Stream Channels, Large Woody Debris and Biogeoclimatic Zones in Managed Watersheds

submitted to:

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Summary

Most research on the effects of streamside logging on channel morphology in British Columbia has focused on low gradient, riffle-pool streams in the Coastal Western Hemlock biogeoclimatic zone. Following the inception of the Forest Practices Code (FPC), results from these studies and existing management practices (e.g., Coastal Fish/Forestry Guidelines) were incorporated into guidebooks for province-wide application and management of riparian and stream environments. These include:

- Channel Assessment Procedure Guidebook
- Channel Assessment Procedure Field Guidebook
- Riparian Management Area Guidebook
- Interior Watershed Assessment Procedure Guidebook
- Coastal Watershed Assessment Procedure Guidebook

However, application of results obtained from coastal environments to the entire province is not entirely appropriate, nor is the application of results obtained from low gradient riffle-pool streams to steep step-pool streams. The untested, province-wide application of coastal research does not ensure development of effective policies, regulations and guidelines in support of a results-based FPC.

The broad objective of this research is to determine the influence of forest management practices on channel morphology by channel type and biogeoclimatic zone. The results are used to assess whether more rigorous management practices have improved channel and riparian conditions and provide a means of accurately extending the results of existing coastal research to all regions of the province. The research objectives of this study are to evaluate the supply rates of woody debris to the stream system and determine the functional role of woody debris by stream type. This includes an evaluation of the role of log jams in creating and modifying riparian zones, a comparison of processes across biogeoclimatic zone, and an assessment of the influence of management practice on channel conditions. The operational objectives are to summarize the research results into guidelines aimed at ensuring the functional integrity of woody debris on managed forest lands. This includes providing operational staff with woody debris management strategies that are regionally and locally relevant (e.g., aid streamside management decisions and road layout in the vicinity of a watercourse), and to assist in the optimization of timber supplies without compromising the integrity of stream environments.

The results will be used to develop regionally based “best riparian management practices” for all streams sizes considered by the FPC, and to develop assessment tools that indicate channel and riparian conditions. The results will form a critical component of the review, revision, and scientific justification of the aforementioned FPC guidebooks, as methods are adapted for the new results-based FPC.

These results will be appropriate for use by professional/technical staff involved in higher level plans and operational forest management and restoration (e.g., Regional and District staff of the Ministry of Forests, Regional staff of the Ministry of Water, Land and Air, First Nations, industry representatives, and consultants). Some applications will include:

- Professional Geoscientists/Hydrologists involved in the development of land use management plans and watershed assessments;
- Riparian ecologists and fisheries biologists completing fish and wildlife habitat assessment; and
- Professional Foresters involved in forest-level planning and silviculture decision-making.
We have adopted a form of the “extensive post-treatment” experimental design. Our approach has been adapted to fit our specific research question and objectives. We have undertaken, essentially, a pair-watershed approach that compares channel and riparian conditions between logged and unlogged watersheds that are otherwise similar in character. However, instead of considering simple watershed pairs, we have undertaken a stronger comparison among watershed quadruplets. This includes an unlogged control watershed and three treatment watersheds in each of seven biogeoclimatic zones. Treatment watersheds have specific management histories.

Treatment A was defined as timber harvesting operations occurring prior to 1985 when most management practices generally did not consider riparian management a priority, at least in the relatively small streams selected for analysis in this report. Treatment B streamside logging was defined as occurring between 1985 and 1995 when management practices began to recognize the importance of the riparian area and the connection amongst woody debris, channel stability and fish habitat (e.g., Coastal Fisheries Forestry Guidelines). Treatment C was defined as streamside logging occurring after the province-wide application of the Forest Practices Code.

Each set of control-treatment watersheds was located in a different biogeoclimatic zone. We assume that each biogeoclimatic zone is unique regarding the supply characteristics of LWD recruited to the channel from the riparian area (e.g., stems per hectare, basal area, height, and species) and that these characteristics influence channel morphology. This allowed for comparison of channel response to riparian management in different regions and development of prescriptions that consider both channel type and biogeoclimatic zone.

Field data was analyzed from 26 riffle-pool streams in the following biogeoclimatic zones (including the unlogged control data):

- Montane Spruce (MS)
- Interior Douglas Fir (IDF)
- Engelmann Spruce Sub-Alpine Fir (ESSF)
- Interior Cedar Hemlock (ICH)
- Sub-Boreal Spruce (SBS)
- Sub-Boreal Pine-Spruce (SBPS)
- Ponderosa Pine (PP)

The treatment type affected the volume of woody debris staged to enter the channel from the riparian area, both by reducing the area from which wood could be supplied (i.e., the natural supply corridor of woody debris extended past the leave-strip), and by reducing the volume of wood standing within the leave-strip itself. Although these processes were not investigated here, the generally positive relation between leave-strip width and volume of trees per unit area of leave-strip suggests that narrow leave-strips may be more susceptible to disturbance (e.g., windthrow).

The wood budget revealed that in most small riffle-pool streams, approximately equal amounts of woody debris are transferred to the channel from bank erosion and from mortality. Following logging operations associated with Treatment C, the total chronic input (mortality and bank erosion) increased (although potential supply was relatively unchanged), as did the change in storage within the channel. However, neither jam frequency nor jam size changed after logging, suggesting the increase in woody debris delivered to the channel increased the storage of woody debris pieces between jams.
Following logging operations associated with Treatment B, the total chronic input decreased with a decreased potential supply, although the change in storage within the channel was similar to that of the unlogged control watersheds. However, neither jam frequency nor jam size changed after logging, suggesting the decrease in woody debris delivered to the channel decreased the storage of woody debris pieces between jams. A similar, but more pronounced response was noted in Treatment C.

The interpretation of these trends are confounded somewhat by time, as each treatment was coincident with a unique period. However, with reference to previous research, the following conclusions are drawn in regards to riffle-pool channel response to streamside logging:

- Streamside logging in each treatment affects the wood budget of the channel.
- Relatively narrow leave-strips (~10 times the bankfull width) may be more susceptible to disturbance that wider strips.
- Buffer strips ~25 times the bankfull width maintain a potential supply of woody debris for a channel (similar to that of unlogged conditions).
- Following logging operations, the rate of chronic delivery of woody debris may initially increase and then gradually decrease over a period of several decades.
- Wood stored in pieces between jams increases shortly after logging with increases with chronic input (and likely with transfer of logging debris to the channel).
- Wood stored in pieces between jams decreases decades after logging (likely as small woody debris is floated out of the reach or into a jam).
- The size and frequency of log jams is unaffected by changes in wood input to the channel.

Development of BMPs for riparian forest management should consider the supply of woody debris to a riffle-pool channel. Recommendations for BMPs include:

- Select retention strategies that maintain chronic input rates of woody debris by biogeoclimatic zone (refer to rates presented in Table 11 for each biogeoclimatic zone).
- Recognize importance of leave-strip width as a potential source of woody debris to a channel (consider both short-term and long-term input of woody debris).
- Along small streams (1 to 10 m wide), leave strips should be ~10 times the bankfull width for low value channels and ~25 times the bankfull width for high value channels.
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1.0 Introduction

Most research on the effects of streamside logging on channel morphology in British Columbia has focused on relatively low gradient, riffle-pool streams located in the Coastal Western Hemlock biogeoclimatic zone (e.g., Toews and Moore 1982; Hogan 1986; 1987). Comparable studies have been undertaken throughout the Pacific Northwest in relatively similar, coastal environments (e.g., Bryant 1980; Salo and Cundy 1987). Following the inception of the Forest Practices Code (FPC) in 1994, results from these studies and existing management guidelines (e.g., BC Ministry of Forests et. al. 1987; 1988; 1993) were incorporated into guidebooks for province-wide application and management of hydoriparian environments (e.g., BC Ministry of Forests and BC Ministry of Environment 1995 a, b, and c; 1996 a and b). Knowledge and practical management applications outlined in these guidebooks will continue to influence riparian forest management as part of the new Results Based FPC (RBC). Full compliance with the RBC is required by December 31, 2005.

However, application of results obtained from coastal environments to the entire province is not entirely appropriate, nor is the application of results obtained from riffle-pool streams to other channel types (e.g., rapids and step-pools amongst others). Regional variation inherent amongst biophysical controls of channel morphology (see Church 1992) and lateral and vertical stability associated with different channel types are both apt to affect channel response to riparian management. The untested, province-wide application of coastal streamside management techniques and guidelines does not necessarily ensure sustainable harvest or support sustainable forest management practices.

The purpose of this project is to determine the influence of forest management practices on channel morphology by channel type and biogeoclimatic zone. The results will be used to evaluate whether more intensive management practices have improved channel and riparian conditions and provide a means of accurately extending the results of existing coastal research to all regions of the province. The results will form a critical component of the review, revision, and scientific justification of the aforementioned FPC guidebooks, as methods are adapted for the new RBC.

1.1 Project History

The results presented in this report form part of a multi-year project originally funded by Forest Renewal BC (FRBC Research Award: HQ96367-RE). The first five years of the project (fiscal 1996-2000) focused on data collection, analysis and reporting on stream channel and riparian area characteristics in unlogged watersheds. This research was undertaken in riffle-pool and step-pool channel types across 10 biogeoclimatic zones located throughout the province, including: Montane Spruce (MS); Interior Douglas Fir (IDF); Engelmann Spruce Sub-Alpine Fir (ESSF); Interior Cedar Hemlock (ICH); Sub-Boreal Spruce (SBS); Sub-Boreal Pine-Spruce (SBPS); Coastal Western Hemlock (CWH); Spruce Willow Birch (SWB); Boreal White and Black Spruce (BWBS); and Ponderosa Pine (PP).

Additional funding was obtained in fiscal 2001 and 2002 from the Forestry Innovation Investment (FII) and the Forest Investment Account (FIA), respectively. The objective of the FII funded research was to develop prescriptions and management guidelines for riparian areas based on data collected as part of previously completed FRBC research. Prescriptions were based on unlogged watershed conditions and did not consider the effects of watershed management. The objective of the FIA funded research was to develop prescriptions and management guidelines for riparian areas adjacent to step-pool channels based on data collected from managed watersheds. The study design made use of data from unlogged sites collected as part of the original FRBC funded project as a control (i.e., a comparison between logged and unlogged conditions).
Results presented in this report are based on one year of funding from FIA. The objective of this research is to build on the results obtained from 2002 and develop prescriptions and management guidelines for riparian areas adjacent to riffle-pool channels. Prescriptions are based on data collected from managed watersheds, again making use of data from unlogged sites collected as part of the original FRBC funded project as a control.

1.2 Objectives

Riparian areas support many of the highest value non-timber resources in a watershed, including water, biodiversity, wildlife and wildlife habitat, and fish and fish habitat (see review by Bunnell et al. 1995). The goal set by government in the Forest Planning and Practices Regulation (BC Reg. 14/2004 effective January 31, 2004) for water, fish, wildlife and biodiversity within riparian areas is simply to conserve these values at the landscape level as part of a forest stewardship plan. Throughout most small streams in British Columbia, woody debris either influences or controls channel morphology (e.g., Hogan et al., 1998) and is an integral component of stream ecology (e.g., Hartman and Scrivener, 1990). The riparian area is an important source of woody debris to a channel (especially in regions characterized by relatively infrequent landslides), however; riparian management prescriptions are currently derived from a simple classification of channel width, presence/absence of fish, and designation as a community watershed and are applied throughout the province to all channel types. Prescriptions do not address the source, residence time, or function of woody debris in a channel. Consequently, current prescriptions may (in some circumstances) unduly restrict access to timber while in other cases, may not provide adequate protection for non-timber resources or conserve values associated with the riparian area.

The research objectives of this study are to evaluate the supply rates of woody debris to the stream system and determine the functional role of woody debris by stream type. This includes an evaluation of the role of log jams in creating and modifying riparian zones, a comparison of processes across biogeoclimatic zone, and an assessment of the influence of management practice on channel conditions. The operational objectives are to summarize the research results into guidelines aimed at ensuring the functional integrity of woody debris on managed forest lands. This includes providing operational staff with woody debris management strategies that are regionally and locally relevant (e.g., aid streamside management decisions and road layout in the vicinity of a watercourse), and to assist in the optimization of timber supplies without compromising the integrity of stream environments.

1.3 Application of Results

The results of this research are used to develop a series of regionally based best management practices (BMPs) for riparian management areas associated with riffle-pool streams, and to develop assessment tools that indicate channel and riparian conditions. The results are appropriate for use by professional/technical staff involved in higher-level plans and operational forest management and restoration (e.g., regional and district staff of the Ministry of Forests, regional staff of the Ministry of Water, Land and Air, First Nations, industry representatives, and consultants). Some applications may include: Professional Geoscientists/Hydrologists (geomorphologists) involved in the development of land use management plans and watershed assessments; Professional Biologists (riparian ecologists and fisheries biologists) completing fish and wildlife habitat assessments; and Professional Foresters involved in forest-level planning and silviculture decision-making.
1.4 Report Organization

Section 2 reviews the influence of streamside logging on riffle-pool channel stability within the framework of a woody debris budget. Section 3 describes the study design adapted for the project and the methods used to collect the appropriate data. Section 4 describes the method used to select and compare study sites. The method enables selection of suitably "similar" watersheds based on biophysical and morphometric parameters. This step is critical to the objective comparison of management and biogeoclimatic differences among watersheds (i.e., it attempts to control for biophysical and morphometric differences). Section 5 evaluates potential woody debris sources in the riparian area and how these sources have been affected by various riparian management schemes used throughout British Columbia since the 1970s. These results are used in Section 6 to evaluate the supply characteristics of woody debris from the riparian area to the channel and to understand how riparian supply influences woody debris function and storage dynamics. This establishes a link between the condition of the riparian area to the condition of the channel, and serves as the basis for evaluating the relative success or failure of past management prescriptions. Finally, Section 7 draws conclusions from the analyses and summarizes the results into regionally and locally relevant riparian BMPs for the supply of riparian woody debris to riffle-pool streams.

2.0 Woody Debris and Streamside Logging

The influence of woody debris on channel dynamics has been investigated for the past three decades. This section reviews wood recruitment and depletion processes, storage and function of woody debris in small streams, and how biogeoclimatic zone and streamside logging influence these processes. The focus here is on small steepland streams with riffle-pool morphology (generally 1 to 10 m bankfull width) typical of study streams selected for analysis in this report. Conclusions are drawn as to the expected response of a channel to streamside logging and this forms the basis for quantitative analysis in subsequent sections.

2.1 Wood sources and recruitment

Both episodic and chronic processes recruit wood from adjacent hillslopes to small streams. Chronic processes include bank erosion, earthflow, and tree mortality, while episodic processes include rapid mass movements, floods, forest fires, windthrow, and insect outbreaks. The relative importance of these processes is dependent on channel size (at least in part), as both large and small channels are generally represented by different hydrologic, geomorphic, and climatic conditions. The spatial and temporal variations of wood recruitment are important linked aspects of woody debris processes in small streams.

2.1.1 Chronic recruitment of woody debris

In many large rivers, bank erosion serves as the dominant chronic source of wood supplied to a channel (Keller and Swanson 1979) given greater available stream power for eroding banks (Murphy and Koski 1989). Rates of bank retreat in some large rivers flowing through an alluvial floodplain may approach 1 m yr\(^{-1}\) (e.g., Hooke 1980). These rivers can transfer large volumes of wood to a channel if the floodplain is heavily forested. Benda et. al. (2002) estimate rates of wood recruitment from bank erosion (by volume) from 1 to 6 m\(^3\) km\(^{-1}\) yr\(^{-1}\) in Northern California, while Martin and Benda (2001) estimate rates from 1 to 16 m\(^3\) km\(^{-1}\) yr\(^{-1}\) in Southeast Alaska. Small streams, however, are often confined by the hillslope, have smaller discharge, are bound by non-alluvial banks (e.g., boulders supported in a matrix
of fine sediment held under heavy turf mat), and thus have a reduced potential for bank erosion. Actual rates of bank retreat in small, headwater streams are poorly documented but may be on the order of 4.4 x 10^3 m yr^-1 (Lehre 1982). Bank erosion is not likely a major chronic wood recruitment process in small streams. In comparison, mortality of senescent trees or mortality of trees weakened by wind, insect or disease is likely the most important chronic wood recruitment process in small streams. Rates for larger streams in Northern California are estimated up to about 7 m^3 km^-1 yr^-1 (Benda et. al. 2002) and up to about 8 m^3 km^-1 yr^-1 in Southeast Alaska (Martin and Benda 2001).

In narrow streams, the inputs of wood derived from chronic processes are often suspended above the channel banks given relatively narrow channel widths (relative to tree heights) and hillslope confinement. Direct input to the channel may not occur until a log is either broken or fragmented (Nakamura and Swanson 1992). Therefore, although chronic recruitment processes are important delivery processes in small streams, their influence on channel processes and morphology may lag behind initial input and may not be directly related to the observed functional role of wood in the channel.

