Structure and Function of Small Foothills Streams and Riparian Areas Following Fire

Version 1.0

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- incorporated in forest and environmental policy and changes;
- widely disseminated to and understood by a broad spectrum of society.

This will be the result of a solid, credible, recognized program of science, technology, demonstration and outreach.

Acknowledgements

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The initial project proposal, a riparian management workshop series and overall project development were completed in collaboration with Dr. David Andison. Tom Daniels, Public Affairs Forester, Sundre Forest Products, and Ed Kulcsar, Forester, Spray Lake Sawmills Ltd. applied for FRIAA support. Ed Wassink, of Sundre Forest Products, provided field support including safety check-in during field work. Study design and data analyses for both the channel assessment and LWD sections were completed in consultation with Dr. Marwan Hassan, University of British Columbia, Department of Geography. Rob Scherer, Watershed Management Specialist, FORREX provided input on field methods for LWD inventory. Other active members of the project advisory group included Rick Bonar and Chris Spytz of Hinton Wood Products – A Division of West Fraser Mills Ltd., Peter Winther of Alberta Newsprint Company, and Bill Tinge and Jamie Bruha of Alberta Sustainable Resource Development – Public Lands and Forests Division.

Field crew members employed by Foothills Model Forest included Scott Wilson and Kim MacLean. The automated stream classification was completed through the efforts of Michal Pawlina of GISMo Solutions Ltd. Large-scale aerial photography and interpretation was lead by Derrick Lalonde of Timberline Forest Inventory Consultants Ltd. of Prince George.

Executive Summary

Very little was known about sediment and large woody debris (LWD) processes within small streams of the Rocky Mountain Foothills. These processes influence water quality and fish habitat and have implications for forest, water and biodiversity management. The influence of fire on sediment and LWD had also not been previously studied. Following a forest fire in 2001, I described channel structure, with a focus on components with a strong connection to forest management. I identified that floodplains associated with most small streams are major sediment storage locations. Streams were classified as either as small alluvial or headwater channels, each characterized by different structure and post-fire disturbances. We also documented LWD recruitment processes, storage and watershed-wide distributions.

Floodplains comprised of fine-textured sediment occurred along all small streams representing a major potential sediment source. Roots from trees and shrubs moderated floodplain erosion processes such as bank erosion and channel relocation. Small streams represent 80% of all mapped Foothills watercourses and the floodplains support a number of land-uses including timber harvest and cattle grazing. Therefore knowledge on floodplain structure and function of these systems may have management applications.

We identified two groups of channels. Small alluvial channels included those with substrate size appropriate for the potential energy of the stream reach based on gradient. Small alluvial channels had a drainage area of more than 200 ha. Headwater channels included those with substrate size smaller than expected based on gradient. In all cases, headwater channels had an upstream drainage area of less than 200 ha. Headwater channels may be consistent with first-order stream channels in mountain streams characterized by accumulation of hillslope sediment rather than downstream transport. In mountainous regions, shallow episodic landslides characterize such streams, however no recent or historic landslides were detected in the study area. Headwater channels had higher total disturbance, higher bed scour and lower pool length than small alluvial channels. When considering parent material, streams in moraine parent material had higher bed scour. Small alluvial channels within colluvial parent material had greatest bar length, while headwater channels within moraine parent material exhibited high bed scour. Based on substrate and vegetation characteristics, post-fire channel disturbances appeared

limited to bed-scour, bank erosion and deposition of sediment wedges. The low levels of channel disturbance may correspond to below average summer precipitation and below average maximum daily rainfall events during the two-year period between the fire and the channel assessment. The importance of vegetation for determining channel structure also increased as the moisture regime of the adjacent riparian area increased. For example, we observed stable root bridges ranging in length from 2 m to 8 m at several reaches. Root bridges only occurred in wet sites dominated by white spruce where moisture was sufficient to exclude lodgepole pine. Root bridges had a higher probability of occurrence in basins with average slope less than 25% and drainage area less than 150 ha.

Key results areas from the LWD studies include recruitment, storage, and watershed-wide distributions of total instream wood volumes. Although the fire severity precluded identification of recruitment source as either pre-fire or fire-generated LWD, we determined that on average, 90% of instream LWD originates from trees growing within 7.6 m of the channel. Within the floodplain, 50% of the terrestrial coarse woody debris (CWD) originates from trees growing within the floodplain and 90% of the CWD originates from trees growing within 6.6 m of the floodplain/upland boundary. With the absence of landslides as a recruitment process, most LWD is recruited to the channel from bank erosion or tree mortality as entire trees, many forming bridges across the channel. These bridges have minimal interaction with flowing water and no interaction with bed load movement. With the lack of mass wasting processes, decay is the dominant mechanism for both converting these bridges to functional instream LWD and exporting LWD from these small systems. Decay rates will differ for those pieces of wood that form bridges versus those that lie within the baseflow channel. These decay rates are the subject of a related Foothills study using dendrochronology. Once determined, these decay rates will be incorporated into the overall LWD budget. Only LWD located within the baseflow channel has the potential to exert a strong influence on channel structure. We found that the proportion of total instream LWD within the baseflow channel decreased in streams with a smaller drainage area. We also established a link between riparian forest productivity and total instream LWD using two different approaches. First, from analysis of post-fire large-scale air photos, we developed a model of instream LWD volume from standing tree volume within 10 m of the channel and total floodplain coarse woody length. Second, we found that total instream LWD

volume was related to standing tree volume from pre-fire Alberta Vegetation Inventory data used for timber management purposes. Within Foothills systems, these strong linkages between LWD volume and stand productivity can be explained by limited input and output processes, while coastal systems with a strong prevalence of landslides and large relative stream size, input and output processes are more complex.

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Chapter 1. Introduction

1. Statement of Problem

Recent large fire events in Alberta have increased economic and environmental pressures on Alberta's forested land base. Economic pressures include meeting long-term wood supply commitments to mills in affected areas. The two methods that timber companies use to meet wood supply targets include increasing productivity through silviculture and minimizing loss of productive land base (Bott et al., 2003). In the Forest Management Agreement area managed by Hinton Wood Products – A Division of West Fraser Mills Ltd. (Hinton Wood Products), riparian reserve zones along all permanent streams represent the largest single reduction in the contributing land base (Bott et al., 2003). In addition to these economic factors, environmental pressures include protecting biodiversity, water quality and fish habitat. To achieve biodiversity conservation goals, several Alberta companies have committed to conducting research on the use of emulation of natural disturbance patterns for forest management planning (Alberta Pacific Forest Industries Inc., 1999; Hinton Wood Products - A Division of West Fraser Mills Ltd., 1999). Natural disturbance emulation is a coarse filter biodiversity conservation strategy whereby forest harvest patterns more closely resemble those created by fire, the dominant natural disturbance agent in most of Alberta's forests. Research on natural disturbance patterns has indicated that fires have historically burnt through riparian zones at similar rates to uplands (Andison and McCleary, 2002) and this knowledge has lead to additional challenges to the riparian reserve strategy. However in addition to protecting terrestrial biodiversity, riparian reserve zones serve as an important tool for conserving water quality and fish habitat specifically through moderating ecosystem processes.

While a multitude of ecological functions occur within riparian zones (Naiman et al., 1993), forest management activities are most closely linked to sediment and large woody debris (LWD) related processes (Boyer et al., 2003; Waters, 1995). Prosecutions in Canada under the Federal Fisheries Act involving alterations to riparian vegetation and streambanks illustrate the high recognition that sediment and wood have been given (Fisheries and Oceans Canada, 2001). Yet despite this importance, very little is known about these elements and related processes in small Foothills streams. The goal of this study was to improve our understanding of structure and function of small Foothills stream systems. An improved understanding is a step toward predicting and evaluating the effects of various riparian management scenarios and meeting the challenges of achieving fibre, production, biodiversity, water quality and fish habitat goals on the forest lands of Alberta.

2. Report Organization

The report contains four additional chapters: Chapter 2 - an organizing system for streams; Chapter 3 - channel structure and sediment inputs; Chapter 4 - large woody debris; and Chapter 5 - conclusions and recommendations. A budget approach was selected for organizing chapters 3 and 4 on sediment and wood (Equation 1). Budgeting, a common accounting process, has been applied to track the inputs, storage and outputs of both sediment and wood (Benda et al., 2003; Reid and Dunne, 2003; Slaymaker, 2003). A budget can be balanced using one of the three arrangements of the standard budget equation, depending on the component of interest and the available information.

Equation 1. Budget equation.

Outputs = Inputs + Change in Storage

A budget approach can be applied to timber management and can also help create linkages with other sustainable forest management components including water quality and fish habitat (Table 1). For example, while standard approaches for measuring water quality include measuring sediment outputs, actual management of water quality requires a knowledge of terrestrial sediment input sources so activities on these sites can be modified to maintain desired water quality objectives. As a second example, consider dead wood which functions to diversify fish habitat structure within a small stream. Long-term fish habitat conservation entails managing wood inputs in order to sustain this important structural element. Management goals for wood and sediment can be developed and implemented once input rates, storage amounts and output rates for these elements are understood. In this study, I attempted to develop qualitative sediment and wood budgets by identifying key components and processes within small Foothills streams. Where possible, I sought to quantity the results.

Table 1. A budget framework for management of timber, sediment and LWD.

	Inputs	Storage	Outputs
1. Timber	tree growth	standing trees	• timber harvest • fire • insects • decay
Tools	• growth & yield models, • ecosite classification	AVI maps with timber volume	• Detailed Forest Management Plan • Annual Allowable Cut
2. Sediment	sediment transport	• landforms, channel forms, lwd	water quality: • suspended sediment • bedload
Tools	reach and watershed process model	Alberta based floodplain and channel assessment	• reach and watershed process model • field measurement
3. Wood	tree fall	Fish habitat: • floodplain • channel	• decay • transport
Tools	adapted growth and yield model	• AVI maps • field inventory	wood decay model

In Chapter 5, I outline a management process informed by knowledge of ecosystem structure and function and identify the stage we are at in the process. Potential management applications from the findings of this study are stated and future initiatives are described.

Chapter 2 - An Organizing System for Streams and Applications for Sample Site Selection

1. Introduction

Forest managers rely on the watercourse classification system from the Operating Ground Rules to guide harvest in proximity to streams (Alberta Sustainable Resource Development - Public Lands and Forests Division, 1994). This field classification utilizes stream width and whether the channel supports perennial, intermittent or ephemeral flow. While this system provides a high level of protection for permanent streams, there are three main shortcomings. First, the effects on aquatic values from the no-retention strategy along intermittent streams is unknown. Second, it can be difficult to consistently apply watercourse classification in the field. Third, it can be difficult to link field layout of riparian reserves to mapped streams and then to map-based landscape level forest management plans.

In a review of the riparian management systems, strengths of Alberta's timber harvesting ground rules (Alberta Sustainable Resource Development - Public Lands and Forests Division, 1994) included the ease of application during layout and compliance audits (Lee and Smyth, 2003). In comparison to other North American riparian management strategies for protection of aquatic resources, the Alberta system provides high protection for perennial streams and lower protection of intermittent and ephemeral streams (Lee and Smyth, 2003). In Alberta, actual effects have not been measured from the varying levels of protection among the four stream types.

Periods of prolonged drought and seasonal changes in precipitation create a wide range of flows within a small stream in the Foothills. As a result, the watercourse classification may be inconsistently applied at one location during different visits. Forestry technicians have been instructed by managers to err on the side of protection, and managers have requested additional knowledge on the requirements for maintaining stream channel structure at these transition channel locations (T. Daniels, 2003 Sundre Forest Products, pers. comm.).

Forest managers have also determined that within the Foothills region, the mapped Alberta stream network often shows small streams that do not occur in the field while other small watercourses are missing. Given these problems with map accuracy, it can be difficult for forest managers to develop landscape level forest harvest plans that include timber volume reductions within riparian reserve zones without extensive field work.

Recognizing these challenges, the goal of this study was to increase the knowledge of the ecological structure and function of these small stream channels as a step towards improving riparian management. Our strategy was to divide the stream network into sections of a similar scale to individual Alberta Vegetation Inventory (AVI) polygons and to provide additional map-based information for each of these stream reaches. While forest managers working with the existing stream network can visually determine Strahlers stream order for the stream of interest, additional descriptors of the stream size (upstream drainage area) and stream energy (channel slope) that were developed for this study may have future riparian management applications.

2. Automated Classification Methods

The stand serves as the operational unit for forest management, and the reach functions as the basic unit of stream organization at a comparable scale. A stream reach is a length of stream of uniform size and energy characterized by a repeating sequence of smaller habitat units (i.e. riffles and pools). The target length for individual stream reaches was 300 m. The structure and function of the riparian area and stream within a reach are influenced by the characteristics of its watershed, or as the entire portion of land that drains to the reach. Important watershed characteristics include topography, surficial materials, vegetation and land-use. Connections between the reach and watershed required a classification capable of describing both the reach and watershed characteristics for all possible stream sections.

We developed a protocol for completing reach and watershed classification using an automated GIS procedure. The areas identified for classification included all streams within the Dogrib and Chisholm fire boundaries and large adjacent un-burned areas (Figure 1 and Figure 2). These expanded areas were visible at the provincial scale (Figure 3).

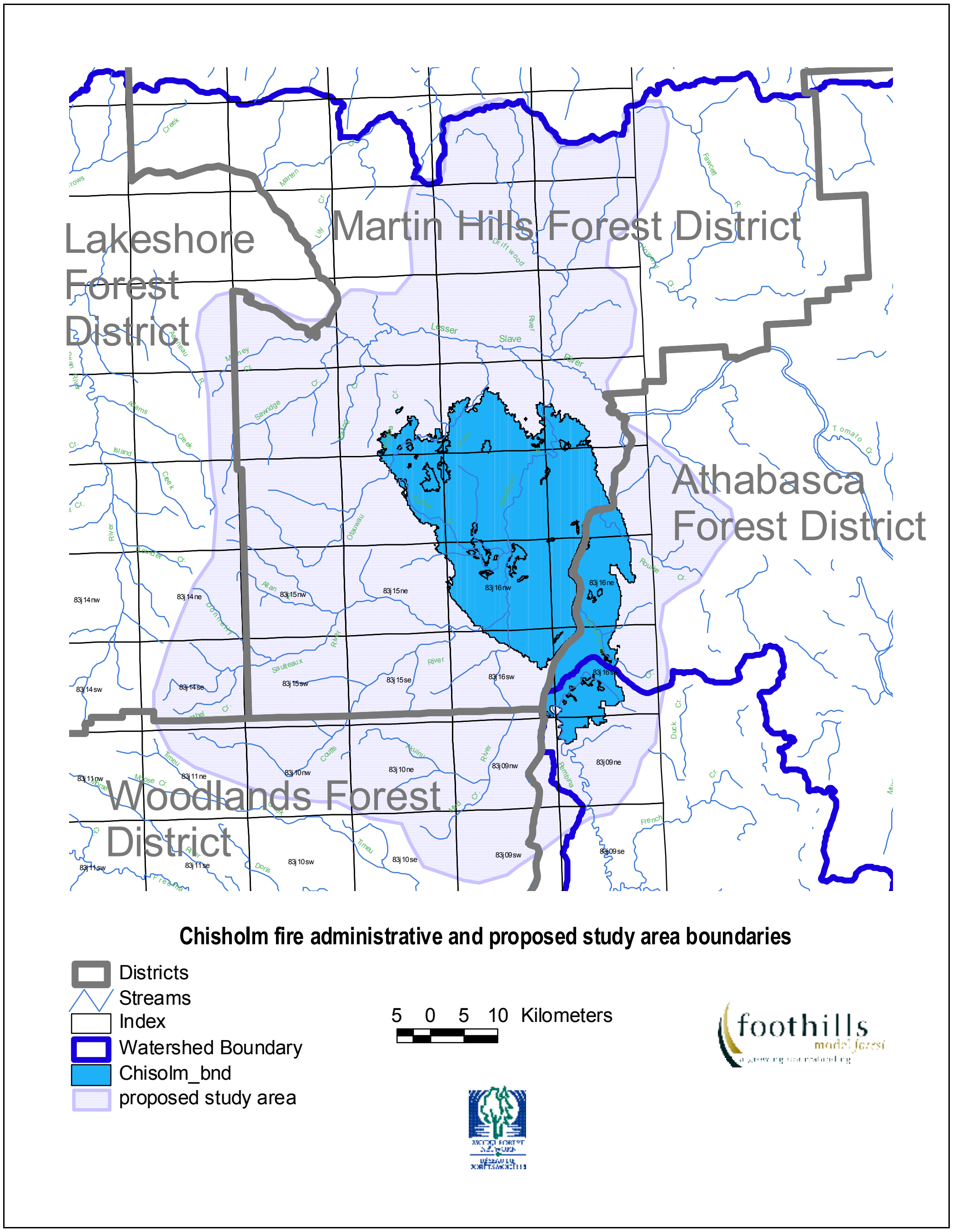


Figure 1. Overview map of expanded study area for stream classification with inset of Chisholm fire boundary.

