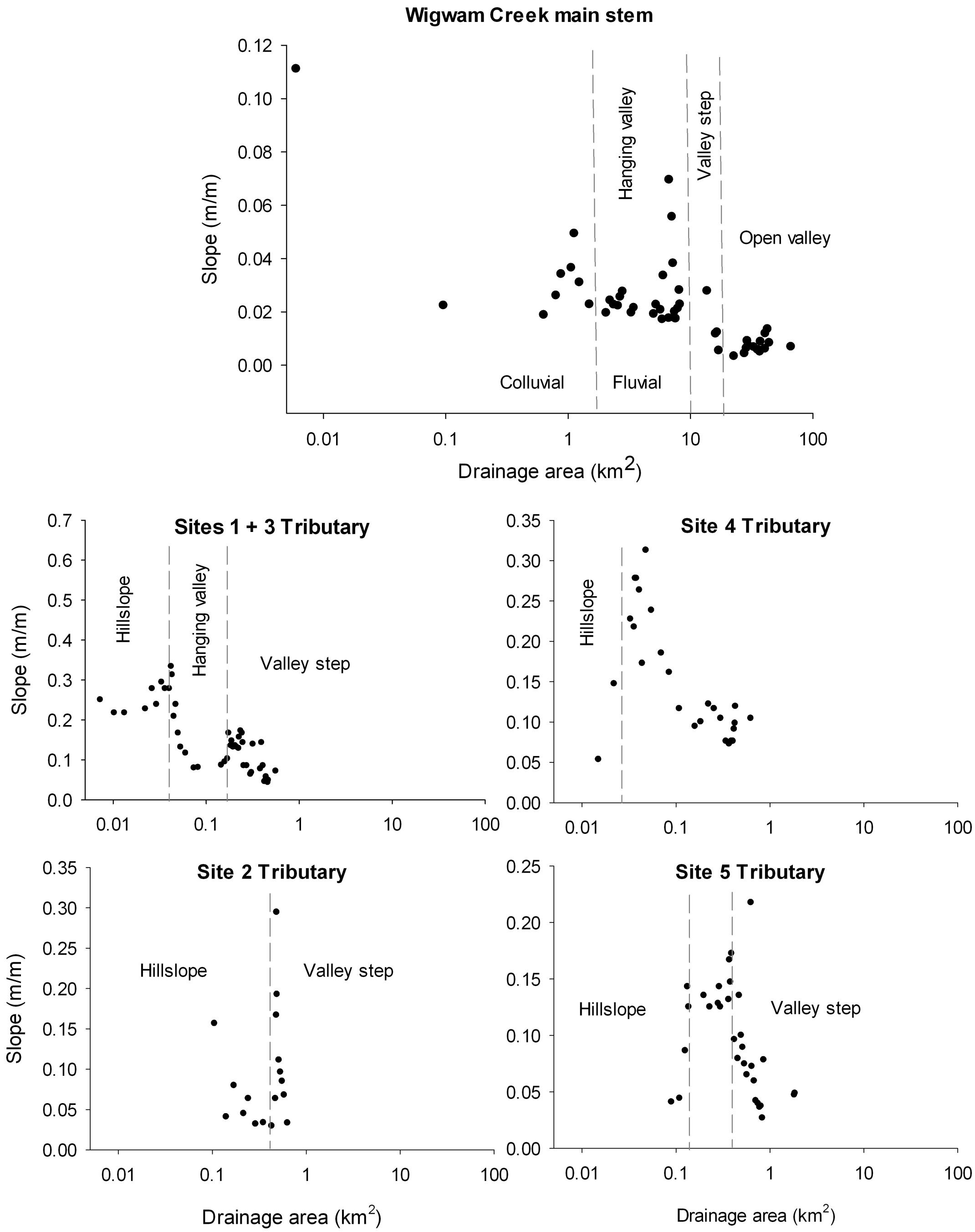

Figure 2.5: Slope-area relationships of Wigwam Creek and tributaries.

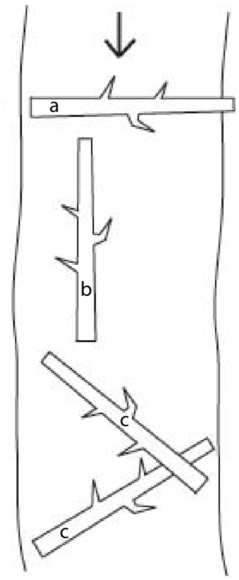

Figure 2.6: Orientation classes used in this study included a) perpendicular b) parallel c) diagonal. Orientation was assessed relative to the thalweg, indicated by arrow.

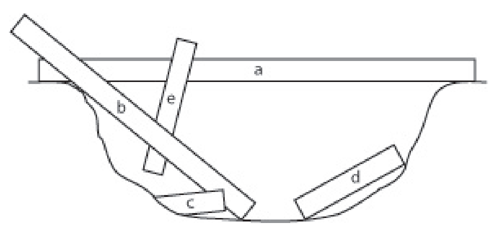

Figure 2.7: Conceptual illustration of log position classes in a stream channel: a) bridge b) partial bridge c) anchored d) loose e) braced.

Figure 2.8: Log in bridged position, Site 10.

Figure 2.9: Log in partial bridge position, Site 11.

Figure 2.10: Examples of decay classes 1-5 (left to right) in cross-sectional disks

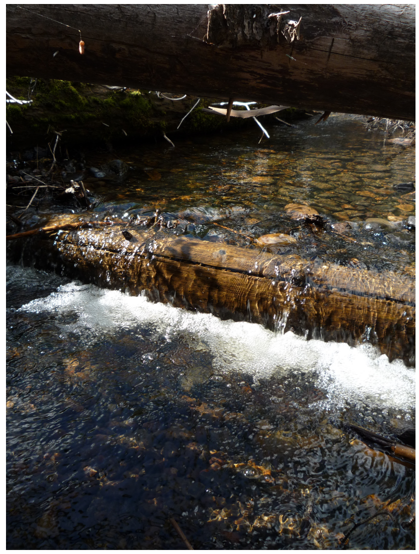

Figure 2.11: Woody debris creating a log step and storing sediment

Figure 2.12: Bridged log storing large and fine wood, Site 13. Larger tagged log is in braced position.

Chapter 3

Results

3.1 Reach characteristics

The study reaches covered a wide range of sediment textures, channel morphologies, channel dimensions and bed surface slopes, and many reach characteristics varied according to their location along the channel network. Characteristics of the study reaches are presented in Tables 3.1 and 3.2. The average stream width and depth increased with drainage area, although stream depth increased more gradually and less consistently downstream. The greater increase in channel width than depth resulted in low downstream velocities (Table 3.2). Because reach length was scaled to stream width, study reaches ranged from 25 m to 250 m long. One 7 by 12 m island was located near the downstream benchmark of Site 14. All other study reaches had simple single channels without vegetated islands. Study reach morphologies were colluvial in the seven smallest reaches (0.1-3 km^2 drainage area) and changed to fluvial step-pool and pool-riffle morphologies downstream (7-60 km^2) (3.1). The colluvial channels had deeply undercut banks and contained fine-grained sediment often overlying cobbles and boulders. In the smallest colluvial reaches, slumped banks sometimes filled the channel, causing the stream to flow underground for short distances (1-4 m).

Fluvial reaches had gravel or cobble beds, moderately undercut banks and meandering paths. Colluvial channels were under 1.5 m in width, while all fluvial channels - excluding Site 10 which was quite deep - were over 2 m wide.

Roughness coefficients were high due to complex channel shape and the presence of woody debris and vegetation on the stream banks (Table 3.2). All channels were low-gradient and channel bed slope generally declined downstream. The slope at Site 9 was moderately high relative to the surrounding area because it was located on the step of a hanging valley. Unit stream power ranged from 14 to 104 kg/s^3 among reaches, and total stream power ranged from 4 to 561 $kg \cdot m/s^3$ (Table 3.2). Total stream power increased significantly with stream depth (r^2=0.64, p<0.001) and drainage area (r^2=0.93, p<0.001), making stream dimensions and drainage area good indicators of stream power (Figure 3.1).

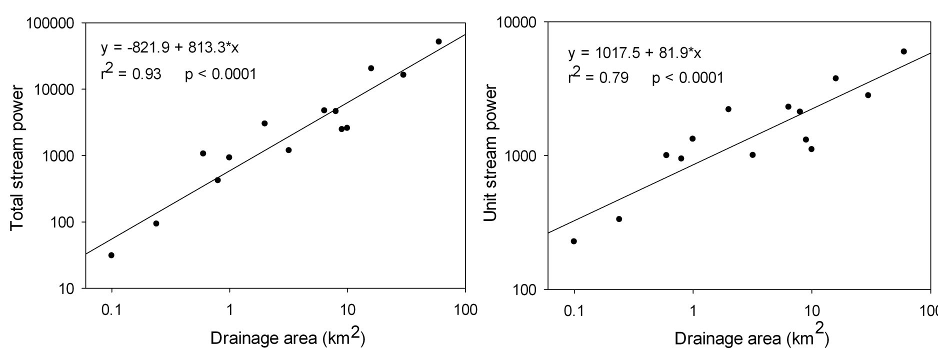

Figure 3.1: Downstream change in unit and total stream power. Both measures of power were significantly related to drainage area within the 14 study reaches.

Table 3.1: Physical characteristics of the 14 study reaches in the Wigwam Creek watershed in the Upper Foothills ecoregion of Alberta, Canada. For stream width and depth, means are followed by the standard deviation in parantheses.

Site	Drainage area[1] (km^2)	Reach length (m)	Bankfull Width (m)	Bankfull Depth (m)	Sediment type		Reach morphology
					Primary	Secondary	
1	0.1	25	0.1 (0.08)	0.1 (0.08)	Clay	Fine sand	Colluvial
2	0.24	30	0.3 (0.12)	0.1 (0.12)	Organic litter	Clay	Colluvial
3	0.6	50	1.1 (0.57)	0.2 (0.09)	Fine sand	Silt	Colluvial
4	0.8	35	0.4 (0.24)	0.3 (0.09)	Med. sand	Cobble	Colluvial
5	1	41	0.7 (0.34)	0.4 (0.11)	Fine sand	Cobble	Colluvial
6	2	75	1.4 (0.63)	0.4 (0.12)	Med. sand	Cobble	Colluvial
7	3	75	1.2 (0.58)	0.4 (0.15)	Med. sand	Gravel	Colluvial
8	7	100	2.1 (0.52)	0.5 (0.11)	Cobble	Med. sand	Step-pool
9	8	100	2.2 (0.51)	0.4 (0.13)	Cobble	Fine sand	Step-pool
10	9	125	1.9 (0.64)	0.7 (0.18)	Cobble	Med. sand	Pool-riffle
11	10	128	2.3 (0.83)	0.4 (0.14)	Cobble	Gravel	Step-pool
12	16	195	5.4 (2.03)	0.6 (0.18)	Cobble	Gravel	Pool-riffle
13	30	250	5.8 (1.72)	0.4 (0.23)	Cobble	Gravel	Pool-riffle
14	60	250	8.6 (2.13)	0.8 (0.24)	Cobble	Gravel	Pool-riffle

[1]Source: Netmap 2009 GIS data

Table 3.2: Stream characteristics used to derive power for the 14 study sites.

Site	Roughness	Bed slope (m/m)	Velocity (m/s)	Unit power (kg/s^3)	Total power ($kg \cdot m/s^3$)
1	0.07	0.12	0.60	24.03	5.29
2	0.07	0.04	0.51	13.52	3.78
3	0.07	0.05	0.78	39.84	42.09
4	0.09	0.08	0.76	58.24	25.78
5	0.12	0.08	0.74	31.90	22.20
6	0.10	0.05	0.88	69.80	94.44
7	0.13	0.03	0.46	16.62	19.63
8	0.10	0.02	0.71	45.92	94.21
9	0.20	0.10	0.72	28.76	62.38
10	0.20	0.02	0.35	22.31	41.94
11	0.16	0.02	0.37	18.95	43.90
12	0.12	0.03	0.83	103.91	561.13
13	0.06	0.01	0.75	20.57	118.81
14	0.09	0.01	0.85	49.40	424.82

3.2 Riparian forest characteristics

The riparian forests growing adjacent to each study reach were similar throughout the drainage network, with the exception of several forest attributes at Sites 2, 4 and 13 (Table 3.3). Riparian forests were dominated by white spruce (n = 12) or black spruce (n = 2), with minor components of pine, subalpine fir, or alder. At all sites forests were mature, having established between 1820 and 1880 (Table 3.3). Stem densities were lower than the regional average for riparian zones, varying from 636 to 2009 trees/ha. Canopy heights were over 18 m at all but Sites 2 and 4, where trees were shorter (Table 3.3). Forest basal area varied moderately among sites but was very low at Site 13 (Table 3.3).

The ranges and distributions of tree diameters were typical of mature riparian stands of the Upper Foothills landscape. Tree diameter ranges were similar among all 14 sites but median tree diameters were small at Sites 2, 4 and 13 (Table 3.3). Diameter distributions were of two general forms: (1) negative exponential, where frequency decreased with diameter (Sites 3-5 and 7-13) and (2) even distribution, where frequencies were similar among diameter classes (Sites 1, 2, 6, 14). Diameter distributions are depicted in in box plots (Figure 3.2) and in histograms (Figure 3.3, 3.4).

Table 3.3: Attributes of the riparian forest surrounding the 14 study streams. Riparian forest attributes are similar among sites, except for several attributes of Sites 2, 4 and 13. Low canopy height, DBH and basal area values are indicated in bold.

	Frequency							DBH (cm)			
Site	White spruce	Black spruce	Pine	Fir	Alder	Establishment (year) [1]	Canopy height (m)[2]	Median	Max	Density (stems/ha)	Basal area (m^2/ha)
1	15	0	0	17	0	1820	28	23.4	58.7	636	46.1
2	17	6	7	0	2	1880	**12**	**12.6**	27.3	1838	31.5
3	15	0	0	14	1	1820	28	22.6	42.6	763	41.7
4	3	26	0	3	0	1880	**16**	**9.4**	48.4	863	19.4
5	20	1	0	11	0	1820	25	16.4	43.5	805	26.6
6	16	15	0	1	0	1820	26	24.1	51.1	1004	58.3
7	24	7	0	1	0	1820	26	16.5	30.0	909	37.2
8	10	15	0	6	0	1820	24	17.5	36.8	1281	39.2
9	18	3	0	11	0	1820	24	16.0	45.9	1156	32.8
10	5	26	0	1	0	1820	24	14.5	37.7	2009	47.9
11	15	6	8	3	0	1920	18	18.5	46.7	1395	60.1
12	14	10	8	0	0	1880	18	19.9	60.3	1181	50.0
13	21	1	10	0	0	1850	20	**13.7**	40.6	872	**8.1**
14	19	6	2	1	3	1880	24	21.5	57.5	844	55.3

[12] Source: Alberta Vegetation Index 2006

3.3 Downstream change in wood characteristics

3.3.1 Similarity of riparian trees and woody debris

Woody debris pieces were generally smaller in diameter than riparian trees, and this difference was more pronounced in the fluvial study reaches. Woody debris and tree diameter distributions are compared in boxplots (Figure 3.2) and in histograms (Figures 3.3 and 3.4). In contrast with the negative exponential or even distributions of the live riparian trees (Figures 3.3, 3.4), woody debris diameter distributions had a negative exponential form at all sites (Figures 3.3, 3.4). The consistent difference between tree and woody debris diameters was in the smallest size class (5-15cm), where woody debris was more abundant than trees by 20 to 40% at all sites (Figure 3.3). Live trees were more abundant in the larger size classes at almost every site. The distributions of tree and wood diameters were significantly different at 9 of the 14 sites (Table 3.4). Similarly, the median diameter of woody debris was smaller than that of trees at all sites, and was significantly smaller at 8 of 14 sites (Table 3.4). The differences in the forms of tree and woody debris diameter distributions may be attributable to stand dynamics of mature forests, where small trees are preferentially recruited to the stream as they are out-competed by large canopy trees.