2.1.2 Episodic recruitment of woody debris

Recruitment of wood from mass movement processes may be of limited importance in large streams (Murphy and Koski 1989; Martin and Benda 2001; Benda et. al. 2002), especially those that flow across a floodplain. Maximum rates estimated by Benda et. al. (2002) in Northern California are about 4 m^3 km^-1 yr^-1 and were considered negligible in Southeast Alaska by Martin and Benda (2001). However, throughout much of coastal British Columbia, about one-third of mountainous terrain is subject to active hillslope failure processes, with some watersheds exceeding 8 failures per km^2 (Schwab 1998).

Coupling between hillslopes and channels affects recruitment and dynamics of in-channel wood and sediment where hillslope failures are prevalent. Most small streams are connected to adjacent hillslopes so that sediment and woody debris are transferred directly to the channel, while larger streams tend to flow across a valley bottom that buffers the hillslope influence on the channel. In coupled watersheds on the Queen Charlotte Islands, Hogan et. al. (1998a) found the age of log jams coincident with episodes of mass wasting (the record spanned more than a century), and that the frequency of newly-formed jams increased as a watershed became smaller and steeper. These results suggest mass wasting on coupled hillslopes may be a dominant wood recruitment process in small streams. Nakamura and Swanson (1993) draw a similar conclusion from steep, narrow, low-ordered streams of western Oregon.

Severe windstorms can snap tree stems and branches, and in many cases, uproot an entire tree or a stand of trees. Windthrow along both large and small rivers is an important recruitment process (e.g., Nakamura and Swanson 1993; Lienkaemper and Swanson 1987; Harmon et. al. 1986) that may be influenced by the position of a reach in a watershed. For example, trees growing in a constricted valley or in the saddle of a main ridge have a relatively high probability of wind damage, as do trees near ridge tops given relatively shallow and dry soil conditions. Since small headwater streams and the adjacent hillslopes are located high in the channel network and often near a ridge top, wood recruitment by wind throw may be greater compared to their lowland counterparts (May and Gresswell 2003b).

2.3 Wood storage and function

The transfer of woody debris from hillslopes and the riparian area to the channel can disrupt sediment transport and adjust local channel gradient through a series of discrete log steps and debris jams. At the channel unit scale, the arrangement and orientation of woody debris is important because
certain channel features, such as pools, riffles, and gravel bars, depends in part on the way in which flow direction is altered (Hogan 1987). For example, channel reaches controlled by wood oriented perpendicular to the channel exhibit greater variation in width and depth than do reaches with woody debris oriented parallel to the banks. Lisle (1986) also found that local bed scour increases with the angle at which flow is deflected. Bars are often protected behind woody debris during high flows, eventually allowing vegetation to establish and stabilize the bar surface, while woody debris positioned against a bank can protect it from the direct erosive force of the water (Madej 1984). In contrast, diagonally occurring woody debris may deflect the flow directly to the bank, promoting local bank instability (Keller and Swanson 1979; Madej 1984). At the reach scale, pool frequency increases (Bilby and Ward 1989) and pool spacing decreases (Montgomery et al. 1995) with increasing amounts of woody debris stored in a channel.

Generally, increasing storage of woody debris reduces sediment transport through a reach. For example, woody debris can alter channel roughness and flow velocity (Buffington and Montgomery 1999) by decreasing the Darcy-Weisbach friction factor (Shields and Gipple 1994) and altering channel geometry (Hogan and Church 1989). In addition, channel spanning woody debris (log steps) reduces local channel gradient as sediment accumulates upstream and dissipates stream power through a series of vertical falls, runs, and hydraulic jumps (Heede 1972; Keller and Swanson 1979; Marston 1982). Experimental removal of woody debris from a reach shows an increase in bedload transport rates and altered channel morphology (e.g., Robison and Beschta 1989; Smith et al. 1993b).

Accumulations of woody debris form log jams and these impede the downstream transport of sediment and promote the upstream aggradation of a sediment wedge. In coastal British Columbia, log jams can regulate sediment transport and control the morphology of small stream channels (Hogan et. al. 1998a). Log jams initiate a series of morphological changes in a stream channel, influencing channel width, depth, local gradient, pool, riffle and bar characteristics, bed texture, bank stability, and the development of the riparian area (see review by Hogan et. al. 1998b). Morphologic changes associated with jams are usually greater than those associated with individual pieces (Nakamura and Swanson 1993).

However, log jams are not permanent features in a channel and slowly break down over time, as physical abrasion during high magnitude floods and consumption of organic matter by stream organisms contribute to a gradual deterioration of individual woody debris pieces (Keller and Swanson 1979; Mosley 1981). As a jam ages, it becomes more permeable to sediment transport and the upstream sediment wedge is gradually transported downstream (Mosley 1981; Hogan 1989; Rice and Church 1996). Severe changes in channel morphology persist for the first decade following the initiation of a log jam; however, the channel begins to resemble normal conditions after the third decade with increasing variability in channel width, depth, and bed texture (Hogan 1989).

Woody debris is also an integral component of stream ecology in British Columbia (Hartman and Scrivener 1990), influencing both the physical and biological characteristics of small stream channels and riparian areas. Pacific salmon, trout and char (salmonids) use stream environments for specific phases of their life cycle and generally require clean, stable riffles for spawning, stable pools to rear in, and access to side channels and tributaries during periods of high flow (Toews and Brownlee 1981). Hogan et. al. (1998a) reviews the influence of woody debris and log jams on the interactions among channel morphology, riparian areas and fish habitat in coastal British Columbia. In the early phases of channel adjustment following jam formation, fish habitat is degraded as spawning areas (riffles) are buried (upstream of the jam) or eroded (downstream of the jam), rearing pools are infilled and egg incubation environments are smothered with fine textured sediments. Over the long term (on the order of half a century), log jams deteriorate and create complex, diverse stream channels, side channels, and riparian areas that become highly productive fish habitats.
2.3 Wood decomposition

Once delivered to a channel, wood is eventually moved downstream through a combination of processes including in-situ decay and transportation to downstream reaches. Rates and residence times of these processes affect the distribution, accumulation, and function of woody debris in a channel which are, in turn, affected by both physical and biological factors.

2.3.1 Decay

The environmental controls of woody debris decay include temperature, oxygen, moisture, surface area, and wood chemistry (Harmon et al. 1986; Naiman et al. 2002). In a lotic environment, temperature and oxygen are the dominant controls of decay (Sedell et al. 1988). Temperature is important as it influences fungal respiration rates and can alter microbial (e.g., fungus and bacteria) activity and the decomposition rates of wood (Harmon et al. 1986). Microbial activity is also dependent on oxygen, as continuously submerged or waterlogged wood (i.e., anaerobic conditions) decays much slower than wood submerged only during higher flow periods (i.e., aerobic conditions) (Sedell et al. 1988).

Decay is an important consideration in any long-term assessment of woody debris in a channel, as decay rates control the residence time of wood in a stream. Decay rates (typically expressed in terms of a decay coefficient, $k$) in a lotic environment are poorly understood, but reported values of $k$ obtained from the Pacific Northwest range from 0.01 to 0.038 yr$^{-1}$ (Murphy and Koski 1989; Bilby et al. 1999; and Hyatt and Naiman 2001). Throughout this region, wood typically resides in a channel for 70 to 100 years, although some pieces may remain for several centuries or longer (Naiman et al. 2002). Overall, decomposition rates of woody debris are relatively low and often assumed negligible when investigating relatively short-term (i.e., timescales on the order of $10^1$ yr) changes in channel-stored woody debris (e.g., Benda et al. 2002).

2.3.2 Transport

Woody debris stored in a channel can be transported to downstream reaches by both episodic and chronic processes. The former occurs during mass movement events (debris flows in particular) while the latter occurs during high water events (i.e., floods of some magnitude). Debris flows can transport relatively large volumes of water-charged clastic sediment and woody debris, and can deplete most woody debris and sediment from source and run-out zones (Gomi et al. 2001; May and Gresswell 2003a). Actual transport distance of woody debris can reach several kilometers depending on channel gradient, valley constraint, and junction angle of a tributary if a debris flow reaches the main channel (Swanson and Lienkaemper 1978; Benda and Cundy 1990; Johnson et al. 2000; May and Gresswell 2003b; Reeves et al. 2003). Average rates of transport are also dependent on the magnitude/frequency of mass wasting events within a watershed.

Woody debris is also transported by flowing water. Braudrick and Grant (2000) describe entrainment by buoyant force as a function of two wood characteristics (log diameter and density) and one hydraulic characteristic (depth). Braudrick and Grant (2000) further describe entrainment by shear force as a function of four wood characteristics (log length, diameter, orientation, and density) and three hydraulic characteristics (slope, water velocity, and depth). Once entrained, average transport rates generally depend on the length and diameter of a log relative to the channel width and depth, respectively, and on channel morphology (see review by Braudrick and Grant 2001). Generally, transport rates are highest when woody debris is relatively small and the channel is relatively straight with a smooth boundary.
The volume of woody debris in a channel tends to decrease with stream order, and likely reflects the tendency for logs to be entrained during high flows in relatively large channels (Keller and Swanson 1979; Lienkaemper and Swanson 1987; Robinson and Beschta 1990).

2.4 Influence of biogeoclimatic zone

Woody debris characteristics in a drainage system are apt to be affected by the position of a reach within a watershed as the distribution of tree species is broadly influenced by local climate and elevation. In coastal British Columbia, large streams found in lowland portions of a watershed are generally coincident with the CWH and occasionally the Coastal Douglas Fir (CDF) biogeoclimatic zone. These forests have relatively high productivity, with a mean annual increment (MAI) of at least 6.4 m³ ha⁻¹ yr⁻¹ (Mackinnon et al. 1991). Typical coniferous tree species in these zones include western hemlock (Tsuga heterophylla), western redcedar (Thuja plicata), and Douglas-fir (Pseudotsuga menziesii), with Sitka spruce (Picea sitchensis) common along relatively wet valley bottoms and floodplains (Nuszdorfer et al. 1991; Pojar et al. 1991a). Stand-destroying disturbance is infrequent, with windthrow being the most common form and may affect either single trees or, more rarely, complete forest stands (Waring and Franklin 1979). In some coastal CWH watersheds, such disturbance likely occurs over intervals of 400 to 1000 years (Clayoquot Sound Scientific Panel 1995).

Further upslope, the subalpine forests of the Mountain Hemlock (MH) biogeoclimatic zone dominate the landscape. Tree growth is limited (progressively with elevation) given a shorter growing season, increased duration of snow cover, and cooler temperatures (Pojar et al. 1991b). Lower elevations throughout the zone are heavily forested but grade into parkland at higher elevations (individual trees or clumps of trees amongst patches of mainly low-lying shrubs). These forests have relatively low productivity, with the MAI ranging from 0.8 to 3.4 m³ ha⁻¹ yr⁻¹ (Mackinnon et al. 1991). Typical coniferous tree species throughout the zone include mountain hemlock (Tsuga mertensiana), amabilis fir (Abies amabilis), and yellow cedar (Chamaecyparis nootkatensis) (Pojar et al. 1991b). Forests of the MH are generally resilient and infrequently disturbed (cycles in excess of 200 years), although slow to recover once a disturbance is initiated (Klinka and Chourmouzis 2001).

Several inferences relating to woody debris processes can be drawn given these broad ecosystem characteristics and their distribution within a watershed. First, the MAI describes the average volume of production per year for a forest of known age and has important consequences to recruitment rates of woody debris to the channel. Assuming an even-aged forest, small subalpine channels will tend to have less woody debris available for recruitment (by volume), despite the common observation that small channels tend to store larger volumes of woody debris (see previous sections). However, this reduction in the potential woody debris supply may be augmented by differences in both episodic and chronic supply rates. For example, episodic windthrow is (apparently) an important episodic delivery agent of woody debris to the channel network, but may occur more frequently adjacent to small subalpine streams (see previous sections). Chronic mortality (as indexed by maximum tree age of common species) ranges from 500 to 1000 years in the CWH and from 590 to 800 years in the MH (Burns and Honkala 1990), so the number of individual stems delivered to the channel through windthrow and mortality are likely greater (at least slightly) in small streams as they pass through subalpine forests of the MH zone. Inputs of woody debris from subalpine forests such as the MH may also reinforce the randomness observed in storage volumes as the forests are often discontinuous (i.e., alternating between forest and parkland).

Second, the size of individual logs delivered to a large channel is expected to differ from that of small channels. Typical mature species in the CWH and CDF zones can range from 50 to 76 m in height, and from 1.0 to 5.9 m in diameter (measured at breast height), while typical mature species in the MH...
zones can range from 30 to 61 m in height, and from 0.6 to 1.5 m in diameter (Burns and Honkala 1990). In both ecosystems, the lengths of the largest logs are generally capable of spanning the banks of most channels. The buoyant depth in small streams in the MH zone is reduced by a factor of 0.3 to 0.6 relative to large streams in the CWH and CDF zones. This suggests that absolute bankfull depth (hence the buoyancy of logs) limits the transport of most logs in small streams (assuming logs have been broken into lengths that permit transport). Although the transport of logs increases with increasing channel size (see previous sections), so too does the size of logs transferred to the channel.

Third, differences in local climate influence decay characteristics of woody debris stored in a channel. In the CWH and CDF zones, mean annual temperature ranges from about 5 to 11 °C while mean annual precipitation ranges from about 650 to at least 4400 mm, with anywhere from 5 to 50% falling as snow (Nuszdorfer et. al. 1991; Pojar et. al. 1991a). In the higher elevations associated with the MH zone, mean annual temperature ranges from 0 to 5°C while mean annual precipitation ranges from 1700 to 5000 mm, with 20 to 70% of this falling as snow (Brooke et. al. 1970; Pojar et. al. 1991b). Lower precipitation as rain and cooler temperatures in the MH zone reduce microbial activity, while smaller log diameters allow a greater proportion of a log to remain submerged (hence limiting the oxygen available to microbes) as channel depth decreases with decreasing channel size. In contrast, increases in light associated with some MH zone forests (especially in parkland ecosystems) may increase microbial activity.

2.5 Influence of streamside logging

Streamside logging involves either clear cutting riparian trees to the channel bank or retaining a linear patch of trees along the bank to buffer the channel from upslope harvesting activities. The width of the buffer is often set as some proportion of the channel width or in relation to channel gradient, and may include full or variable retention of trees within the management area.

Generally, streamside logging can affect the stability of sediment stored along the banks and in the bed of a riffle-pool channel. Bird (2001) summarizes these effects into direct and indirect impacts to a channel. Direct effects of streamside logging include operating machinery in or across the channel, operating machinery on top of banks, salvaging logs out of the active channel, and delivering logging debris to the channel from surrounding hillslopes or valley bottoms. These effects are usually evident in the channel immediately following logging operations. Indirect effects include the loss of bank cohesion following decay of the riparian tree-root network, and a lack of large riparian trees available to the channel from overbank sources. These effects may not be fully apparent for several years or even decades. The nature of these effects is twofold. First, stored sediment may be mobilized as stable storage elements such as bars and banks are disturbed. Second, streambank logging can alter the wood budget of a stream by changing the size and amount of woody debris pieces delivered to the channel. These are considered below.

2.5.1 Sediment mobilization

In riffle-pool streams, the removal of riparian vegetation can lead to bank retreat and transfer of sediments from the riparian area into the active channel (e.g., Roberts and Church 1986). Millar (2002) shows the dependence of channel planform on dense, deep rooting streamside vegetation, and how a meandering gravel bed river can be transformed into a braided river following streamside logging. Additional sediment may be released from storage as logs are salvaged from the channel. Once delivered to the channel, these sediments may promote additional bank attack as flow is deflected into the streambanks.
2.5.2 Woody debris budgets

Streambank logging can alter the wood budget of a stream by changing the size and amount of woody debris pieces delivered to the channel (Toews and Moore 1982; Hogan 1987). These changes can occur if the transfer of large trees from the riparian area to the channel is interrupted following logging operations. These changes can also occur if existing woody debris pieces are salvaged from the channel and/or logging debris is delivered to the channel during logging operations. Overall, this results in a reduction in the size of woody debris in the channel or staged to enter the channel. Small, individual debris pieces are less effective in promoting scour or storing sediments and this generally results in reduced channel complexity (Hogan 1987).