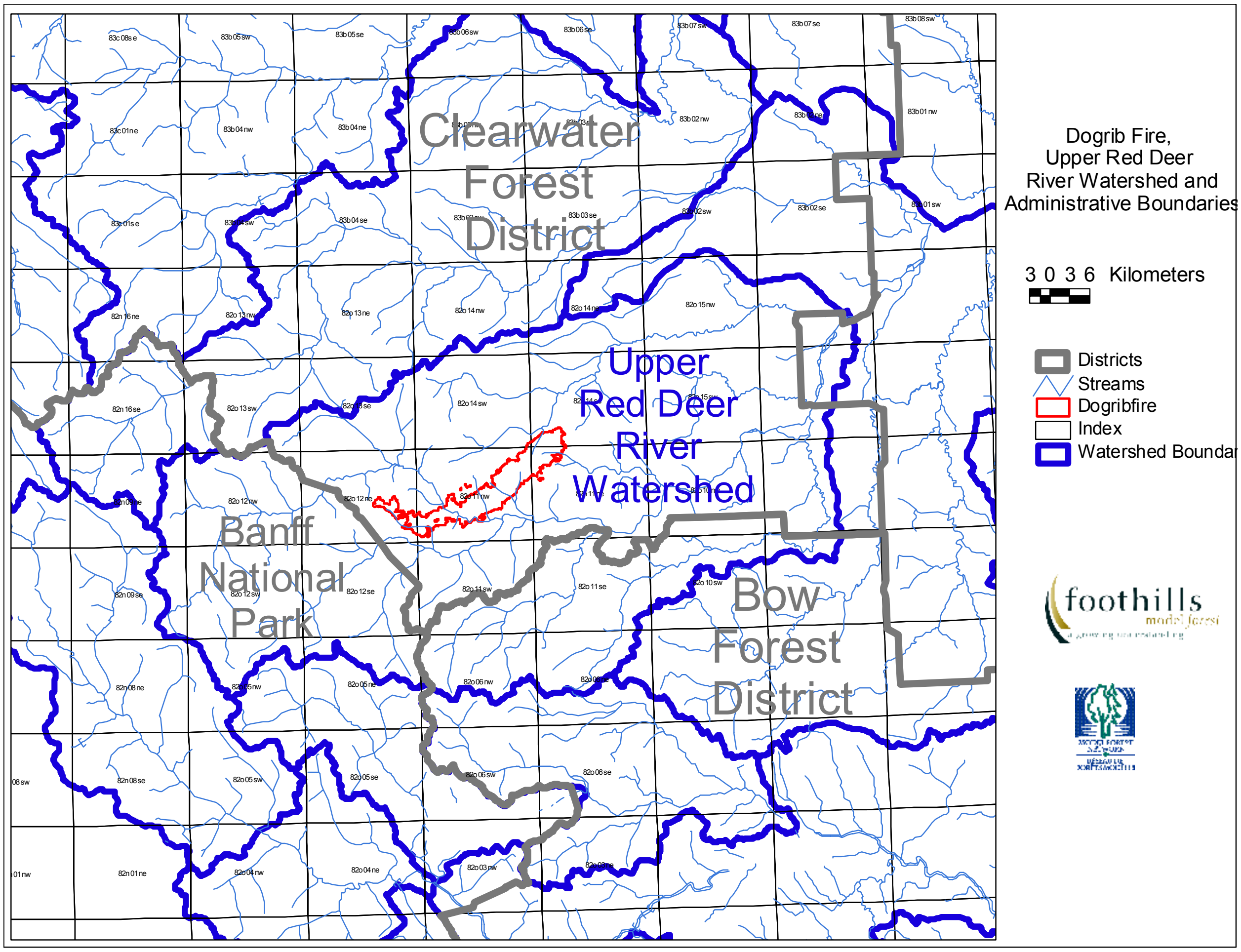


Figure 2. Overview map of Upper Red Deer River watershed boundary selected for stream classification and inset of Dogrib fire boundary.

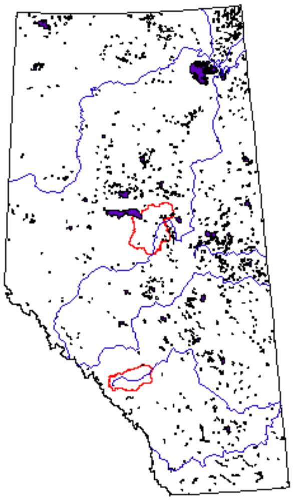


Figure 3. Map of Alberta with boundaries for stream classification.

In the spring of 2002, the classification was completed for these areas under contract (see Appendix 1 for a detailed description of the processes and resultant data sets). Following the completion of classification, the results were made available to several other users for various applications (provided that these users had authorized access to the digital provincial streams layer).

I had intended to complete field studies within both the Chisholm and Dogrib fires, however forest industry support for field studies was limited to the Dogrib fire only. Within the Dogrib fire, we limited the study area to those portions within the Forest Management Agreement (FMA) area held by Sundre Forest Products - A Division of West Fraser Mills Ltd. (Sundre Forest Products).

3. Sample Site Selection

I considered two variables in our initial stratification – drainage area (three strata) and reach slope (four strata). To assist with extrapolation of findings to other managed forest lands, I compared the distributions of these variables between those streams within the study area and other streams within the Upper Red Deer River portion of the FMA held by Sundre Forest Products (Figure 4 and Figure 5). While percentage of stream within the three drainage area classes was similar, there were fewer low gradient streams and more steep streams within the burnt portion of the FMA.

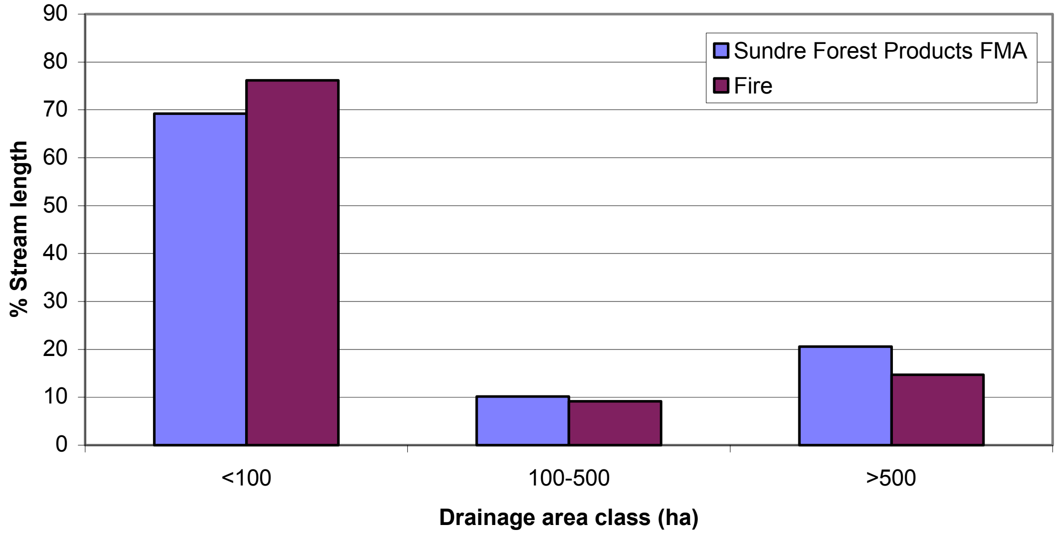


Figure 4. Percent stream length by drainage area class within the Upper Red Deer River watershed portion of the Sundre Forest Products FMA and within the burnt portion of the FMA.

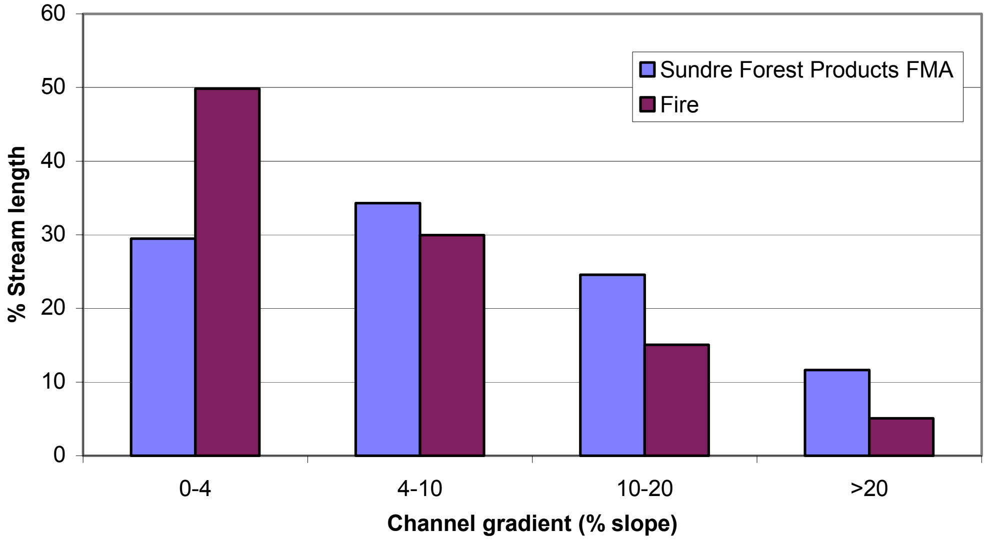


Figure 5. Percent stream length by slope class within the Upper Red Deer River watershed portion of the Sundre Forest Products FMA and within the burnt portion of the FMA.

Reaches were considered for field assessment only if they met the three following criteria:

1. The entire reach was completely burned by the Dogrib fire based on digital ASRD-FPD fire boundary information.
2. The reach was bordered by a forest stand potentially suitable for harvest based on minimum stand height of 15m based on digital Alberta Vegetation Inventory.
3. The reach was bordered by a forest stand that was not harvested prior to the fire, salvaged after the fire or heavily influenced by road building (Sundre Forest Products land-use data).

Based on these criteria, I used a GIS exercise to identify a total of 22 candidate reaches (Table 2).

Table 2. Summary of candidate reaches based on slope and drainage area.

Slope Class	Drainage Area Class			% of samples
	0-100 ha	<100-500 ha	>500 ha	
0-4%	3	3	3	41
>4-10%	5	2	1	36
>10-20%	4	0	0	18
>20%	1	0	0	5
% of samples	59	23	18	100

During field reconnaissance, 20 of these reaches were found suitable for more detailed studies.

Chapter 3. Channel Structure and Disturbance Assessment

1. Introduction

The goal of this chapter was to describe the channel structure and post-fire disturbance state of the streams within the Dogrib Fire portion of the Sundre Forest Products FMA. Given the forest management goals and applications of this study, the functions of live and dead trees for maintaining channel structure were of particular interest. This chapter has four additional sections. Study area description, methods, results, and summary of key findings.

2. Study Area Description

The following subsections describe the geology, surficial materials, climate, vegetation, water resources and land-use within the study area. To promote the application of the findings during regular and fire-salvage forest management in the Foothills of Alberta, I established connections between this background information and key riparian processes including hillslope erosion, stream channel and floodplain formation, and vegetation dynamics.

2.1. Description of Dogrib Fire

The Dogrib Fire originated from an abandoned backcountry campfire in the Panther Corners Forest Land Use Zone in September 2001. The fire area spread across a portion of the R11 Forest Management Unit and entered the Forest Management Agreement (FMA) area held by Sundre Forest Products - A Division of West Fraser Mills Ltd. (Sundre Forest Products) (Figure 6). The fire encompassed 9,214 hectares within the Red Deer River watershed, including portions of both the James River basin and other tributaries to the Red Deer River. Our research area was limited to the 6,740 ha portion of the fire located within the Sundre Forest Products FMA (Figure 7).

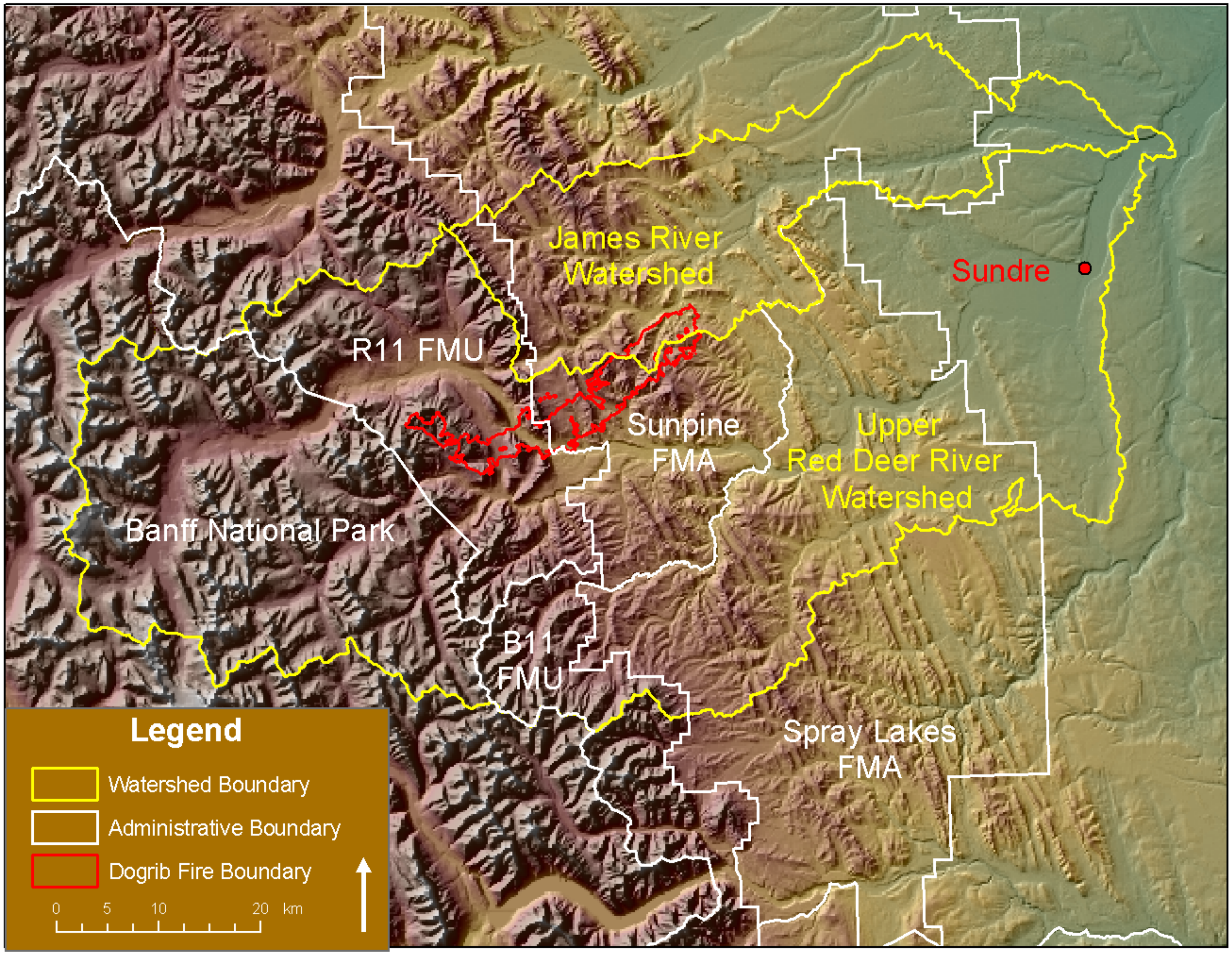


Figure 6. Overview of Dogrib Fire with watershed and administrative boundaries.