The pattern of tree-wood similarity over the stream network indicated that the size of woody debris ceased to correspond to the size of riparian trees as drainage area increased. Significant differences in diameter distributions and medians occurred in the majority of fluvial reaches (Sites 8-14) and in approximately half of all colluvial sites (Sites 1-7) (Table 3.4). With few exceptions, wood resembled tree diameters in only the smallest colluvial streams of $\leq$1 km^2 drainage area (Sites 1, 3-5). The decoupling of woody debris from riparian trees occurred upstream of the transition from colluvial to fluvial reaches identified in the domain analysis between Sites 7 and 8.

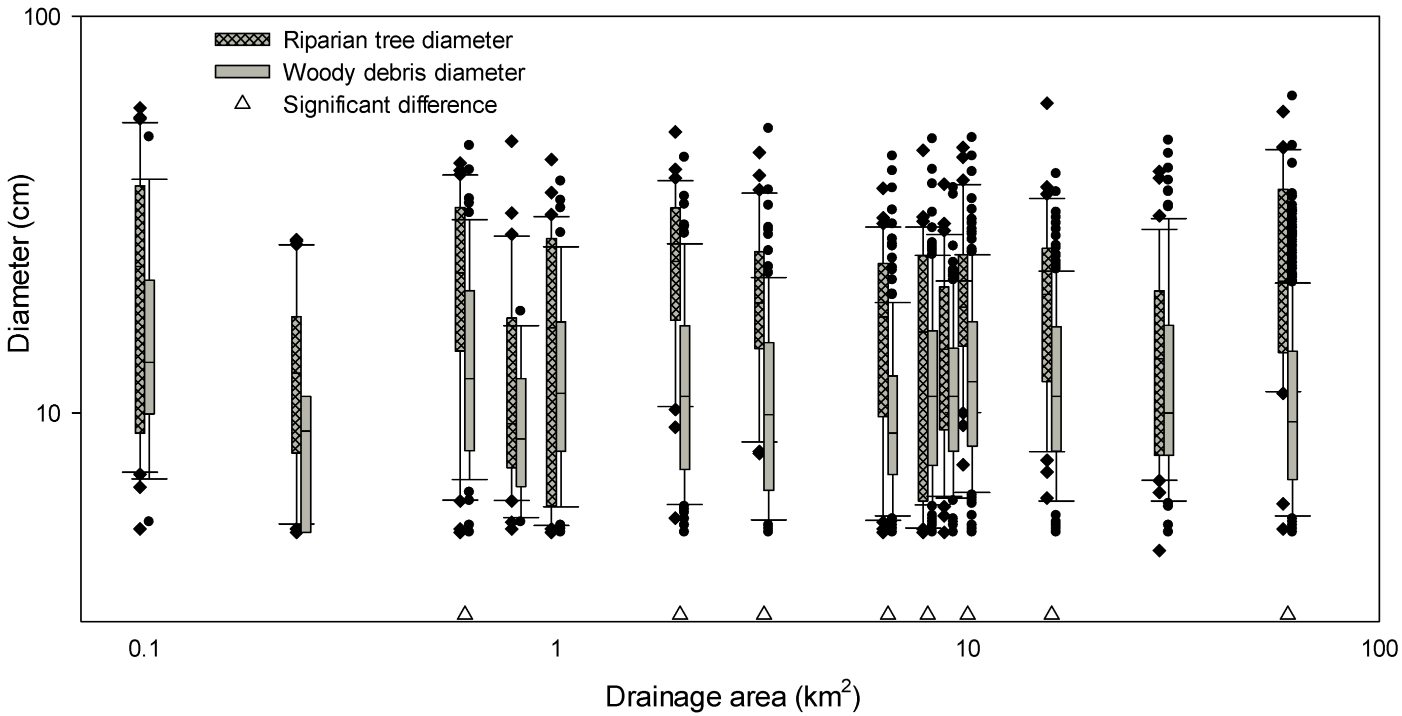

Figure 3.2: Diameter distributions of live riparian trees and woody debris with drainage area. The horizontal line in each box is the median, the lower and upper limits of each box are the 25^{th} and 75^{th} percentiles, the lines are the 5^{th} and 95^{th} percentiles, and the circles are outliers. Significant differences between diameter distributions are indicated with triangles. Tree diameters are larger than woody debris diameters at all sites. Tree and woody debris diameters are also presented in the Tree and Wood panels of Figures 3.3 and 3.4.

Table 3.4: Site-level comparisons of riparian trees and woody debris diameters. Median tree and wood diameters are shown, along with the results of the test of diameter means (Mann-Whitney U-statistic) and of distributions (Kolmogorov-Smirnov D-statistic) of site-level pairs of trees versus logs. Non-significant differences are indicated in bold.

Site	Median diameter (cm)		Mann-Whitney		Kolmogorov-Smirnov	
	Wood	Tree	U	p-value	D	p-value
1	13.4	23.4	234	**0.18**	0.35	**0.08**
2	9.0	12.6	22	**0.13**	0.63	**0.23**
3	12.0	22.6	556	<0.01	0.40	<0.01
4	8.6	9.4	227	**0.22**	0.26	**0.34**
5	11.2	16.4	710	**0.26**	0.28	**0.09**
6	11.0	24.1	493	<0.01	0.60	<0.01
7	9.9	19.0	665	<0.01	0.50	<0.01
8	8.9	17.5	1322	<0.01	0.51	<0.01
9	10.9	16.0	2147	**0.41**	0.33	<0.01
10	10.8	14.5	1203	0.03	0.29	0.04
11	11.8	22.6	1559	<0.01	0.43	<0.01
12	11.0	19.9	1646	<0.01	0.40	<0.01
13	10.0	13.7	1217	**0.34**	0.23	**0.16**
14	9.4	21.5	3440	<0.01	0.57	<0.01

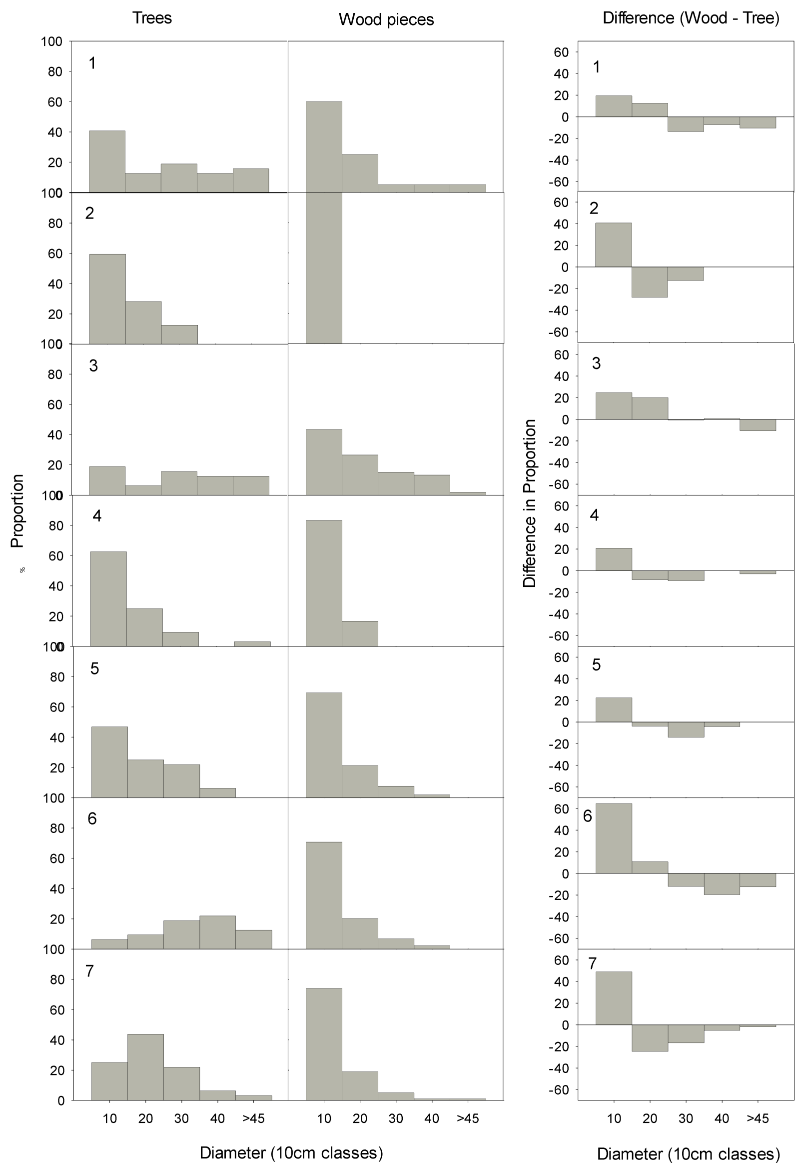

Figure 3.3: Diameter histograms of live riparian trees and woody debris at Sites 1-7. Each row of three histograms represents data for one study reach, and includes the proportional distribution of tree diameter, woody debris diameter and the positive or negative difference between them. Diameter classes are 10 cm bins beginning with 5 to 15 cm. Site numbers are shown in the top left-hand corner of each row. Sites 1-7 were classified as colluvial reaches, which lack the power to transport the materials that compose the channel bed. Tree and wood diameter distributions for all 14 sites are also presented in box plots in Figure 3.2.

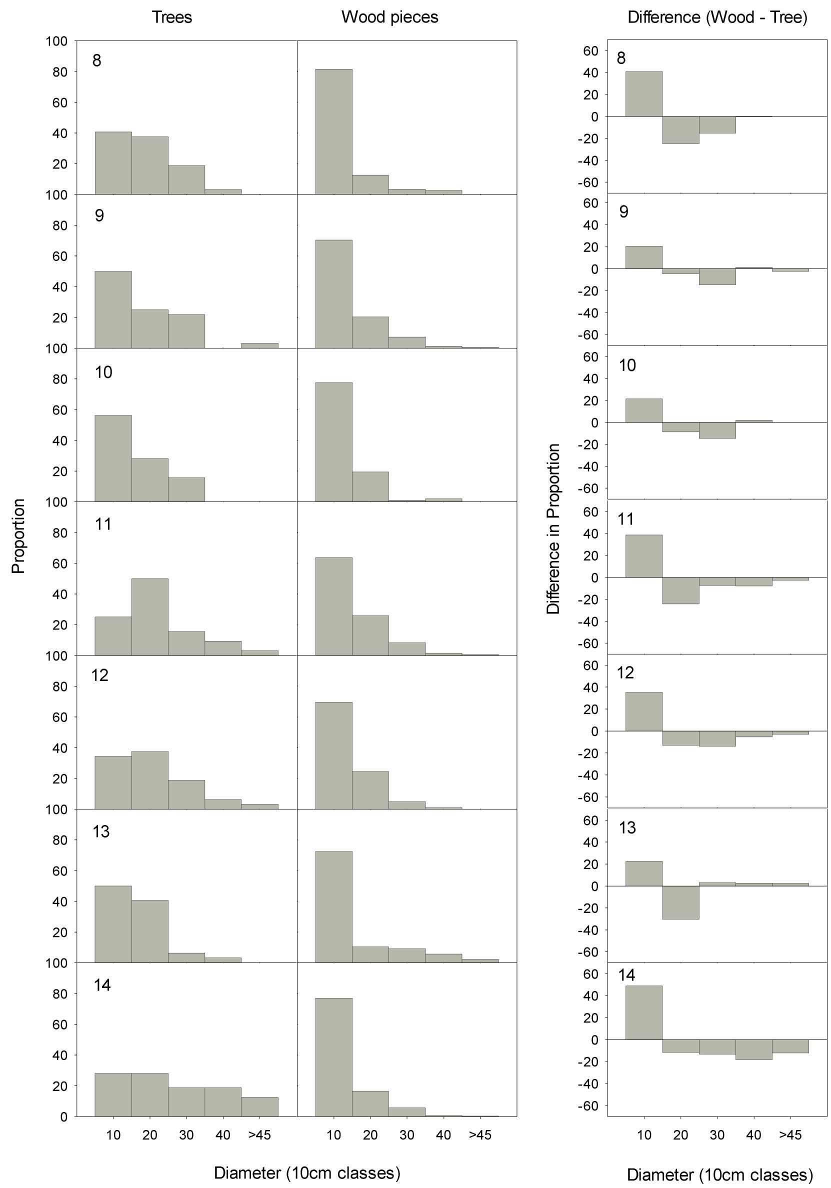

Figure 3.4: Diameter histograms of live riparian trees and woody debris at Sites 8-14. Data are presented as in Figure 3.3. Sites 8-14 were classified as fluvial reaches, which can transport bed materials.

3.3.2 Dimensions of individual wood pieces

A total of 1816 woody debris pieces were surveyed in the 14 study reaches. The mean diameter of wood pieces ranged from 8.3-17.3 cm among sites. Diameter ranges were similar among all sites except for Sites 2 and 4, where piece diameters were small because the wood was derived from low-diameter riparian stands (Figure 3.5). Most diameter distributions had a strong positive skew, indicating that thin pieces were more abundant than thick pieces of wood in the study reaches. Mean total piece length ranged from 3.0-8.9 m among sites, and the longest length observed was 30.2 m. The range of wood piece lengths varied little among sites (Figure 3.5) with the exception of Site 2 (n=3, maximum length=11.8 m), where the riparian canopy trees were only 12 m in height. Short wood pieces were more abundant than long wood pieces at most sites. In contrast to total wood piece length, the range of in-stream lengths varied considerably among sites. Maximum values ranged from 2.0 to 21.0 m, and means ranged from 0.9-3.8 m among sites (in-stream length, Figure 3.5).

The mean volumes of individual wood pieces ranged from 0.04 to 0.44 m^3 among sites. The mean in-stream volumes of the same wood pieces were smaller, ranging from 0.005 to 0.125 m^3 among sites, because they accounted for only the section of the log lying between the stream banks. Mean in-stream volumes were particularly low at Sites 1 and 2 due to small channel dimensions. Volume distributions were positively skewed at most sites, indicating that wood loads were composed of many small- to medium-sized pieces and fewer large logs (Figure 3.5). The range of in-stream piece volumes increased with drainage area and wood piece sample size.

A large range of wood stability ratios were observed. Wood piece diameters were 0.05-5.47 times as deep as the channel depth (Figure 3.6) and wood pieces were 0.05-118.0 times as long as stream width (Figure 3.6) over the stream network. Wood piece diameters that exceeded stream depth (L_d:$D_b > 1$) were observed as far downstream as Site 13. Extremely high maximum values for the stability ratios L_d:D_b and L_l:W_b were found at Site 2, the headwater stream with the smallest channel dimensions, because at this site wood pieces were longer than at other sites and the stream was narrow.

3.3.3 Downstream change in wood piece dimensions

Contrary to my hypothesis, the average size of wood pieces did not increase downstream. The mean diameter of wood pieces varied among sites but had no downstream trend (r^2<0.001, p-value = 0.99) while the average total length and total volume of wood pieces remained constant downstream (r^2=0.002, p-value=0.88 and r^2<0.001, p-value=0.98 respectively; Figure 3.7). However, the in-stream size and the stability of wood pieces showed significant downstream trends. The mean length and volume of logs within the channel increased with drainage area (r^2=0.70, p-value<0.01 and r^2=0.33, p-value=0.03 respectively; Figure 3.7). This trend corresponds to the downstream increase in channel width and depth. As predicted, the average stability ratios L_d:D_b and L_l:W_b declined significantly with drainage area (r^2=0.39, p-value=0.009 and r^2=0.83, p-value<0.001 respectively, Figure 3.6).