In the absence of any post-logging landslides, logging debris will usually enter the stream channel during or immediately after logging operations (e.g., Toews and Moore 1982). Generally, logging debris contains slash, bark, and woody debris pieces with detached root wads that are easily floated downstream at high flows and can accumulate into log jams. Newly formed log jams, especially those formed with logging debris, are usually effective sediment traps and are relatively impermeable to sediment transport (see review by Hogan et. al. 1998b). Upstream of a jam, bed aggradation reduces local channel gradient and promotes the accumulation of fine-textured sediments, and causes the streambanks to erode as the channel widens. Stable sequences of riffles and pools are replaced by extensive riffles as pools are infilled. Downstream of a jam, the channel becomes coarse-textured and can be scoured down to bedrock as sediment supply is restricted from upstream.

Bryant (1980) investigated the development of log jams following streamside logging in a riffle-pool stream in southeast Alaska (results are summarized in Figure 1). Historic channels maps of Maybeso Creek show the presence of several small log jams consisting of large individual debris pieces prior to logging. During streamside logging operations, logging debris was delivered to the channel and then floated downstream during high flow where it accumulated into either new log jams or on top of existing log jams. The overall frequency of log jams initially increased after logging, with most logging debris stored in relatively large log jams. However, most of these structures did not persist in the channel. A decade after logging, the channel was dominated by still large but less frequent log jams. By 1978, both the frequency and the size of individual log jams decreased below pre-logging levels as increasing amounts of woody debris was transferred overbank or to downstream reaches. In some cases, the channel was forced around a jam entirely and into the riparian area as the channel aggraded (i.e., the channel avulsed), while in other cases, logging debris destabilized existing jams and these eventually broke apart. Only jams that pre-dated logging operations remained in the channel. Hogan (1987) reports similar results from a paired watershed study of riffle-pool streams on the Queen Charlotte Islands. Several decades after streamside logging, the number of sites (log jams and log steps) with significant volumes of stored sediment decreased, however, the total volume of sediment stored at these individual sites increased. Both Bryant (1980) and Hogan (1987) suggest these changes result in an overall reduction in channel stability as large accumulations of sediment stored behind logging debris are more likely to fail during high flows than their unlogged counterparts, and this can lead to a sudden and widespread redistribution of channel sediments.

2.6 Conclusions

Throughout most small streams in British Columbia, woody debris either influences or controls channel morphology and is an integral component of stream ecology. The riparian area is an important source of woody debris to a channel, especially in regions characterized by relatively infrequent landslides and along small streams (log length and diameter ~ channel width and depth, respectively) where transport and delivery from upstream sources is restricted.
Streamside logging can influence both the character and rate of woody debris delivered to a channel, provided that total stand volume and the size of individual trees in the riparian area are reduced. Generally, this can reduce both the total volume and the size of individual pieces of woody debris stored in a channel. The introduction of logging debris can further reduce the average size of woody debris pieces. Given that woody debris transport rates are inversely related to log length and diameter, streamside logging may ultimately increase the mobility of woody debris stored in the channel. This can result in formation of larger, less frequent, and less stable log jams. This can also result in depletion of woody debris from a reach as input rates are reduced and transport rates are increased, at least over relatively short timescales.

Changing ecosystem characteristics is a confounding influence on the study of woody debris process, including comparisons of woody debris input, storage, transport and decay, and underscores the importance of considering ecosystem characteristics or classification such as biogeoclimatic zonation in understanding processes associated with woody debris. It also underscores the importance of the debris budget as a conceptual framework for making comparisons at the watershed and/or regional scale.

3.0 Methods

3.1 Study Design

This study was based on a modified form of the extensive post-treatment experimental design. Essentially, the method uses a pair-watershed approach that compares channel and riparian conditions between logged and unlogged watersheds that are otherwise similar in character. Generally, the method is a statistically powerful means of achieving the objectives of a large-scale ecological experiment (Mellina and Hinch 1995). However, instead of considering single watershed pairs (i.e., one treatment per control), this study considered three treatments of different intensity per control. Each treatment (A, B, and C) was associated with a specific management history (details are given in section 5.0), which allowed for an evaluation of the effectiveness of different management practices on channel and riparian conditions following streamside logging. Treatment A, B and C watersheds were logged prior to 1985, between 1985 and 1995, and after 1995, respectively.
The location of each set of control-treatment watersheds is given in Figure 2. Refer to Appendix I for a small-scale map of each study area. Each set of control-treatment watersheds is located in one of seven biogeoclimatic zones, including the ICH, IDF, PP, ESSF, MS, SBS, and SBPS zones. The data were stratified as biogeoclimatic zone influences stand characteristics (e.g., stems per hectare, basal area, height, and species) and these are likely to affect the character and rates of woody debris supplied to the channel. This design allowed for comparison of different treatments on channel and riparian conditions, an evaluation of the response to treatment in different ecologic settings, and development of prescriptions unique to each biogeoclimatic zone.

![Location Map for all study sites for 2003.](image)

**Figure 2.** Location Map for all study sites for 2003.

### 2.2 Data Collection

Detailed longitudinal profiles were surveyed over extensive channel lengths (approximately 40 to 50 bankfull channel widths) to document the morphological condition of each channel. Profiles were surveyed with an automatic level and stadia rod, while distance along the thalweg was measured with a surveyor’s hip chain. Thalweg, water surface, bar and bank elevations were measured at a set interval of one bankfull channel widths to document the morphological condition of each channel. Profiles were surveyed with an automatic level and stadia rod, while distance along the thalweg was measured with a surveyor’s hip chain. Thalweg, water surface, bar and bank elevations were measured at a set interval of one bankfull channel widths to enable objective analyses of channel characteristics. Other morphological features (e.g., morphologic breaks separating pools and riffles) were added as supplementary survey points. These were identified in the field by their topographical, sedimentological and hydraulic characteristics as defined by Keller and Melhorn (1973) and Sullivan (1986). Channel and valley floor widths were measured every fifth channel width.
All woody debris was categorized at each survey interval according to the size (length and mean diameter), position (orientation relative to the banks and vertical placement of a log above the bed or bank), and function (ability to trap bed and bank sediments or promote local scouring) of each piece. Each log jam was classified according to Hogan and Bird (1998) and Hogan (1989). Jam age was determined from the ages of nursed trees and trees growing on the sediment wedge associated with the jam. A standard increment tree bore was used to obtain cores at, or near, the point of germination. If wedge or nursed trees were not present, jam age was approximated from the decay characteristics of individual woody debris pieces (Hogan 1989).

Four sample plots were established along each reach to characterize the riparian forest. Plots were 3.99 m in radius and at least six live dominant trees were present in each plot. Plots were placed approximately 10 bankfull widths apart along the reach and adjacent to the stream banks. Within each plot, tree species, breast height diameter, and the crown height of each tree were determined. Breast height diameter was measured with a DBH tape and used to estimate tree basal area. Crown heights less than 2 to 3 m were measured with a stadia rod, while taller trees were measured with a survey laser or an inclinometer and chain. The width of the riparian buffer (if present) was measured as a slope distance with a survey chain and an inclinometer.

4.0 Drainage Basin Comparisons

Hogan (1986) noted that basin morphometry must be considered as part of any post-treatment experimental design (i.e., comparison of so-called paired watersheds), given drainage basin morphometry is an important control of channel morphology. Although no two watersheds are identical, the confounding influence of basin morphometry can be minimized if differences are known and accounted for in subsequent analysis. This section describes both the methods and results of drainage basin comparisons undertaken for this report. Watershed pairs are based on a comparison of biophysical parameters and a dissimilarity analysis of morphometric parameters that characterize each watershed.

4.1 Methods

A standard method of comparing two drainage basins has not been widely accepted. Various procedures have been used to determine similarity, but no single method has become dominant, and rarely are these procedures explained in published documents (Cheong 1992). In British Columbia, Hogan (1986) made one of the first quantitative attempts at pairing watersheds based on drainage basin morphometrics. However, the work of Cheong (1992) likely represents the first comprehensive, clearly defined, and quantitative procedure for classifying basins based on biophysical and morphometric parameters. Essentially the method combines two elements: the comparison of filter parameters (typically nominal-scale data such as geology) and the assessment of morphometric similarity.

4.1.1 Biophysical similarity

Biophysical parameters were selected to reflect factors that govern physical processes in streams and hence their morphology (see Church 1992). These were curbed into eight unique parameters (Table 1), each extracted from a digital map and modeled in a geographic information system (GIS). Candidate watersheds were advanced to the second stage (morphometric similarity) if a reach at the
outlet of the watershed matched the same biogeoclimatic criteria as the control watershed with the appropriate streamside logging treatment. Most candidate watersheds identified via the biophysical filter encompassed multiple biogeoclimatic zones.

4.1.2 Morphometric similarity

One way to compare watersheds is by calculating the dissimilarity of two watersheds based on key morphometric parameters. In general, several methods may be employed to analyze the dissimilarity between two objects. Most procedures incorporate some form of Euclidean distance measure in order to calculate the ‘proximity’ between two objects (Gordon 1981). For example,

$$d_{ij}^{(\lambda)} = \left[ \sum_{k=1}^{p} w_k |x_{ik} - x_{jk}|^{\lambda} \right]^{1/\lambda}$$

where $w_k (k = 1 \ldots p)$ is a set of weights, $i$ represents the first object, $j$ represents the second object, $k$ is the $k^{th}$ characteristic, $\lambda > 0$ and higher values of $\lambda$ give relatively more emphasis to larger differences $|x_{ik} - x_{jk}|$ (Gordon 1981; Cheong 1992). When $\lambda = 2$, one has the weighted root mean square. The dissimilarity between any two objects increases as $d_{ij}^{(\lambda)}$ increases.

Standardization can also be used for variables with a relatively large range of variation, which may skew dissimilarity calculations. Hence,

$$d_{ijk}^{(z)} = \left[ \frac{x_{ik} - x_{jk}}{\sigma_k} \right]^2$$

The morphometric parameters selected for dissimilarity analysis (listed in Table 2) are largely based on the key basin attributes identified by Cheong (1996). They represent the basic geometry of the landscape, are correlated to many hydrological and geomorphological processes, and are relatively easily to extract from base maps. Roughly one half of the parameters are dimensionless. This places the focus on the intensive measures of the system. However some scale-referenced parameters are also included. For example, basin area is included as it directly relates to the physical scale of the system, which ultimately reflects the general hydrology of the basin. Morphometric data for each candidate watershed were extracted via GIS models using digital BC TRIM series maps (1:20,000 scale) and digital elevation models (25 m resolution).
Table 1. Biophysical parameters and criteria used to identify areas similar to each control.

<table>
<thead>
<tr>
<th>Biophysical parameter</th>
<th>Source (scale)</th>
<th>Criteria and description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physiographic zone</td>
<td>Scanned and digitized from hardcopy (1: 5 million)</td>
<td>Zone identical to the control. Zones of similar landforms resulting from similar processes of erosion and deposition, similarities of bedrock response to erosion, and similarities of orogenic history (Holland 1976)</td>
</tr>
<tr>
<td>Hydrologic zone</td>
<td>Scanned and digitized from hardcopy (1: 7 million)</td>
<td>Zone identical to the control. Ten zones are identified in BC based on expected hydroclimatic uniformity (Church 1997).</td>
</tr>
<tr>
<td>k-factor</td>
<td>Scanned and digitized contours from hardcopy (1: 9 million)</td>
<td>Within +/- 0.5 of the control. A scale-independent runoff factor, representing the effect of the physical control of runoff at the regional scale of order $10^1$ to $10^2$ km (see Eaton et al. 2002 for details).</td>
</tr>
<tr>
<td>Vegetation cover</td>
<td>Soil Landscape of Canada V2.2; Agriculture and Agri-Food Canada (1:1 million)</td>
<td>Proportion of unvegetated cover within +/- 0.1 of the control. May influence, among other things, infiltration rate, runoff patterns, soil development, snow pack, snowmelt, and the hydrological response of a watershed.</td>
</tr>
<tr>
<td>Surface material (hard rock)</td>
<td>Soil Landscape of Canada V2.2; Agriculture and Agri-Food Canada (1:1 million)</td>
<td>Proportion of surface material classified as hard rock within +/- 0.1 of the control. May be related to vegetation patterns, disturbance regimes (i.e., landslide history), dominant erosion mechanisms, hydrological response, and infiltration rate and runoff patterns.</td>
</tr>
<tr>
<td>Drainage class</td>
<td>Soil Landscape of Canada V2.2; Agriculture and Agri-Food Canada (1:1 million)</td>
<td>Dominant and/or subdominant drainage class (e.g., rapid, well, moderately well, poor, and very poor) matching the control. May be related to slope stability, infiltration rate, runoff patterns, hydrological response, and soil characteristics.</td>
</tr>
<tr>
<td>Soil type</td>
<td>Soil Landscape of Canada V2.2; Agriculture and Agri-Food Canada (1:1 million)</td>
<td>Dominant and/or subdominant Great Group matching the control. Soil properties are determined by climatic factors and organisms, as conditioned by the relief and the moisture regime acting on geological materials.</td>
</tr>
<tr>
<td>Biogeoclimatic zone</td>
<td>BC Ministry of Forests V5, Forest Science Sections in each Regional Office (1: 20,000 to 600, 000)</td>
<td>Zone identical to the control. BEC Zones group together ecosystems with similar climate, soils and vegetation at the broad landscape level.</td>
</tr>
</tbody>
</table>
Table 2. Morphometric parameters extracted for dissimilarity analysis.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basin area</td>
<td>km²</td>
</tr>
<tr>
<td>Perimeter</td>
<td>km</td>
</tr>
<tr>
<td>Proportion of ice cover</td>
<td>km²/km²</td>
</tr>
<tr>
<td>Proportion of lake cover</td>
<td>km²/km²</td>
</tr>
<tr>
<td>Proportion of steepland area (&gt; 60 % slopes)</td>
<td>km²/km²</td>
</tr>
<tr>
<td>Proportion of valley flat area (&lt; 7 % slopes)</td>
<td>km²/km²</td>
</tr>
<tr>
<td>Mean basin gradient</td>
<td>m/m</td>
</tr>
<tr>
<td>Mean basin elevation</td>
<td>m</td>
</tr>
<tr>
<td>Maximum, middle, and minimum channel elevation</td>
<td>m</td>
</tr>
<tr>
<td>Main channel length</td>
<td>m</td>
</tr>
<tr>
<td>Magnitude</td>
<td></td>
</tr>
<tr>
<td>Drainage density</td>
<td>km/km²</td>
</tr>
<tr>
<td>Relief</td>
<td>m</td>
</tr>
<tr>
<td>Shape factor</td>
<td>km²/km²</td>
</tr>
<tr>
<td>Main channel gradient</td>
<td>m/m</td>
</tr>
</tbody>
</table>

Dissimilarity values were then calculated for each watershed pair. The dissimilarity testing procedure involved two steps. First, the dissimilarity of each parameter for any given watershed pair combination was calculated. For example, the 'basin area' dissimilarity between basin A and basin B was calculated as,

\[
d_{ij}^{\text{basin area}} = \frac{(x_i - x_j)^2}{(\sigma_{\text{basin area}})^2}
\]  

where \(i\) represents basin A, \(j\) represents basin B, \(x\) represents the basin area value for a given watershed, and \(\sigma\) is the standard deviation of all the basin area values in the control-treatment group. Once dissimilarity values were calculated for each parameter, the total dissimilarity was determined by taking the square root of the sum of all dissimilarity values calculated for each parameter.

4.2 Watershed Pairs

Separate dissimilarity tests were completed for each control-treatment group. Approximately nine candidate watersheds were identified from the biophysical filter for each control watershed. The candidate watersheds that best matched the control watersheds (i.e., had the lowest dissimilarity) were selected for this study (Table 3). It is important to note that watershed pairs are not deemed “identical” to one another by this analysis. They are simply a "best fit" when selected from a large sample of candidates. Refer to Figure 2 for locations of each watershed.
Overall, dissimilarity values were lowest in the IDF control-treatment group (ranging from 0.09 to 4.88) and highest in the SBS group (ranging from 5.03 to 8.51). Watersheds in the IDF were located in close proximity to one another, and this likely contributed to the relatively low dissimilarity values. Watersheds in the SBS were difficult to locate, as there were relatively few candidate watersheds identified by the biophysical filter with the appropriate treatment. The most significant differentiating factor in this group was watershed area, as candidate watersheds were up to six times smaller than the control. Although the biophysical filter revealed only a few candidate watersheds for the PP control-treatment group, basin morphometry was relatively similar among selected watersheds. Note, however, that both Carabine and Charette were converted to agricultural use (despite information presented on forest cover maps) and did not meet the study design requirements of this report. Unfortunately, no other Treatment A or C watershed was identified.

Dissimilarity values averaged 6.16, 5.03, and 5.57 for treatments A, B, and C, respectively. A single factor analysis of variance (ANOVA) suggested no significant difference existed by treatment ($F_{0.05 (1), 2,18}$), and it was concluded the study design was not confounded by basin morphometry (i.e., basin pairs are equally dissimilar in each of the three treatments).