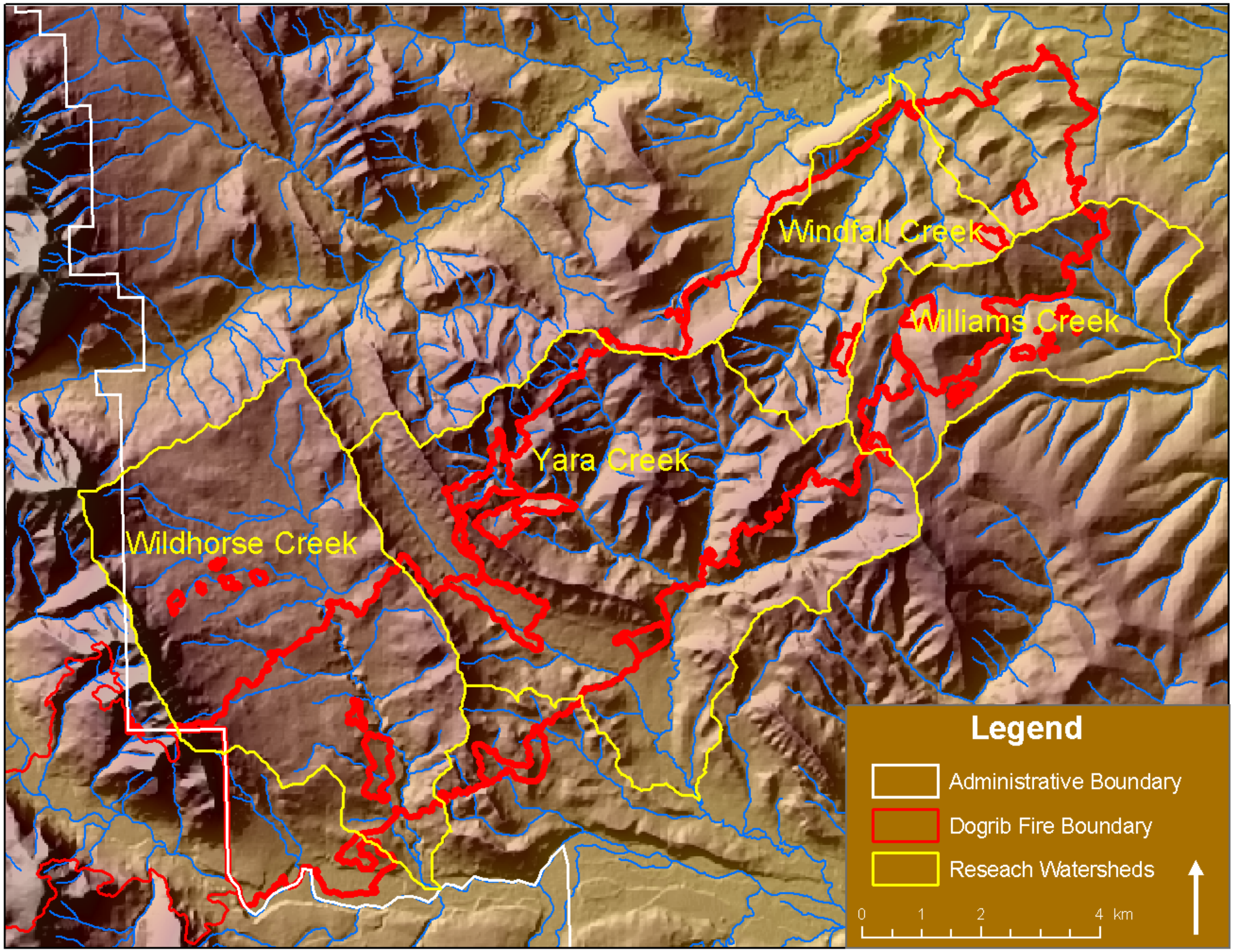


Figure 7. Study area including four main watersheds.

2.2. Geology

The western boundary of the study area corresponds to the thrust fault where the older carbonate layers of the Rocky Mountains have overridden young clastic layers of the foothills, which are comprised of eroded particles (Gadd, 1995) (Figure 8). The carbonate formations of the Rocky Mountains are much harder than the sandstone, shale and siltstone formations of the Foothills area. As a result, the Rocky Mountains have retained a rugged, blocky form. The Foothills formations have eroded to a rounded surface form, with pronounced ridges usually capped with more resistant sandstones, while valleys and hillslopes eroded into softer shales and siltstones (Stelfox 1981).

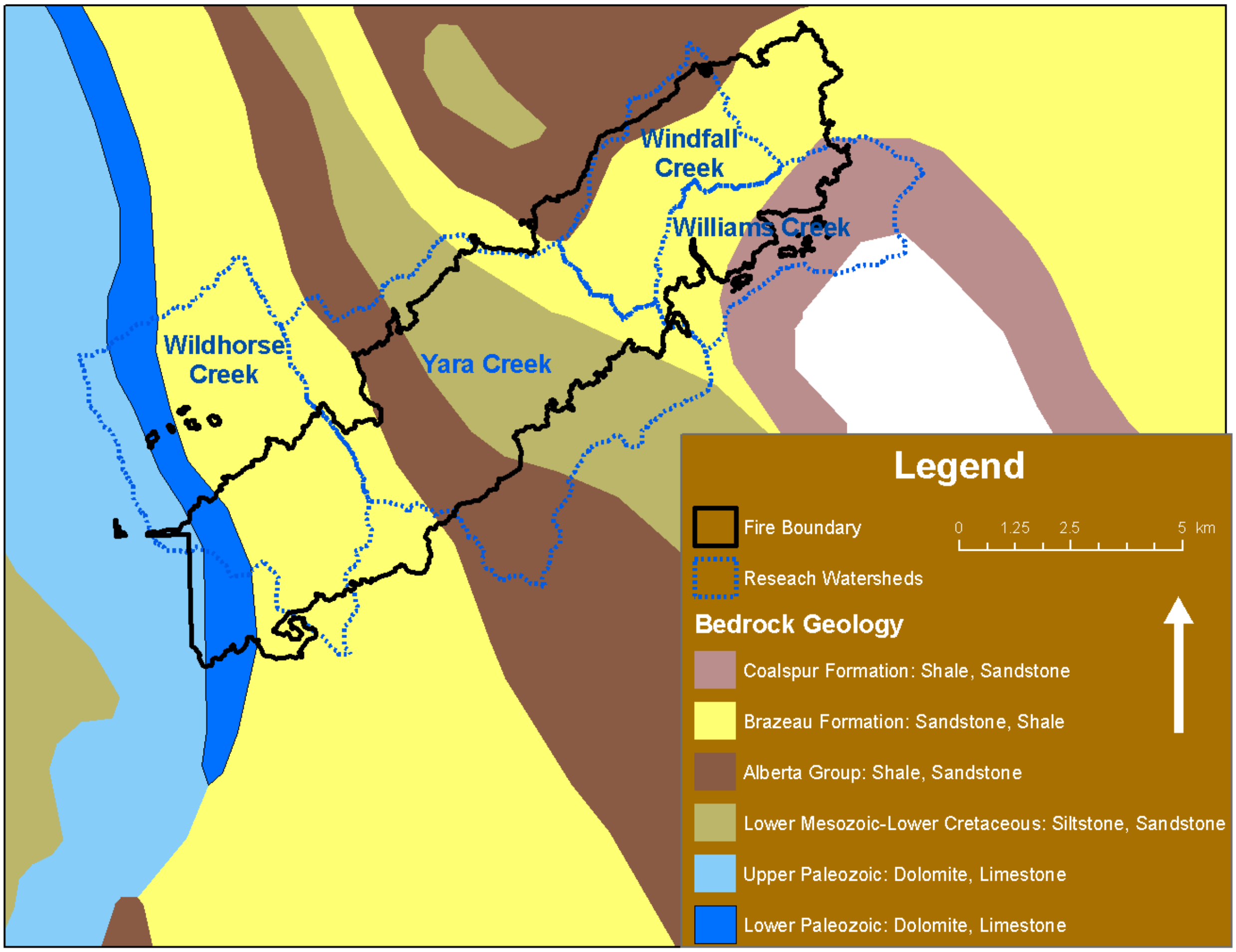


Figure 8. Surficial geology of the study area.

2.3. Surficial Material

Surficial materials vary from west to east across the study area. Thick till deposits are typically limited to areas with less than 30% slope (Stelfox 1981) and such deposits cover much of the moderate sloping Wildhorse Creek basin (Figure 9 and Figure 10). In contrast to the Wildhorse Creek basin, weathered bedrock covers the poorly glaciated terrain within much of the Yara, Windfall and Williams Creek basins. The residual material and colluvium within these three basins covers more than 50% of the study area (Table 3). Portions of the Yara Creek watershed represent the steepest terrain within the study area with some areas exceeding 40% slope (Figure 10), which is considered the upper limit for use of conventional feller-buncher-skidder harvest techniques.

Table 3. Surficial material types and extent within study area.

Surficial Material from Ecodistrict Classification (Stelfox 1981)	Ha	%
Fluvial	373	6
Moraine	1026	15
Moraine/Colluvium	540	8
Moraine/Residual	1048	16
Organic	160	2
Residual/Colluvium	3578	53
Rock	16	0
Total	6740	100

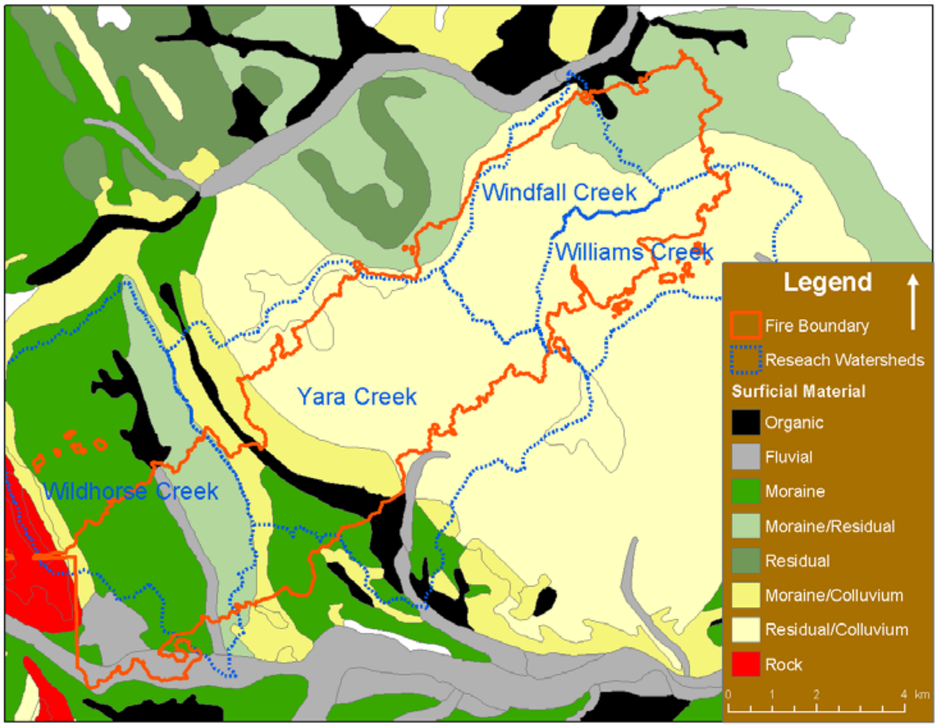


Figure 9. Surficial material from Stelfox (1981).

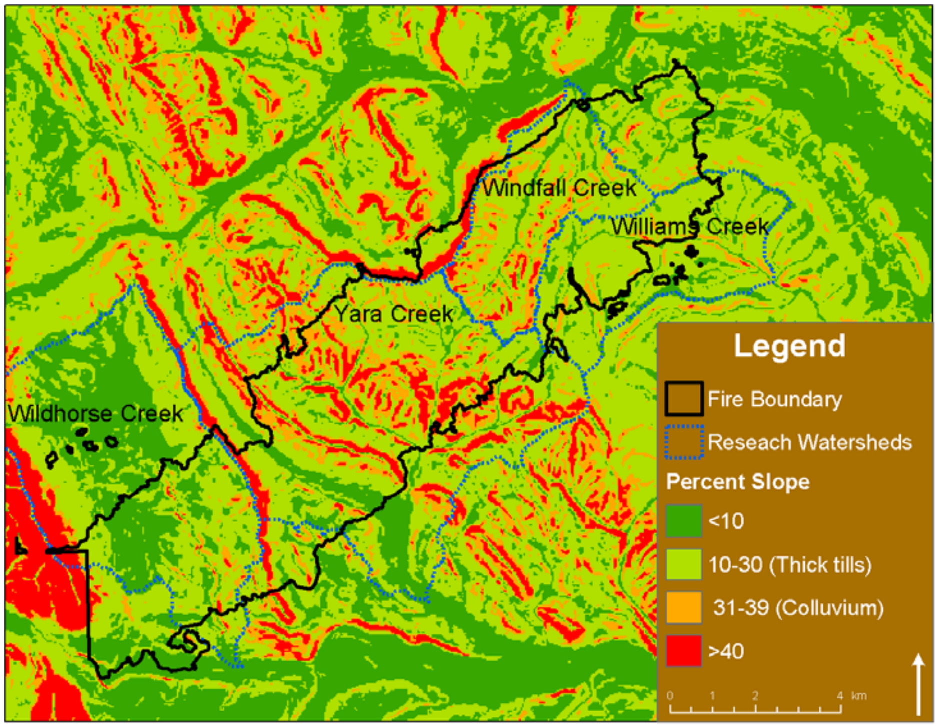


Figure 10. Study area slope class map.

During an ecological land classification for the study area, the lead scientist observed different fluvial landform characteristics and erosional processes in the Rocky Mountains versus Foothills terrain (Stelfox, 1981). These differences were observed in large rivers and small streams.

Floodplains associated with the Red Deer and James Rivers contain different materials. The Red Deer River has a coarse-textured gravel and cobble floodplain with a braided channel pattern, whereas the James River has a fine textured floodplain and meandering channel pattern (Stelfox 1981). These contrasting floodplain characteristics suggest that different erosional processes dominate the Rocky Mountains versus the Foothills.

While there is an abundance of knowledge on fluvial landform processes within mountainous environments, much less is known about these processes in Foothills environments and the contrasting nature of the floodplain materials suggests that different processes are at work. For example, the high relief, heavily-glaciated mountains have generated larger floodplain particles than the foothills, where water erosion of surficial material may have been relatively more important. We will attempt to identify the dominant Foothills erosional processes through the analysis and literature review in the remainder of this section.

Two types of headwater streams within the study area are streams along the Front Range of the mountains characterized by straight, steep channels with flashy flows, versus meandering Foothills streams with more stable flows within broad, low gradient valleys (Stelfox 1981).

The texture of the surficial material influences response of watersheds to disturbance. Soil texture is one of several factors that influence strength of post-fire water repellency and hence post-fire infiltration, run-off and erosion rates (MacDonald and Huffman, 2004; MacDonald and Stednick, 2003). Other factors include burn severity, vegetation type, soil moisture, and time since burning. During a fire, organic matter within the surface soil horizon can volatize to form water repellent compounds. In soils with high sand content, the low surface area on sand particles creates a relatively high concentration of the water repellent compounds and a strong water repellent layer. Soils formed in the Brazeau formation typically have either a sandy loam (55-85% sand) or silt loam (0-50% sand) texture, while soils formed in till of Cordilleran origin within hilly Foothills terrain typically have sandy loam (55-85% sand) or loam (25-55% sand) textures (Dumanski et al., 1972). These textural characteristics indicate a potential for formation of water repellent soils within most of the surficial material in the study area.

2.4. Climate

Climate information for the Upper Foothills Natural Subregion has been described (Strong, 1992). Of the main climatic variables, rainfall in the immediate post-fire period is the most important variable for influencing erosion (MacDonald and Huffman, 2004) and therefore was important for this study. The duration of the high-risk erosion period is related to a number of factors. First, water repellency recovers rapidly following fire and second, as ground cover establishes on exposed soils, the effects of rain-splash erosion will decrease (MacDonald and Huffman, 2004).

The Upper Foothills Natural Subregion receives an average of 464 mm of precipitation annually, with 64% falling in summer (May-August), 13% during winter (November-February) and the remaining 23% during the shoulder seasons (Archibald et al., 1996). Violent summer thunderstorms are a common occurrence within this subregion (Archibald et al., 1996). At the Blue Hill Provincial Fire Weather Station, located on a high ridge near the southern boundary of Yara Creek watershed within 1.5 km of the southern fire perimeter, the average total monthly rainfall over the 25-year period between 1980 and 2004 ranged between 29 and 101 mm, with the highest monthly average occurring in the month of July (Figure 11, Figure 12 and Figure 13). Therefore, actual post-fire erosion during the first few years following a fire in the Upper Foothills will be largely dependent upon the precipitation patterns throughout the summer months. For the two year period between the fire and our field assessments, both the total summer precipitation and the maximum daily rainfall were well below average (Figure 12 and Figure 13).

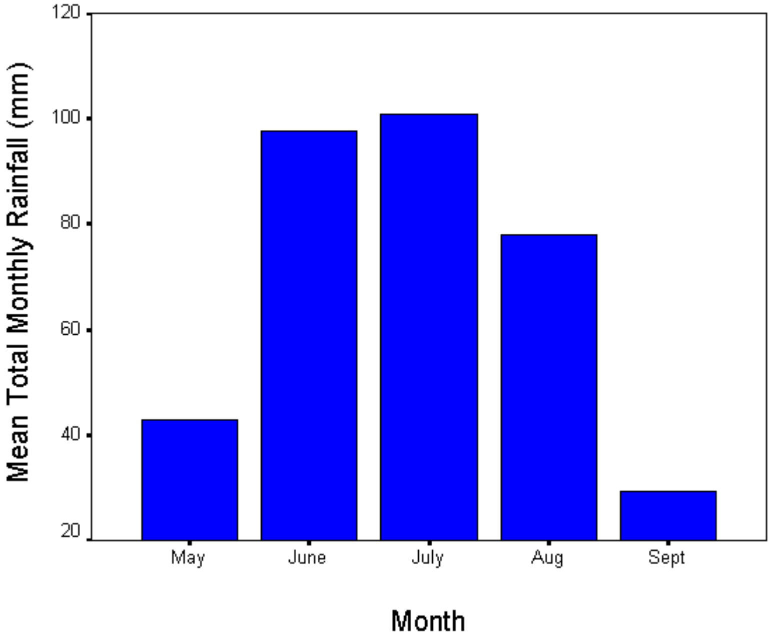


Figure 11. Average total monthly rainfall for May to September from the Blue Hill Fire Weather Station for the 25-year period between 1980 and 2004.