Several outliers were noted in the analysis of average piece dimensions and stability. Sites 2 and 4 were outliers with small mean wood diameters. At both sites, the adjacent riparian stands were composed of thinner-than-average trees. It is likely that these forests contributed correspondingly thin wood pieces to these reaches. As outliers with high values, Sites 1 and 2 were excluded from the regressions of total length and total volume against drainage area. At Site 1, the mean length and volume of wood pieces were exceptionally high because here, unlike most sites, longer logs were more abundant than shorter logs for reasons unknown. At Site 2, the mean length and volume of wood pieces were high because no highly decayed and snapped wood pieces were present in this channel. Unusual forest conditions such as low tree diameter and canopy height, high tree density and the general absence of downed wood on the forest floor led me to suspect that this site experienced some disturbance and may have established more recently than the GIS survey indicated. Because wood pieces were long and channel width was low (0.1 m), Site 2 was an outlier with a high average log length to stream width (L_l:W_b) stability ratio. As such this site was excluded from the L_l:W_b regression analysis.

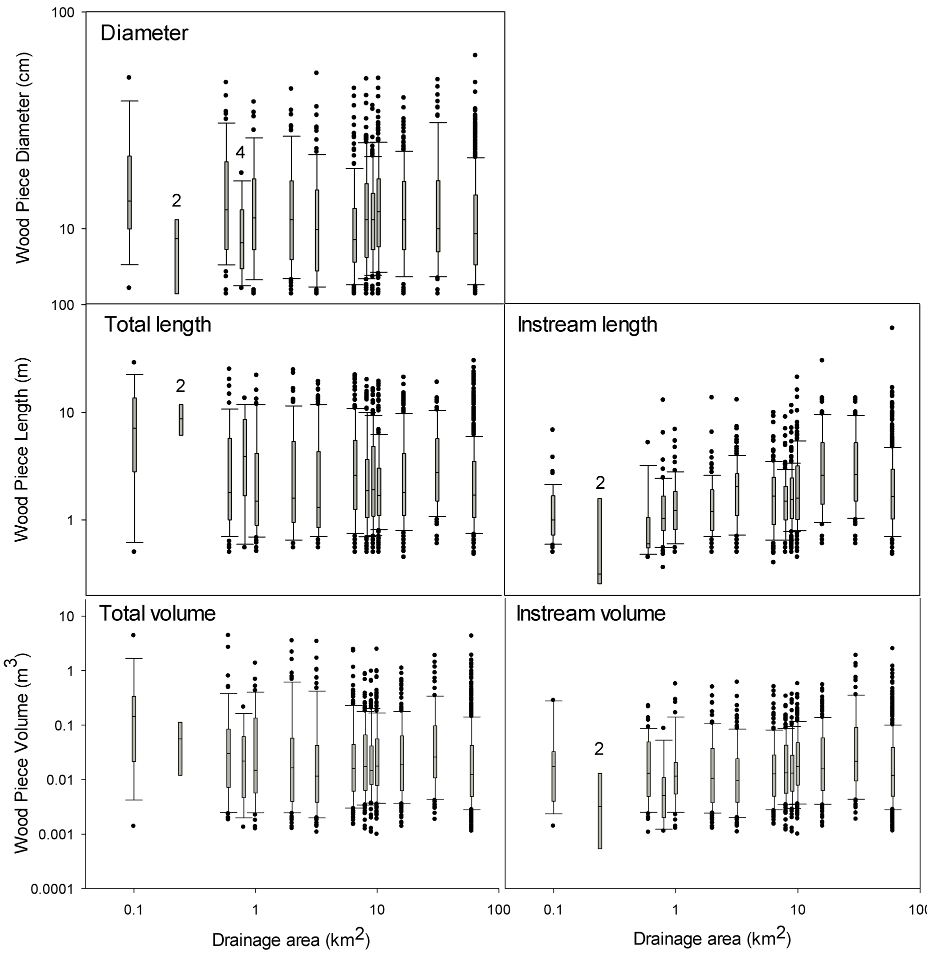

Figure 3.5: Downstream trends in the distributions of individual log diameter, total length, in-stream length, total volume and in-stream volume. Wood piece dimensions are not scaled to stream size. The horizontal line in each box is the median, the lower and upper limits of each box are the 25^th and 75^th percentiles, the lines are the 5^th and 95^th percentiles, and the circles are outliers. Numbers identify sites referenced in the text. Note, the y-axes vary among attributes.

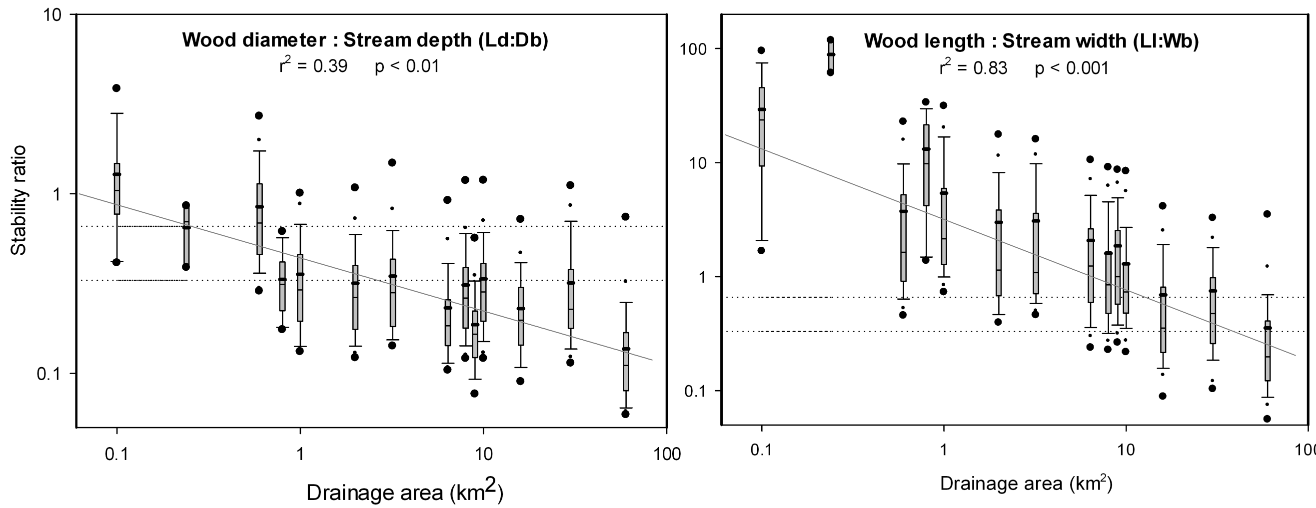

Figure 3.6: Downstream change in wood stability ratios or scaled wood dimensions. This figure shows site-level distributions of the ratio of wood diameter to mean stream depth (L_d:D_b; left panel) and the ratio of wood piece length to mean stream width (L_l:W_b; right panel). The horizontal line in each box is the median, the dot in each box is the mean, the lower and upper limits of each box are the 25^th and 75^th percentiles, the lines are the 5^th and 95^th percentiles, and the circles are outliers. The two horizontal dotted lines in each chart indicate the boundaries between different stability classes; low (<33% L_d:D_b or L_l:W_b), moderate (33-66%) and high >66%) stability. The proportions of wood in each stability class per site are shown in Figure 3.15. Note the different y-axes.

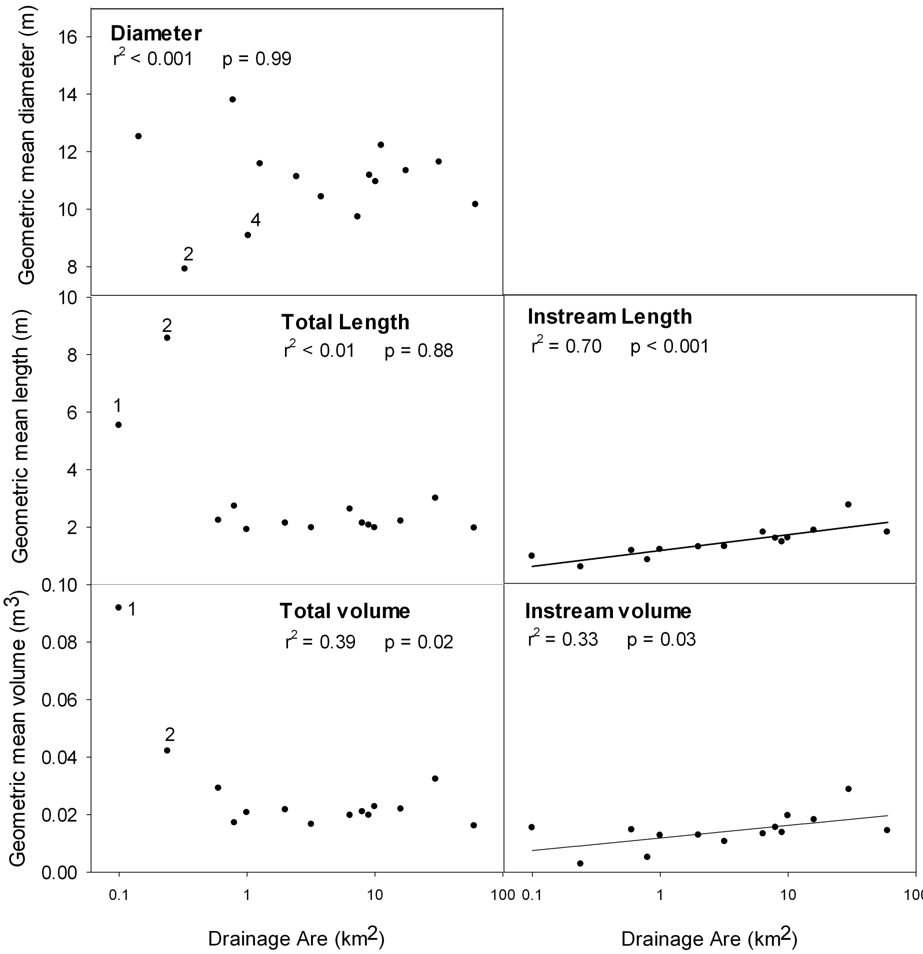

Figure 3.7: Change in average piece dimensions and drainage area. Geometric means of wood piece diameter, total and in-stream length and total and in-stream volumes are shown for each site. The complete distributions of each variable are shown in boxplots in Figure 3.5. Outliers are labelled with their site names. Sites 2 and 4 were outliers in some cases because of forest conditions. Site 1 was also an outlier in some cases but the cause is unknown. All regression lines are semi-log and do not include outliers.

3.3.4 Reach-scale wood load

The total amount of woody debris per site (wood load) is presented in Figure 3.8. In this figure, wood loads are presented by (1) absolute wood piece frequency, (2) frequency per 100 m of stream length, (3) the total and in-stream volume of wood per 100 m stream length and (4) the in-stream volume of wood per square metre of stream surface. These four ways of measuring and scaling yielded very different results.

The number of woody debris surveyed per reach ranged from 3 to 671 pieces. Scaled by stream length, wood piece frequencies varied less, ranging from 10 to 261 pieces (Top right panel, Figure 3.8). Total wood volume per 100 m ranged from 0.6 to 29.8 m^3. in-stream wood volumes were smaller and varied less between sites. They ranged from 0.05 to 5.07 $m^3/100$ m at Sites 1-13, and reached 12.7 $m^3/100$ m at Site 14 which was an outlier due to the presence of an extensive log jam. in-stream wood load scaled to stream surface area was $9.63 \cdot 10^{-4}$ m^3/m^2 on average and ranged from $5.09 \cdot 10^{-6}$ to $4.38 \cdot 10^{-3}$ m^3/m^2.

3.3.5 Downstream change in reach-scale wood load

The absolute number of wood pieces in each reach increased with drainage area because reach length increased downstream. Piece frequency scaled per 100 m of stream length increased with drainage area until 8-10 km^2. When outlying Sites 2 and 4 were excluded this trend was pronounced. For areas 10-30 km^2 piece frequency per 100 m declined. The extremely high piece frequency of Site 14 was caused by the presence of an extensive log jam

(Figure 3.9).

Total wood volume showed the strongest downstream trend of all measures of wood load (Figure 3.8). Unlike wood piece frequency, the total volume of wood per 100 m declined downstream. This trend was statistically significant when outliers (Sites 2, 4 and 14) were excluded from the regression (r^2=0.83, p-value$<$0.01) for reasons discussed above. In contrast, both measures of in-stream wood volume showed a gradual increase with drainage area. The volume of in-stream wood per 100 m increased slightly downstream (Figure 3.8). When scaled by square metre of stream surface area, in-stream wood volume increased significantly downstream (Figure 3.8). Excluding the Site 14 outlier the relationship was very strong (r^2=0.82, p-value$<$0.01).

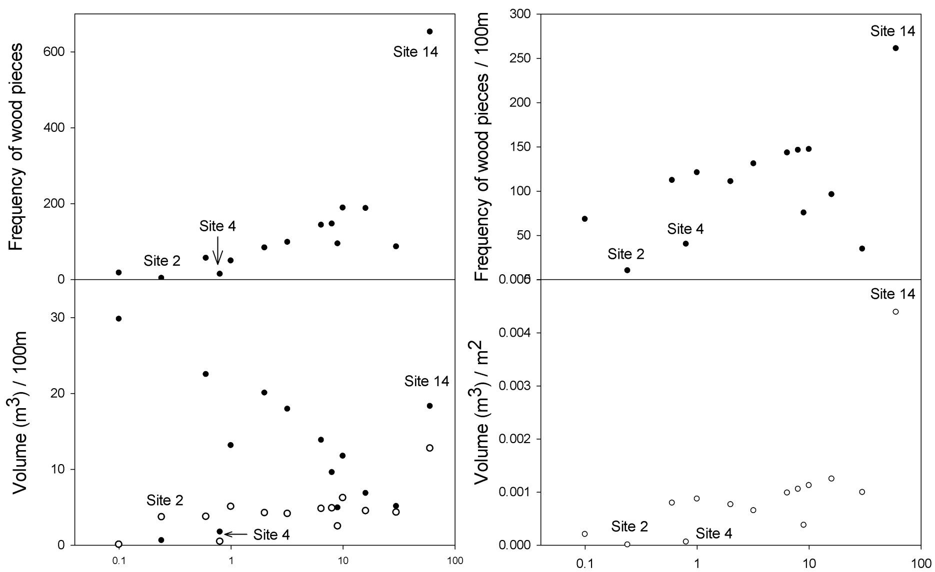

Figure 3.8: Downstream change in the absolute (top left) and scaled frequency of wood pieces (top right), in wood volume scaled by 100 m stream length (bottom left) and by unit of stream surface (bottom right). In the volume panels, solid data points indicate the total wood load per site, and hollow points indicate the in-stream wood load. Sites names of outliers are labelled. Site 14 was an outlier because it contained an extensive (>100 m) log jam. Sites 2 and 4 were outliers with low frequency and volume values because unusual riparian forests may contribute less woody debris to these reaches.

Figure 3.9: One of many log jams at Site 14.

3.3.6 Reach-scale wood attributes

At all sites but one, wood was present in every orientation, position, decay, function, origin and stability class. The proportion of wood in each wood attribute class is shown in Figures 3.10 to 3.15. At 13 of the 14 sites the largest proportion of wood was oriented diagonally to the direction of stream flow (Figure 3.10 and Table A.1). The proportions of parallel and perpendicular logs were smaller and similar to each other. Site 1 was an outlier with few perpendicular and many parallel wood pieces. Parallel orientation tends to be associated with larger reaches, yet it is certain that the Site 1 channel, whose mean width was 0.2 m, was not capable of transporting wood of $\geq$5 cm. The reason that many wood pieces were parallel at Site 1 is likely related to its slope. The hillside at Site 1 was very steep, and since the channel was small and had poorly-developed stream banks and nearly no valley, trees would probably have fallen preferentially downhill rather than toward the stream. In each orientation class, Site 2 was an outlier with values of either 0% or 100%. This tendency is an artifact of the sample size at Site 2 (n=3), and occurs in many cases throughout the wood attributes section.