### 5.0 Potential Woody Debris Sources

The riparian area represents an important source of woody debris to a channel, especially in a watershed that lacks extensive landslides (e.g., Benda et al. 2002; Lienkaemper and Swanson 1987) or in a channel that cannot transport large logs from upstream reaches (see Braudrick and Grant 2001). Riparian forest management can reduce this supply and alter the character of woody debris available to a channel (e.g., Bryant 1980; Lisle 1986; Hogan 1987). This section compares riparian woody debris sources in managed and unmanaged watersheds, and evaluates how these sources have been affected by various riparian management schemes used throughout British Columbia since the 1970s. The results are used to evaluate the effectiveness of current management techniques on maintaining a potential woody debris source and assess the improvement (if any) over past management techniques.

### 5.1 Evolution of riparian management practices in British Columbia

During the past fifty years, there has been a growing awareness of the negative impacts of forestry operations on biological and physical stream channel characteristics. Resource managers, industry and government agencies gradually recognized that one of the most viable ways to maintain stream channel integrity was through protection of the riparian area. Throughout the early 1970s to the mid 1990s, formal guidelines were introduced into many jurisdictions around the province, and by 1995 these were standardized, set into regulations under the FPC, and applied across the entire province.

The evolution in riparian management allowed for an assessment of the effectiveness of different management practices on channel and riparian conditions following streamside logging. However, with a few exceptions, actual management practices are not well documented. The objective here is to understand the historical shifts in recommended forest practices provided by both government agencies and scientific research results. General management trends and practices are inferred from published guidelines, management reports, and supporting research. The discussion is limited to the treatment of riparian areas located on Crown lands and excludes external factors such as changes in timber accessibility, shifts in forest harvesting technology and environmental controls.
### Table 3. Dissimilarity results with all selected watershed pairs. Note that dissimilarity values were only calculated for watershed pairs involving the control (i.e., the similarity amongst treatment watersheds was not considered). Note that some of study streams are unnamed in the BC Gazetteer and have been named here for convenience after the major river systems to which they flow.

<table>
<thead>
<tr>
<th>Study watershed</th>
<th>Control</th>
<th>Treatment</th>
<th>Treatment type</th>
<th>Biogeoclimatic zone</th>
<th>Dissimilarity</th>
<th>Discriminating parameters</th>
</tr>
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<tbody>
<tr>
<td>Chauncey</td>
<td>McLatchie</td>
<td>A</td>
<td>ESSF</td>
<td>6.80</td>
<td>Mean &amp; maximum elevation Perimeter, steepland area &amp; drainage density</td>
<td></td>
</tr>
<tr>
<td>Cross</td>
<td>B</td>
<td>ESSF</td>
<td></td>
<td>3.98</td>
<td></td>
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</tr>
<tr>
<td>Fenwick</td>
<td>C</td>
<td>ESSF</td>
<td></td>
<td>4.52</td>
<td>Basin area, minimum elevation, minimum channel elevation &amp; magnitude</td>
<td></td>
</tr>
<tr>
<td>Sweehaw</td>
<td>Ladybird</td>
<td>A</td>
<td>ICH</td>
<td>5.47</td>
<td>Maximum channel elevation, mean &amp; maximum elevation</td>
<td></td>
</tr>
<tr>
<td>Deer Lower</td>
<td>B</td>
<td>ICH</td>
<td></td>
<td>6.39</td>
<td>Basin area, magnitude &amp; drainage density</td>
<td></td>
</tr>
<tr>
<td>Deer Upper</td>
<td>C</td>
<td>ICH</td>
<td></td>
<td>6.63</td>
<td>Shape factor, valley flat area, magnitude &amp; basin gradient</td>
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</tr>
<tr>
<td>Junction</td>
<td>Beaverdam</td>
<td>A</td>
<td>IDF</td>
<td>4.81</td>
<td>Mid-channel elevation &amp; shape factor</td>
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</tr>
<tr>
<td>Ore</td>
<td>B</td>
<td>IDF</td>
<td></td>
<td>4.88</td>
<td>Magnitude</td>
<td></td>
</tr>
<tr>
<td>Junction Upper</td>
<td>C</td>
<td>IDF</td>
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<td>0.09</td>
<td>None</td>
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<tr>
<td>Albert</td>
<td>North White</td>
<td>A</td>
<td>MS</td>
<td>5.22</td>
<td>Basin and steepland area, lakes &amp; relief</td>
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</tr>
<tr>
<td>Thunder</td>
<td>B</td>
<td>MS</td>
<td></td>
<td>4.92</td>
<td>Lakes</td>
<td></td>
</tr>
<tr>
<td>Sulphur</td>
<td>C</td>
<td>MS</td>
<td></td>
<td>7.27</td>
<td>Basin area, mean and maximum elevation &amp; lakes</td>
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</tr>
<tr>
<td>Arrowstone</td>
<td>Carabine</td>
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<td>PP</td>
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<td>Basin and steepland area &amp; drainage density</td>
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</tr>
<tr>
<td>Charette</td>
<td>A</td>
<td>PP</td>
<td></td>
<td>6.06</td>
<td>Lakes, main channel length &amp; basin area</td>
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</tr>
<tr>
<td>Cache</td>
<td>B</td>
<td>PP</td>
<td></td>
<td>4.10</td>
<td>Steepland area &amp; channel gradient</td>
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</tr>
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<td>Kappan</td>
<td>Baezaeko</td>
<td>A</td>
<td>SBPS</td>
<td>6.61</td>
<td>Relief, shape factor &amp; channel gradient</td>
<td></td>
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<tr>
<td>McFarland</td>
<td>B</td>
<td>SBPS</td>
<td></td>
<td>5.91</td>
<td>Relief &amp; minimum elevation</td>
<td></td>
</tr>
<tr>
<td>Blackwater</td>
<td>C</td>
<td>SBPS</td>
<td></td>
<td>6.62</td>
<td>Basin area &amp; shape factor</td>
<td></td>
</tr>
<tr>
<td>Forfar</td>
<td>Stuart T1</td>
<td>A</td>
<td>SBS</td>
<td>8.51</td>
<td>Steepland and flatland area, gradient &amp; mid-channel elevation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sidney</td>
<td>B</td>
<td>SBS</td>
<td>5.03</td>
<td>Basin &amp; valley flat area</td>
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</tr>
<tr>
<td></td>
<td>Stuart T2</td>
<td>C</td>
<td>SBS</td>
<td>8.26</td>
<td>Steepland area</td>
<td></td>
</tr>
</tbody>
</table>
5.1.1 Prelude to formal riparian management

Management of riparian forestlands in the 1950s and 1960s was limited by our incomplete knowledge and appreciation for the hydriparian environment. Some larger fish-bearing streams were protected with leave strips of variable widths, but there were no formal guidelines or regulations requiring buffer strip implementation (Bustard and Wilford 1986). Small streams were typically logged to the streambanks, and logging operations often included cross-stream felling and yarding, in-stream skidding, and salvage of merchantable woody debris (e.g., Roberts and Church 1986). The majority of stream protection measures in this period (if any) were incorporated into the cutting permits granted by the Ministry of Forests. During these years, the Department of Fisheries and Oceans (DFO) had only a limited involvement in approving cutting permits, and played a minor role in the protection of coastal fish bearing streams located within federal jurisdiction (Bustard and Wilford 1986).

By the 1970s, scientists and industry professionals began to recognize more formally the importance of riparian leave strips to maintain bank and stream channel stability, provide habitat for fish and wildlife, supply shade and nutrients to the aquatic environment, enhance the aesthetic value for recreational users and protect streams from logging debris (see, for example, Moore 1977). In this period, a more formal interagency referral process was instituted whereby a number of government agencies, such as the DFO and provincial ministries played a greater role in cutting permit approvals (Bustard and Wilford 1986). An example of riparian management prescriptions in this period is given by Slaney et al. (1977). In a relatively small area of the central interior (approximately 80 km east of Prince George), four streamside-harvesting practices were evident between 1971 and 1975. These include:

1. Reserve strips between 20 to 200 m wide that retained both coniferous and deciduous trees alongside the stream;
2. Selective strips up to 20 m wide that retained all non-commercial trees and leaning conifers (equipment operation was restricted within this zone);
3. Directional falling and skidding (timber was fallen and skidded away from streams wherever possible) that retained non-commercial timber; and,
4. Non-directional falling and skidding (falling and skidding occurred across the stream).

Channel widths were not given in this study. However, given that the maximum watershed area was 26 km², maximum channel width was likely on the order of 10 m. Slaney et al. (1977) conclude that streamside practices varied as a result of inclusion of stream protection clauses in cutting permits, compliance by the logging contractor with the cutting plans, season of cut, and terrain conditions.

Throughout the interior of the Prince Rupert Forest Region, Bustard and Wilford (1986) found three types of riparian treatments in the mid 1980s (summarized below). These include:

1. Leave strips of variable width (all vegetation remained intact), dependent upon terrain and stream value characteristics;
2. Machine reserves that retained leaning, immature trees and deciduous vegetation (equipment operation was restricted from within 10 to 30 m of the streambank); and,
3. Logging to the edge and across small streams (leaners and deciduous trees were occasionally retained).
The most predominant practice in this region was to either log the streambanks or designate a machine reserve zone. The majority of small streams (< 3 m) were logged to the banks, while leave strips and machine reserves were more typical along larger fish bearing streams. In areas with steep topography, it was common to leave timber standing between the topographic break and the stream edge due the dangers and difficulty of machine access.

Additional legislative acts that afforded stream protection were enacted in the 1970s and 1980s (see review by Bunnell et. al. 1995) and are assumed to have further influenced management practices in this period. These include the Forest Act (RS 1979), Waste Management Act (SBS 1982), Water Act (RS 1979), and Federal Fisheries Act (RS 1979). The Forest Act ensures that forested lands are managed for multiple timber and non-timber values such as preserving wildlife habitat, providing for wilderness recreation, and accommodating other forest uses. Both the Waste Management Act and Water Act address water quality concerns and may limit development within the riparian zone. The federal Fisheries Act prohibits the harmful alteration, disruption or destruction of fish habitat, and protects fish from the discharge of deleterious substances.

5.1.2 Riparian management research

Preliminary riparian management practices (i.e., retention of a leave strip) were developed in the 1960s and 1970s with the intent of buffering the stream environment from upslope harvesting activities. However, there was little agreement between forest and fisheries managers as to what conditions necessitated buffer strips, how wide a buffer strip should be, what species should be maintained therein, or how effective leave strips were at mitigating negative impacts from timber harvesting activities (see, for example, Bustard and Wilford 1986). The 1970s saw the initiation of several major research programs, designed in part to help resolve these issues. The study designs and recommendations of these projects are described here as they reveal the kinds of management activities either practiced or contemplated during this period.

The Carnation Creek Fisheries-Forest Interaction Project was initiated in 1970 after serious conflict began to arise between forest and fisheries managers (Narver and Chamberlin 1976 cited in Lewis 1988). This study was located on the west coast of Vancouver Island and was the first major undertaking of its kind in Canada (the project remains the longest, continuous case study of the effects of forest practices on biological and physical watershed processes in western North America). Three streamside treatments were compared adjacent to the 15 m wide riffle-pool channel, including (Tschaplinski et. al. 1998):

1. Retention of a variable-width leave strip (1 to 70 m wide);
2. Careful logging on both sides of the channel, retaining non-merchantable timber and in-stream woody debris, avoiding in-stream activities, and avoiding the addition of debris into the stream; and,
3. Logging on both sides of the channel (including non-merchantable timber) with some cross-stream falling and yarding.

The Carnation Creek research was pivotal in providing a greater understanding of the physical and biological processes operating within a coastal watershed, and revealing how harvesting practices were
employed in the 1970s (see, for example Hartman 1987; Holtby 1987). The results of this study were used to make practical and useful technical decisions regarding land and aquatic stewardship (discussed in further detail in Section 5.1.3).

At the same time, a short-term research project was underway in the central interior. The goals of the “Slim-Tumuch” project were to examine the impacts of streamside logging practices on the physical character of stream channels and to extend a set of operational procedures aimed at minimizing stream channel disturbance in the central interior (Slaney et. al. 1977). The authors conclude that non-directional falling and skidding caused the greatest damage, whereas selective strips and reserve strips were more effective at minimizing disturbance. In addition, non-directional practices led to increases in both fine and coarse debris causing bottom scouring of substrate, and bank instability. The authors recommend the use of reserve strips and selective strips to prevent channel alterations in areas with high fishery values and those not susceptible to windthrow. In addition, they suggest that falling and skidding operations should be directed away from the stream channel, and equipment operation within reserve zones should be prohibited to at least 20 m away from stream channels.

The Fish Forestry Interaction Program (FFIP) was initiated in 1981 after a large storm triggered major landslides on the Queen Charlotte Islands in 1978. Logging was blamed for helping to trigger the landslides and for subsequently damaging valuable salmonid habitat. The main focus of FFIP was to investigate the effects of landslides on channel morphology and fish habitat, as well as to develop sound watershed rehabilitation techniques and silvicultural treatments (Lewis 1998). Hogan (1986) found that logging practices typical of the late 1970s (in particular, the retention of a leave strip adjacent to a large riffle-pool channel) were effective in minimizing disturbance of in-stream woody debris and maintaining morphological conditions and habitat features that closely resembled those associated with an unlogged channel. Hogan (1986) also notes that leave strips helped to maintain a future source of woody debris to the channel.

Bustard and Wilford (1986) reviewed riparian forest management in the interior of the Prince Rupert forest region. Some of the resource professionals interviewed in this study were unsure of the effectiveness of buffer strips due to extensive windthrow that had occurred along a number of watercourses. The main concern was that excessive windthrow along streams could pose a barrier to fish movements, cause significant streambank damage, or become a breeding habitat for beetle populations. Forest managers saw this as a loss of valuable timber and were reluctant to leave buffers along stream channels where timber could be successfully harvested. However, Bustard and Wilford (1986) highlight the effectiveness of buffer strips as an effective means of minimizing damage incurred by logging, provided they are not exposed to strong winds or they are wide enough to compensate for negative windthrow effects. In addition, they stress the importance of protecting smaller channels, due to the vulnerability of small channels to site disturbance and the observation that a number of these streams had been logged to the banks.

5.1.3 Development of riparian management guidelines

Throughout the 1970s and 1980s, empirical evidence was beginning to accumulate in British Columbia regarding the importance of streamside protection measures. The significant role that riparian zones play in preserving fish values, preventing erosion and sedimentation, and maintaining stream stability was highlighted by projects such as Carnation Creek, Slim-Tumuch, and FFIP amongst others. These and other research projects led to the development of forest management guidelines in the 1970s, 1980s and 1990s that designed site-specific streamside recommendations for resource managers.
Planning Guidelines for Coast Logging Operations

BC Ministry of Forests (1972) developed a set of management measures to protect water quality, fish habitat and other values. These guidelines prohibited the removal of leaning trees along watercourses (where their removal will incur environmental damage), and recommended temporary filter strips between roads and streams until runoff had restabilized. It is also stated that greater care must be taken when logging near watercourses. Some special measures included felling away from the channel and selectively logging along watercourses.

Streamside Management: A Decision-Making Procedure for Coastal British Columbia

Moore (1980) devised a set of site-specific guidelines to determine streamside logging practices and how much vegetation (if any) should remain intact along streambanks. Prescriptions were developed from research results and expert opinion, and were intended for application on Vancouver Island and along the Southern Coast of British Columbia. Prescriptions were broadly based on channel gradient and streamside users. Then, depending on particular uses and users, prescriptions considered the value of the stream for stream shading, debris buffering, channel and bank stability, and flood protection for each user. Channel width played a minor role in determining riparian prescriptions and was only considered in assessing debris buffering potential. Management strategies consisted of falling and yarding techniques (either directional or non-directional), riparian tree maintenance or removal (leaving non-merchantable and/or deciduous), and buffer strips varying from 20 to 100 m in width or to the topographic break. In some instances, prescribed strategies allowed some selective logging within the buffer, while others recommended retaining both merchantable and non-merchantable timber.

A Handbook for Fish Habitat Protection on Forest Lands in British Columbia

Toews and Brownlee (1981) designed a handbook primarily for DFO field staff dealing with forest operation and planning. It was not intended as a strict set of guidelines, but rather as a compilation of useful technical information upon which to base sound aquatic habitat protection recommendations in forested ecosystems. The handbook provided a number of forest ‘treatment’ options along the streamside zone, including:

1. Diversion of stream away from logging area;
2. Removal of all trees to the stream edge (either falling and yarding across the channel or away from channel);
3. Removal of all merchantable timber, retaining non-merchantable and deciduous trees, and shrubs intact (fall and yard away from channel);
4. Selective logging within the riparian area (fall and yard away from channel); and,
5. Retention of a leave strip.