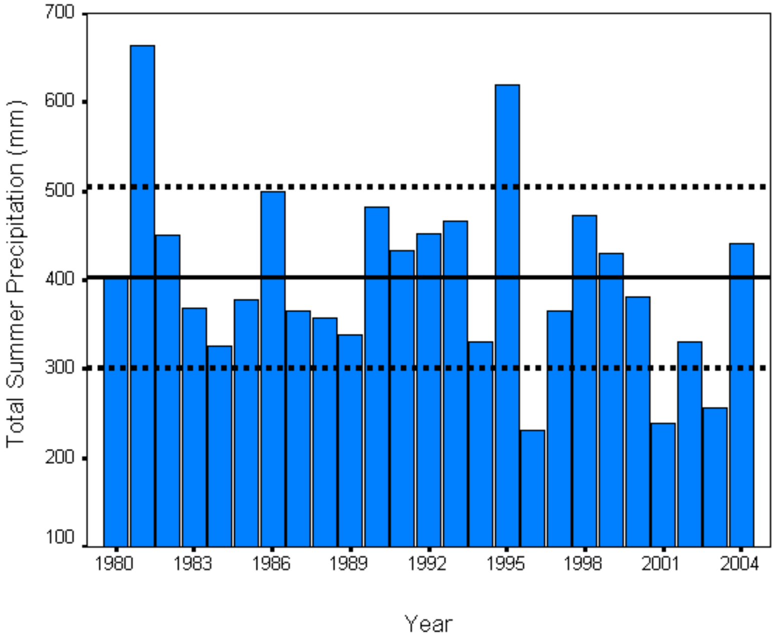


Figure 12. Total summer precipitation (mm) at the Blue Hill fire weather station for the 25-year period between 1980 and 2004. Solid line indicates average, and dashed lines indicate +/- one standard deviation. Fire year was 2001 and field assessment year was 2003.

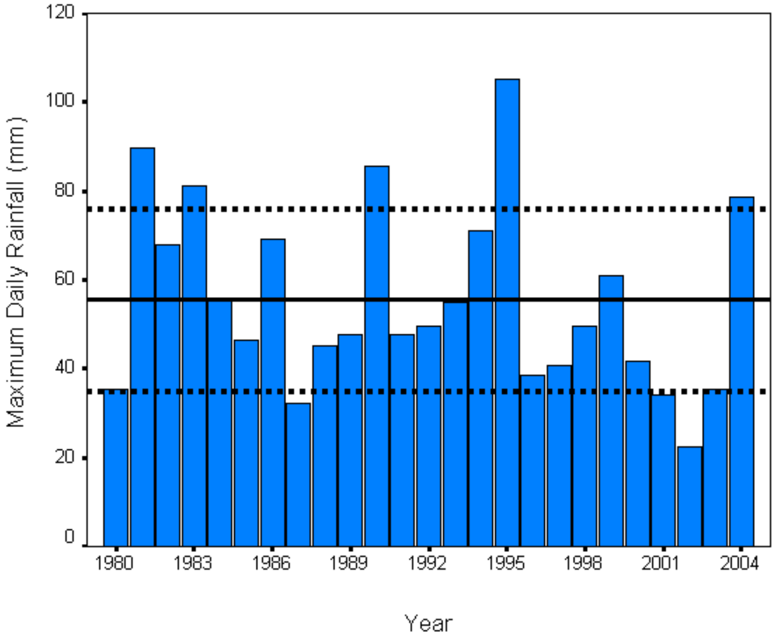


Figure 13. Maximum annual daily rainfall (mm) at the Blue Hill fire weather station for the 25-year period between 1980 and 1994. Solid line indicates average and dashed lines indicate +/- one standard deviation. Fire year was 2001 and field assessment year was 2003.

2.5. Vegetation and Natural Disturbance

The study area is dominated by the Upper Foothills Natural Subregion, with the Subalpine Natural Subregion occurring on high elevation areas along the western boundary of the Wildhorse Creek watershed and also along the ridgetops of the Yara Creek watershed (Archibald et al., 1996). Fire is the dominant natural disturbance influencing forest vegetation in the Upper Foothills natural subregion in Alberta. Although a detailed analysis of fire cycle has not been conducted for the study area, in other Upper Foothills locations stand replacing fires have an average cycle of between 60 and 90 years (Andison, 2000).

2.6. Management of Multiple Resources

To achieve watershed protection along with timber management objectives, the Rocky Mountain Forest Reserve was created within the foothills in 1911 (Bott et al., 2003), and maintenance of water quality and protection of fish habitat remain key goals for this land base. The region is currently intensively managed for a number of uses including timber production, cattle grazing, oil and natural gas extraction and recreation.

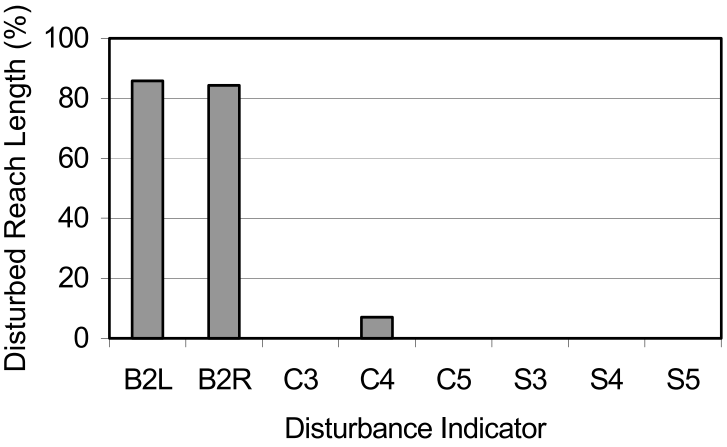
3. Methods

The methods to describe channel structure and disturbance state were adapted from the Channel Assessment Procedure Field Guidebook (Anonymous, 1996). In this procedure a number of disturbance indicators provide information on the state of each of the four main channel features including sediment deposition features, bank features, channel bed features (pools and riffles) and LWD. Rather than tracking the distance by disturbance level, as recommended in the procedure, I added another level of detail and measured the distance of each disturbance indicator. Although the original methodology identified 16 different disturbance indicators, I identified the seven that were most applicable to our study area streams (Table 4). This approach of tracking the extent of each disturbance type enabled the production of a disturbance signature graph for each reach (Figure 14) and also permitted a detailed analysis based on the extent of each disturbance indicator within each reach.

Table 4. Descriptions of key channel disturbance indicators in small Foothills streams following fire (adapted from (Anonymous, 1996).

Indicator Category and Abbreviation	Disturbance indicator	Photo	Characteristics
Banks: B2L B2R	Eroding bank, left Eroding bank, right		•Recently exposed bank material or lack of undercut.
Channel bed features: C2	Minimal pool area		•Pools limited in frequency & extent. •Often associated with LWD pieces •Applicable even in dry, intermittent channels.
Channel bed features: C3	Elevated mid-channel bars		•Channel bars with elevations near bank-tops.

Indicator Category and Abbreviation	Disturbance indicator	Photo	Characteristics
Channel bed features: C4	Multiple channels or braids		•Develop when capacity of original channel is reduced to sediment deposition or debris accumulation.
Sediment deposition features: S3	Sediment wedges		•Particle size is smaller than average bed material •Associated with channel bends, LWD features •Occurs in aggrading channels
Sediment deposition features: S4	Extensive bars		•Bars extend throughout the channel, usually to bankfull height •Minimal flowing water •Occurs in aggrading channels
Sediment deposition features: S5	Extensively scoured zones		•Majority of bed material is absent due to scouring •Typical in degrading channels



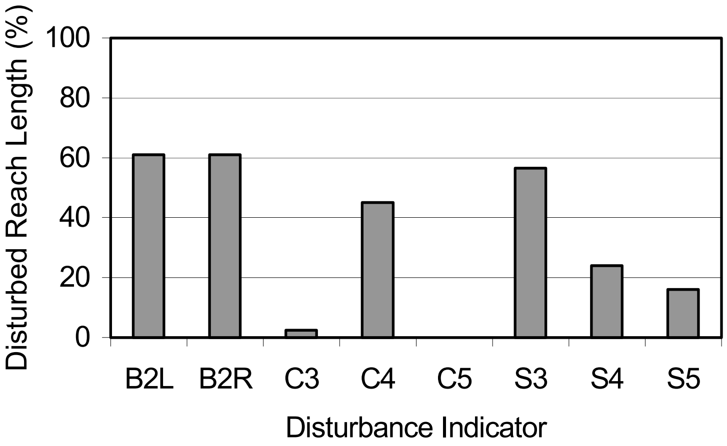


Figure 14. Example disturbance signature graphs from two sample reaches.

Floodplain boundaries were delineated using soil characteristics (Anonymous, 1996; Archibald et al., 1996; Platts et al., 1987) with a confirmation based on Rosgen and Silvey (1998). Given the range of stream sizes selected for this study, it was important to scale key channel structure elements based on stream size. Therefore minimum pool size was based on bankfull width (Table 5).

Table 5. Minimum residual pool depth and pool surface area based on channel bankfull width (Schuett-Hames et al., 1999)

Bankfull Width (m)	Min. Residual Pool Depth (m)	Min. Unit Size (m^2)
0 to < 2.5	0.1	0.5
2.5 to <5	0.2	1.0
5 to < 10	0.25	2.0
10 to < 15	0.3	3.0
15 to < 20	0.35	4.0
> 20	0.4	5.0

4. Results

The findings are presented in two main sections including channel structure and channel stability assessment. The four structural elements that were described included channel morphology type, floodplain, channel bed and stream banks. In the channel stability assessment, I explained the amount of channel disturbance for each disturbance indicator by key factors including channel type and parent material. For each of the 20 reaches, we prepared a two-page summary report including photographs, morphology details and a disturbance signature graph (Appendix 4).

4.1 Channel Structure

4.1.1 Channel Classification

While nine of the 20 sample reaches displayed characteristics consistent with the five major channel types from the channel assessment procedure nomogram (Anonymous, 1996), 11 reaches were located outside of the classification band (Figure 15) (Table 6). In all 11 cases, the relative channel size (the product of the relative width and relative roughness) was less than expected given the gradient of these channels. All 11 reaches had drainage areas of less than 1.7 km^2 and the other nine channels had larger drainage areas (Table 6). This indicates that given the potential energy based on channel slope, the size of the largest particles in the channel was much smaller than expected. These channels may be consistent with previously described first-order steepland channels characterized by accumulation of hillslope sediment rather than downstream transport (Reid and Dunne, 2003). In coastal mountain areas, such channels have been characterized by shallow episodic landslides in steeper terrain (Reid and Dunne, 2003). Within the Northern Rocky Mountain Physiographic Province in Idaho and Wyoming, headcutting was a dominant erosional process near headwater streams in steep valleys (Platts et al 1987). However, the dominant erosional processes within Foothills headwater streams was not documented.

To explore potential differences in channel disturbance patterns between those reaches within the CAP classification belt and those outside the belt, two channel categories were identified – small alluvial and headwater respectively (Table 6). All 20 sample reaches were also characterized by parent material type based on existing maps (Stelfox, 1981) complemented by field verification (Table 7).

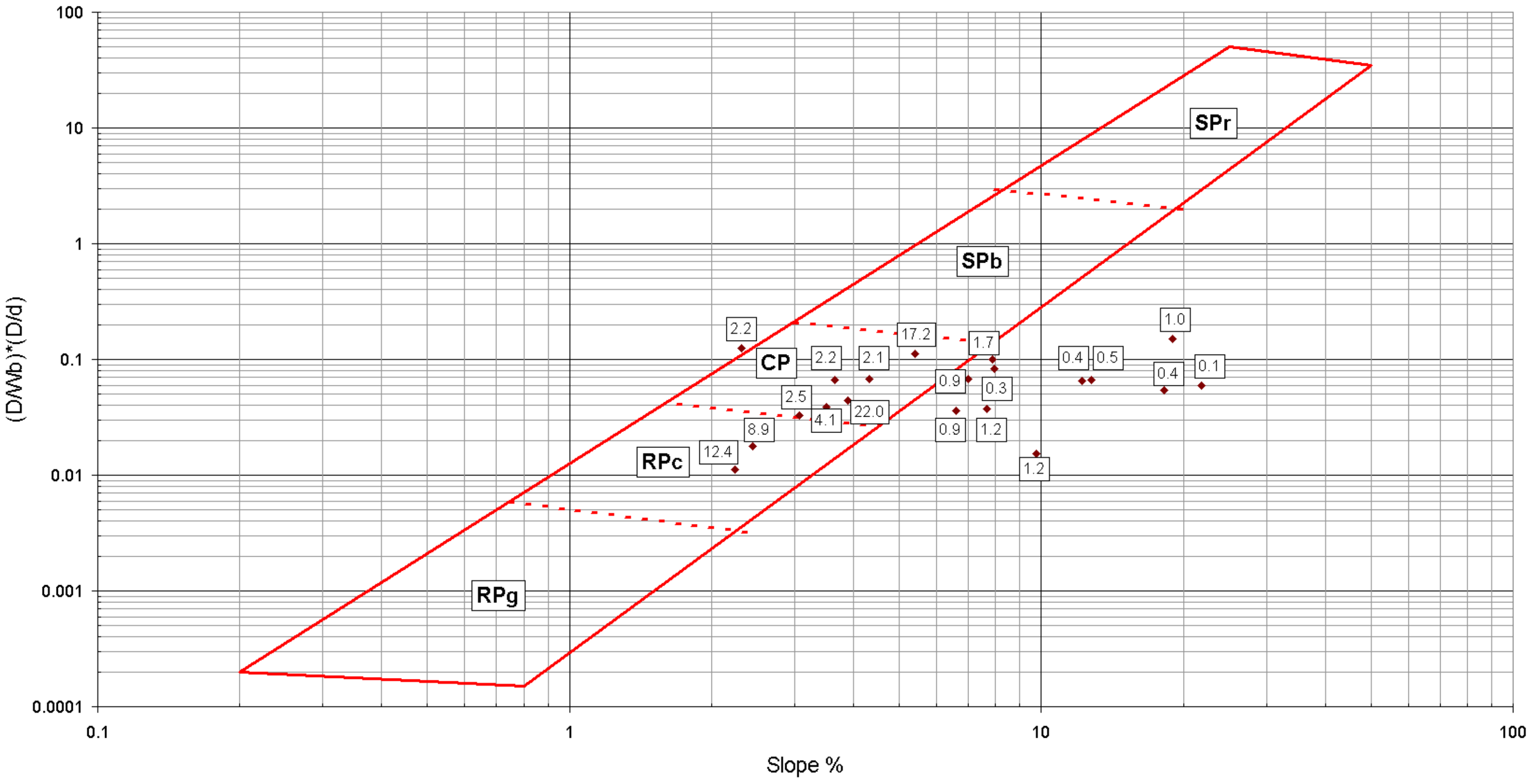


Figure 15. Nomogram to determine channel morphology (1996) with drainage area (km^2) for each sample reach. Small alluvial streams include sample reaches located within red rectangle and headwater streams include those located outside red rectangle.

Table 6. Summary of key channel morphology attributes and channel type for 20 study area reaches.

Reach Number	(D/Wb)*(D/d)	Slope (%)	Drainage Area (km^2)	Channel Type[1]	Small Stream Type	Parent Material Type
8	0.06	21.8	0.12	PF	headwater	residual
18	0.08	8.0	0.31	PF	headwater	residual
27	0.07	12.2	0.36	PF	headwater	residual
17	0.05	18.2	0.39	PF	headwater	moraine
13	0.07	12.8	0.49	PF	headwater	residual
11	0.04	6.6	0.89	PF	headwater	residual
24	0.07	7.0	0.90	PF	headwater	residual
7	0.15	19.0	1.03	PF	headwater	moraine
4	0.02	9.8	1.19	PF	headwater	colluvial
25	0.04	7.7	1.24	PF	headwater	residual
1	0.10	7.9	1.66	PF	headwater	moraine
5	0.07	4.3	2.14	CP	small alluvial	residual
22	0.07	3.6	2.23	CP	small alluvial	moraine
21	0.13	2.3	2.25	CP	small alluvial	residual
2	0.03	3.1	2.45	CP	small alluvial	moraine
12	0.04	3.5	4.11	CP	small alluvial	residual
26	0.02	2.4	8.87	RPc	small alluvial	fluvial
3	0.01	2.2	12.40	RPc	small alluvial	fluvial
15	0.11	5.4	17.21	CP	small alluvial	colluvial
6	0.04	3.9	22.03	CP	small alluvial	colluvial

[1] BC Channel Assessment Procedure channel morphology type: PF = Poor fit, CP = cascade-pool, RPc = riffle-pool cobble.

Table 7. Examples of streams formed in each of the four dominant parent materials within the study area including residual, colluvial, alluvial and morainal deposits.

	
Stream formed in residual material.	Stream formed in colluvial material.
	
Stream formed in alluvial material.	Stream formed in morainal deposits.

4.1.2 The Floodplain

The two objectives of this section were to first develop a model to estimate the quantity of floodplain sediment stored within every stream reach within the study area and then display the sediment storage estimates on a map. For an individual stream reach, an estimate of floodplain sediment storage can be calculated using four different variables (Equation 2 and Figure 16). Of these four variables, only reach length was available for all study area reaches and models of floodplain width, bankfull width and bankfull depth were required.