Bridged and anchored positions were the most abundant position classes (Figure 3.11 and Table 2.3). They composed up to 100% and 54% of site-level wood loads respectively. Up to 37% of logs were braced on other wood (Figure 3.11). Partial bridges and loose pieces comprised smaller portions of wood loads, up to 22% and 19% each. Most wood pieces were located in the active stream channel except at Sites 2 and 4 (Figure 3.11). The low proportion of wood in active positions at Sites 2 and 4 may be linked to low sample size and to unusual riparian forest conditions at these sites.

The majority of wood pieces were moderately and highly decayed (Figure 3.12 and Table 2.4). The amount of wood in decay class 3 varied the most between sites, ranging from 0-73%. Large portions of the wood loads were in decay class 4 at all sites (20-60%) with the exception of Site 2 (0%). Intact wood with needles, bark and branches (decay class 1), and nearly intact wood with most branches and bark (decay class 2) composed smaller proportions of site-level wood loads (Figure 3.12). The portion of extremely decayed wood (decay class 5) was also small (Figure 3.12).

At all sites a large proportion of wood pieces were identified as having originated in the adjacent riparian forest, but, with the exception of Site 2, origin could not be determined for every wood piece in a reach. Excluding Site 2, where sample size was very low (n=3) and all wood was of local origin, the proportion of wood pieces with known local origin ranged from 24-83% (Figure 3.13).

Woody debris performed none of the seven function classes at Sites 1, and only two functions at Site 2 (Table A.4). At all other sites, five to seven functions were present. Figure 3.14 presents the relative frequency of wood in each function class by site. The most abundant function classes were fine wood storage, sediment storage and bank stability. Wood pieces storing large wood occurred primarily in downstream reaches and were absent at Sites 1, 2, 4 and 5. Similarly, jam-initiating functions were absent at all sites up to Site 7. The proportion of wood pieces involved in forming log steps and pools varied the least between sites, composing only 0-24% and 0-22%

of reach-scale wood loads respectively. However, the proportion of pool unit morphologies that were forced by woody debris varied greatly among sites (Figure 3.14).

The portion of the wood load in low (<33%) and high (>66%) stability classes varied greatly among sites (Figure 3.15 and Table A.5). The amount of wood with moderate stability varied less for both the diameter:depth (L_d:D_b) and the length:width (L_l:W_b) stability ratios. More wood was classed as low-stability by the diameter:depth (L_d:D_b) ratio than by the length:width (L_l:W_b) ratio (compare panels in top row of Figure 3.15).

3.3.7 Downstream change in wood attributes

Downstream changes were observed in all reach-scale wood attributes that were quantified, except orientation. For most wood attributes, only a subset of the attribute classes showed downstream trends. As expected, the proportion of perpendicular wood declined downstream and the proportion of parallel wood increased (Figure 3.10). These relationships were significant, but for both attribute classes the rate of change was gradual. No significant relationship was found between the amount of diagonal wood and drainage area.

Significant trends in three of the five position classes supported the hypothesis that wood was less associated with stream banks and more easily mobilized as drainage area increased (Figure 3.11, Table A.2). The strongest relation was the downstream decline in the proportion of bridged wood, which corresponded to the hypothesis that fewer wood pieces span the channel as channel width increases. In Sites 10-14, the proportion of bridged wood was nearly constant. The amount of braced and loose wood pieces increased significantly downstream. The proportion of partial bridges and anchored pieces remained fairly static throughout the stream network. When position classes were grouped into active and inactive position types, a strong positive relationship was found between active wood and drainage area (Figure 3.11).

The hypothesis that more wood would be highly decayed in upstream than downstream reaches was not supported by my results. Instead, the amount of sound and intact wood in decay classes 1 and 2 was high in upstream reaches and declined with drainage area, and the amount of moderately decayed wood in decay class 3 increased downstream. The portion of highly decayed wood in classes 4 and 5 remained low throughout the stream network and showed no significant relation to drainage area, although the amount of wood in decay class 5 did decline downstream (Figure 3.12, Table A.3). Wood was distributed more evenly between all five decay classes in the upstream reaches, and became more concentrated in the moderately decayed classes (2-4) as drainage area increased.

Significant downstream trends were observed in four of the seven wood function classes (Figure 3.14, Table A.4). Jam-initiating wood pieces were absent at all sites up to Site 7 and were present at Sites 8-14, indicating a downstream threshold of log jam occurrence in the channel. Contrary to the hypothesis that storage functions would occur primarily upstream, the proportion of wood pieces that stored fine wood, large wood or sediment increased downstream. Similarly, the hypothesis that wood had a greater influence on channel morphology in upstream reaches was not supported by the results. Instead, the proportion of wood pieces that formed pools, log steps and stabilized riverbanks had no relation to drainage area. The proportion of wood-forced pool unit morphologies were highest in mid-sized reaches. Over 50% of pools were forced by wood in Sites 5-12, in contrast to under 40% in all other reaches (Figure 3.14, Table A.4).

As predicted, the proportion of wood with known local origin declined downstream (Figure 3.13, Table A.3). Over 60% of all wood pieces were of local origin at Sites 1-8. From Sites 8 to 10, the proportion of local wood fell sharply to less than 40%. Thus, although the rate of downstream decline fits a semi-log slope reasonably well (r^2=0.72), the downstream trend could also be interpreted as a threshold of decline occurring between Sites 8 and 10.

The regressions of stability classes against drainage area showed that the size of wood pieces relative to stream dimensions declined downstream (Figure 3.15, Table A.5). For both L_d:D_b and L_l:W_b ratios, the proportions of low-stability wood increased with drainage area, and the proportions of low-stability wood declined (Figure 3.15). Proportions of moderate-stability L_d:D_b had large variance and no downstream trend, and the proportions of moderate L_l:W_b increased (Middle row, Figure 3.15).

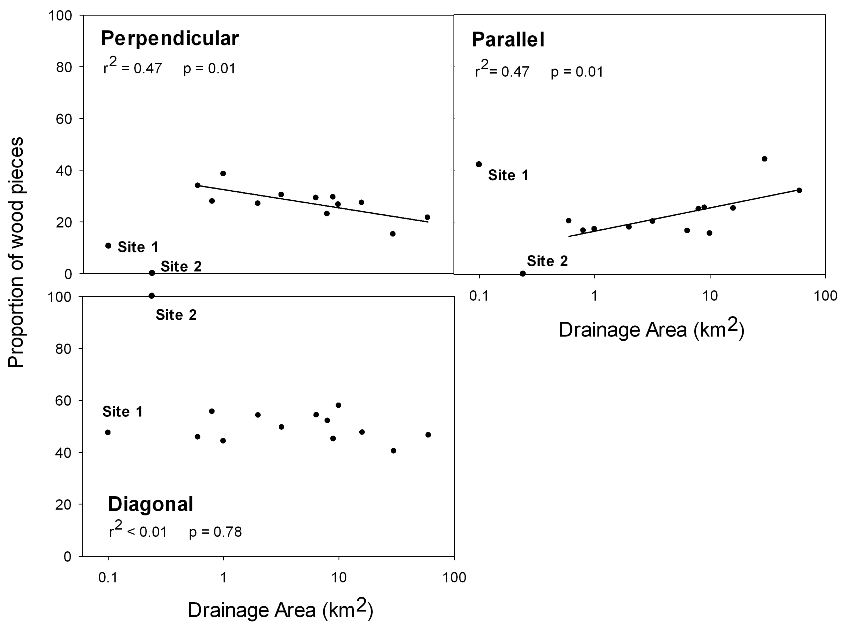

Figure 3.10: Relative frequency of wood orientation classes with drainage area. Significant semi-log regressions are shown.

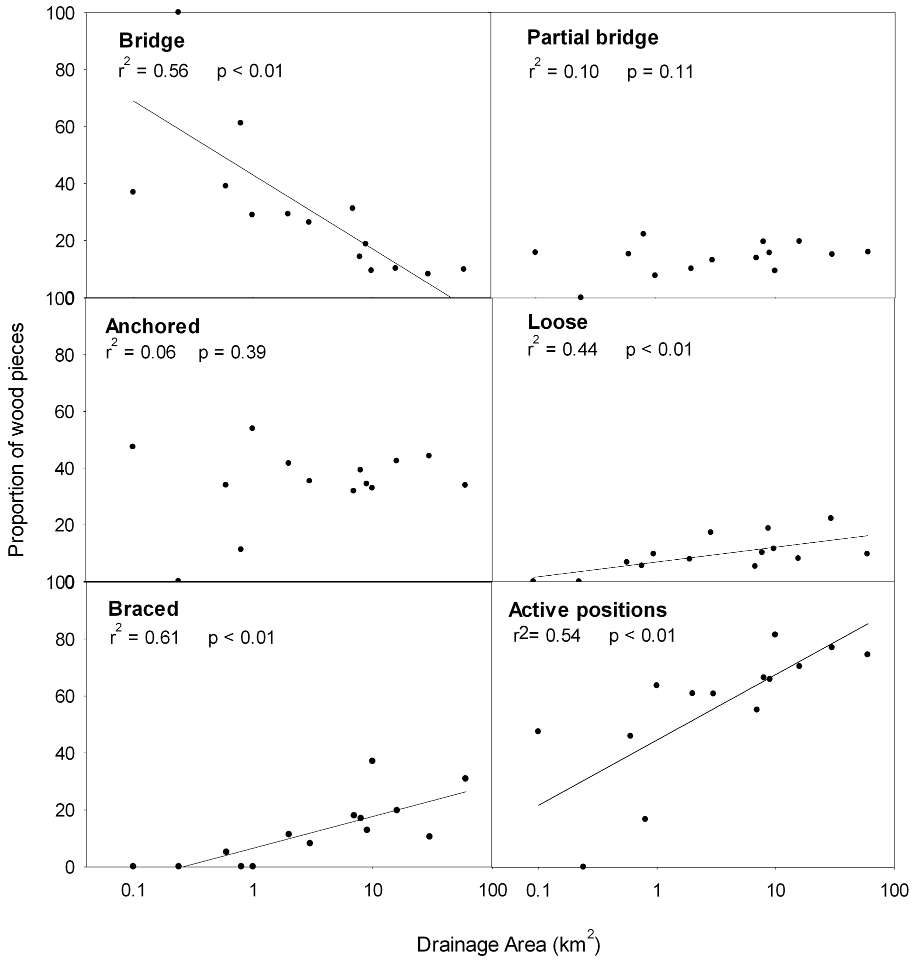

Figure 3.11: Downstream change in the proportion of wood pieces in the five position classes and in the active position type. Active positions, shown in the bottom right panel, are the sum of anchored, loose and braced position types. Semi-log regression lines are shown for classes with significant downstream trends.

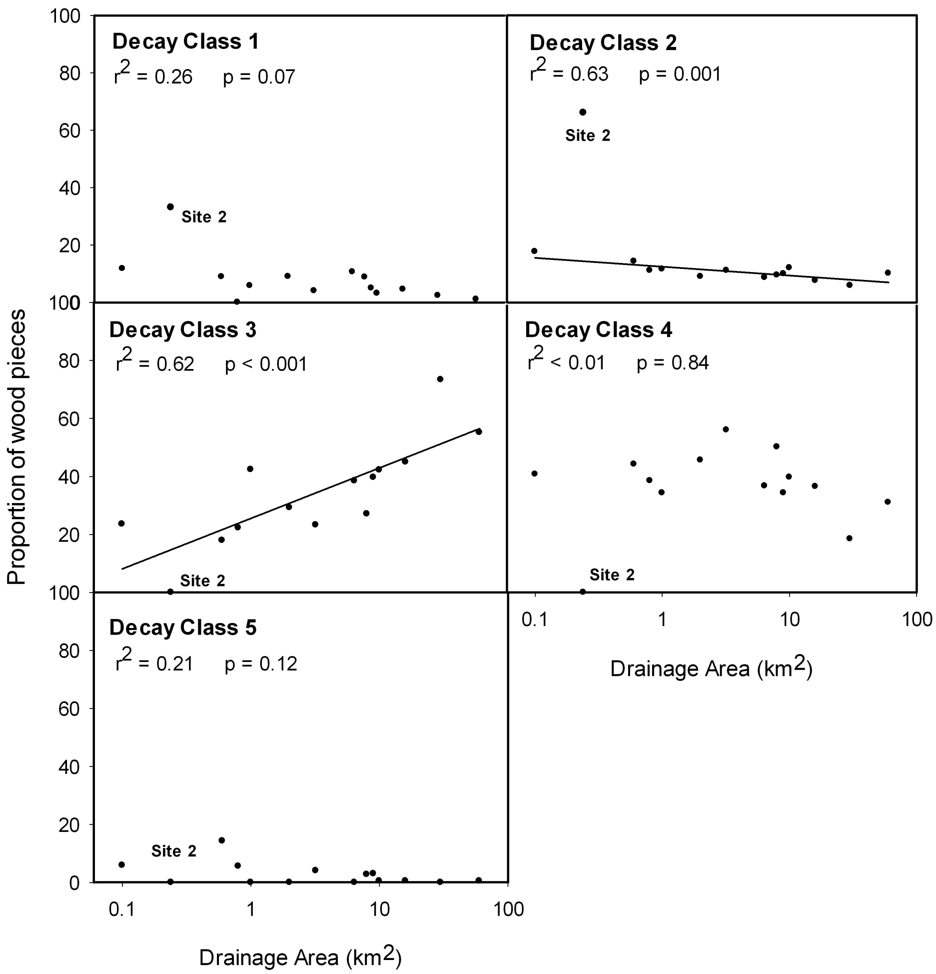

Figure 3.12: Downstream change in the proportion of wood in the five decay classes. Semi-log regression lines are shown for classes with significant downstream trends.

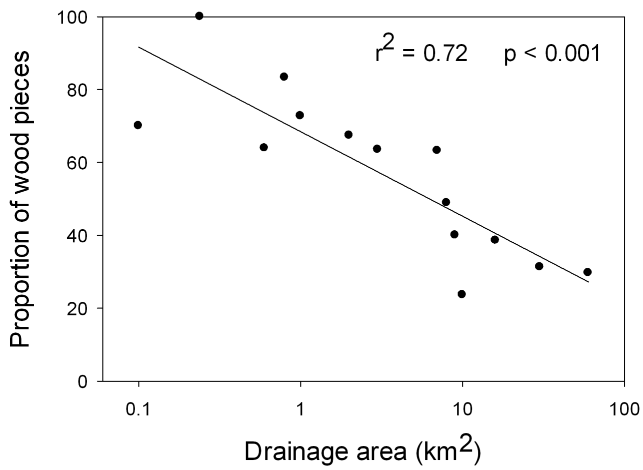

Figure 3.13: Downstream change in the proportion of wood pieces with known local origin. Anchored wood was excluded from this analysis because it was not possible to identify rootball attachments on buried pieces. The trendline shown is semi-log.