Leave strips ranged from 20 to 200 m in width and could depend in part on the location of a topographic break (e.g., a break in slope were a channel is incised into a hillside) or width of the floodplain. It was suggested that prescribed streamside treatments should be analyzed on a site-specific basis, and that leave strip width should be based upon the value of the vegetation for fish habitat protection. Treatments 1 and 2 (above) were not recommended for use along salmon streams.
Coastal Fisheries Forestry Guidelines

BC Ministry of Forests et. al. (1987, 1988, and 1993) developed a set of guidelines that recognized the riparian area and woody debris as vital for maintaining fish habitat integrity, as well as stream bank, and riparian vegetation stability. The guidelines were applied to all forest tenures in coastal British Columbia but were not legally binding unless incorporated into cutting permit conditions. Management prescriptions were derived from a stream classification (based on gradient and fish values) and included delineation of a streamside management zone. Along low gradient fish streams (Class I and II), the management zone extended one bankfull width into the riparian area on both sides of the channel (to either a minimum or maximum width of 10 to 30 m, respectively). Selective tree removal was permitted only beyond 10 m of the stream bank, but a variety of tree species and ages should be retained. Along Class III and IV streams, the retention of mature streamside trees was recommended (if deemed important for channel stability) as a future source of woody debris.


The Ministry of Forests (1992) developed another set of guidelines for the Vernon, Penticton, and Salmon Arm Forest Districts, that required a 20 m no-machine buffer strip along both sides of all streams. Within the no-machine buffer, all non-merchantable timber was retained. In addition, along the mainstem of watersheds greater than 1,500 ha or along significant fish bearing reaches, a riparian management subzone was to extend an additional 20 m past the no-machine zone. Within the riparian management subzone, selective logging was allowed except along particularly sensitive streams or stream reaches.

5.1.4 Development of riparian management regulations

In 1994, the Forest Practices Code was enacted in legislation to afford greater protection for forested lands and to ensure compliance with best management practices. Experience gained from the application and evaluation of previous management guidelines and knowledge gained from riparian research were incorporated into guidebooks for province-wide application and management of hydric riparian environments (e.g., BC Ministry of Forests and BC Ministry of Environment 1995 a, b, and c; 1996 a and b). Full compliance was required by December 31, 1995.

The Riparian Management Area Guidebook (BC Ministry of Forests and Ministry of Environment 1995a) specified both a reserve zone and a management zone based on a classification of channel width, fish presence, and status as a community watershed (Table 4), although the width of the prescribed management area could be altered based on landform (e.g., floodplain or topographic break). The reserve zone required full retention of the riparian forest, while the management zone permitted various levels of retention. The guidebook recommended that cross-stream falling and yarding should be limited to S5 and S6 channel types, and only when trees could be felled so that individual stems spanned the channel and could be yarded without damaging the streambanks or any woody debris stored in the channel (some exceptions were permitted). The guidebook also provided guidelines for stream clean-out if logging debris was introduced into the channel. Although the classification was applied to all regions of the province, the guidebook did include coastal and interior BMPs for various channel types.
Table 4. Riparian management areas as defined by BC Ministry of Forests and Ministry of Environment (1995a).

<table>
<thead>
<tr>
<th>Class</th>
<th>Definition</th>
<th>Riparian Reserve Zone (m)</th>
<th>Riparian Management Zone (m)</th>
<th>Riparian Management Area (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1 (Large rivers)</td>
<td>&gt;100m wide</td>
<td>0</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>S1</td>
<td>&gt;20m wide</td>
<td>50</td>
<td>20</td>
<td>70</td>
</tr>
<tr>
<td>S2</td>
<td>&gt;5-20m wide</td>
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<td>20</td>
<td>50</td>
</tr>
<tr>
<td>S3</td>
<td>1.5-5m wide</td>
<td>20</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>S4</td>
<td>&lt;1.5m wide</td>
<td>0</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>S5</td>
<td>≥3m wide</td>
<td>0</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>S6</td>
<td>&lt;3m wide</td>
<td>0</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

5.1.5 Summary

Until the mid-1980s, riparian buffers were only common along relatively large fish-bearing streams. However, riparian buffers extending to a topographic break were also found along smaller channels located within steep valleys or gullies, given relatively primitive logging technologies and access difficulties. Leave strips varied in width from at least 10 to 200 m (typical buffer widths are unknown). Although government-issued recommendations were developed in this period, these efforts were largely regional in nature with particular emphasis and application throughout coastal regions. Buffer strips were only required along a channel when stipulations were written into cutting permits, and these were applied at the discretion of resource managers. Overall, professional opinion was mixed as to the effectiveness of buffer strips and management practices were variable. Riparian management practices prior to 1985 are termed Treatment A in this report.

From the mid-1980s until the mid-1990s, an increasing number of guidelines were used for riparian management. Recommended buffer widths along fish-bearing streams ranged from 10 to 100 m, while streambank logging was often permitted along small, non-fish bearing streams. In some instances, prescribed strategies allowed some selective logging within the buffer, while others recommended retaining both merchantable and non-merchantable timber. Increasing recognition was given to the benefits of machine buffers along streambanks, falling and yarding techniques (either directional or non-directional), and the role of the riparian area as a future source of woody debris. However, guidelines developed in this period were not always followed, even when prescriptions and site-specific recommendations were written into cutting permits (see, for example, Moore 1991; Tripp et al. 1992; Tripp 1994). Compliance with streamside management prescriptions made under the Coastal Fisheries Forestry Guidelines was 42% (Tripp 1994). Overall, the importance of the riparian area gained increasing recognition in this period, although regional variation of management practices and relatively low rates of compliance were apparent. Riparian management practices from 1985 to 1995 are termed Treatment B in this report.

Following the implementation of the Forest Practices Code, riparian management practices were standardized across the province. Riparian management areas ranged from 20 to 100 m, while reserves ranged from 0 to 50 m along a fish-bearing stream or a stream located in a community watershed. Overall, compliance with the requirements was relatively high, as was compliance with the BMPs except for tree retention along streambanks and in the riparian management zone of small streams (Forest Practices Board 1998). Riparian management practices after 1995 are termed Treatment C in this report.
5.2 Comparison of riparian treatments

5.2.1 Riparian buffer width

Riparian buffer widths in each treatment were compared by randomized block ANOVA to determine the effect of different management guidelines and regulations on actual management practice in each of three treatments. The data were standardized by mean bankfull width given the tendency for prescriptions in each treatment to scale buffer width by channel width (Table 5). Although use of a linear scalar is not entirely appropriate to the data (given that management prescriptions are typically stepped and nonlinear), it was used here given that channel widths were all relatively narrow (typically two to 11 m).

Table 5. Summary of riparian buffer widths. Buffer width was recorded in the field as slope distance and converted here to horizontal distance.

<table>
<thead>
<tr>
<th>Site</th>
<th>Biogeoclimatic zone</th>
<th>Bankfull width (m)</th>
<th>Buffer width (m)</th>
<th>Standardized buffer width (m/m)</th>
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</thead>
<tbody>
<tr>
<td>Treatment A</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>McLatchie</td>
<td>ESSF</td>
<td>7.3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ladybird</td>
<td>ICH</td>
<td>8.9</td>
<td>48</td>
<td>5</td>
</tr>
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<td>Beaverdam</td>
<td>IDF</td>
<td>3.4</td>
<td>0</td>
<td>0</td>
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<td>North White</td>
<td>MS</td>
<td>6.9</td>
<td>0</td>
<td>0</td>
</tr>
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<td>Baezaeko</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Stuart T1</td>
<td>SBS</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Treatment B</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross</td>
<td>ESSF</td>
<td>7.0</td>
<td>48</td>
<td>7</td>
</tr>
<tr>
<td>Deer Lower</td>
<td>ICH</td>
<td>9.2</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>Ore</td>
<td>IDF</td>
<td>1.9</td>
<td>48</td>
<td>25</td>
</tr>
<tr>
<td>Thunder</td>
<td>MS</td>
<td>11.3</td>
<td>50</td>
<td>4</td>
</tr>
<tr>
<td>McFarland</td>
<td>SBPS</td>
<td>1.3</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>Sidney</td>
<td>SBS</td>
<td>7.4</td>
<td>49</td>
<td>7</td>
</tr>
<tr>
<td>Cache</td>
<td>PP</td>
<td>4.3</td>
<td>321</td>
<td>75</td>
</tr>
<tr>
<td>Treatment C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fenwick</td>
<td>essf</td>
<td>8.7</td>
<td>217</td>
<td>25</td>
</tr>
<tr>
<td>Deer Upper</td>
<td>ICH</td>
<td>8.4</td>
<td>94</td>
<td>11</td>
</tr>
<tr>
<td>Junction Upper</td>
<td>IDF</td>
<td>3.6</td>
<td>127</td>
<td>35</td>
</tr>
<tr>
<td>Sulphur</td>
<td>MS</td>
<td>6.9</td>
<td>58</td>
<td>8</td>
</tr>
<tr>
<td>Blackwater</td>
<td>sbps</td>
<td>2.8</td>
<td>118</td>
<td>42</td>
</tr>
<tr>
<td>Stuart T2</td>
<td>SBS</td>
<td>2.1</td>
<td>66</td>
<td>32</td>
</tr>
</tbody>
</table>

A randomized block ANOVA was chosen as it was assumed biogeoclimatic zone influenced management practice (i.e., riparian areas with a relatively high stand volume were harvested more heavily than a riparian area with low stand volume). The design is given in Table 6. As such, it was expected that variation among buffer widths might, in part, be related to environmental factors (i.e., biogeoclimatic zone). Treating biogeoclimatic zone as a random block accounted for more variability amongst the data, produced a smaller error mean square, and greater statistical power (Zar 1996).
Table 6. Randomized block design with standardized buffer widths classified into fixed treatment factor (riparian treatment A, B, and C) and random block factor (biogeoclimatic zone). Cache Creek was omitted from the analysis given missing data in the PP block.

<table>
<thead>
<tr>
<th>Random Block</th>
<th>Fixed treatment factor</th>
<th>Standardized buffer width (m/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>ESSF</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>ICH</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>IDF</td>
<td>0</td>
<td>25</td>
</tr>
<tr>
<td>MS</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>SBPS</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>SBS</td>
<td>0</td>
<td>7</td>
</tr>
</tbody>
</table>

The results of the ANOVA are given in Table 7. The null hypothesis of equal buffer widths in all treatments was rejected and it was concluded that the standardized buffer width values were significantly different among treatments ($F>F_{crit}$, reject $H_0$). Overall, mean standardized buffer width has increased from 1 to 11 to 26 m/m for treatments A, B, and C, respectively (Figure 3).

Table 7. Randomized block ANOVA test results for standardized buffer width.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>SS</th>
<th>DF</th>
<th>MS</th>
<th>F</th>
<th>$F_{0.05(1, 2, 10)}$</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>3210.84</td>
<td>17</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Treatments</td>
<td>1846.36</td>
<td>2</td>
<td>923.18</td>
<td></td>
<td></td>
<td>Treatment has influenced the width of riparian buffers</td>
</tr>
<tr>
<td>Blocks</td>
<td>705.87</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Remainder</td>
<td>658.61</td>
<td>10</td>
<td>65.86</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3. Mean standardized buffer width for each logged treatment. Buffer width is reported in units of bankfull width.
5.2.2 Riparian stand volume

The volume of wood standing in the riparian forest represents the total potential input of woody debris from a riparian area to a channel. Given differences in riparian management amongst treatments, the volume of standing wood in each treatment was compared by randomized block ANOVA. Riparian stand volumes were first adjusted by the MAI to a common canopy age. This enabled a comparison amongst study sites logged at different times (given that stand volume generally increases with increasing canopy age in a mature forest). The MAI (representing the mean annual volumetric growth rate) was estimated for each site by the average stand volume standardized by average canopy age (Table 8). This approach is appropriate for a canopy between the ages of 60 and 200 years (Luttmerding et. al. 1990).

A randomized block ANOVA was chosen for analysis, given the relation between biogeoclimatic zone and MAI. The design is given in Table 9 while the results are given in Table 10. The null hypothesis of equal standardized timber volumes in all treatments was rejected and it was concluded that differences in stand volumes were significant among treatments \( F>F_{\text{crit}} \), reject \( H_0 \). Overall, the volume of standing timber in the riparian area increased with treatments A, B and C, respectively (Figure 4). With the exception of Ladybird Creek, treatment A was logged to the streambanks and the potential source-volume of woody debris was negligible (assumed here as 0.0 m\(^3\) ha\(^{-1}\)). The potential source-volume of woody debris in Treatment B ranged from 0.0 to 245 m\(^3\) ha\(^{-1}\), or about half that of Treatment C. Generally, the mean volume of treatment C was similar to the control sites, although the variation among treatment sites was relatively high.

Table 8. Summary of riparian stand volumes. Where a canopy was absent (less than 60 years old or logged with no buffer) the standardized volume was assumed as 0.0 m\(^3\) ha\(^{-1}\). Volumes are standardized to a common age of 75 years.

<table>
<thead>
<tr>
<th>Site</th>
<th>Biogeoclimatic zone</th>
<th>Mean canopy age (yr)</th>
<th>Stand volume (m(^3) ha(^{-1}))</th>
<th>MAI (m(^3) ha(^{-1}) yr(^{-1}))</th>
<th>Standardized stand volume (m(^3) ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Treatment A</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>McLatchie*</td>
<td>ESSF</td>
<td>16</td>
<td>28</td>
<td>n/a</td>
<td>0</td>
</tr>
<tr>
<td>Ladybird</td>
<td>ICH</td>
<td>138</td>
<td>357</td>
<td>2.59</td>
<td>194</td>
</tr>
<tr>
<td>Beaverdam*</td>
<td>IDF</td>
<td>36</td>
<td>214</td>
<td>n/a</td>
<td>0</td>
</tr>
<tr>
<td>North White*</td>
<td>MS</td>
<td>37</td>
<td>39</td>
<td>n/a</td>
<td>0</td>
</tr>
<tr>
<td>Baezaeko*</td>
<td>SBPS</td>
<td>41</td>
<td>28</td>
<td>n/a</td>
<td>0</td>
</tr>
<tr>
<td>Stuart T1*</td>
<td>SBS</td>
<td>35</td>
<td>73</td>
<td>n/a</td>
<td>0</td>
</tr>
<tr>
<td><strong>Treatment B</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross</td>
<td>essf</td>
<td>131</td>
<td>283</td>
<td>2.17</td>
<td>163</td>
</tr>
<tr>
<td>Deer Lower</td>
<td>ICH</td>
<td>132</td>
<td>420</td>
<td>3.18</td>
<td>239</td>
</tr>
<tr>
<td>Ore</td>
<td>IDF</td>
<td>30</td>
<td>34</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Thunder</td>
<td>MS</td>
<td>138</td>
<td>112</td>
<td>0.82</td>
<td>61</td>
</tr>
<tr>
<td>McFarland</td>
<td>SBPS</td>
<td>86</td>
<td>160</td>
<td>1.85</td>
<td>139</td>
</tr>
<tr>
<td>Sidney</td>
<td>SBS</td>
<td>132</td>
<td>431</td>
<td>3.27</td>
<td>245</td>
</tr>
<tr>
<td>Cache</td>
<td>PP</td>
<td>84</td>
<td>351</td>
<td>4.16</td>
<td>312</td>
</tr>
<tr>
<td><strong>Treatment C</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fenwick</td>
<td>ESSF</td>
<td>88</td>
<td>12</td>
<td>0.14</td>
<td>10</td>
</tr>
<tr>
<td>Deer Upper</td>
<td>ICH</td>
<td>93</td>
<td>1189</td>
<td>12.9</td>
<td>964</td>
</tr>
<tr>
<td>Junction Upper</td>
<td>IDF</td>
<td>101</td>
<td>755</td>
<td>7.48</td>
<td>561</td>
</tr>
<tr>
<td>Sulphur</td>
<td>MS</td>
<td>86</td>
<td>50</td>
<td>0.58</td>
<td>44</td>
</tr>
<tr>
<td>Blackwater</td>
<td>SBPS</td>
<td>135</td>
<td>276</td>
<td>2.05</td>
<td>153</td>
</tr>
<tr>
<td>Stuart T2</td>
<td>SBS</td>
<td>121</td>
<td>274</td>
<td>2.27</td>
<td>170</td>
</tr>
<tr>
<td><strong>Control</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chauncey</td>
<td>ESSF</td>
<td>112</td>
<td>234</td>
<td>2.09</td>
<td>156</td>
</tr>
<tr>
<td>Sweethaw</td>
<td>ich</td>
<td>72</td>
<td>924</td>
<td>12.9</td>
<td>970</td>
</tr>
<tr>
<td>Junction</td>
<td>idf</td>
<td>142</td>
<td>450</td>
<td>3.18</td>
<td>239</td>
</tr>
<tr>
<td>Albert</td>
<td>ms</td>
<td>60</td>
<td>27</td>
<td>0.45</td>
<td>34</td>
</tr>
<tr>
<td>Kappan</td>
<td>sbps</td>
<td>61</td>
<td>165</td>
<td>2.73</td>
<td>205</td>
</tr>
<tr>
<td>Forfar</td>
<td>sbs</td>
<td>110</td>
<td>479</td>
<td>4.36</td>
<td>327</td>
</tr>
<tr>
<td>Arrowstone</td>
<td>PP</td>
<td>66</td>
<td>314</td>
<td>4.75</td>
<td>356</td>
</tr>
</tbody>
</table>

* study sites where no buffer was retained; mean ages represent second growth and/or residual trees left adjacent to the streambank.
Table 9. Randomized block design with standardized volume of standing timber classified into fixed treatment factor (riparian treatment A, B, and C) and random block factor (BEC zone).