Equation 2. Calculating floodplain sediment volume from floodplain and stream channel dimensions.

$$V = {}^{1}/_{2}\,(\text{floodplain width} - \text{bankfull width}) * \text{bankfull depth} * \text{reach length}$$

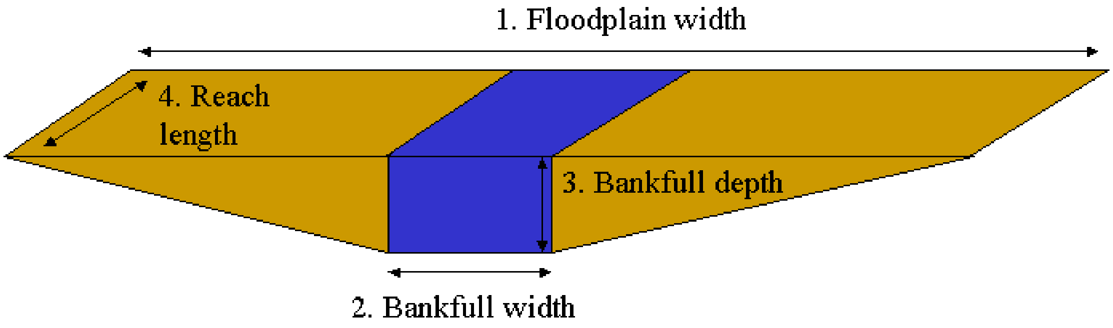


Figure 16. Determining floodplain sediment storage by reach from models of floodplain width, bankfull width and bankfull depth and a measure of reach length.

Four candidate variables for model development included drainage area, reach slope, mean basin slope and average slope of the terrain within 10m of the stream reach. Four outliers were identified during a graphical analysis of each independent variable versus floodplain width. Outliers included the three largest streams (Reaches 3, 6 and 15), which were all confined by the adjacent hill slopes. This valley configuration limited both floodplain width and opportunities for conventional forest harvest using conventional techniques, and as a result these three reaches were excluded from the modeling exercise. The final outlier (Reach 17) was located within a small basin with its headwaters in the Subalpine natural subregion and was not representative of the study area. The 16 remaining model training sites had a maximum drainage area of 886 ha, therefore model extrapolation was limited to stream reaches with a drainage area of less than 1,000 ha.

4.1.2.1 Floodplain width model

Using backward stepwise regression, two of the four candidate variables were incorporated into a floodplain width model (Table 8 and Figure 17). To map these results, the model was extrapolated to all study area reaches with a drainage area of less than 1,000 ha (Figure 18). These findings were consistent with Rosgen (1994), where floodplain width decreased with increasing slope. However, according to Rosgen (1994), the upper limit for fine texture floodplain was 5% slope, whereas within the study area, channels with slopes even greater than 10% had floodplains with fine textured soils. The processes of floodplain development for headwater streams described for Northern Rocky Mountain Physiographic Province, including parts of Wyoming and Idaho (Platts et al 1987) appear consistent with Upper Foothills. In the Northern Rocky Mountains, upland parent material weathers in place into various fractions of sand, silt and clay that are transported downslope either onto the floodplain or into the stream channel (Platts et al 1987). Water, gravity, and wind are the processes that transport sediment from upland to alluvial positions for future incorporation into the floodplain (Platts et al 1987). In addition to these three processes, tree throw can be another important process for erosion, transport and production of sediment (Reid & Dunne 2003), and this process was common within the Dogrib Fire study area.

Table 8. Floodplain model variables and diagnostics

Model Form	Model variables	Coefficient	df	R^2	Sig.
$y= a + b_1x_1 + b_2x_2$	Constant	14.793	15	0.926	0.000
	Drainage area	0.027			
	Reach slope	-0.578			

Excluded variables: mean basin slope, 10m buffer slope

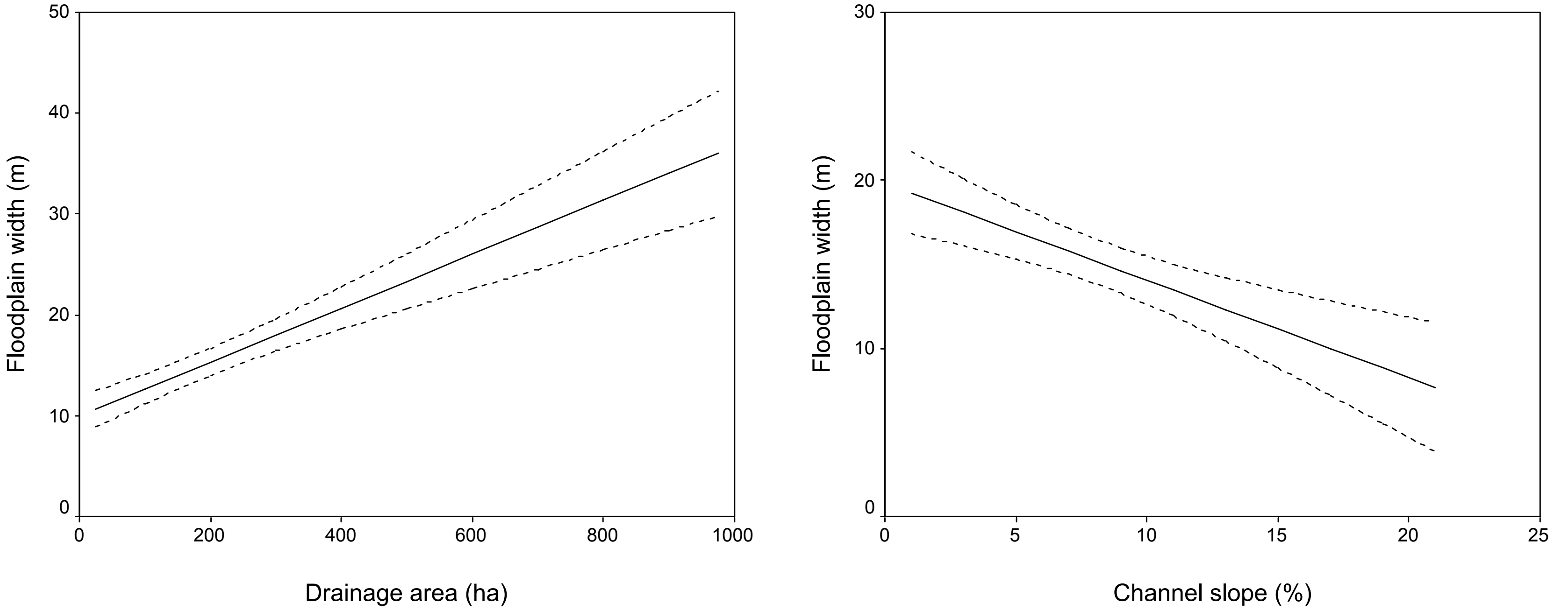


Figure 17. Predicted floodplain width (solid line) and 95% confidence intervals (dashed lines) for range of drainage area and reach slope values. Mean value of model training sample sites of 8.3% slope and 189ha used to generate graphs respectively.

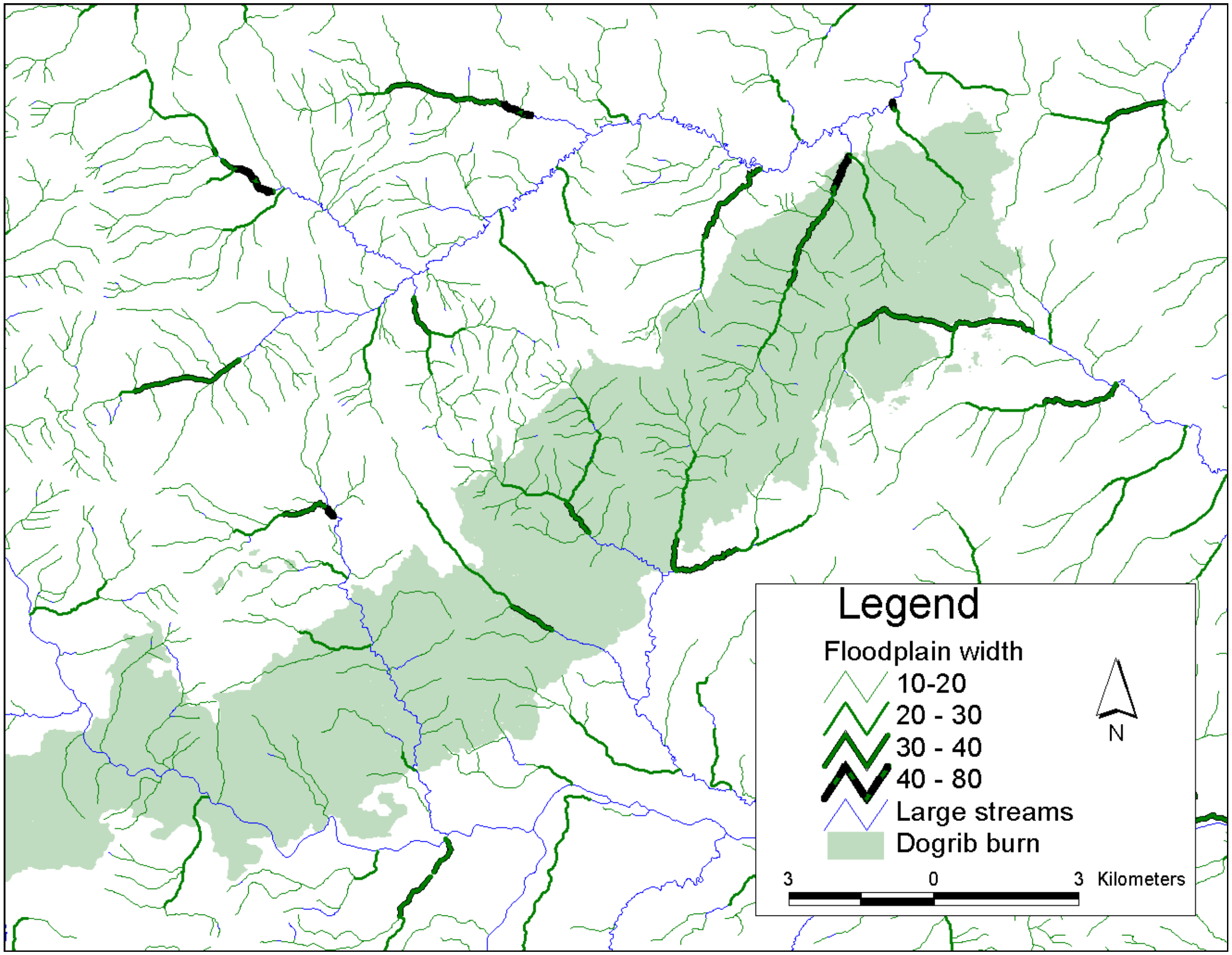


Figure 18. Map of predicted floodplain width for small streams (<1,000 ha drainage area) within the study area.

4.1.2.2 Bankfull width model

Using the power function, a stream width model was produced (Table 9). Based on this model, streams with a drainage area of less than 1,000 ha have predicted widths of less than 5 m and therefore would generally fall within the small permanent watercourse class (Figure 19).

Table 9. Bankfull width model and diagnostics

Model Form	Model variables	Coefficient	df	R^2	Sig.
$y= ax^b$	Constant	0.3800	14	0.479	0.003
	Drainage area	0.2834			

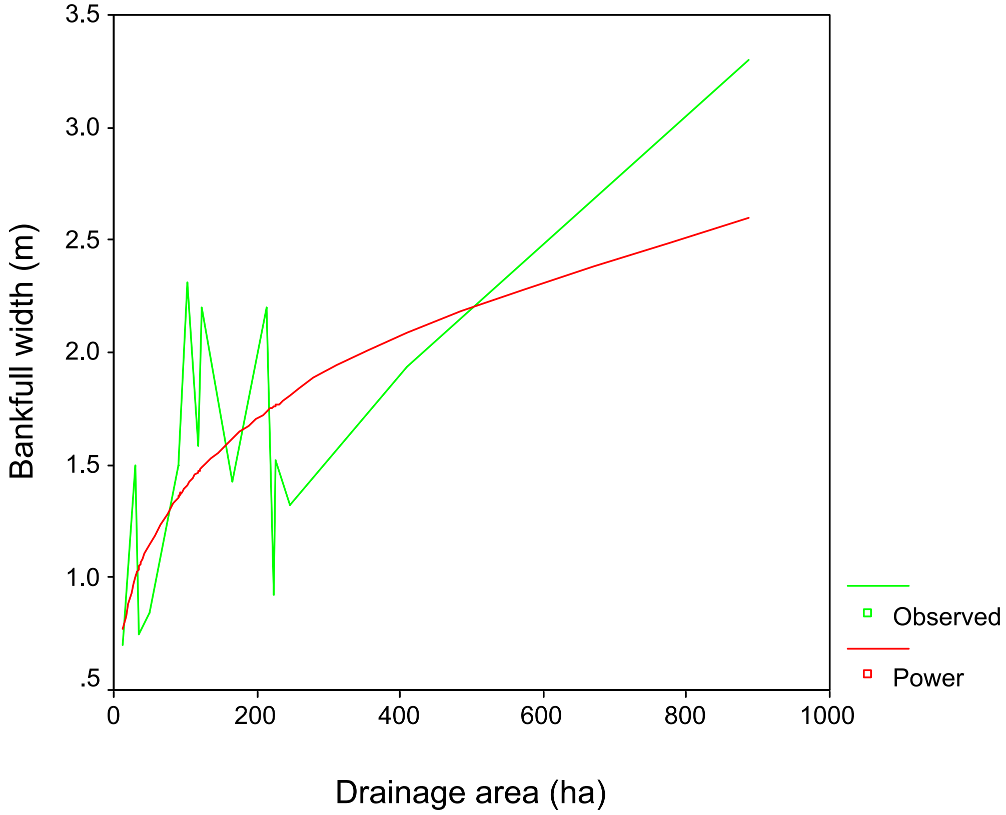


Figure 19. Observed and predicted bankfull widths by drainage area.

4.1.2.3 Bankfull depth model

Using the power function, a bankfull depth model was produced (Table 10 and Figure 20).

Table 10. Average bankfull depth model and diagnostics

Model Form	Model variables	Coefficient	df	R^2	Sig.
$y = ax^b$	Constant	0.1627	14	0.475	0.003
	Drainage area	0.1318			

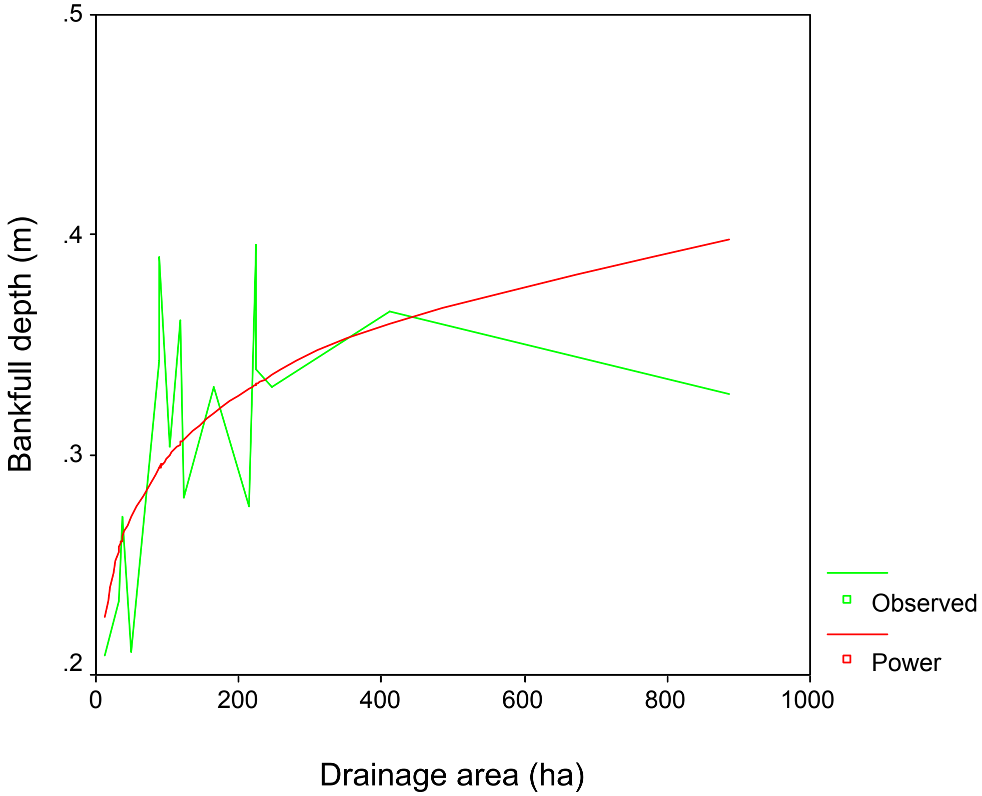


Figure 20. Observed and predicted bankfull depth verses drainage area.