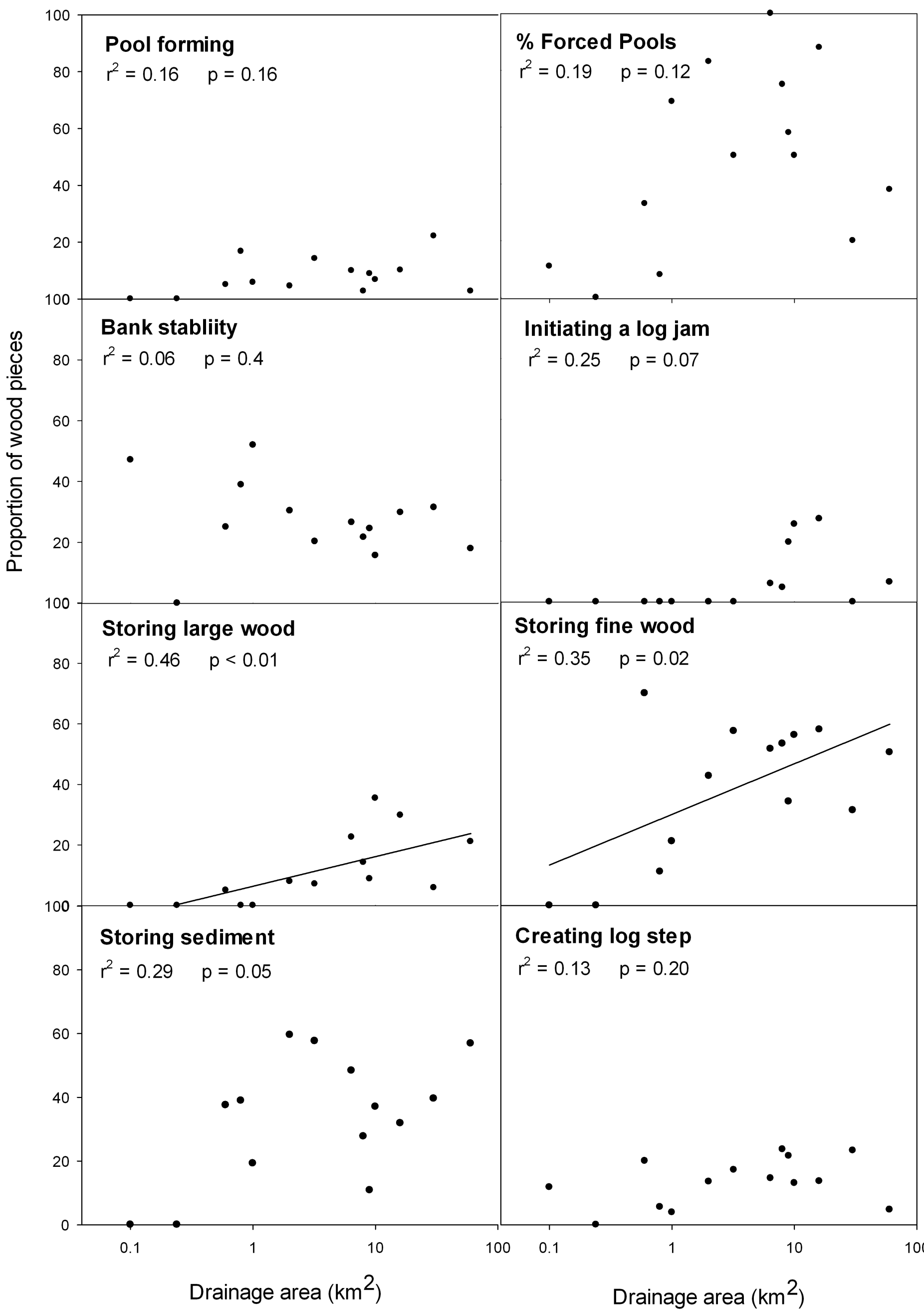

Figure 3.14: Downstream change in the proportion of wood with various functions. Many wood pieces had multiple functions. Semi-log regression lines are shown for classes with significant downstream trends.

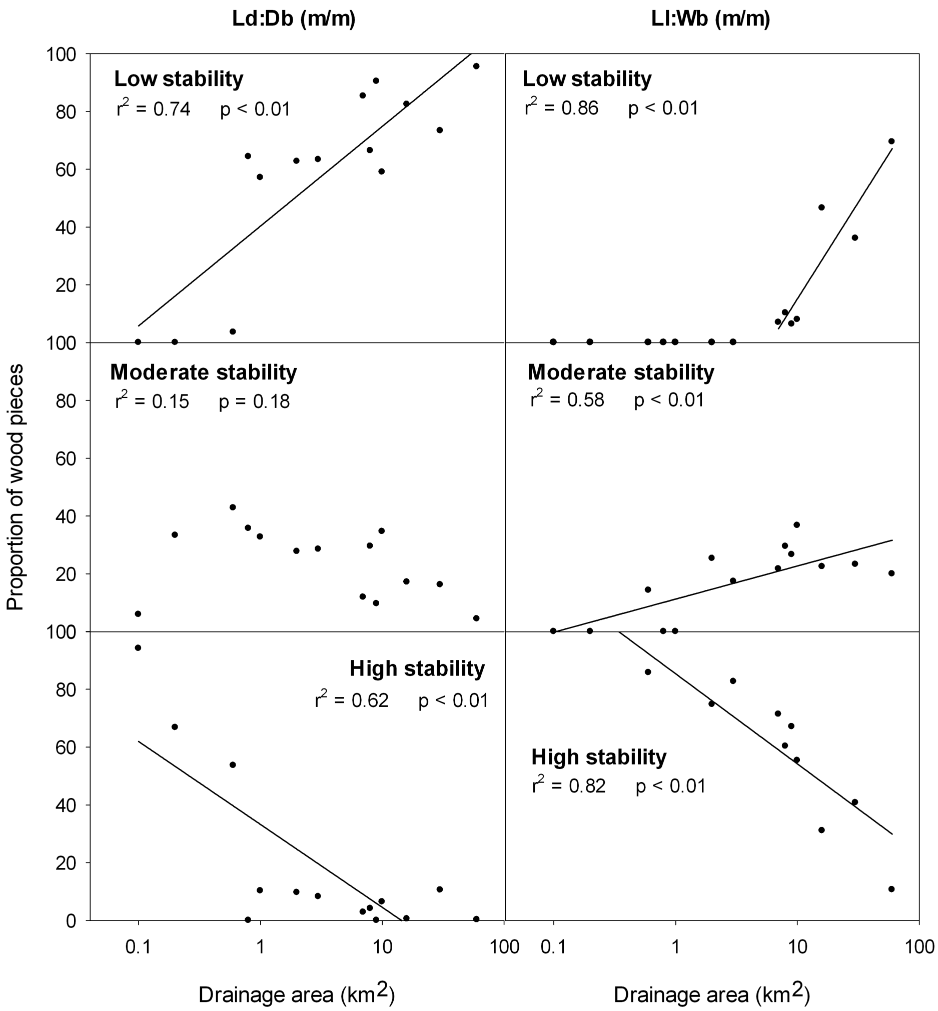

Figure 3.15: Downstream change in the proportions of wood among stability classes. Regressions are semi-log.

3.3.8 Woody debris distribution

To identify where in the stream network wood became aggregated by fluvial processes, I performed a distribution analysis of the total wood load. Subsequent distribution analyses were performed on subsets of the wood load to examine the composition of wood aggregations. As hypothesized, significant aggregation of wood pieces occurred only in larger, downstream reaches. However, wood was not aggregated in all downstream reaches and the location of aggregation varied with wood size, position type and stability class. Figure 3.16 provides an example of how the distribution pattern and its significance were determined for a range of scales at each study site. The locations and scales at which wood was aggregated are depicted in Figure 3.17.

The analysis of the total wood load showed that the pattern of wood distribution shifted from segregated to aggregated between Sites 6 and 7, or between 2-3 km^2 drainage area (Figure 3.17). Of all distribution analyses performed, this was the only test that detected aggregation upstream of Site 8, likely because the wood load was the largest. Among the reaches with aggregated wood, the scale of aggregation increased with drainage area. At Sites 7, 8 and 10 wood was aggregated at small scales of <5 m. At Sites 11 and 12, the maximum scales of aggregation were larger (9 and 14 m), and at Site 14 wood was aggregated at scales up to 127 m.

Wood pieces located within the channel were aggregated at more sites than were wood pieces located partly or wholly above stream flow (Figure 3.17). Active wood aggregated at Sites 11, 12 and 14, while inactive wood aggregated only at Site 14 (Figure 3.17). This finding supports the premise that wood aggregations occurred as a result of fluvial reorganization of wood within the channel, rather than external processes that may cause clustering, such as treefall (Richmond and Fausch, 1995). Inactive wood may have been aggregated at Site 14 by wood build-up above bankfull margins on the extensive log jams found within this channel.

Fine wood (5-10 cm diameter) was expected to aggregate upstream of large wood (>10 cm diameter) because fine wood requires less stream power to be transported. Contrary to this hypothesis, fine wood aggregation occurred downstream of large wood aggregation, at fewer sites and at smaller scales (Fine wood, Figure 3.17). Large wood was aggregated at Sites 10 to 14, excluding Site 13, while fine wood was aggregated at Sites 12 and 14 only. Large wood was aggregated at scales of up to 43 m but fine wood was aggregated up to only 39 m in the most powerful study reach.

Interestingly, neither the large wood nor the fine wood formed aggregations at Sites 7-9 when analyzed separately, but when all wood pieces were grouped together, aggregation occurred. This suggests that in study reaches near the zone of transport initiation, fine wood pieces were transportable but large wood obstacles prevented significant aggregations from forming, creating log jams that are composed of small logs snagged on large, immobile logs.

The distributions of wood categorized by stability class partly supported the expectation that low-stability wood pieces would aggregate in most reaches while high-stability wood would have random or segregated distributions. For both the ratio of diameter to depth (L_d:D_b) and the ratio of length to stream width (L_l:W_b), low-stability wood was aggregated at more sites and at larger scales than high-stability wood (Figure 3.17). Wood with low-stability L_d:D_b was aggregated at Sites 11, 12 and 14 at scales of 5 to 117 m, whereas wood with moderate- and high-stability L_d:D_b was segregated in all reaches. Similarly, wood with low-stability L_l:W_b was aggregated at Sites 12 and 14 at scales of up to 69 m, whereas wood with moderate- and high-stability L_l:W_b was aggregated at only 1-2 m scales. Because so little aggregation was found for moderate- and high-stability wood, these data were not plotted in Figure 3.17. In summary, narrow, short logs located in the active channel were more likely to be aggregated than were large logs or logs outside of bankfull margins. Aggregated patterns developed in most fluvial reaches, and the scale of aggregation generally increased with drainage area.

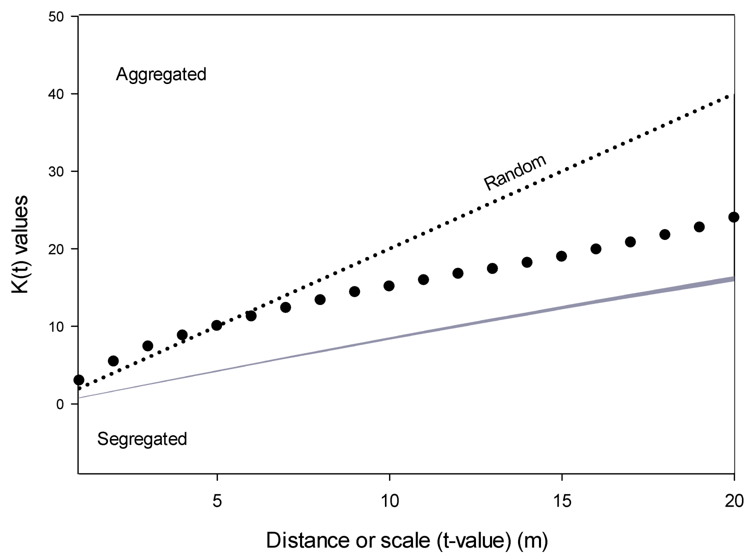

Figure 3.16: Spatial distribution and confidence intervals of wood pieces at Site 11. Black dots indicate the K(t) values of inter-piece distances at Site 11. The grey line indicates the 5^th-95^th percentiles predicted results from the Monte Carlo simulation of this site. The dotted line is the K(t) threshold of distribution pattern types; the area below this line is segregated, on the line the pattern is random and above it is aggregated.

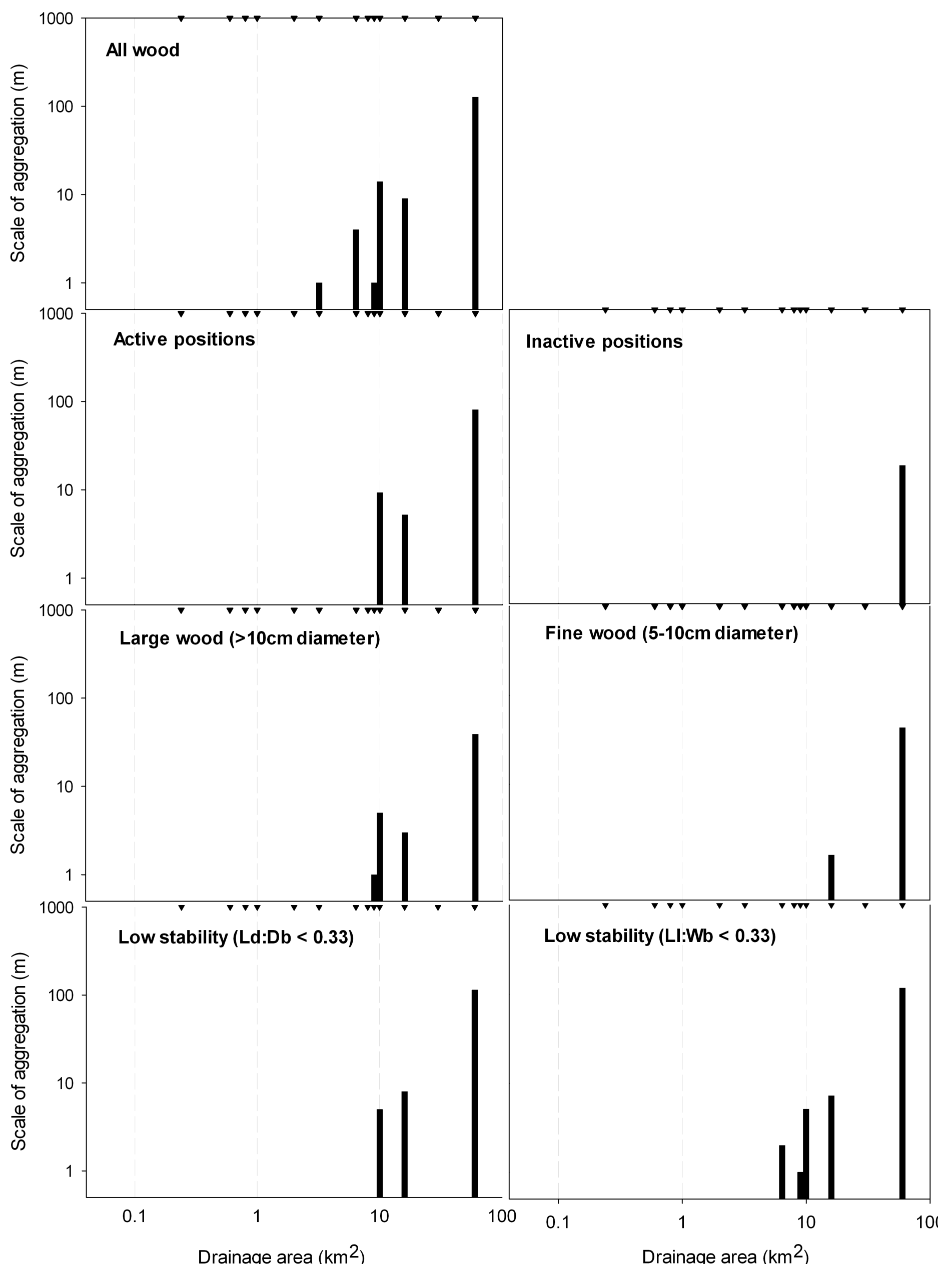

Figure 3.17: Occurrence and scale of aggregated wood distributions for all wood pieces and for subsets of the total wood load. Triangles indicate the location of study sites and black bars indicate the presence of aggregated wood distributions. All sites that were not aggregated had segregated distributions.

3.3.9 Year of death

Crossdating success rate

Of the 101 collected cross-sectional disks sampled, I successfully crossdated 95 (Table 3.5). Four samples, all taken from Site 13, could not be crossdated because their ring series were complacent and too short (<40 rings). Two samples at Site 3 were excluded because they were missing unknown numbers of outer rings. Despite the advanced state of decay of some samples, intact ring series of sufficient length were present in all other cross-sectional disks and crossdating was possible. Outer-ring dates ranged from 1880-2007.