<table>
<thead>
<tr>
<th>Random blocks</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESSF</td>
<td>0</td>
<td>163</td>
<td>10</td>
<td>156</td>
</tr>
<tr>
<td>ICH</td>
<td>194</td>
<td>239</td>
<td>964</td>
<td>970</td>
</tr>
<tr>
<td>IDF</td>
<td>0</td>
<td>0</td>
<td>561</td>
<td>239</td>
</tr>
<tr>
<td>MS</td>
<td>61</td>
<td>44</td>
<td>205</td>
<td></td>
</tr>
<tr>
<td>SBPS</td>
<td>0</td>
<td>139</td>
<td>153</td>
<td>205</td>
</tr>
<tr>
<td>SBS</td>
<td>0</td>
<td>245</td>
<td>170</td>
<td>327</td>
</tr>
</tbody>
</table>

Table 10. Randomized block ANOVA test results for standardized stand volumes.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>SS</th>
<th>DF</th>
<th>MS</th>
<th>F</th>
<th>F_{0.05}(1,3)</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>1685218.95</td>
<td>23</td>
<td>75411.79</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Treatments</td>
<td>360353.37</td>
<td>3</td>
<td>120117.79</td>
<td></td>
<td>3.45</td>
<td>Treatment has influenced the volume of standing timber</td>
</tr>
<tr>
<td>Blocks</td>
<td>802062.88</td>
<td>5</td>
<td>160412.58</td>
<td></td>
<td>3.29</td>
<td></td>
</tr>
<tr>
<td>Remainder</td>
<td>522802.70</td>
<td>15</td>
<td>34853.51</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4. Mean standardized volume of standing timber for all treatments including control sites.

5.4 Discussion

The mean standardized buffer width increased from 1 to 26 m/m for Treatments A through C, respectively. Although most management guidelines were not explicitly based on channel width (with the exception of riparian management guided by the FPC), it is apparent that narrow streams have received increasing management attention over the period of study. In particular, there has been both recognition of the need for a buffer strip and an increase in the width of the buffer strip. For example, under the current management regime (Treatment C), all fish-streams or streams in a community watershed ≥ 1.5 m wide must retain a buffer (some exceptions apply). In contrast, most small streams < 10 m wide were logged to both streambanks in Treatment C, especially if they were not recognized as supporting high fisheries values.
Differences in management practice also affected the volume of potential woody debris stored within a buffer (if present). For example, the overall mean standardized volume of standing timber in Treatment C and the unlogged control were 317 and 322 m$^3$ ha$^{-1}$, respectively, suggesting that the potential volumetric supply of woody debris has essentially been maintained using current management guidelines. However, past management practices have had a significant impact on supply (this is obvious in the case of Treatment A were most streambanks had been logged) and this is expected to influence the large woody debris budget associated with these streams. Note, however, that this analysis only considered the supply of woody debris from within a buffer (if present). This potential supply does not consider the actual width of the buffer (a narrow buffer will reduce the actually supply), only the integrity of the stand within the buffer. Actual supply of woody debris is considered in Section 6.

5.5 Conclusions

This section identified three unique riparian management regimes employed in British Columbia over the past four decades. A randomized block ANOVA was used to compare the effects of different management treatments on stand characteristics associated with the riparian area, specifically buffer width and standing wood volume. The analysis suggests that past management practices have evolved through time with research initiatives and the development of riparian management guidelines. Current management practices are effective in maintaining a potential supply of woody debris from a buffer to a fish bearing stream or a stream in a community watershed (i.e., stand volume was relatively unchanged), while past harvesting activities have had a significant impact on the character of the riparian area, and in turn, on the potential supply of woody to the stream channel.
6.0 Woody Debris Budgets

Sediment budgets have become a common and valuable approach to geomorphological research, with results directly applicable to watershed management in British Columbia (e.g., Roberts and Church, 1986). However, construction of a woody debris budget has not been a focus for research. Some researchers have approached components of the problem. For example, Van Sickle and Gregory (1990) modeled input of woody debris to streams, while Murphy and Koski (1989) measured both LWD input and depletion rates in streams in southeast Alaska. Hogan et. al. (1998) describe volumes and ages of woody debris storage in coastal streams in British Columbia, while Braudrick et. al. (1997) describes dynamics of woody debris transport based on flume data. Lienkaemper and Swanson (1987) monitored the input and movement of woody debris in several stream reaches over periods of seven to nine years. However, none of these studies have assembled all the components of a woody debris budget to document the long-term dynamics of woody debris that are relevant to sustainable management of second growth forests (i.e., budgeting across timescales of approximately 100 years).

Recently, Benda and Sias (2003) describe a framework for woody debris budgeting that considers input, storage, and output of woody debris at timescales of 10^2 yr. Benda et. al. (2002) describes a variant of this method for comparing woody debris recruitment processes and rates in old growth and second growth forests. In this section, a method of wood budgeting is derived for estimating changes in woody debris storage before and after logging. The method is then used to assess the long-term impacts of various management practices adopted in British Columbia in recent decades. These results are used to predict future channel response as second growth forests grow towards maturity, forming the basis for management recommendations.

6.1 Derivation of the wood budget

Benda et. al. (2002) present a wood budget in the form of a mass balance equation

$$\Delta S = \left[ I \Delta x - L \Delta x + (Q_i - Q_o) - D \right] \Delta t$$

[Eq. 3]

where \(\Delta S\) is the change in wood storage (m³), \(I\) and \(L\) are the recruitment and loss of wood per unit length of channel (m³ m⁻¹ yr⁻¹), respectively, \(x\) is the reach length (m), \(Q_i\) and \(Q_o\) are the transport rates of wood in and out of a reach (m³ yr⁻¹), \(D\) is the in situ decay of wood (m³ yr⁻¹), and \(t\) is the time (yr) over which the budget is calculated. The input of woody debris is described by

$$I = (I_m + I_b) + (I_f + I_l + I_e + I_a)$$

[Eq. 4]

where total input is the sum of chronic processes, including mortality \((I_m)\) and bank erosion \((I_b)\), as well as episodic processes of fire \((I_f)\), landslide \((I_l)\), exhumation \((I_e)\), and anthropogenic delivery \((I_a)\).

Several terms of the wood budget were omitted in this report. The net change in storage as a result of transport was assumed negligible, as each study reach was actually a small segment of a larger reach and overall transport rates were assumed constant throughout. The volumetric loss of woody debris to decay is generally low over short timescales, and was assumed negligible over the periods of the respective budgets. In addition, each study reach was located so as to avoid landslide and recent wildfire in the riparian area. Anthropogenic inputs of woody debris were not accounted for directly, but
considered part of separate processes of bank erosion and mortality. Finally, both exhumation of woody debris and loss to overbank sources were assumed as offsetting and likely negligible for the purposes of the wood budget (relatively minor amounts of each were noted along some study reaches). Similar assumptions were made by Benda et al. (2002).

Given these assumptions, the wood budget was reduced to

\[ \Delta S = [Ic \Delta x] \Delta t \]  \hspace{1cm} [Eq. 5]

where \( Ic \) is the chronic input of woody debris (mortality and bank erosion). Murphy and Koski (1989) suggest the period over which a wood budget operates is equivalent to the mean weighted age of woody debris stored in a reach

\[ \Delta t = \sum a_i p_i \]  \hspace{1cm} [Eq. 6]

where \( a \) is the age of a wood and \( p \) is the proportion of total woody debris stored of a given age. In this report, log jams in the unlogged control reaches were used to calculate the mean weighted age of woody debris, as the age and volume of each jam was known, and jams typically represented about 3/4 of all wood stored in a reach. Essentially, this method assumes a normal distribution of jam ages and sizes. However, this assumption proved problematic in the logged reaches, as the distribution is clearly binomial (assuming streambank logging has the potential to alter the input rates of woody debris). Further, the distribution representing the time since logging was difficult to estimate as there was relatively few log jams persisting in the channel that post-dating logging.

As an alternative, a model devised by Murphy and Koski (1989) was used to assess changes in stored woody debris after logging by accounting for both depletion of woody debris (removal) and for reduction of chronic input rates from buffer strips. The model is given by

\[ T_i = OG_i + B_i + SG_i \]  \hspace{1cm} [Eq. 7]

where \( T_i \) is the total wood stored in a channel after logging at time \( t \), \( OG_i \) is the proportion of pre-logging woody debris stored in a channel, \( B_i \) is the woody debris input from the riparian buffer, and \( SG_i \) is the total woody debris input from the second growth forest located beyond the buffer. The chronic riparian input terms are each expressed as a proportion of unlogged rates. An estimate of \( OG_i \) is then obtained by

\[ OG_i = e^{-kt} \]  \hspace{1cm} [Eq. 8]

where \( k \) is the depletion coefficient (estimated as the inverse of the mean weighted age of woody debris), and \( t \) is the time since logging (yr).

In this report, \( k \) was estimated from the unlogged control watershed, \( SG_i \) was considered negligible (see Section 5), and \( B_i \) was estimated by the ratio of buffer width to maximum canopy height within the buffer (see Van Sickle and Gregory 1990). Given \( T_i \) was measured in the field, an estimate of the total storage of post-logging woody debris input into a reach, \( S_p \), was derived from Equation 7. Post-logging input rates were assumed constant, and a mean weighted age of post-logging woody debris was obtained from
\[ \Delta t_i = \sum S_i \frac{t}{2} \]  
\[ \text{Eq. 9} \]

where \( \frac{t}{2} \) is the average age of all post-logging woody debris. Rearranging Equation 1 and substituting terms, the wood budget used in this report is given by

\[ \Delta S = \Delta S_{og} + \Delta S_l \]  
\[ \text{Eq. 10} \]

where \( \Delta t_{og} \) is the change in old growth storage, given by

\[ \Delta S_{og} = \left[ I_{og} \Delta x \right] \Delta t_{og} \]  
\[ \text{Eq. 11} \]

and \( \Delta S_l \) is the change in logged storage, given by

\[ \Delta S_l = \left[ I_l \Delta x \right] \Delta t_l \]  
\[ \text{Eq. 12} \]

Budget terms \( I_{og} \) and \( I_l \) are the total chronic inputs of woody debris from unlogged and logged periods, respectively, while \( \Delta t_{og} \) is the mean weighted age of old growth wood remaining in the channel at time \( t \).

6.2 Woody debris input

6.2.1 Mortality

Depending on the riparian vegetation, the relative rates of forest mortality may impact in-stream wood storage volumes. The volume of a single tree entering a channel following mortality was estimated using the tree fall model described by Van Sickle and Gregory (1990)

\[ E(V) = \int_{a_s}^{180-a_s} V(a) f(a) da \]  
\[ \text{Eq. 13} \]

where \( E(V) \) is the average volume of a log entering a channel, \( V(a) \) is the log volume entering a channel at angle \( a \), and \( f(a) \) is the probability of a log falling at angle \( a \). We assumed a random fall probability for each standing tree, although it is possible that a preferred fall direction exists in many riparian areas (e.g., trees may be more likely to fall towards the stream channel, especially along a riparian buffer). Our estimate then represents a minimum input to the channel. Equation 13 is integrated over the limits of \( 180-a_s \) to \( a_s \), representing an arc defined by the tree crown as it intersects the channel banks at angle \( a_s \) and then again at \( 180-a_s \). The model accounts for tree height, log taper (we assumed each log could be...
described by a cone), and distance from the stream bank (see Van Sickle and Gregory (1990) for details).

The total volume of trees entering a channel following mortality was estimated by (modified from Van Sickle and Gregory 1990)

\[ E(V_{t_{in}}) = \sum D\Delta z_k P_F E(V) \]  

[Eq. 14]

where \( D \) is the stand density, \( z_k \) represents the distance of a tree from the stream banks, and \( P_F \) is the probability of a tree falling during \( t_i \) to \( t_{i+1} \). We assumed \( P_F \) could be defined by the inverse of the average age at which mortality occurs for a given tree species. Most age parameters used in this analysis were acquired from Urban et. al. (1993), who collated mortality age parameters from published and unpublished sources for tree species in the Pacific Northwest. We further assume that \( P_F \) includes chronic mortality by wind, fire, insect and competition from other stems. The equation is summed over all tree species, tree heights, and distance classes \((z_k)\) from the stream bank (see Van Sickle and Gregory (1990) for additional details).

The results of the model are shown in Table 11. Generally, mortality input is greatest in biogeoclimatic zones dominated by large trees (ICH, IDF and PP). Rates were standardized by unit bankfull area of channel and compared using a randomized block ANOVA. The variable in question is standardized mortality input rate; the fixed effects factor whose effect to be tested is treatment (including the control); and, the six random blocks are unique biogeoclimatic zones (PP contains missing data and was omitted from the analysis). Table 12 displays the results of the randomized block ANOVA. It was concluded that the standardized rates of woody debris input by mortality were significantly different among treatments \((F>F_{crit}, \text{ reject } H_0)\). The overall mean rates of woody debris input by mortality are shown in Figure 5.

![Figure 5. Mean standardized rates of woody debris input by mortality for each treatment including the controls.](image)

6.2.2 Bank erosion

Bank erosion recruits trees at rates depending on the erodibility of banks, flood frequency and stand density (Benda and Sias 2003). The total volume of trees entering a channel from bank erosion was estimated from (modified from Van Sickle and Gregory 1990)
where $E$ is the rate of bank erosion typical of small steepland streams with riffle-pool morphology (assumed 0.0044 m yr$^{-1}$ after Lehre 1982). In this equation, $P_F$ is assumed 1.0 as each log undermined by a collapsing bank is assumed to enter the channel. The equation is summed over all tree species, and tree heights, for all trees within 1 m of the stream banks.

The results of the model are shown in Table 11. As with mortality input, woody debris input due to bank erosion is greatest in biogeoclimatic zones dominated by large trees (ICH, IDF and PP). Rates were standardized by a unit bankfull area and compared using a randomized block ANOVA. The variable in question is the standardized rate of input due to bank erosion; the fixed effects factor whose effect to be tested is treatment (including the control); and, the six random blocks are unique biogeoclimatic zones (PP contains missing data and was omitted from the analysis). Table 12 displays the results of the randomized block ANOVA. It was concluded that the standardized rates of woody debris input by bank erosion were not significantly different between treatments ($F < F_{crit}$, accept $H_0$). The overall mean rates of woody debris input by bank erosion are shown in Figure 6.

6.3 Storage

Changes in channel storage were calculated from Equation 10 and the results are given in Table 11. As with mortality and bank erosion input, the change in woody debris storage volume is greatest in biogeoclimatic zones dominated by large trees (ICH, IDF and PP). Rates were standardized by the unit bankfull area and compared using a randomized block ANOVA. The variable in question is the standardized change in wood storage volumes; the fixed effects factor whose effect to be tested is treatment (including the control); and, the six random blocks are unique biogeoclimatic zones (PP contains missing data and was omitted from the analysis). Table 12 displays the results of the randomized block ANOVA. It was concluded that the changes in woody debris storage were significantly different between treatments ($F > F_{crit}$, reject $H_0$) (see Figure 7). The weighted mean age of woody debris in each reach was tested using a similar procedure, and it was concluded that weighted mean ages were not significantly different among treatments ($F < F_{crit}$, accept $H_0$) (see Figure 8).
## Table 11. Wood input to study reaches. Data considers input from a single bank.