4.1.2.4 Distribution of floodplain sediment

The importance of the interaction of stream size and slope for determining floodplain sediment storage became apparent when viewing a map of predicted relative floodplain sediment storage (Figure 21).

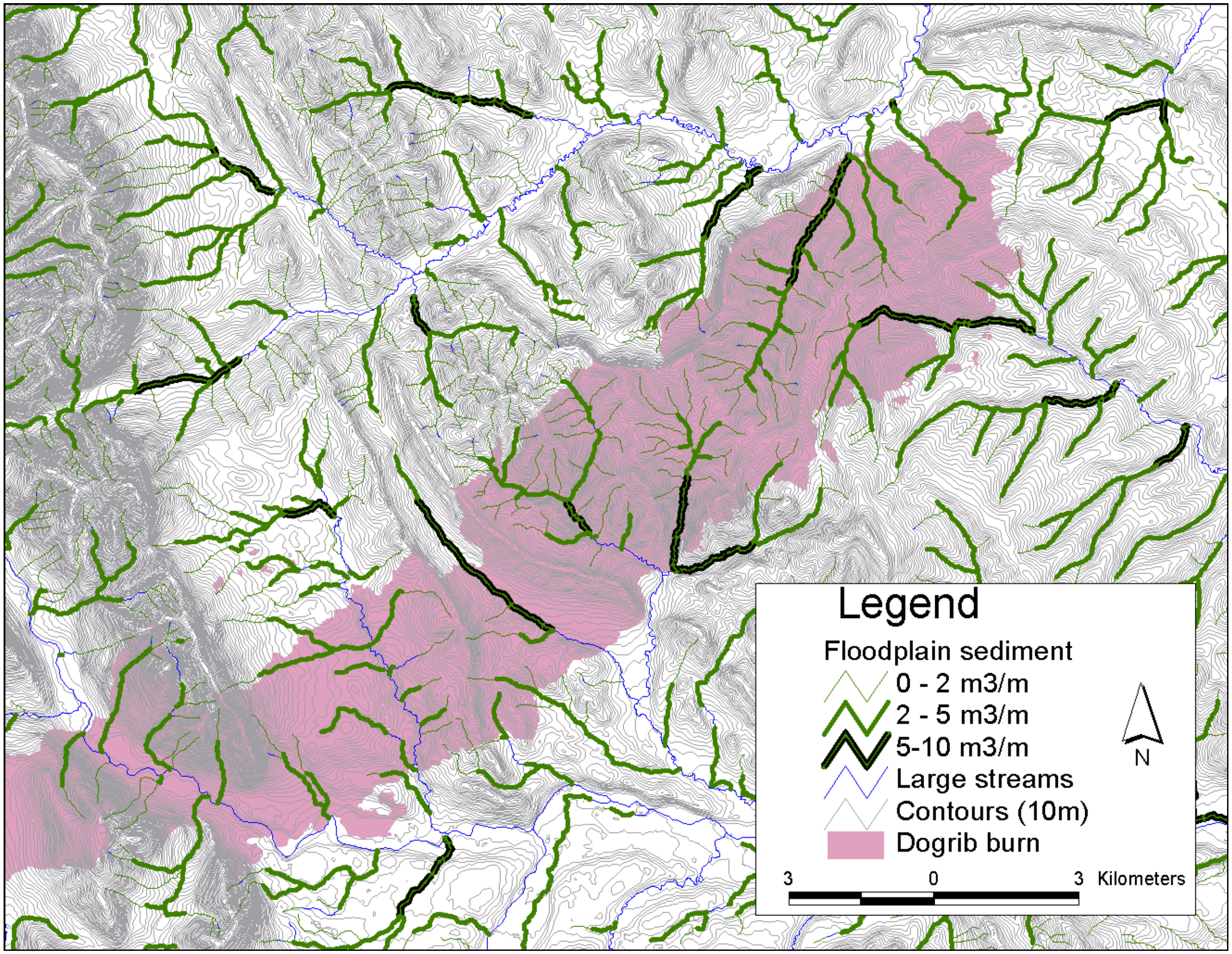


Figure 21. Relief map illustrating relative disturbance of floodplain sediments throughout study area.

4.1.3 Channel Bed Structure - Pool Spacing and Extent

The two pool parameters used to describe bed structure included pool spacing and pool extent. The measure of pool spacing selected for this analysis was the number of bankfull widths between pools (Montgomery et al., 1995). This measure was appropriate given the range of stream sizes within the study area. The measure of pool extent was percent of reach as pools determined as the total pool length over the reach length (Anonymous, 1996). The three reaches formed in colluvial material were excluded from this analysis. In addition, Reaches 8 and 24, with pool spacing of 22 and 51 bankfull widths between pools respectively, were identified as outliers and excluded from the analysis. While these two reaches had drainage areas of less than 1 km^2, five other reaches with a drainage area of less than 1 km^2 were included in the analysis. Candidate variables to predict relative pool spacing and percent pools included drainage area and reach slope. Using stepwise regression, only reach slope was significant for predicting both pool spacing and percent pools (Figure 22 and Figure 23).

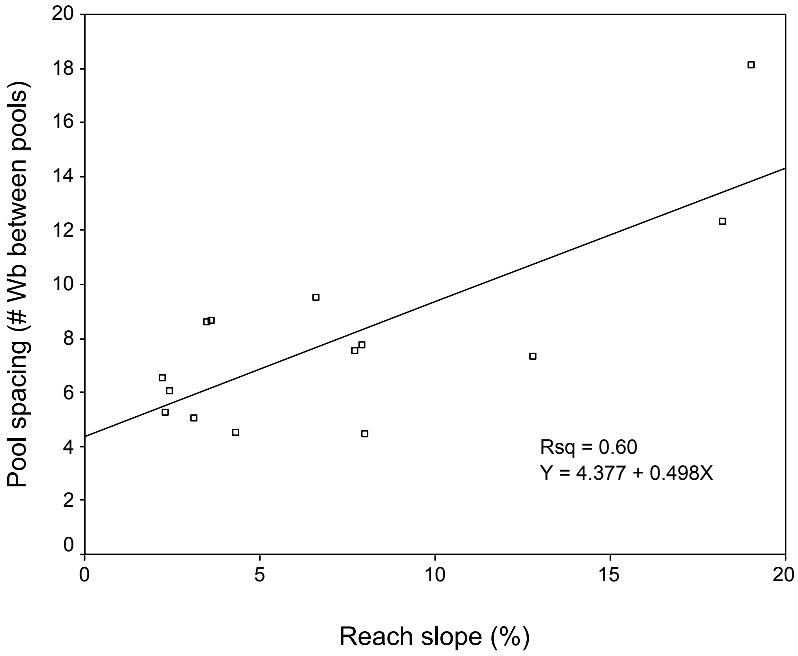


Figure 22. Model for predicting pool spacing (channel widths/pool) from reach slope (%) based on values from 14 reaches.

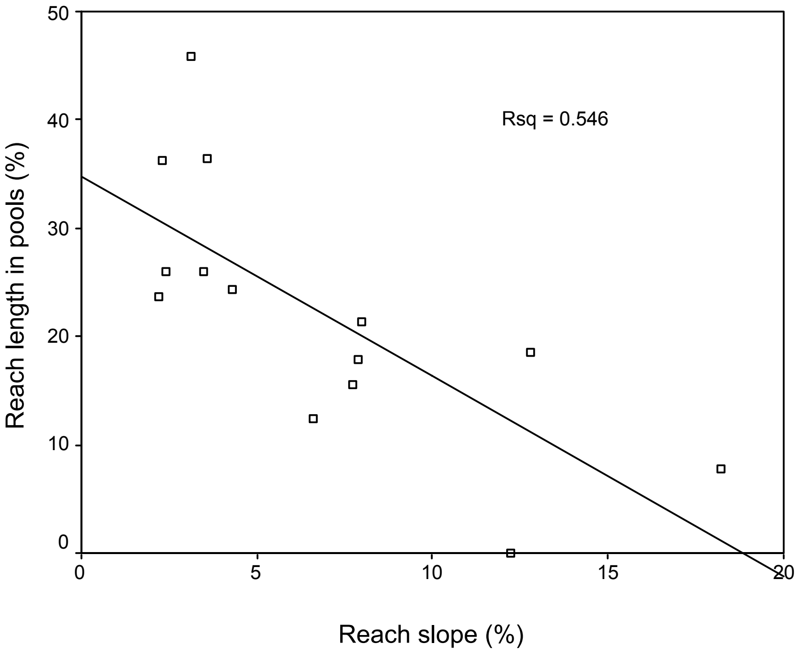


Figure 23. Model for predicting reach length in pools (%) from reach slope (%) based on values from 14 reaches.

As part of the field assessment, I identified the geomorphic factor contributing to the formation of each pool. The four candidate factors included fluvial processes, scouring around a bedrock feature, scouring around a live or dead root wad and LWD related. To address forest management considerations, I completed analyses to determine the role of wood (root wads and LWD) for pool formation. Two candidate variables to predict spacing between pools formed by wood included: drainage area and reach slope. Using stepwise regression, neither of these variables met the criteria for use in a model. On average, 65 percent of all pools were formed by wood (LWD and root wads).

4.1.4 Stream Bank Structure

Two channel features selected to quantify stream bank structure included width/depth ratio and the occurrence of root bridges.

4.1.4.1 Channel Width/Depth Ratio

Channel width/depth ratio was selected as an indicator of the relative importance of vegetation for maintaining channel structure. Channels that are narrow and deep (i.e. width/ratio less than 12) have steep banks that are held together by roots of the stream bank vegetation, while vegetation has less of an influence in maintaining structure for channels that are wide and shallow (i.e. width/depth ratio greater than 12) (Rosgen, 1994). In addition, when considering the susceptibility of channels to various types of disturbance, sediment deposition features including bars tend to form only in channels that have room for them (width/depth ratio of greater than 12) (Sullivan et al., 1987).

Candidate variables to predict the width/depth ratio included drainage area and reach slope. Using backward stepwise regression, both of these variables were retained in the model (Table 11 and Figure 24).

Table 11. Width/depth ratio model summary.

Model Summary	Model variables	Variable coefficient	Coefficient sig.
Model Form: $y= a + b_1x_1 + b_2x_2$	Constant	0.154	0.942
Model R^2: 0.692	log drainage area	6.579	0.000
Model Sig.: 0.000	log reach slope	5.877	0.002

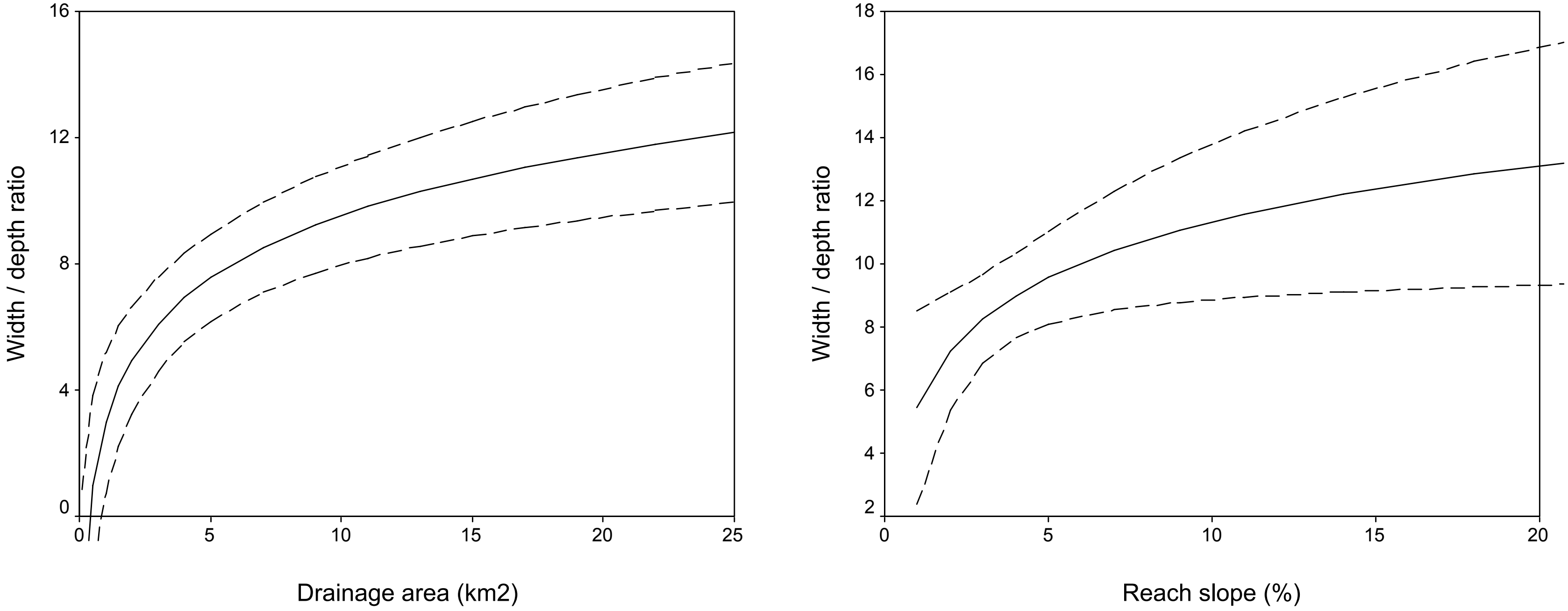


Figure 24. Predicted width/depth ratio (solid line) and 95% confidence intervals (dashed lines) for range of drainage area and reach slope values. A reach slope of 3% and a drainage area of 1.0 km^2 were used to generate graphs respectively.

4.1.4.2 Bank structures maintained by vegetation

During field assessments, a stream bank feature maintained by roots of large trees was observed at a number of the sample reaches. The feature resembled a stable bridge that supported vegetation on the upper surface and permitted continuous flow underneath. The typical entrance and exit to a root bridge resembled a stable undercut stream bank. The surface of most bridges blended with the adjacent floodplain with recent silt deposits integrated with moss and duff. The sound of flowing water could be heard under the longer root bridges and pooling of water at base flow discharge was not observed at the entrance. Based on these sounds and velocity observations, water seemed to pass beneath the bridge in a continuous tunnel. Root bridges have also been observed in other Upper Foothills streams in the Hinton area.

If a stream reach with root bridges was classified as an intermittent stream under the Operating Ground Rules, all trees in the adjacent riparian area could be harvested. If classified as a small permanent stream, a no-harvest buffer up to 30m in width would be required. The apparent role of tree roots in the formation and maintenance of root bridges and potential riparian management applications warranted further investigation into the occurrence of these features.

The purpose of this section was to attempt to develop a model to predict the presence/absence of root bridges based on terrain and vegetation. Root bridges occurred at three of the 20 sample reaches (Table 12).

Table 12. Summary of root bridges by reach.

Reach Number	Bankfull width (m)	Survey length (m)	Count of Bridges	Avg. bridge length (m)	Max. bridge length (m)	Reach length in root bridges (%)
2	1.3	200	2	6.4	8.0	6.4
22	0.9	200	2	2.8	3.5	2.8
27	0.8	100	8	1.2	2.0	9.5

Using logistic regression, I considered five variables from existing GIS data sources to predict the occurrence of root bridges (Table 13). Of these five, I selected three non-correlated variables (Table 14). Preference between two correlated variables was based on strength of the relationship with root bridge occurrence as determined from graphical analysis. Based on backward stepwise elimination with the likelihood-ratio criterion, all three of these variables were retained in the final model (Table 16). A review of the likelihood-ratio and other model evaluation statistics from the final model and other models representing all possible combination of variables indicates that there was a strong interaction between all three variables in the final model (Table 16). Probability of root bridge occurrence increased as basin relief and drainage area decreased (Figure 25) and thresholds seemed apparent in both variables. When drainage area and basin slope were held constant below these thresholds, root bridges were predicted only in complete absence of a lodgepole pine component in the adjacent mapped forest stand (Figure 25). Based on this model, a map was developed to illustrate the location of stream reaches with high probability of root bridge occurrence (Figure 26). Detailed field studies, including comparing soil profiles between bridges and adjacent forest may further improve the understanding of the formation and duration of root bridges.

Table 13. Candidate variables for root bridge occurrence.

Variable name	Data source	Description	Relevance
1. Pine cover	Alberta vegetation inventory.	Proportion of overstory canopy in lodgepole pine coded to 0-10 representing nearest 10%.	Forms leading tree species in stands on ecosites with subxeric – subhygric moisture regime. Less likely to form root bridges due to deep rooting. Likelihood of bridges should decrease as pine cover increases.
2. Spruce cover	Alberta vegetation inventory.	Proportion of overstory canopy in white spruce coded to 0-10 representing nearest 10%.	Forms leading tree species in stands on subhygric – hydric sites. More likely to from root bridges due to shallow rooting. Likelihood of bridges should increase as spruce cover increases.
3. Drainage area	Reach and watershed classification for study area derived from DEM and provincial streams layer.	Size of upstream drainage area (ha).	Likelihood of bridges should decrease as drainage area increase (stream size).
4. Basin slope	Same as above	Average slope of all 30m x 30m grid cells within basin.	Steeper basins should have higher surface erosion rates and sediment loads. Likelihood of bridges should decrease as basin slope increases.
5. Reach slope	Same as above	Slope of reach that contains sample stream section.	Steeper reaches have higher erosion potential. Likelihood of bridges should decrease as reach slope increases.