Table 3.5: Number and genus of successfully dated samples per site.

Site	Crossdated	Excluded	Spruce	Pine
3	19	2	16	3
5	20	0	18	2
7	20	0	20	0
10	20	0	20	0
13	16	4	13	3

Downstream change

No downstream change in the median year of death (YOD) of sampled logs was observed, but the range or variability of YOD declined downstream (Figures 3.18, 3.19). The median YOD ranged from 1966-1976 among sites and distributions did not differ significantly (Table A.8). However, the range of YOD declined downstream. The oldest YOD ranged from 1880 to 1894 among sites, except at Site 13 (1938) where the older age classes were missing. The most recent years of death were similar among sites, ranging from 2006-7 - just 2 and 3 years before sampling took place. YOD distributions were relatively even at Sites 3, 5 and 7, and were uneven with strong modal classes at Sites 10 and 13 (Figure 3.18). Each distribution was skewed toward the second half of the century (1960-1990).

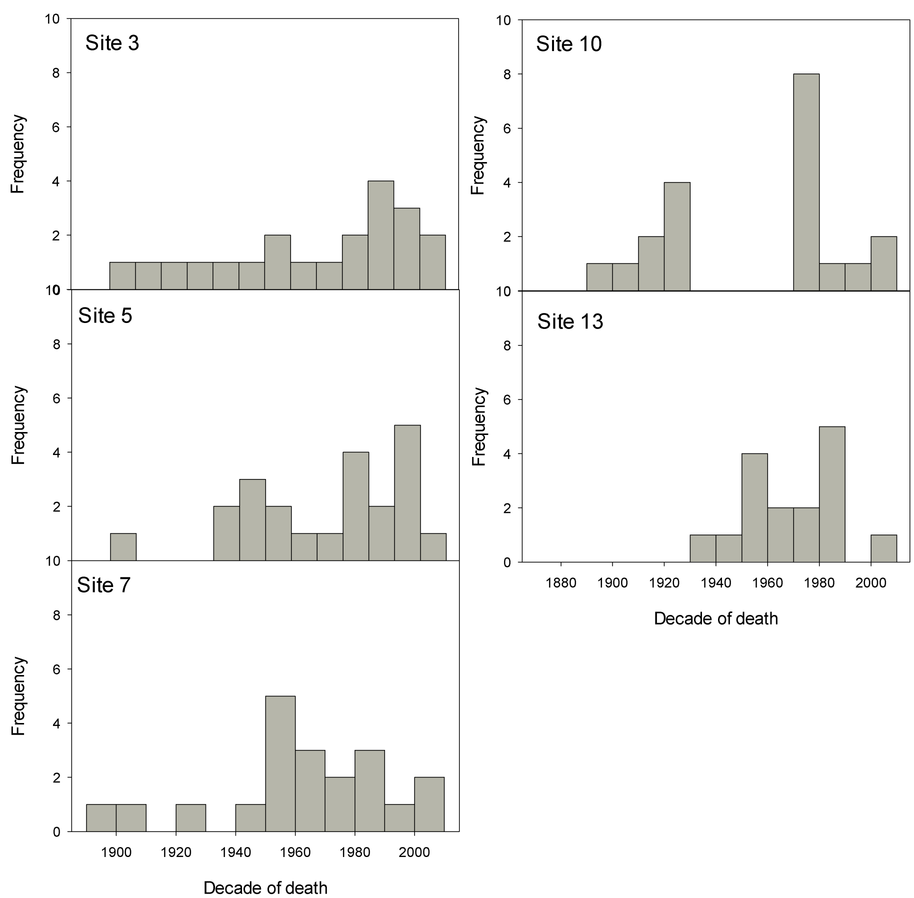

Figure 3.18: Year of death (YOD) distributions of randomly-sampled wood pieces from Sites 3, 5, 7, 10 and 13. YOD distributions are also presented in boxplots in Figure 3.19.

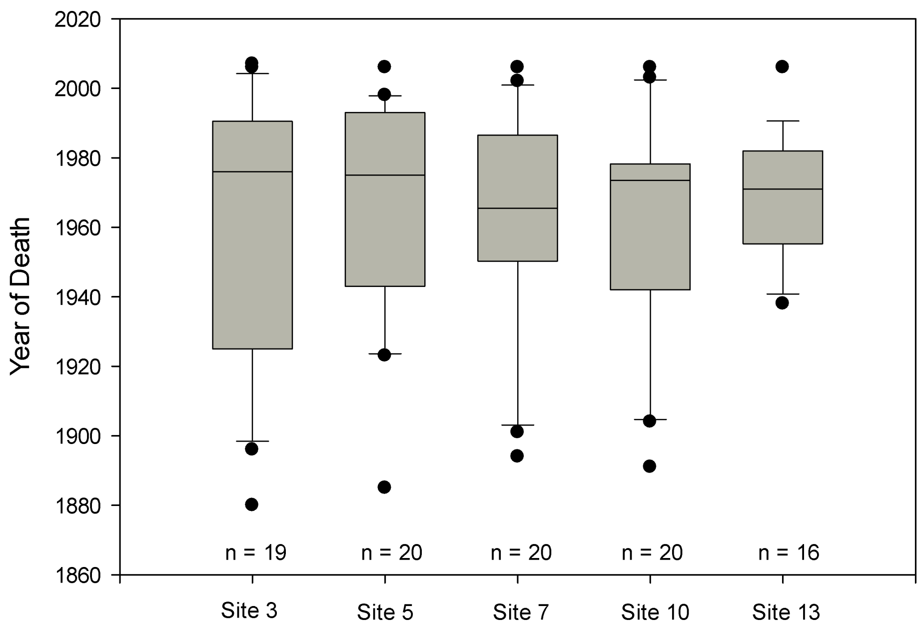

Figure 3.19: Year of death distributions of sampled wood pieces. The horizontal line in each box is the median, the lower and upper limits of each box are the 25^th and 75^th percentiles, the lines are the 5^th and 95^th percentiles, and the circles are outliers. The range of YOD declined downstream but median YODs did not differ significantly. Older size classes were absent at Site 13.

Change in year of death with wood attributes

Time since tree death did not vary among orientation, function or stability classes, but did differ among position and decay classes. The majority of crossdated logs were oriented parallel to the stream at Sites 3, 5 and 7. Most logs were diagonally oriented at Site 10 and were parallel at Site 13. YOD did not differ among orientation classes (Figure 3.20). The position classes of crossdated logs also differed in frequency among sites. Bridges were the most frequently sampled position class at the three upstream reaches (Sites 3, 5 and 7) (Table A.6) while partial bridges and anchored pieces were the most abundant position at Sites 10 and 13, respectively. Significant differences in year of death were found between all position class pairs except for bridges and partial bridges, and between anchored and loose pieces. This suggests two distinct groups exist within position classes with respect to year of death (Figure 3.21, Table A.9), in which bridged and partially bridged logs in inactive positions died more recently than did loose and anchored logs in the active channel (Figure 3.22). The median YOD for inactive position types was 1976, while the median for active position types was 1950. The majority of crossdated logs were in decay classes 3 and 4 at all sites (Table A.10).

Year of death was strongly related to decay class (Figure 3.23). Wood in decay class 1 died more recently than decay classes 2, 3 and 4. Year of death did not differ significantly between decay classes 2 - 3 and 3 - 4. However, logs in decay class 4 were significantly older than class 2 (Table A.10).

Of the 95 crossdated logs, 24 had no function. All other function types were represented in three or more YOD samples. The median YOD of logs with at least one function (1965) was older than those without function (1979), but groups were not significantly different (p-value=0.07). Similarly, high-stability wood pieces died more recently than low- and moderate-stability pieces, but differences in YOD among stability classes were not significant (Table A.7). Wood pieces with high-stability L_d:D_b ratios were absent from the YOD sample.

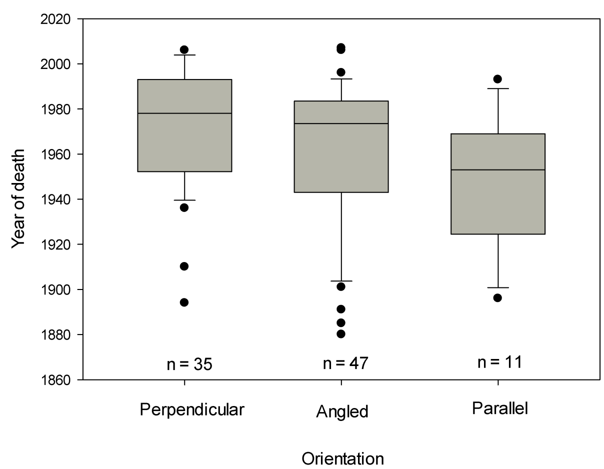

Figure 3.20: Year of death distributions by orientation class. The horizontal line in each box is the median, the lower and upper limits of each box are the 25^th and 75^th percentiles, the lines are the 5^th and 95^th percentiles, and the circles are outliers.

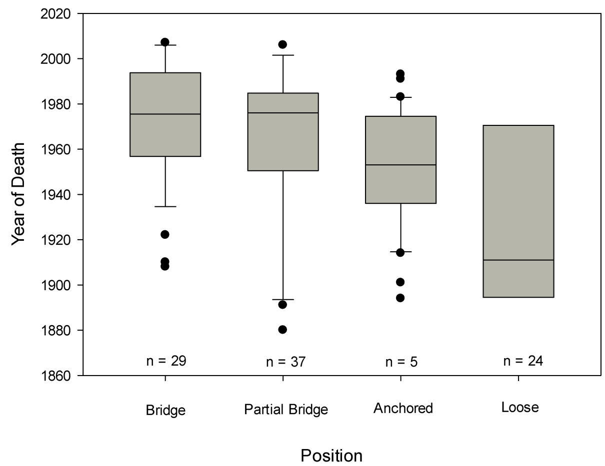

Figure 3.21: Year of death distributions by position class. The horizontal line in each box is the median, the lower and upper limits of each box are the $25^t h$ and $75^t h$ percentiles, the lines are the $5^t h$ and $95^t h$ percentiles, and the circles are outliers.

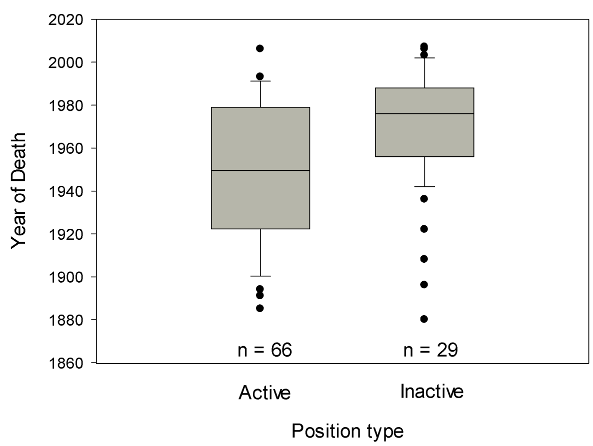

Figure 3.22: Year of death distributions by position type. The horizontal line in each box is the median, the lower and upper limits of each box are the $25^t h$ and $75^t h$ percentiles, the lines are the $5^t h$ and $95^t h$ percentiles, and the circles are outliers.

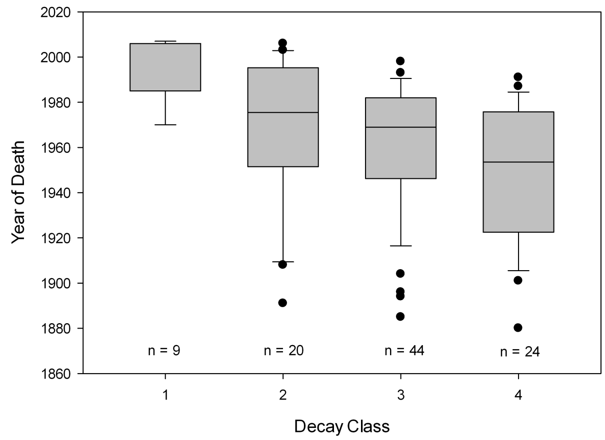

Figure 3.23: Year of death distributions by decay class. The horizontal line in each box is the median, the lower and upper limits of each box are the 25^th and 75^th percentiles, the lines are the 5^th and 95^th percentiles, and the circles are outliers.

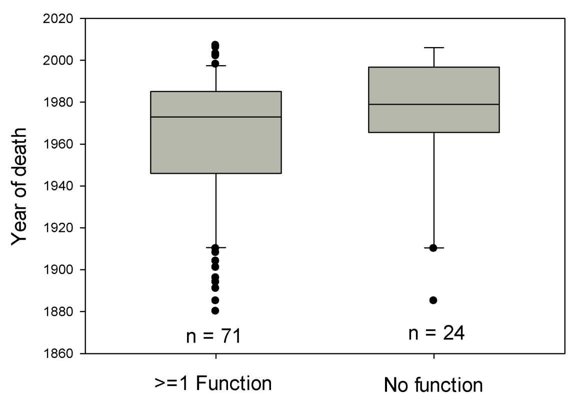

Figure 3.24: Year of death distributions by function class. The horizontal line in each box is the median, the lower and upper limits of each box are the 25^th and 75^th percentiles, the lines are the 5^th and 95^th percentiles, and the circles are outliers.

Chapter 4

Discussion

The objectives of this study were to document downstream patterns of wood characteristics in relation to the channel, and to identify the threshold of wood transport initiation in Wigwam Creek. This chapter begins with a discussion of the process domains and wood inputs within the study watershed, after which the second objective is met by comparing how and where wood characteristics change downstream, and how they indicate wood transport.

4.1 Landscape processes

Erosional processes influence channel morphology, wood sources in the stream, and wood storage and transport. Topography is an important control on the type of erosional processes that occur within watersheds (Brardinoni and Hassan, 2006). In Wigwam Creek the process domains I identified were colluvial and fluvial, and a debris flow process domain was absent because channel gradients along Wigwam Creek were well below the typical channel gradients found in debris flow domains (Benda et al., 2005). The absence of a debris flow domain indicates that debris flows do not occur in this basin and do not supply wood to the channel. This conclusion is supported by an analysis of air photos of the Upper Foothills landscape which showed that

90% of wood in small headwater streams is recruited from within $\leq$7.6 m of the stream edge, and input mechanisms were bank erosion or mortality (McCleary, 2005). Hill slope decoupling marks a major difference between the Upper Foothills landscape and the more frequently studied high-gradient coastal landscapes. Debris flows deliver large quantities of wood and sediment downstream, routing materials through stream networks episodically and rapidly (Benda et al., 2005; Reeves and Burnett, 2003; May and Gresswell, 2003). In contrast, stream decoupling from hill slope wood sources means that upslope trees do not enter the stream, resulting in lower overall wood recruitment rates (Jones and Daniels, 2008; Powell et al., 2009). This limits wood sources to bank erosion, mortality and tree fall in the riparian zone, and fluvial transport from upstream reaches.

To explain the ability of the fluvial system to transport wood, I calculated the total available stream power in each study reach. Since stream power is a primary control on wood transport (Merten et al., 2010), the observed trend in total stream power indicated that the transport capacity of Wigwam Creek generally increased from Sites 1 to 14. However, since stream power increased rapidly between 10-16 km^2 drainage area (Sites 11-12), wood transport was most likely to occur in reaches downstream of this point. The rapid increase in power was not concurrent with the change in process domains but instead occurred downstream of the boundary between colluvial and fluvial reaches, indicating that fluvial wood transport did not coincide with fluvial sediment transport in this stream. Instead, the rapid increase in power corresponded to a break in slope at the bottom of the hanging valley step and a widening of the channel from 2.1-5.3m.