<table>
<thead>
<tr>
<th>Biogeo climatic zone</th>
<th>Treatment</th>
<th>Reach</th>
<th>Weighted mean age (yr)</th>
<th>Mortality input ( \times 10^{-5} \text{ m}^3\text{m}^{-2}\text{yr}^{-1} )</th>
<th>Bank erosion input ( \times 10^{-5} \text{ m}^3\text{m}^{-2}\text{yr}^{-1} )</th>
<th>Change in storage ( \times 10^{-5} \text{ m}^3\text{yr}^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESSF</td>
<td>Control</td>
<td>Chauncey</td>
<td>28.7</td>
<td>0.38</td>
<td>0.51</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>McLatchie</td>
<td>20.0</td>
<td>0.05</td>
<td>0.06</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>Cross</td>
<td>28.6</td>
<td>0.17</td>
<td>1.43</td>
<td>1.60</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>Fenwick</td>
<td>28.6</td>
<td>0.02</td>
<td>0.04</td>
<td>0.07</td>
</tr>
<tr>
<td>ICH</td>
<td>Control</td>
<td>Sweehaw</td>
<td>32.7</td>
<td>1.86</td>
<td>3.20</td>
<td>5.05</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>Ladybird</td>
<td>32.5</td>
<td>1.51</td>
<td>1.21</td>
<td>2.72</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>Deer Lower</td>
<td>29.0</td>
<td>1.19</td>
<td>1.34</td>
<td>2.53</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>Deer Upper</td>
<td>32.6</td>
<td>3.49</td>
<td>4.03</td>
<td>7.52</td>
</tr>
<tr>
<td>IDF</td>
<td>Control</td>
<td>Junction</td>
<td>42.8</td>
<td>1.91</td>
<td>1.06</td>
<td>2.97</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>Beaverdam</td>
<td>29.1</td>
<td>2.07</td>
<td>0.89</td>
<td>2.96</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>Ore</td>
<td>40.8</td>
<td>0.55</td>
<td>0.38</td>
<td>0.93</td>
</tr>
<tr>
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<td>C</td>
<td>Junction Upper</td>
<td>42.7</td>
<td>4.04</td>
<td>2.84</td>
<td>6.89</td>
</tr>
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<td>MS</td>
<td>Control</td>
<td>Albert</td>
<td>6.8</td>
<td>0.02</td>
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<td>0.08</td>
</tr>
<tr>
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<td>A</td>
<td>North White</td>
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<td>0.11</td>
<td>0.12</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>Thunder</td>
<td>6.7</td>
<td>0.60</td>
<td>0.65</td>
<td>1.24</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>Sulphur</td>
<td>6.7</td>
<td>0.54</td>
<td>0.45</td>
<td>0.99</td>
</tr>
<tr>
<td>PP</td>
<td>Control</td>
<td>Arrowstone</td>
<td>31.0</td>
<td>1.88</td>
<td>1.54</td>
<td>3.43</td>
</tr>
<tr>
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<td>Cache</td>
<td>30.8</td>
<td>5.14</td>
<td>1.66</td>
<td>6.80</td>
</tr>
<tr>
<td>SBPS</td>
<td>Control</td>
<td>Kappan</td>
<td>13.0</td>
<td>1.14</td>
<td>1.19</td>
<td>2.33</td>
</tr>
<tr>
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<td>A</td>
<td>Baezaeko</td>
<td>11.6</td>
<td>0.54</td>
<td>0.58</td>
<td>1.25</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>McFarland</td>
<td>12.9</td>
<td>0.76</td>
<td>0.85</td>
<td>1.61</td>
</tr>
<tr>
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<td>C</td>
<td>Blackwater</td>
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<td>3.52</td>
<td>2.15</td>
<td>5.67</td>
</tr>
<tr>
<td>SBS</td>
<td>Control</td>
<td>Forfar</td>
<td>16.0</td>
<td>2.12</td>
<td>1.28</td>
<td>3.39</td>
</tr>
<tr>
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<td>A</td>
<td>Stuart T1</td>
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<td>1.46</td>
</tr>
<tr>
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<td>B</td>
<td>Sidney</td>
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<td>1.92</td>
<td>1.70</td>
<td>3.62</td>
</tr>
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<td></td>
<td>C</td>
<td>Stuart T2</td>
<td>15.9</td>
<td>2.15</td>
<td>1.61</td>
<td>3.76</td>
</tr>
</tbody>
</table>

* Data has been standardized by bankfull width and reach length (per unit area) to allow comparison of streams of different size.
Table 12. Results of the randomized block ANOVA for mortality, bank erosion, weighted mean age and storage. Input data was standardized to a unit area of channel.

<table>
<thead>
<tr>
<th>source of variation</th>
<th>SS</th>
<th>DF</th>
<th>MS</th>
<th>F</th>
<th>F &lt;0.05(1)</th>
<th>Conclusion</th>
</tr>
</thead>
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<td>Mortality</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>total</td>
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<td>23</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>treatments</td>
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<td>3</td>
<td>2.71</td>
<td></td>
<td></td>
<td>Treatment has influenced woody debris input via</td>
</tr>
<tr>
<td>blocks</td>
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<td>5</td>
<td></td>
<td></td>
<td></td>
<td>mortality</td>
</tr>
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<td>15</td>
<td>0.54</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.03</td>
<td></td>
<td>3.29</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bank erosion</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>total</td>
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<td>23</td>
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<td></td>
<td>Treatment has not influenced woody debris input</td>
</tr>
<tr>
<td>treatments</td>
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<td>3</td>
<td>1.74</td>
<td></td>
<td></td>
<td>via bank erosion</td>
</tr>
<tr>
<td>blocks</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>remainder</td>
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<td>15</td>
<td>0.53</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>3.28</td>
<td></td>
<td>3.29</td>
<td></td>
<td></td>
<td>Treatment has not influenced woody debris input</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>via bank erosion</td>
</tr>
<tr>
<td>Change in storage</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>total</td>
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<td>23</td>
<td></td>
<td></td>
<td></td>
<td>Treatment has influenced change in woody debris</td>
</tr>
<tr>
<td>treatments</td>
<td>22.49</td>
<td>3</td>
<td>7.50</td>
<td></td>
<td></td>
<td>storage</td>
</tr>
<tr>
<td>blocks</td>
<td>48.51</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>remainder</td>
<td>28.37</td>
<td>15</td>
<td>1.89</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.96</td>
<td></td>
<td>3.29</td>
<td></td>
<td></td>
<td>Treatment has influenced change in woody debris</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>storage</td>
</tr>
<tr>
<td>Weighted mean age</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>total</td>
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<td>23</td>
<td></td>
<td></td>
<td></td>
<td>Treatment has not influenced weighted mean age</td>
</tr>
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<td>8.69</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>blocks</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>remainder</td>
<td>215.63</td>
<td>15</td>
<td>14.38</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.60</td>
<td></td>
<td>3.29</td>
<td></td>
<td></td>
<td>Treatment has not influenced weighted mean age</td>
</tr>
</tbody>
</table>
6.4 Log jams

Jam volumes were standardized by unit channel volume and the average volume in each reach is given in Table 13. Jam volumes were compared using a randomized block ANOVA. The variable in question is the volume of log jams; the fixed effects factor whose effect to be tested is treatment (including the control); and, the six random blocks are unique biogeoclimatic zones (PP contains missing data and was omitted from the analysis). Table 14 displays the results of the randomized block ANOVA. It was concluded that the changes in jam volume were not significantly different between treatments ($F<F_{crit}$, accept $H_0$) (see Figure 9). The frequency of log jams in each reach was tested using a similar procedure (data was transformed by arsine), and it was concluded that jam frequencies were not significantly different among treatments ($F<F_{crit}$, accept $H_0$) (see Figure 10).
### Table 13. Standardized jam volumes and frequencies.

<table>
<thead>
<tr>
<th>Biogeoclimatic zone</th>
<th>Treatment</th>
<th>Reach</th>
<th>Jam volume&lt;sup&gt;a&lt;/sup&gt; (m&lt;sup&gt;3&lt;/sup&gt;/m&lt;sup&gt;3&lt;/sup&gt;)</th>
<th>Jam frequency&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESSF</td>
<td>Control</td>
<td>Chauncey</td>
<td>0.10</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>McLatchie</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>Cross</td>
<td>0.25</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>Fenwick</td>
<td>0.48</td>
<td>0.09</td>
</tr>
<tr>
<td>ICH</td>
<td>Control</td>
<td>Sweehaw</td>
<td>0.29</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>Ladybird</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>Deer Lower</td>
<td>0.15</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>Deer Upper</td>
<td>0.39</td>
<td>0.18</td>
</tr>
<tr>
<td>IDF</td>
<td>Control</td>
<td>Junction</td>
<td>0.91</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>Beaverdam</td>
<td>0.46</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>Ore</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>Junction Upper</td>
<td>0.23</td>
<td>0.03</td>
</tr>
<tr>
<td>MS</td>
<td>Control</td>
<td>Albert</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>North White</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>Thunder</td>
<td>0.01</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>Sulphur</td>
<td>0.25</td>
<td>0.04</td>
</tr>
<tr>
<td>PP</td>
<td>Control</td>
<td>Arrowstone</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>Cache</td>
<td>2.61</td>
<td>0.06</td>
</tr>
<tr>
<td>SBPS</td>
<td>Control</td>
<td>Kappan</td>
<td>0.30</td>
<td>0.08</td>
</tr>
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<td></td>
<td>A</td>
<td>Baezaeko</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>McFarland</td>
<td>4.11</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>Blackwater</td>
<td>0.57</td>
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</tr>
<tr>
<td>SBS</td>
<td>Control</td>
<td>Forfar</td>
<td>0.30</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>A</td>
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<td>0.80</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>Sidney</td>
<td>0.17</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>Stuart T2</td>
<td>2.32</td>
<td>0.04</td>
</tr>
</tbody>
</table>

<sup>a</sup> Volumes standardized by bankfull area and depth

<sup>b</sup> Frequencies standardized by number of bankfull widths surveyed

**Figure 9.** Standardized volume of woody debris in all treatment reaches.
Table 14. Results of the randomized block ANOVA. Frequencies were normalized by the arcsine transformation.

<table>
<thead>
<tr>
<th>source of variation</th>
<th>SS</th>
<th>DF</th>
<th>MS</th>
<th>F</th>
<th>F_{0.05(1)}</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
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<td>Jam volume</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
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<td>23</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
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<td>3</td>
<td>0.48</td>
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<td></td>
<td></td>
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<tr>
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<td>4.34</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>remainder</td>
<td>13.32</td>
<td>15</td>
<td>0.89</td>
<td></td>
<td>5.03</td>
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</tr>
<tr>
<td>Jam frequency</td>
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<td>2.46</td>
<td>Treatment has not influenced jam frequency</td>
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<td>total</td>
<td>2873.53</td>
<td>23</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>treatments</td>
<td>665.10</td>
<td>3</td>
<td>221.70</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>blocks</td>
<td>857.13</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>remainder</td>
<td>1351.30</td>
<td>15</td>
<td>90.09</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6.5 Discussion

Streambank logging can alter the woody debris budget of a channel and this can alter the spatial and temporal characteristics of woody debris storage and function (e.g., Bryant 1980; Toews and Moore 1982; Lisle 1986; Hogan 1987). In this report, the chronic input of woody debris (mortality and bank erosion) was dependent on streamside Treatment (A, B, and C). The average rate of mortality input in the unlogged control watersheds was $1.24 \times 10^{-5} \text{m}^3 \text{m}^{-2} \text{yr}^{-1}$ compared to $2.29 \times 10^{-5} \text{m}^3 \text{m}^{-2} \text{yr}^{-1}$ in Treatment C watersheds, suggesting more woody debris has entered the channel from the riparian buffer than from the unlogged riparian area. However, chronic input was reduced to $0.88$ and $0.86 \times 10^{-5} \text{m}^3 \text{m}^{-2} \text{yr}^{-1}$ in Treatments A and B, respectively. Bank erosion inputs were also highest in Treatment C ($1.85 \times 10^{-5} \text{m}^3 \text{m}^{-2} \text{yr}^{-1}$). The total accumulation of in-stream woody debris appears to depend almost equally on the supply due to mortality and that due to bank erosion (Figure 11). Overall, the proportion of woody debris input from mortality range from approximately 40 to 60 % (considering for all treatments) and these appear unaffected by treatment. Change in storage of woody debris was also affected by treatment.
Treatment A had the highest change in woody debris storage volume \((4.15 \times 10^{-5} \text{ m}^3)\) and Treatment C has the lowest \((1.66 \times 10^{-5} \text{ m}^3)\).

The results suggest that streambank logging has altered the wood budgets of the study streams. Relative to the control watersheds, Treatment C channels received an increase in chronic woody debris and have increased storage rates along the reach. With the exception of a slight reduction in the rate of mortality input, the wood budget of Treatment B channels was relatively unchanged from the control. Change in storage rates in Treatment A channels were again relatively similar to the control watershed, although both mortality and bank erosion rates of input have decreased.

Although the wood budgets have changed, the function of wood in the channel has not. Log jams in each treatment were of similar size and frequency as the respective control. In Treatment C, this suggests that the increase in the rate of storage has resulted in more woody debris stored as pieces along the channel. In contrast, the decrease in the rate of storage in Treatment B and C channels has resulted in less woody debris stored as pieces along the channel.

![Figure 11. Proportion of total woody debris input supplied from tree mortality and bank erosion (averaged by treatment).](image-url)
7.0 Management Recommendations

This report has adopted a form of the "extensive post-treatment" experimental design to examine the influence of streamside logging on channel conditions. Essentially, a paired-watershed approach has been undertaken to compare channel and riparian conditions between logged and unlogged watersheds that are otherwise similar in character. The results are used in this section to assess the effectiveness of current management standards and to develop a series of best management practices for riffle-pool channels in select biogeoclimatic zones.

7.1 Channel response to streamside logging

Channel response to streamside logging appears complex. Research by Bryant (1980), Toews and Moore (1982), and Hogan (1987) suggests that in the absence of any post-logging landslides, logging debris will usually enter the stream channel during or immediately after logging operations. Generally, logging debris contains slash, bark, and woody debris pieces with detached root wads that are easily floated downstream at high flows and can accumulate into log jams. Newly formed log jams, especially those formed with logging debris, are usually effective sediment traps and are relatively impermeable to sediment transport (see review by Hogan et. al. 1998b). In addition, the overall frequency of log jams increases after logging, with most logging debris stored in relatively large log jams. However, these structures do not generally persist in the channel and the channel eventually becomes devoid of woody debris.

In this study, three riparian management treatments were considered. These included:

- Treatment A – generally no leave-strip retained
- Treatment B – average width of leave-strip ~ 10 times the bankfull width
- Treatment C – average width of leave-strip ~ 25 times the bankfull width

The treatment type affected the volume of woody debris staged to enter the channel from the riparian area, both by reducing the area from which wood could be supplied (i.e., the natural supply corridor of woody debris extended past the leave-strip), and by reducing the volume of wood standing within the leave-strip itself. Although these processes were not investigated here, the generally positive relation between leave-strip width and volume of trees per unit area of leave-strip suggests that narrow leave-strips may be more susceptible to disturbance (e.g., windthrow).

The wood budget revealed that in most small riffle-pool streams, approximately equal amounts of woody debris are transferred to the channel from bank erosion and from mortality. Following logging operations associated with Treatment C, the total chronic input (mortality and bank erosion) increased (although potential supply was relatively unchanged), as did the change in storage within the channel. However, neither jam frequency nor jam size changed after logging, suggesting the increase in woody debris delivered to the channel increased the storage of woody debris pieces between jams.

Following logging operations associated with Treatment B, the total chronic input decreased with a decreased potential supply, although the change in storage within the channel was similar to that of the unlogged control watersheds. However, neither jam frequency nor jam size changed after logging, suggesting the decrease in woody debris delivered to the channel decreased the storage of woody debris pieces between jams. A similar, but more pronounced response was noted in Treatment C.
The interpretation of these trends are confounded somewhat by time, as each treatment was coincident with a unique period. However, with reference to previous research, the following conclusions are drawn in regards to riffle-pool channel response to streamside logging:

- Streamside logging in each treatment affects the wood budget of the channel.
- Relatively narrow leave-strips (~ 10 times the bankfull width) may be more susceptible to disturbance than wider strips.
- Buffer strips ~ 25 times the bankfull width maintain a potential supply of woody debris for a channel (similar to that of unlogged conditions).
- Following logging operations, the rate of chronic delivery of woody debris may initially increase and then gradually decrease over a period of several decades.
- Wood stored in pieces between jams increases shortly after logging with increases with chronic input (and likely with transfer of logging debris to the channel).
- Wood stored in pieces between jams decreases decades after logging (likely as small woody debris is floated out of the reach or into a jam).
- The size and frequency of log jams is unaffected by changes in wood input to the channel.

7.2 Best Management Practices

This section reviews BMPs for riparian areas for other jurisdictions with similar biophysical characteristics, and compares their application to those used in British Columbia under the FPC, and in light of the research results of this study.

7.2.1 Other jurisdictions

A number of different riparian treatment strategies are apparent in the United States. The following section will discuss some of the riparian treatment prescriptions currently practiced in some western United States. The states selected for examination were Idaho, Washington, Oregon, and California.