Table 14. Correlation matrix.

	Pine cover	Spruce cover	Drainage area	Basin slope	Reach slope
Pine cover	1.00	-0.91**	-0.24	-0.11	0.58**
Spruce cover	-0.91**	1.00	0.27	0.22	-0.51*
Drainage area	-0.24	0.27	1.00	-0.51*	-0.44
Basin slope	-0.11	0.22	-0.33	1.00	0.24
Reach slope	0.58**	-0.51*	-0.44	0.24	1.00

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

Variables in bold selected for model training.

Table 15. Summary of model selected by backward stepwise selection using likelihood-ratio (LR) test and all possible combinations of variables.

Model	-2 LL	Model LR χ^2	Sig.	dev. (%)	PCC (1)	PCC (0)	PCC
Pine cover	12.892	4.0	0.05	0.32	0	100	85
Drainage area	16.071	0.8	0.36	0.07	0	100	85
Basin slope	16.109	0.8	0.37	0.07	0	100	85
Pine cover + Drainage area	11.691	5.2	0.07	0.40	0	100	85
Pine cover + Basin slope	11.237	5.7	0.06	0.43	0	94	80
Drainage area + Basin slope	14.461	2.4	0.29	0.20	0	94	80
Pine cover + Drainage area + Basin slope	0	16.9	0.001	1.00	100	100	100

Table 16. Logistic regression parameter estimates of selected model.

Parameter	Estimate
Intercept	546.6248
Pine cover	-194.429
Drainage area	-0.36954
Basin slope	-20.7663

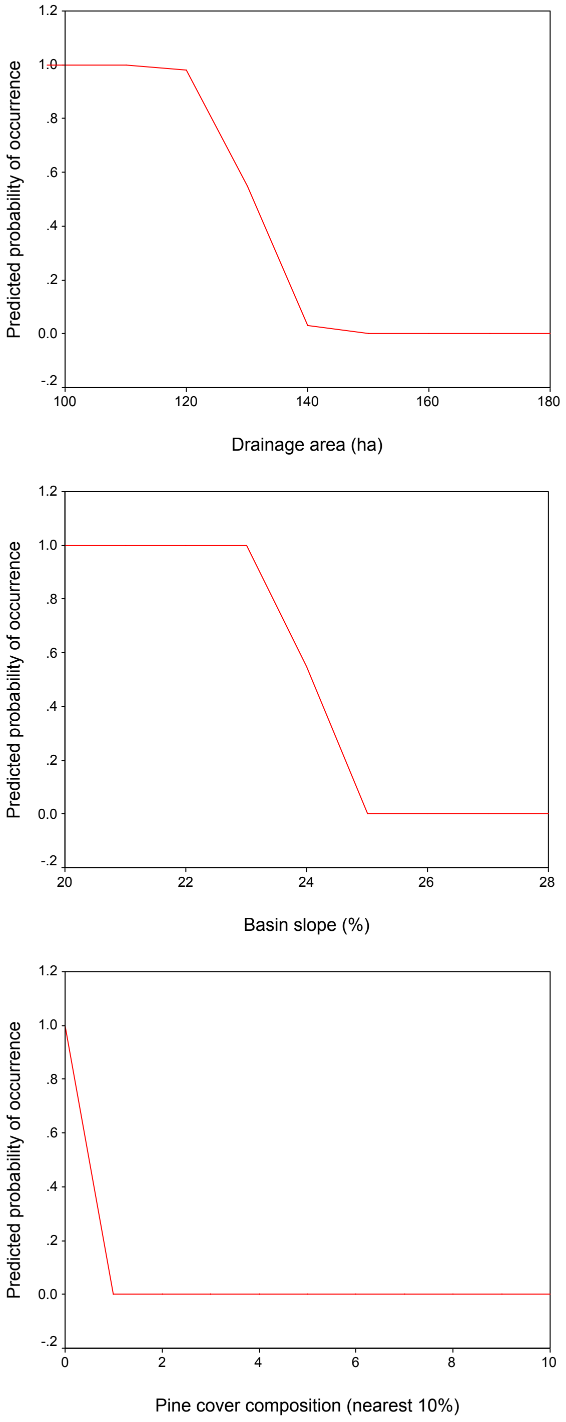


Figure 25. Predicted probability of occurrence for each of final model variables. The range of the X axis represents the transition zone of each variable. For drainage area, basin slope was standardized to the mean value of 24% and pine cover was standardized to 0. For basin slope, the drainage area was standardized to 130 ha or slightly less than the median value of 140 ha and pine cover was standardized to 0. For pine cover, drainage area was standardized to 120 ha and basin slope was standardized to 20%.

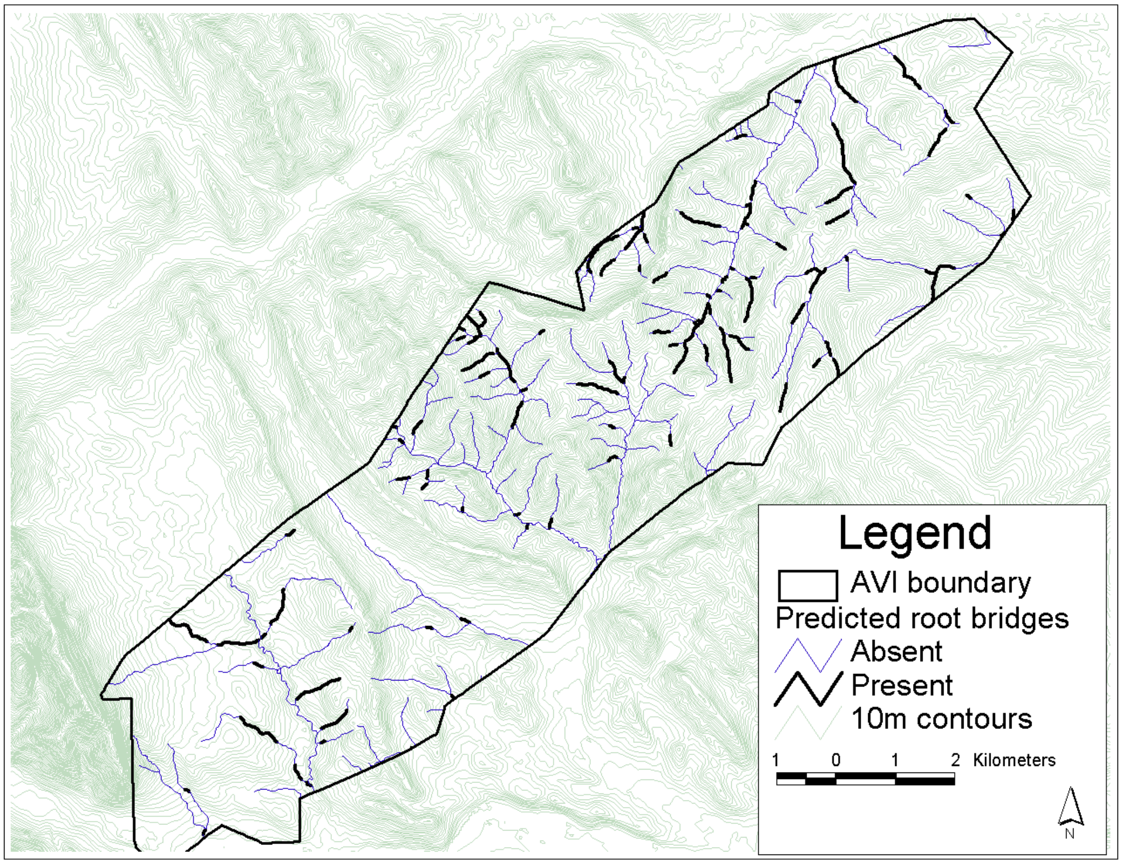


Figure 26. Map of predicted occurrence of root bridges within study area streams.

4.1.5 Channel Structure Conclusion

Three types of channels emerged from this analysis. Low gradient headwater channels were characterized by smaller than expected relative channel size, well developed floodplains and low width/depth ratios (Figure 27). High gradient headwater channels had smaller than expected relative channel size, poorly developed floodplains and high width/depth ratios (Figure 27). Small alluvial channels displayed appropriate relative channel size based on stream slope, well developed floodplains and higher width/depth ratios (Figure 27). Pools were a common feature in all channel types but were less frequent and smaller in steeper streams (Figure 28). In all stream types, wood was an important pool-forming element for an average of two out of three pools (Figure 28). These three channel types correspond to the three geomorphic forms of riverine valleys described for the Northern Rocky Mountain Physiographic province, which include glaciated headwaters, narrow V-canyons and broad valleys (Platts et al., 1987).

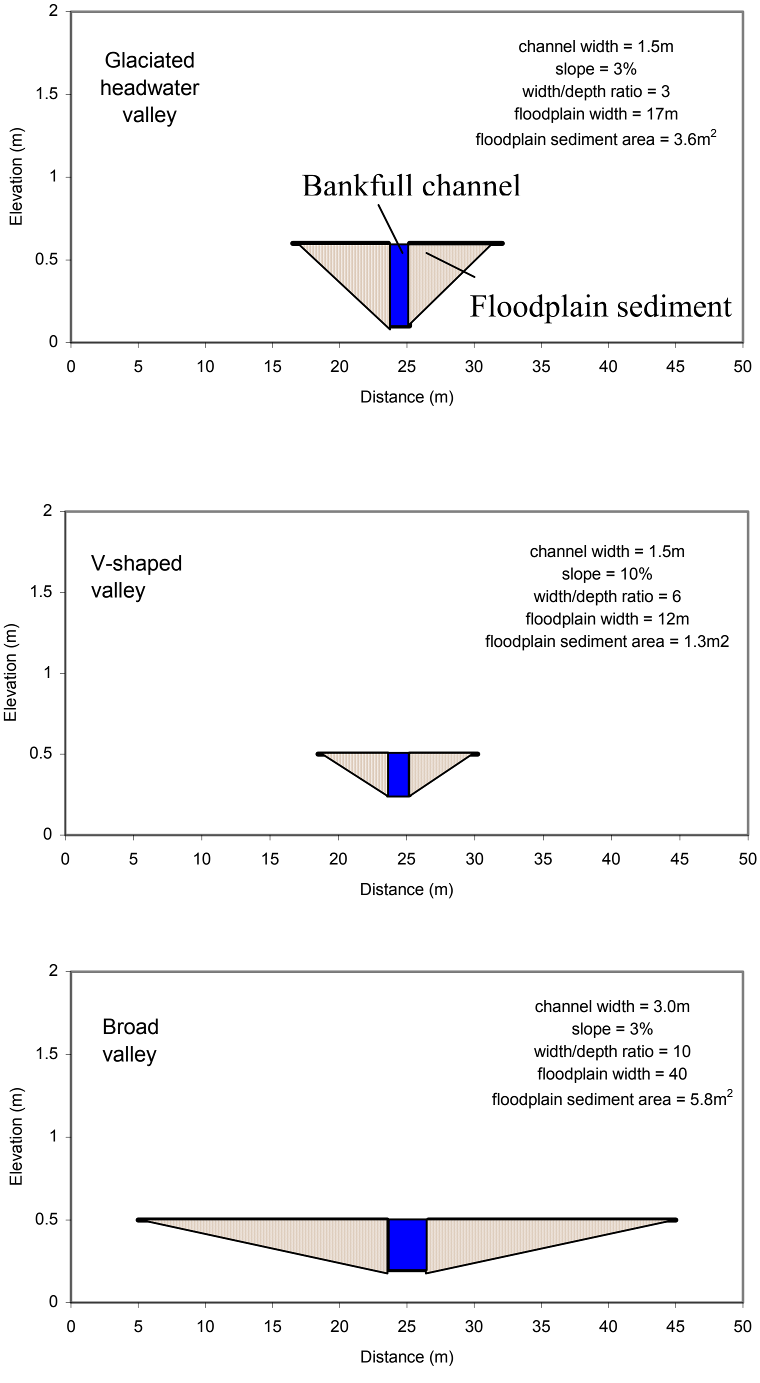


Figure 27. Floodplain and channel cross-sections for streams within the three valley types; glaciated headwater valley, V-shaped valley and broad valley.

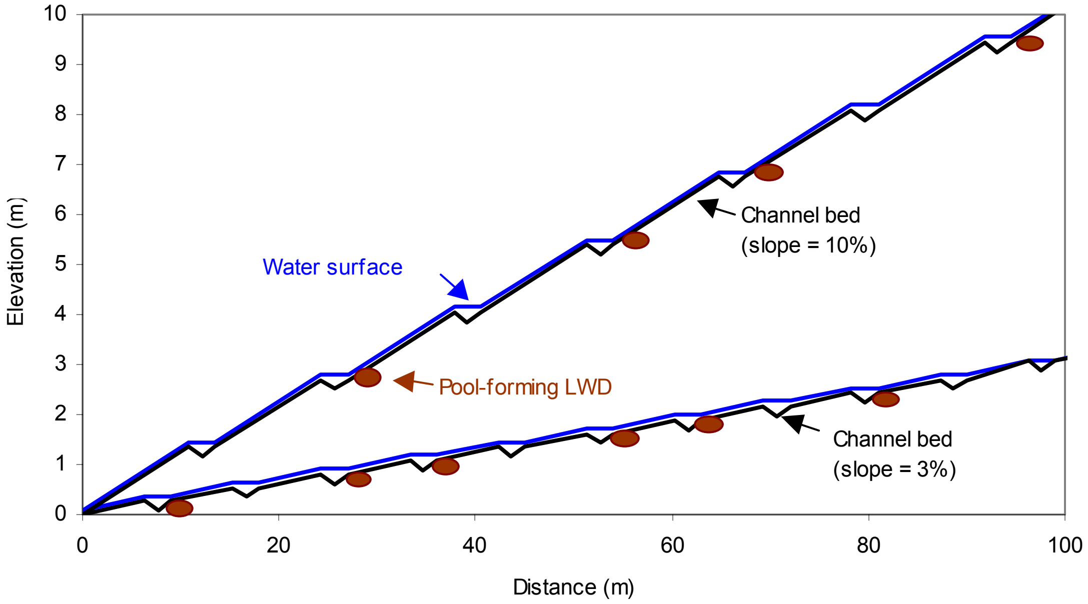


Figure 28. Longitudinal profiles of two headwater streams (3% slope and 10% slope) with pool extent, pool frequency and LWD function.

4.2 Channel Stability Assessment

Local channel disturbances consistent with Anonymous (1996) were observed in all channels. No evidence of shallow episodic landslides was observed within sample reaches or within any other streams that were viewed while traveling within or flying over the study area. Within the headwater channels of the study area, characterized by sediment accumulation rather than downstream transport, there was no evidence of shallow episodic landslides. However, there was some evidence of headcutting. These findings indicate that dominant erosional processes within the study area resemble those previously described for the Northern Rocky Mountain physiographic region (Platts et al) and do not resemble those of the coast (Reid & Dunn).

Using univariate analysis of variance, I detected significant between-subject effects between channel types for three disturbance descriptors including total disturbance extent, pool extent and bed scour extent (Figure 29). In comparison to small alluvial channels, headwater channels had greater total disturbance extent and bed scour extent and lower pool extent (Figure 29). For parent material, significant between-subject effects were present only for bed scour extent (Figure 30). Of the four parent materials, moraine had a much higher estimated marginal mean extent of bed scour. When considering the interaction between parent material and channel type, there was evidence for significant differences for two channel disturbance descriptors including bars extent and bed scour extent (Figure 31). Small alluvial channels in colluvial material had the highest estimated marginal mean for extent of bars and headwater channels in moraine parent material had the highest estimated marginal mean for extent of bed scour (Figure 31).