In spite of downstream changes in channel morphology, riparian forests were similar throughout the Wigwam basin and were comparable to other mature riparian spruce stands in this natural subregion. All riparian sites had mixed-age spruce-dominated stands which had established over 80 years ago. The diameter at breast height, density and basal area of canopy trees varied as little as could be expected in riparian spruce stands in this landscape (Andison, personal communication 2011). The riparian stands at Sites 2 and 4 may have been subject to disturbances, and consequently these sites had low wood loads. However, all other sites were consistent with mature spruce riparian forests in the Upper and Lower foothills region described by Powell et al. (2009) and Andison and McCleary (2002). The overall similarities of the riparian stands imply that wood was supplied in similar volumes and rates among the stream reaches included in this study.

To conclude the discussion of landscape processes, I should note that the differences in year of death (YOD) among position and decay classes in Wigwam Creek were very similar to those in other Upper Foothills streams described by Powell et al. (2009). In both studies, the mean age of logs increased significantly with each decay class with overlap between classes 3-4 in Powell et al. (2009) and between classes 2-3 and 3-4 in this study. The mean age of logs also increased with successive position classes, with overlap between loose and buried positions in both studies and between bridges and partial bridges in this study. The consistency of YOD relationships with wood attributes between studies provides evidence that temporal woody debris dynamics within this stream system are normal for this landscape.

4.2 Downstream changes in wood attributes

Wood attribute classes were divided into groups pertaining to their strengths as indicators of wood transport. Strong indicators changed (1) at critical thresholds or (2) gradually downstream. The distinctions between thresholds of change and gradual downstream changes were scale- and study design-dependent, but are nevertheless reliable and useful at the scale addressed in this study.

All eleven wood attributes that were measured in Wigwam Creek had significant downstream trends within one or more of their attribute classes. Thirteen attribute classes changed at thresholds or critical values of drainage area. Figure 4.1 illustrates the thresholds from which transport initiation processes were identified. In addition to the threshold indicators, nineteen attribute classes had significant gradual relationships with drainage area and fifteen attributes were weak indicators of transport (Table 4.1).

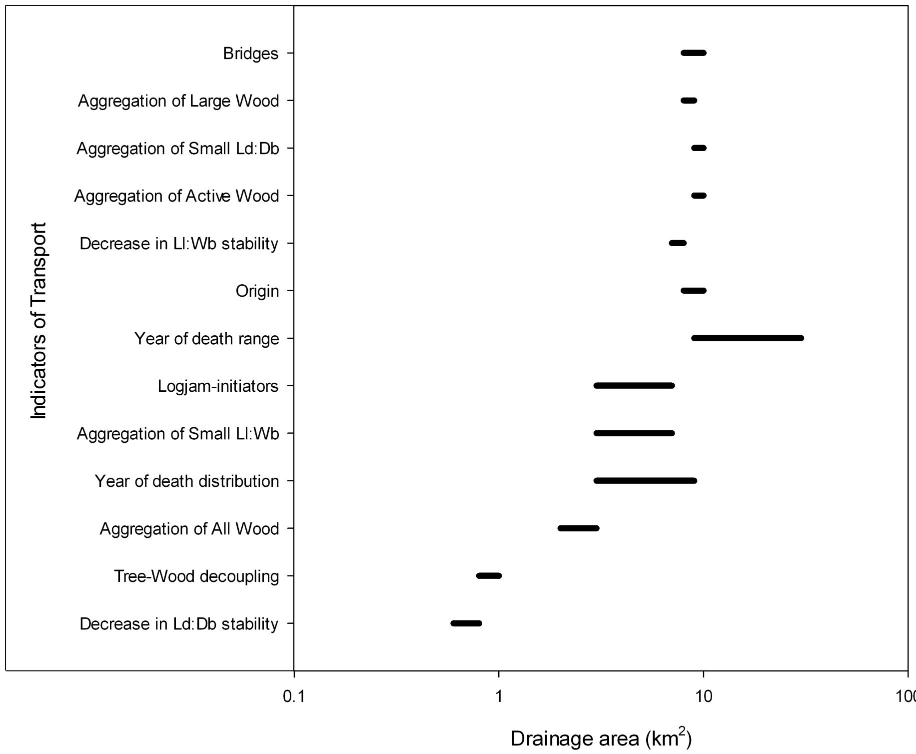

Figure 4.1: Thresholds of downstream change among wood attributes in Wigwam Creek, Alberta. Black horizontal bars indicate critical drainage area values. Most thresholds were grouped near 7-10 km^2 drainage area, indicating the transition to transport-dominated wood regimes in this stream. The thresholds of change in YOD attributes appear elongated because no sites were sampled for YOD between 3, 9 and 30 km^2.

Table 4.1: Other indicators of transport

Significant directional (gradual) downstream trends ($p<0.05$)	
Increase	Decrease
in-stream piece length and volume	Moderate and high L_l:W_b stability
in-stream wood load (m^3/100m and m^3/m^2)	Total wood load* (m^2/100m)
Loose, Braced and Active positions	Piece frequency* (n/100m)
Parallel orientation	Perpendicular orientation
Decay class 3	Decay classes 1 and 2
Storage functions (FW, LW and sediment)	
Weak indicators	
Average piece diameter, length and volume	
Diagonal orientation	
Partial bridges and anchored positions	
Decay classes 4 and 5	
Bank stability and log step formation	
Aggregation of moderately stable, high stability, active and fine wood	
Median YOD	

*Trend was not statistically significant

4.2.1 Critical thresholds

The critical thresholds from which the wood transport initiation zone was identified will now be discussed individually, beginning with those that occurred the farthest upstream. Only three thresholds occurred upstream of 7 km^2 (Site 8), and each of these was related to wood diameter. At 0.8 km^2 drainage area (Site 4), the proportion of wood with low stability L_d:D_b (<33%) increased dramatically as stream reaches grew deeper. At about the same drainage area (Site 5), the differences between riparian tree and woody debris diameters became significant. In general, woody debris may be narrower than source trees for several reasons unrelated to transport. These include preferential mortality of young trees during stand thinning, decay of sapwood and contribution of woody debris from thin tree crowns and branches. However, the pattern of tree-wood similarities and differences along the channel suggested that a downstream trend toward tree-wood decoupling did occur. Thus, this measure was a useful indicator of preliminary stages of wood movement and transport, which can provide a conservative estimate of the how much of the stream network is not affected by transport. In Wigwam Creek, wood only resembled trees in 1^{st} order channels smaller than 0.7 m wide and 0.4 m deep. Another study of downstream tree-wood similarity by Urabe and Nakano (1998) yielded a similar pattern of downstream decoupling, but in their study this transition occurred in larger streams (3.7-5.6 m wide). Forest-stream decoupling could occur even farther upstream in high-gradient basins subject to debris flows. In these settings, tree-wood differences would not indicate fluvial transport. Regardless of the setting in which it is used, this indicator is labour intensive, requiring detailed measurements both within and beside the stream. It would be efficient to conduct this comparison on other existing datasets of forests and woody debris.

The third critical threshold was the aggregation of all wood size classes that occurred as far upstream as 3 km^2 (Figure 4.1). This result was surprising because in this reach, large wood pieces (>10 cm diameter) were still segregated and evidently not transported. Aggregations of fine wood (5-10 cm diameter) did not form in this reach either. Instead, the aggregations that formed at 3 km^2 were composed of mixed size classes as fine wood was mobilized and was caught on large, immobile wood pieces before being exported from the reach. These aggregations are not logjams in the traditional sense, but rather "combination jams" (Abbe and Montgomery, 2003) that occur upstream of the transition to transport (and export) dominated reaches. This threshold shows the initial deposits of transported fine wood in this channel.

Excluding these three upstream thresholds, all other thresholds were grouped around 7-10 km^2 (Sites 8-11), which I interpreted as the zone of transport initiation. This was located between the fluvial-colluvial boundary at 3 km^2 and the increase in stream power at 10 km^2. In this area, the channel width began to exceed the median wood piece length of 1.9 m. Consequently, some wood had low stability ratios ($\leq$33% L_l:W_b) and the proportion of bridges declined considerably, which is consistent with other downstream studies of woody debris including Baillie et al. (2008) and Chen et al. (2006). The amount of wood with identifiable local origin declined as well. Since local origin was assessed according to the presence or absence of identifiable connections to the stream bank or the adjacent riparian forest, this indicator was strongly related to the proportion of wood that was partly positioned outside of the stream channel as bridges or partial bridges. Not all wood pieces had identifiable origins even in the smallest, non-transporting reaches. This is because wood can lose its visible attachments to stream banks through decay, repositioning and reorientation, regardless of the stream's transport capacity. As well, a significant portion of wood was derived from local sources even in transporting reaches since the percent of locally derived wood was never below 20%. Nevertheless, the significant decline in the proportion of locally-derived wood implies that more wood came from fluvial transport downstream. This trend was consistent with other models of downstream change (Abbe and Montgomery, 2003).

Within the same small area of 7-10 km^2, wood aggregations of most wood types first occurred including wood with low stability (<33% L_l:W_b and L_d:D_b), large woody debris and actively positioned wood. The aggregation of large woody debris indicated that the stream was capable of forming transport jams composed of mobile wood, as opposed to the partial transport combination jams of 3 km^2 (Abbe and Montgomery, 2003). The presence of wood that initiated logjams was a related function type that also occurred in this area.

Aggregation was the strongest direct indicator of transport used in this study. I assumed that fluvial transport was the only mechanism that formed wood aggregations in Wigwam Creek due to the absence of debris flows, recent forest fires, ice storms or other large-scale disturbances which also create jam-like wood accumulations (May and Gresswell, 2003; Hogan et al., 1998; Kraft and Warren, 2003). My results strongly support this assumption because aggregation occurred only in downstream reaches. However, the absence of aggregation does not mean that the stream is incapable of transporting wood. Wide channels with few obstructions may be regularly flushed of wood, rather than accumulate wood. In such cases, wood distribution can be segregated. Flushed reaches are often found between logjam-rich reaches (Martin and Benda, 2001). An example of this pattern in Wigwam Creek was at 30 km^2 (Site 13), which had segregated wood despite its high stream power and its location within the transporting zone.

Finally, two thresholds in year of death (YOD) attributes were observed. The YOD of woody debris indicates how long wood can persist in storage affecting stream structure and ecology, and can reflect downstream trends in wood characteristics. In mature spruce forests of the Alberta Foothills, fine-scale disturbances such as windthrow or mortality of individual trees recruit wood to streams slowly and continuously over time (Powell et al., 2009). In non-transporting streams, these recruitment conditions result in even year of death distributions of woody debris (Powell et al., 2009). Within Wigwam Creek, YOD dates were evenly spread over time in the three upstream reaches (<3 km^2), resembling transport-limited conditions. However, in the two downstream reaches (9 and 30 km^2) many YOD age classes were absent, which I interpreted as a sign of wood transport. Given the high turnover of wood load observed elsewhere after high-flow transport events (e.g., Lienkaemper and Swanson, 1987), it is possible that cohorts of similarly-aged logs could be exported en masse during extreme high flow events or seasons.

Just downstream of the change in YOD distribution, the range of YOD changed, which also indicated transport. In reaches $\leq$9 km^2 (Sites 3, 5, 7 and 10), YOD ranges (1880-2007) were similar to those reported in transport-limited Upper Foothills streams near Wigwam Creek (1862-2005) (Powell et al., 2009). However, at 30 km^2 the older size classes were absent, making the range of YOD much smaller than upstream sites (1938-2005). Since the oldest logs tend to be highly decayed and have broken into smaller pieces (Jones et al., 2010), these logs could have been preferentially transported out of the reach during peak flows. I also considered whether the four cross sections from this reach that could not be crossdated represented the missing older age classes. However, the undated pieces were intact and did not display the wood decay and grayish colouration I noted in most cross sections over 80 years old. As well, the reason these samples could not be dated was because their ring series were too short (<40 years), rather than too decayed. Therefore I consider the reduced range of YOD at Site 13 an actual downstream pattern indicating wood transport. There is a lack of downstream woody debris YOD data in the literature; so to my knowledge these interpretations are unprecedented and cannot be corroborated with studies at this time.

To summarize, the location of transport thresholds described a complex story of the gradual occurrence of transport-related processes over a long segment of the stream. In the 2^{nd} order reach at 3 km^2 drainage area, small diameter wood pieces were transported and formed aggregations on immobile large wood (>10 cm diameter), creating combination jams. At 7 km^2 the stream was still less than 2 m wide but was no longer colluvial. Significant wood depletion by fluvial transport began between 8-10 km^2 drainage area, where mean stream width just exceeded 2 m, and beyond 10 km^2, all reaches were transport dominated.

4.2.2 Directional downstream changes

To better understand wood dynamics, I shall now examine the wood attributes that changed gradually downstream. Directional or gradual changes do not identify boundaries between transport-limited and transport-dominated parts of the watershed. Nevertheless, they demonstrate that stream size and power control many important wood characteristics, and they provide insight into how woody debris changes within watersheds.

As the channel widened downstream, the stability of wood gradually declined and the size of wood within bankfull margins increased. This was shown by the positive downstream trends in the average in-stream length and volume of wood pieces, and by the transfer of highly stable L_l:W_b wood into the moderate L_l:W_b stability class. Since the total length and volume of wood pieces did not differ among sites, the increase in in-stream length and volume merely showed that larger parts of wood pieces fit into the channel as it widened and there was no change in the wood itself. As in Wigwam Creek, other studies have reported that the in-stream wood length increases from small to intermediate streams (e.g., Robison and Beschta., 1990; Chen et al., 2006; Baillie et al., 2008).

In general, small streams in the Alberta Foothills contain a higher frequency of wood pieces than do steep coastal streams because low-gradient headwater streams have very limited transport capacities (Jones et al., 2010). In Wigwam Creek, wood frequencies were even higher than elsewhere in the Upper Foothills because I included smaller wood pieces in my survey (see Jones et al., 2010, Table II). Conversely, the total wood loads in Wigwam Creek reaches were normal for the Alberta Foothills but were low compared to coastal streams. Overall the wood load within Wigwam Creek was similar to the global average for coniferous forests (Gurnell, 2003).

Conceptual models by Wohl and Jaeger (2009) and Seo et al. (2010) have suggested that the frequency and total wood load decline downstream as more wood is transported. While total wood load did decline downstream in Wigwam Creek, the pattern of piece frequency pointed to greater complexity than described by these models. Piece frequency tended to increase downstream until 10 km^2, where reaches became transport-dominated and after which the frequency of wood pieces declined. This change in trend appears to correspond with the model by Marcus et al. (2003), who noted that different linear trends occur within non-transporting and transporting zones of stream networks. In non-transporting streams, channel widening increases the likelihood that wood will fall into the stream resulting in increasing piece frequency, while in transporting reaches wood export causes piece frequency to decline (Marcus et al., 2003; Hassan et al., 2005; Seo et al., 2008). However, the reaches at 16 and 30 km^2 may have had low frequencies simply because they were located downstream of a wetland that contributed very little wood.

Gradual downstream trends in wood attributes reflected the increasing integration of woody debris into the stream (Jones et al., 2010). The attributes of highly integrated wood, including loose, braced, moderately decayed, parallel and highly functional wood were found to increase downstream. As well, the attributes of poorly integrated wood, including bridged, low decay class, perpendicular and less functional wood declined downstream. Although the relationships between these attributes were not determined in this study, these downstream trends suggest that associations among wood attributes in Wigwam Creek are consistent with the model by Jones et al. (2010). The directional trends of wood attributes are discussed separately below.

As stream power and wood submersion increased downstream, the dominant wood orientation changed from perpendicular to parallel. This trend was consistent with other studies (Bilby and Ward, 1989; Nakamura and Swanson, 1993) in which successively larger proportions of the wood load were reorganized by stream flow downstream. Within transporting reaches, wood orientation depended on piece frequency and deposition type. In general, when a log is deposited alone it tends to be oriented parallel to stream flow, which is the direction of the least flow resistance (Braudrick and Grant, 2000). However, if transported wood is caught on a logjam, boulder or other obstruction, the tendency is toward perpendicular orientation (Abbe and Montgomery, 2003). In Wigwam Creek, transporting reaches with high piece frequency and logjams (10, 16 and 60 km^2) had relatively large proportions of perpendicular wood. In contrast, the transporting reach that had lower piece frequency and few logjams (30 km^2) had the largest proportion of parallel wood (44%) of any site. Thus, wood orientation is a useful indicator of wood transport but it can be confounded by transport type.