**Idaho**

Protection of Idaho’s water quality and aquatic habitats from forest harvesting activities is afforded by the Idaho Forest Practices Act (Idaho Forests Product Commission. 2004). This act regulates timber harvesting on public and private lands and provides for the protection of riparian zones termed Stream Protection Zones (SPZs). Under this act, streams are classified according to their importance as a source of domestic water supply, or fisheries value (either spawning, rearing or migratory function), and downstream fisheries value. Idaho sets a minimum buffer width for each stream class varying from a minimum of 1.5m along non-fish bearing streams to 23m along fish-bearing watercourses.

Class I streams are those that are significant to fish production or as a source of domestic water supply. Class I streams are protected with a 23 m wide SPZ and all deciduous trees must be left intact as a future source of LWD. Mature trees may be logged, but 75% of the present canopy must be retained to provide shade and maintain soil integrity. The minimum number of trees to be left standing, per 300 m of stream is specified depending on the stream width (Belt et al. 1992).
Washington

Washington State uses the term Riparian Management Zones (RMZs) to refer to protected riparian administrative units. The requirements differ between western and eastern regions and streams or stream segments in both regions are classified into one of five classes. The classification of channels is broadly based on stream size, and value for fish, wildlife, or human use. Depending of the stream class, RMZ widths are determined based on stand age, soil class, total basal area, % conifer basal area, and other regional characteristics. RMZ widths vary between 23 and 60 m.

The number of leave trees is determined by minimum basal area specifications and take into account canopy closure. Leave tree requirements are specified in terms of a minimum number of trees at a particular diameter per acre.

Oregon

In Oregon, riparian buffers are called Riparian Management Areas (RMAs) and their requirements are laid out in the Oregon Forest Practice Rules. These rules, like the recent FCP RBC, are based on desired future conditions so that stands will eventually resemble mature unmanaged stands. Buffer widths requirements vary depending on stream size, fish presence and domestic use (see Table 15).

Leave tree requirements are predicated on desired basal area and density targets. Depending on these targets, conifer and hardwood leave tree requirements are specified for each stream size as a certain number of trees at a particular diameter per 300m of channel.

| Table 15. Width (in meters) of RMAs as specified in Oregon Forest Practice Rules |
|---------------------------------|----------|--------|-------------|
| Stream Size                     | Fish Use (F) | Domestic Use (D) | Neither F nor D (N) |
| Large                           | 30        | 21     | 21          |
| Medium                          | 23        | 15     | 15          |
| Small                           | 15        | 6      | varies      |

(adapted from Adams 1996)

California

In California riparian areas delineated for protection purposes are termed Watercourse and Lake Protection Zones (WLPZs). Under the California Forest Practice Rules (California Department of Forestry and Fire Protection 2002) watercourses are classified into one of four classes depending on fish presence and beneficial use (see Table 16).

Buffer widths vary between 15-45 m depending on stream width, side slope and beneficial use (see Table 14). Along Class III and IV waters, buffer widths are determined on a site-specific basis and are designed to take into account downstream impacts.

Leaf tree requirements in the riparian area vary depending on stream class (see Table 16). Within 15 m of all class I and II watercourses, at least two living conifers per acre at least 40 cm in diameter and 15 m tall must be left in the WLPZ to provide for recruitment of large woody debris (in addition to specifications outlined below).
Table 14. Buffer width specifications and leave tree requirements in California

<table>
<thead>
<tr>
<th>Water Class Characteristics / Beneficial Use</th>
<th>Class I</th>
<th>Class II</th>
<th>Class III</th>
<th>Class IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Class Characteristics / Beneficial Use</td>
<td>Width (m)</td>
<td>Protection Measure</td>
<td>Width (m)</td>
<td>Protection Measure</td>
</tr>
<tr>
<td>&lt;30</td>
<td>23</td>
<td>50% over and understory</td>
<td>15</td>
<td>50% of total canopy, 25% existing conifers</td>
</tr>
<tr>
<td>30-50</td>
<td>30</td>
<td>50% over and understory</td>
<td>23</td>
<td>50% of total canopy, 25% existing conifers</td>
</tr>
<tr>
<td>&gt;50</td>
<td>45</td>
<td>50% over and understory</td>
<td>30</td>
<td>50% of total canopy, 25% existing conifers</td>
</tr>
</tbody>
</table>

2 Subtract 50 feet width for cable yarding operations.
3 Subtract 25 feet width for cable yarding operations.

(7.2.2 Recommended BMPs)

Riparian zone management prescription determination and application in the Western United States differs from those in British Columbia (summarized in Table 17). First of all, buffer width specifications may be wider or narrower than specified in BC’s RMA guidebook. For example along a 3 m wide stream in BC, the reserve zone is set at 20 m wide. In eastern Washington, along a stream of identical width, the inner zone of the RMZ (similar to BC’s reserve zone) is set at 9 m. The buffer width may also be dependent upon other factors than beneficial use and stream width. For example, in California buffer widths are based, in part, on side slope angle, allowing for variability in terrain characteristics. In addition, some states take into account downstream values in order to protect negative impacts from propagating downstream. For example, in Washington, small headwater streams that flow into fish-bearing reaches are protected with additional requirements; Washington forest practices state that lower order stream practices must apply to higher order streams from point of confluence for 457 m upstream.
Secondly, leave tree requirements in some states are dependent on a number of factors other than stream width and fish presence. They may be dependent upon canopy density (as in California), or stem diameter, basal area, and streambed material as in the other states. In addition, some states specify the particular stand distribution that must be left. For example, in California a certain percentage of the leave trees must be in the overstory and/or understory.

**Table 17. Streamside buffer strip requirements in selected western US states.**

<table>
<thead>
<tr>
<th>State</th>
<th>Stream class</th>
<th>Buffer width</th>
<th>Shade or canopy requirements</th>
<th>Leave tree requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Idaho</td>
<td>Class I*</td>
<td>Fixed minimum (23 m)</td>
<td>75% of existing shade</td>
<td># per 300m depending on stream width and stem diameter</td>
</tr>
<tr>
<td></td>
<td>Class II**</td>
<td>Fixed minimum (1.5 m)</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Washington</td>
<td>Type 1, 2, &amp; 3*</td>
<td>Variable depending on stream width (23-60m)</td>
<td>50% of shade, or 75% if temperature greater than 60F</td>
<td># per 300m of particular diameter depending on stream width and bed material</td>
</tr>
<tr>
<td></td>
<td>Type 4**</td>
<td>None</td>
<td>None</td>
<td>25 per 300m, &gt; 6inches diameter</td>
</tr>
<tr>
<td>California</td>
<td>Class I &amp; II*</td>
<td>Variable by slope and stream class (15-45 m)</td>
<td>50% overstory, and/or 50% understory</td>
<td># determined by canopy density</td>
</tr>
<tr>
<td></td>
<td>Class III*</td>
<td>None</td>
<td>50% understory</td>
<td>None</td>
</tr>
<tr>
<td>Oregon</td>
<td>Class I*</td>
<td>Variable – 3 times stream width (6-30m)</td>
<td>50% existing canopy, 75% existing shade</td>
<td># per 300m in terms of basal area; determined by stream width</td>
</tr>
<tr>
<td></td>
<td>Class II, Special Protection**</td>
<td>None</td>
<td>75% existing shade</td>
<td>None</td>
</tr>
</tbody>
</table>

*fisheries use or human consumption.
**streams capable of sediment transport (California) or significant impact (Oregon) or other influence (Idaho and Washington) on downstream values.
(after Belt & O’Laughlin 1994 and adapted from California Department of Forestry and Fire Protection. 2002)

Thirdly, best management practices in the selected States differ from those in BC. In the FPC guidebook best management practices are specified for each riparian class, active floodplains, and for large rivers. BMPs specify optimal retention levels and harvesting strategies to provide for other non-timber values such as wildlife, and channel stability (among others). A number of the American Forest Practice Rules provided best management strategies also. Although, it is not entirely possible to compare management approaches directly due to the variation in stream classification systems, it is possible to compare some
of the retention strategies regardless of buffer width and stream class. For instance, in Washington, tree retention strategies are based on minimum basal area, density and stand characteristic targets. As mentioned above, the targets are based on desired future conditions. Timber harvesting is only allowed to occur, if the stand meets minimum target basal area requirements. In contrast, the RMA guidebook specifies retention strategies in terms of a percentage of existing stems (in some cases specifying diameter dimensions). This strategy is based on an absolute value rather than desired density and stand characteristics. This may be problematic in a disturbed area, where removal of 25% of the trees may represent a significant loss of the total volume of large woody debris available to the channel.

Additionally, in BC, timber operators choose the best management practice available to maintain a mix of ages, species and size distribution (when allowed to harvest within the RMA). In contrast, in some states such as Washington, harvesting options are only available once stand density and vegetation characteristics meet the necessary requirements. Both Washington and Oregon outline more detailed leave tree requirements to ensure that a particular proportion of ages, sizes and species are left in particular geographic regions. If the stand meets the specifications then various harvesting options are provided. These options are designed not only to ensure a minimum basal area, but also to specify the tree dimension that must be left. This reduces the possibility for timber operators to select only the largest conifers.

In sum, the various strategies practiced in the western United States offer potential strategies for protecting large woody debris that may have some applicability to British Columbia. In particular, BMPs should:

- Select retention strategies that maintain chronic input rates of woody debris by biogeoclimatic zone (refer to rates presented in Table 11)
- Recognize importance of leave-strip width as a potential source of woody debris to a channel
- Along small streams (1 to 10 m wide), leave strips should be ~ 10 times the bankfull width for low value channels and ~ 25 times the bankfull width for high value channels
8.0 References


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Appendix I. Study site locations
Figure AI-1. Study site location in Chauncey Creek (ESSF, Control).
Figure Al-2. Study site location in McLatchie Creek (ESSF, Treatment A).
Figure AI-3. Study site location in Cross Creek (ESSF, Treatment B).
Figure AI-4. Study site location in Fenwick Creek (ESSF, Treatment C).
Figure AI-5. Study site location in Sweehaw Creek (ICH, Control).
Figure A1-6. Study site location in Ladybird Creek (ICH, Treatment A).
Figure AI-7. Study site location in Deer Creek Lower (ICH, Treatment B).
Figure AI-8. Study site location in Deer Creek Upper (ICH, Treatment C).
Figure AI-9. Study site location in Junction Creek (IDF, Control).
Figure AI-10. Study site location in Beaverdam Creek (IDF, Treatment A).
Figure A1-11. Study site location in Ore Creek (IDF, Treatment B).
Figure AI-12. Study site location in Junction Creek Upper (IDF, Treatment C). No forest cover information available.
Figure AI-13. Study site location in Albert Creek (MS, Control).
Figure AI-14. Study site location in North White Creek (MS, Treatment A).
Figure Al-15. Study site location in Thunder Creek (MS, Treatment B).
Figure AI-16. Study site location in Sulphur Creek (MS, Treatment C).
Figure AI-17. Study site location in Arrowstone Creek (PP, Control).
Figure AI-18. Study site location in Cache Creek (PP, Treatment B).
Figure AI-19. Study site location in Kappan Creek (SBPS, Control).
Figure Al-20. Study site location in Baezaeko Creek (SBPS, Treatment A).
Figure AI-21. Study site location in McFarland Creek (SBPS, Treatment B).
Figure AI-22. Study site location in Blackwater Creek (SBPS, Treatment C).
Figure AI-23. Study site location in Forfar Creek (SBS, Control).
Figure AI-24. Study site location in Stuart Trib 1 (SBS, Treatment A).
Figure AI-25. Study site location in Sidney Creek (SBS, Treatment B).
Figure A1-26. Study site location in Stuart Trib 2 (SBS, Treatment C).
Appendix II. Longitudinal characteristics
Figure AII-1. Longitudinal characteristics for Chauncey. Detailed longitudinal profile describing thalweg and water surface; distribution of total sediment volume along reach; and distribution of total woody debris volume along reach.
Figure AII-2. Longitudinal characteristics for McLatchie. Detailed longitudinal profile describing thalweg and water surface; distribution of total sediment volume along reach; and distribution of total woody debris volume along reach.
Figure AII-3. Longitudinal characteristics for Cross. Detailed longitudinal profile describing thalweg and water surface; distribution of total sediment volume along reach; and distribution of total woody debris volume along reach.
Figure AII-4. Longitudinal characteristics for Fenwick. Detailed longitudinal profile describing thalweg and water surface; distribution of total sediment volume along reach; and distribution of total woody debris volume along reach.
**Figure AII-5.** Longitudinal characteristics for Sweehaw. Detailed longitudinal profile describing thalweg and water surface; distribution of total sediment volume along reach; and distribution of total woody debris volume along reach.
**Figure AII-6.** Longitudinal characteristics for Ladybird. Detailed longitudinal profile describing thalweg and water surface; distribution of total sediment volume along reach; and distribution of total woody debris volume along reach.
Figure AII-7. Longitudinal characteristics for Deer Lower. Detailed longitudinal profile describing thalweg and water surface; distribution of total sediment volume along reach; and distribution of total woody debris volume along reach.
Figure AII-8. Longitudinal characteristics for Deer Upper. Detailed longitudinal profile describing thalweg and water surface; distribution of total sediment volume along reach; and distribution of total woody debris volume along reach.
Figure AII-9. Longitudinal characteristics for Junction. Detailed longitudinal profile describing thalweg and water surface; distribution of total sediment volume along reach; and distribution of total woody debris volume along reach.
Figure AII-10. Longitudinal characteristics for Beaverdam. Detailed longitudinal profile describing thalweg and water surface; distribution of total sediment volume along reach; and distribution of total woody debris volume along reach.
Figure AII-11. Longitudinal characteristics for Ore. Detailed longitudinal profile describing thalweg and water surface; distribution of total sediment volume along reach; and distribution of total woody debris volume along reach.
Figure AII-12. Longitudinal characteristics for Junction Upper. Detailed longitudinal profile describing thalweg and water surface; distribution of total sediment volume along reach; and distribution of total woody debris volume along reach.
**Figure AII-13.** Longitudinal characteristics for Albert. Detailed longitudinal profile describing thalweg and water surface; distribution of total sediment volume along reach; and distribution of total woody debris volume along reach.
Figure AII-14. Longitudinal characteristics for North White. Detailed longitudinal profile describing thalweg and water surface; distribution of total sediment volume along reach; and distribution of total woody debris volume along reach.
Figure AII-15. Longitudinal characteristics for Thunder. Detailed longitudinal profile describing thalweg and water surface; distribution of total sediment volume along reach; and distribution of total woody debris volume along reach.
Figure AII-16. Longitudinal characteristics for Sulphur. Detailed longitudinal profile describing thalweg and water surface; distribution of total sediment volume along reach; and distribution of total woody debris volume along reach.
Figure AII-17. Longitudinal characteristics for Arrowstone. Detailed longitudinal profile describing thalweg and water surface; distribution of total sediment volume along reach; and distribution of total woody debris volume along reach.
Figure AII-18. Longitudinal characteristics for Cache. Detailed longitudinal profile describing thalweg and water surface; distribution of total sediment volume along reach; and distribution of total woody debris volume along reach.
Figure AII-19. Longitudinal characteristics for Kappan. Detailed longitudinal profile describing thalweg and water surface; distribution of total sediment volume along reach; and distribution of total woody debris volume along reach.
Figure AII-20. Longitudinal characteristics for Baezaeko. Detailed longitudinal profile describing thalweg and water surface; distribution of total sediment volume along reach; and distribution of total woody debris volume along reach.
Figure AII-21. Longitudinal characteristics for McFarland. Detailed longitudinal profile describing thalweg and water surface; distribution of total sediment volume along reach; and distribution of total woody debris volume along reach.
**Figure AII-22.** Longitudinal characteristics for Blackwater. Detailed longitudinal profile describing thalweg and water surface; distribution of total sediment volume along reach; and distribution of total woody debris volume along reach.
Figure AII-23. Longitudinal characteristics for Forfar. Detailed longitudinal profile describing thalweg and water surface; distribution of total sediment volume along reach; and distribution of total woody debris volume along reach.
Figure AII-24. Longitudinal characteristics for Stuart Trib 1. Detailed longitudinal profile describing thalweg and water surface; distribution of total sediment volume along reach; and distribution of total woody debris volume along reach.
Figure AII-25. Longitudinal characteristics for Sidney. Detailed longitudinal profile describing thalweg and water surface; distribution of total sediment volume along reach; and distribution of total woody debris volume along reach.
**Figure AII-26.** Longitudinal characteristics for Stuart Trib 2. Detailed longitudinal profile describing thalweg and water surface; distribution of total sediment volume along reach; and distribution of total woody debris volume along reach.