I observed strong downstream increases in the proportions of loose, braced and active wood positions. Like orientation these trends were probably the result of downstream channel widening, which allowed more wood to enter the stream rather than rest suspended above it as bridges, and which provided more room for wood to float freely without being caught on stream banks and eventually buried. Loose positions do occur in small amounts in non-transporting reaches (Jones et al., 2010), so the presence of braced wood is a more direct indicator of fluvial transport. Small reaches from 0.1-2 km^2 had similar proportions of loose and braced wood to other transport-limited streams in the Foothills described by Jones et al. (2010). In contrast, the proportions of loose and braced wood in downstream reaches were comparable to the amount found in transporting reaches (Berg et al., 1998; Wohl and Goode, 2008). The amount of braced wood depended on both the transport capacity of the stream and on the frequency of wood pieces in the reach. This is why only 11% of wood pieces were braced at the wood-flushed 30 km^2 reach, while 31% of wood pieces were braced at the logjam-rich 60 km^2 reach.

Gradual downstream trends occurred in three of the five decay classes. The amount of wood in decay class 3 increased downstream, while the proportions of decay classes 1 and 2 declined. Decay classes are often assumed to generally represent time since death (e.g., Powell et al., 2009), but my results suggest that states of decay may not correspond with the same year of death periods in different parts of the watershed due to different levels of abrasion. To qualify as decay class 1 or 2, wood had to have all or most of its bark, branches and needles. This stage lasts for 15-30 years during in-situ decay in this landscape (Powell et al., 2009). However, in transporting streams where more abrasion occurs (Seo et al., 2010), branches and bark could be lost more rapidly than under non-transporting conditions. Thus, in-stream processing in downstream reaches could produce decay class 3 qualities in younger wood.

Several function types had gradual downstream trends, but generally not in the directions I had predicted. Contrary to my expectations the amount of functional wood increased downstream. This may have been because most wood pieces were longer than stream width until 10 km^2 drainage area, and wood that is longer than stream width has little geomorphic function (Jones and Daniels, 2008; Nakamura and Swanson, 1993; Gurnell, 2003; Jones et al., 2010). The high proportion of wood that stored large wood, fine wood and sediment in downstream reaches is consistent with Nakamura and Swanson (1993), who found that wood stored the most materials in 3^{rd}-5^{th} order streams. Large wood storage functions were rarely observed upstream of the fluvial-colluvial boundary, but fine wood storage was a common function throughout the basin, which implies that fine wood was mobile in most reaches. The weak relationship between drainage area and the proportion of wood storing sediment was also observed by Baillie et al. (2008). In steep terrain wood has a greater impact on sediment and wood storage in colluvial than alluvial reaches (May and Gresswell, 2003), so perhaps downstream change in these functions depends on stream gradient. Finally, the role of wood in pool formation was also greatest in the mid-sized reaches from 2-16 km^2 (Sites 6-12), although the proportion of pieces causing pool formation changed little downstream.

Some wood attributes showed no critical threshold or directional relationship with drainage area. These weak indicators either (1) varied greatly without relation to drainage area or (2) did not change with drainage area. Contrary to my hypothesis and the findings of others (e.g., Bilby and Ward, 1989; Chen et al., 2006; Robison and Beschta., 1990), mean wood piece dimensions (diameter, total length and total volume) did not change downstream. This may have been due to the similarity of the riparian forests along the stream network, the continuous input of wood over time (as shown by the YOD distributions) and abundance of fine wood pieces which are typically not included in wood surveys. Most other weak indicators were attributes that are not transport-related, and can occur in both transport-limited and -dominated parts of the stream. These included partially bridged, anchored, diagonally oriented and highly decayed wood (decay classes 4 and 5).

4.2.3 Wood transport initiation

The location of wood transport initiation in Wigwam Creek must also be compared with similar studies. Few watershed-scale studies have been conducted to assess downstream changes in wood transport. As well, comparisons between studies are difficult because the initiation of wood transport varies with the arrangement of stream tributaries and confluences, the glacial history of the basin, the morphology of the channel, the size of wood supplied by the riparian forest and the definition of woody debris. Nevertheless, the location of transport initiation in Wigwam Creek was fairly similar to other studies that used inclusive definitions of woody debris.

In Wigwam Creek, large wood transport began in reaches 1.9-2.3 m wide, and small wood transport began in reaches 1.2 m wide. Several studies report similar transport thresholds as those observed in Wigwam Creek. In a high-gradient coastal basin in British Columbia, Millard (2001) found that large (10-50 cm diameter) and small (3-10 cm diameter) woody debris was transported in 2.8 m and 1.6 m wide reaches respectively. Within the Upper Foothills of Alberta, McCleary (2005) found partial transport of small woody debris (3-10 cm diameter) in streams as small as 1 km^2 drainage area. As an upstream boundary of wood transport rather than the transition to transport dominance, this threshold is very similar to the findings from Wigwam Creek. Finally, the method of classifying streams by wood mobility proposed by Gurnell (2003) also accurately described my findings. Gurnell (2003) suggested that streams should be divided into areas defined by L_l:W_b stability ratios (50%, 75% or 100% $L_l < W_b$). In Wigwam Creek, the transition from transport-limited to transport-dominated wood regimes occurred where 50% of wood pieces were shorter than bankfull width.

Downstream studies that used exclusive woody debris definitions found that wood transport thresholds occurred in wider reaches. Studies of large woody debris (≥10 cm diameter) conducted in the interior of British Columbia found that transport was significant in streams ≥3 m wide (Ewan, 2010; Chen et al., 2006). These streams were similar to Wigwam Creek in terms of stream gradient and average wood piece size, yet large wood was transported in wider reaches than in Wigwam Creek. Using an even more exclusive definition of woody debris (≥30 cm in diameter and ≥2 m long), Marcus et al. (2003) found that the transition to transport dominance occurred at 30 m bankfull width. Transport thresholds move downstream for larger size classes, and the threshold observed in Wigwam Creek represents conditions on the small, upstream end of this spectrum.

Chapter 5

Conclusion

The domain analysis revealed that the boundary between colluvial and fluvial channels occurred between 3-7 km^2 drainage area. This differs from reported values for the coastal mountains of British Columbia and glaciated basins of the Pacific Northwest. The boundary implies that fluvial processes, including significant wood transport, occur in channels within basins larger than 7 km^2. However, since I worked on one basin only, there is a need to conduct further analysis in other basins to determine if these results are generally applicable. Stream power increased systematically downstream, but it increased significantly nearby at the valley step at 10 km^2, which also indicated that the channel had a high capacity to move sediment and wood.

Wood characteristics changed significantly in response to increased downstream transport capacity. Wood loads ceased to resemble adjacent forests near the colluvial-fluvial boundary as wood began to be affected by transport. The total wood load decreased, and wood orientation changed from perpendicular to parallel as transport capacity increased downstream. Upstream of the colluvial-fluvial boundary, decay was the main wood output, while downstream outputs include decay and transport. Decay classes 1, 2 and 5 were more abundant in transport-limited reaches while decay class

3 was more abundant downstream. The position of logs within the channel varied with transport capacity, with fewer bridges and more loose or braced wood downstream of the valley step. Partial bridges and anchored wood occurred in the same amounts throughout the channel network. Wood distribution changed from segregated in transport-limited reaches to aggregated in transporting reaches. Most logs had been dead for less than 40 years, but some had persisted for over 125 years in transport-limited reaches. The mean age of woody debris did not change downstream since riparian stands were similar along the stream network.

Wood transport strongly depended on stream and basin characteristics. The transport initiation zone in Wigwam Creek occurred exactly between the fluvial-colluvial process domain boundary and the increase in stream width and power on the valley step at 10 km^2. Mobilization of successive wood size classes occurred gradually between these points, beginning with the transport of fine wood at the fluvial-colluvial boundary, and continuing to the mobilization of large wood on the valley step.

My findings illustrate that the conceptual model of wood transport proposed by Wohl and Jaeger (2009), which divided headwater streams into transport-limited and transport-dominated zones, was applicable to this low-gradient watershed, with the important difference that the transition zone was gradual rather than a discrete threshold. The transition occurred in very narrow reaches of 1.9-2.3 m wide. Therefore, wood transport is an important component of wood budgets even in small headwater streams.

Further woody debris research should be conducted at the watershed or landscape scale, as more data about large-scale patterns of wood recruitment, storage and output are needed (Hassan et al., 2005; Martin and Benda, 2001). In future large-scale studies, spatial patterns of woody debris could be better understood by increasing the density of study reaches, or by conducting continuous surveys of stream networks (Hassan, personal communication, 2011). As well, longer-term studies should be carried out to capture the variability of hydrological and geomorphic processes that affect wood recruitment and transport (Hassan et al., 2005). To make long-term monitoring of wood movement more efficient, alternative wood tagging techniques such as passive radio frequency identification tags could be considered. For all woody debris studies regardless of their scope, the need remains to present wood data in common language and using common concepts in order to facilitate knowledge sharing. Specifically, there is still a lack of agreement about how to define woody debris, as well as how to scale it to streams (Wohl et al., 2010; Hassan et al., 2005). Small wood and fine organic matter, which are typically excluded from woody debris inventories, deserve more research attention to establish their impact on stream morphology and function as well as their abundance and role in the wood budget (McCleary, 2005).

Finally, in order to effectively manage streams to maintain woody debris loads further work is needed to strengthen several components of the wood budget. These include differentiating and quantifying sources of woody debris Hassan et al. (2005), understanding decay processes and quantifying decay rates in different forests, climates and stream conditions (Merten et al., 2010; Scherer, 2004), and directly measuring rates of wood transport in a wider range of stream and basin types. Further work should be done to describe watershed scale processing of wood of different sizes, particularly in smaller streams. Such data could be used to improve models of wood transport in watersheds.

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Appendix A

Wood attribute tables

Table A.1: Proportion of wood orientation by site

Site	Perpendicular	Parallel	Diagonal	Standing
1	11	42	47	0
2	0	0	100	0
3	34	20	44	2
4	28	17	44	11
5	39	17	42	2
6	27	18	52	3
7	30	20	48	2
8	29	17	52	2
9	23	25	49	3
10	29	26	43	2
11	27	16	50	7
12	27	25	36	12
13	15	44	34	7
14	22	32	42	4

Table A.2: Proportion of position classes by site.

Site	Bridge	Partial Bridge	Anchored	Loose	Braced	Active	Inactive
1	37	16	42	0	5.3	47	53
2	100	0	0	0	0	0	100
3	39	15	34	7	5	46	54
4	61	22	11	6	0	17	83
5	29	8	54	10	0	64	37
6	29	10	42	8	11	61	39
7	26	13	35	17	8	61	39
8	21	14	32	5	18	55	45
9	14	20	39	10	17	66	34
10	19	16	34	19	13	66	34
11	9	9	33	12	37	81	19
12	10	20	42	8	20	70	30
13	8	15	44	22	11	77	23
14	10	16	34	10	31	74	26

Table A.3: Proportion of wood pieces among decay and origin classes.

	Decay class					Origin	
Site	1	2	3	4	5	Known	Unknown
1	33	67	0	0	0	70	30
2	12	18	24	41	6	100	0
3	9	14	18	45	14	64	36
4	0	14	29	50	7	83	17
5	6	12	45	37	0	73	27
6	10	10	31	49	0	67	33
7	4	11	24	57	4	64	36
8	11	9	41	39	0	63	37
9	9	10	27	51	3	49	51
10	5	11	43	38	3	40	60
11	3	12	43	41	1	24	76
12	5	8	48	39	1	38	61
13	2	6	73	19	0	31	69
14	1	10	56	32	1	30	70

Table A.4: Proportion of function classes by site. LJ = initiates a log jam, LW = stores large wood, FW = stores fine wood, SED = stores sediment, LS = forces a log step, BS = stabilizes stream bank, P = pool-forming wood. FP = the proportion of pool morphologies per reach that were forced by wood. This data is plotted against drainage area in Figure 3.14. Note that wood pieces could have multiple functions.

	Function types							
Site	LJ	LW	FW	SED	LS	BS	P	FP
1	0	0	0	0	12	47	0	11
2	0	0	0	0	0	0	0	0[1]
3	0	5	70	38	20	25	5	33
4	0	0	11	39	6	39	17	8
5	0	0	21	19	4	52	6	69
6	0	8	43	60	14	30	5	83
7	0	7	58	58	17	20	14	50
8	6	23	52	48	15	27	10	100
9	5	14	53	28	24	22	3	75
10	20	9	34	11	22	25	9	58
11	25	35	56	37	13	16	7	50
12	27	30	58	32	14	30	10	88
13	0	6	31	40	23	31	22	20
14	7	21	51	57	5	18	3	38

[1]No pools present therefore pool forcing not applicable

Table A.5: Proportion of wood by stability class (wood size scaled to stream dimensions). The ratios of wood piece diameter to bankfull stream depth (L_d:D_b) and length to bankfull stream width (L_l:W_b) are classed by size and stability: low 0-33%, moderate 33-66% and high 66-100%.

Site	L_d:D_b			L_l:W_b			n
	Low	Moderate	High	Low	Moderate	High	
1	0	6	94	0	0	100	17
2	0	33	67	0	0	100	3
3	4	43	54	0	14	86	56
4	64	36	0	0	0	100	14
5	57	33	10	0	0	100	49
6	62	28	10	0	25	75	83
7	63	29	8	0	17	83	98
8	85	12	3	7	22	71	143
9	66	30	4	10	30	60	146
10	90	10	0	6	27	67	94
11	59	35	6	8	37	55	188
12	82	17	1	47	23	31	187
13	73	16	11	36	23	41	86
14	95	5	0	70	20	11	652

Table A.6: Relative frequency of crossdated logs among orientation and position classes. B = bridge, PB = partial bridge, A = anchored, L = loose.

Site	Orientation			Position				Position type	
	perp	diag	parallel	B	PB	A	L	active	inactive
3	38	43	19	52	24	24	0	76	24
5	40	45	15	50	10	35	5	60	40
7	25	56	19	55	20	20	5	75	25
10	35	60	5	30	40	20	10	70	30
13	45	45	10	0	31	63	6	31	69

Table A.7: Relative frequency of crossdated logs among decay and stability classes.

Site	Decay				L_d:D_b			L_l:W_b		
	1	2	3	4	low	moderate	high	low	moderate	high
3	6	13	69	13	90	10	0	0	5	95
5	19	19	24	38	100	0	0	0	0	100
7	5	25	60	10	95	5	0	0	5	95
10	5	25	35	35	95	5	0	0	5	95
13	10	20	45	25	81	19	0	13	19	69

Table A.8: Kolmogorov-Smirnov test comparing year of death distributions among sites.

Site pair	Test statistic (D)	p-value
3 - 5	0.19	0.86
3 - 7	0.22	0.68
3 - 10	0.27	0.40
3 - 13	0.29	0.45
5 - 7	0.20	0.82
5 10	0.20	0.82
5 13	0.29	0.45
7 10	0.20	0.82
7 13	0.23	0.70
10 13	0.28	0.51

Table A.9: Differences in year of death among position class pairs.

Position class pair	Test statistic	p-value
Bridge - Partial Bridge	516	0.39
Partial Bridge - Anchored	228	0.02
Anchored - Loose	103	0.20
Bridge - Anchored	301	<0.001
Bridge - Loose	157	0.02
Partial Bridge - Loose	30	0.09

Table A.10: Post-hoc test results for year of death with decay class pairs

Decay class pair	W	$p - value$
1 - 2	148	0.01
2 - 3	527	0.21
3 - 4	644	0.14
1 - 3	357	< 0.001
1 - 4	202	< 0.001
2 - 4	326	0.05