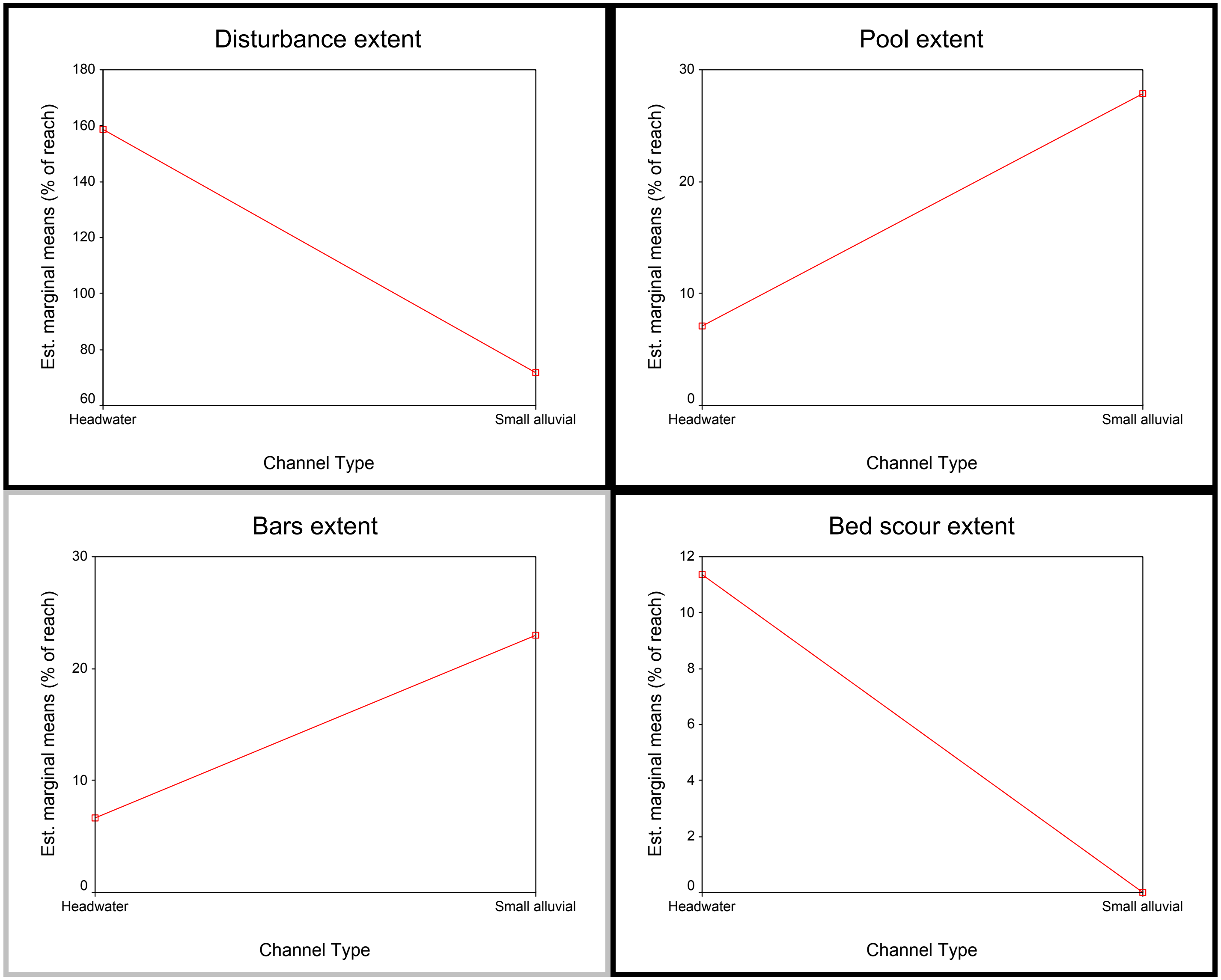


Figure 29. Profile plots of marginal means of four channel disturbances (total channel disturbance extent, pool extent, bars extent and bed scour extent) for channel type. Black outline indicates significant between-subject effects from Univariate analysis of variance.

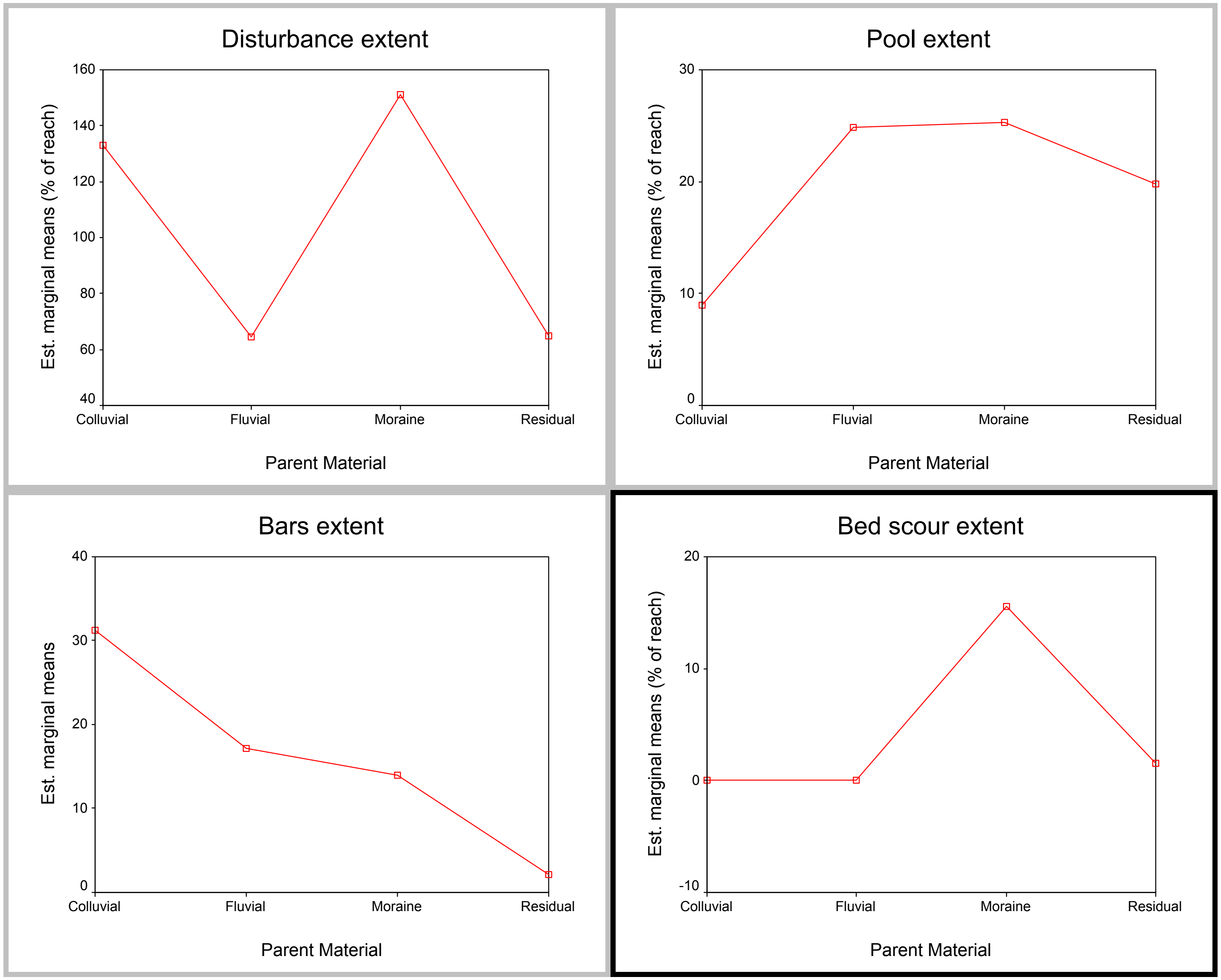


Figure 30. Profile plots of marginal means of four channel disturbances (total channel disturbance extent, pool extent, bars extent and bed scour extent) for parent material. Black outline indicates significant between-subject effects from Univariate analysis of variance.

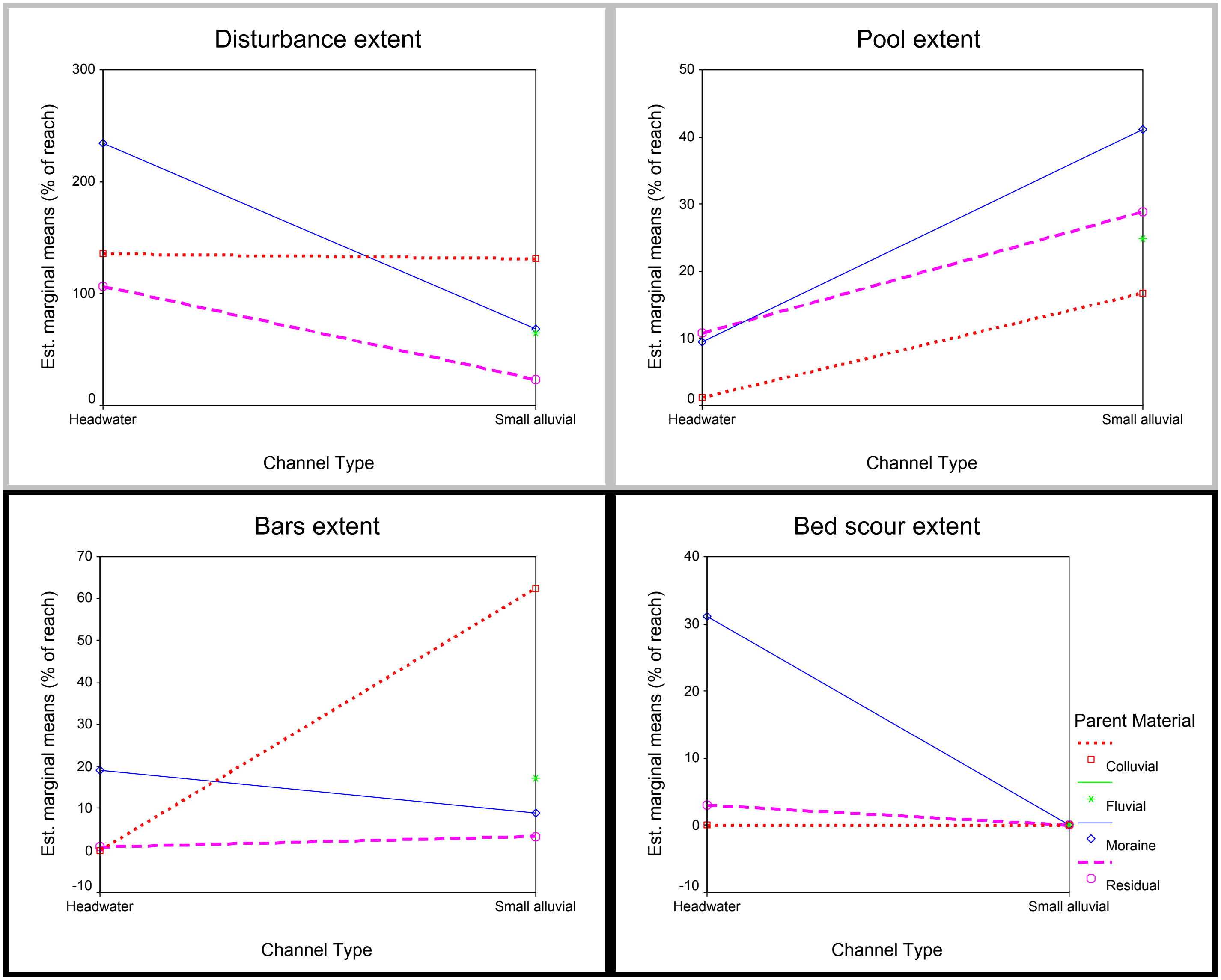


Figure 31. Profile plots of marginal means of four channel disturbances (total channel disturbance extent, pool extent, bars extent and bed scour extent) for interaction of channel type and parent material. Black outline indicates significant between-subject effects from Univariate analysis of variance.

No significant between-subject effects were detected for the remaining four disturbances including eroding banks, multiple channels, mid-channel bars and sediment wedges (Figure 32). Without any pre-fire information, I discerned post-fire disturbance based on substrate and vegetation characteristics that develop over time, including establishment of herbaceous and woody vegetation on fluvial deposits and staining of substrate from algae and macrophytes. Considering these factors, obvious post-fire channel disturbances were largely limited to bank erosion, deposition of fine-textured sediment wedges and bed scour.

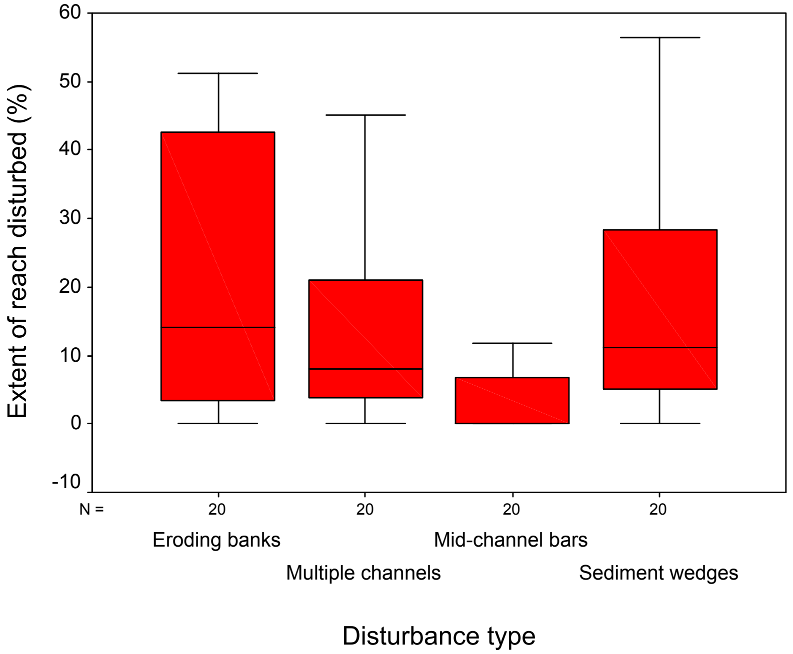


Figure 32. Extent of disturbance by type for four variables with no significant between-subject effects from Univariate analysis of variance.

5. Conclusions

Prior to this study, little was known about channel structure and disturbances within small Foothills streams. We identified three categories of streams based on valley type (Figure 33) and these corresponded to those previously described by (Platts et al., 1987). Each stream category displayed different structural characteristics and disturbance patterns (Table 17). These different characteristics translated into a variety of forest management considerations based on the functional role of live and dead vegetation (Table 18).

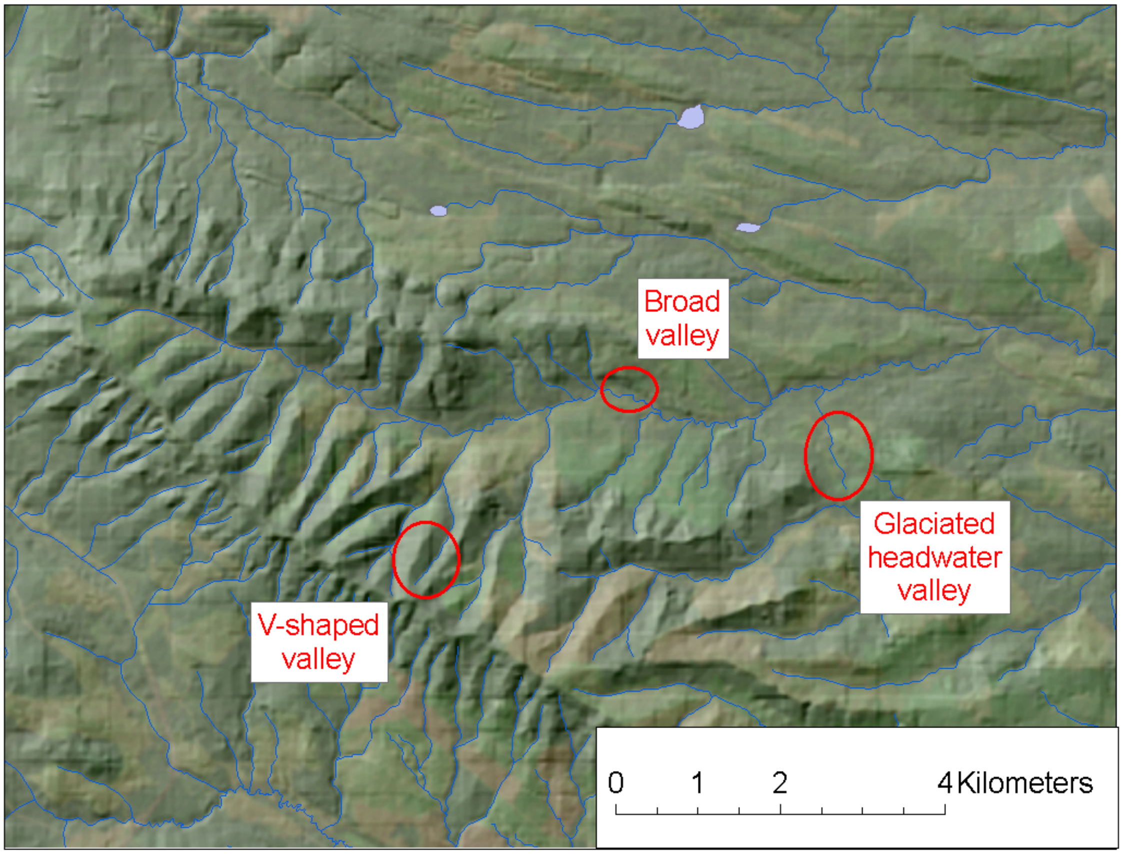


Figure 33. Relief map showing landscape location of three valley types adopted from Platts et al 1987.

Table 17. Summary of channel structure and disturbance processes for the streams within the three main valley types.

Upper Foothills valley type	Channel structure element						Dominant disturbance processes
	Substrate size	Floodplain development	Channel bed		Channel banks		
			Pool spacing (channel widths)	Pool extent (%)	Width/ depth ratio	Root bridges	
V-shaped headwater valley	Smaller than expected based on channel slope.	Low	8-12	0-20	4-8	No	• Bed scour • Bank erosion • Headcutting
Glaciated headwater valley	Smaller than expected based on channel slope.	High	4-8	10-40	2-6	Yes	• Bank erosion • New channels
Broad valley	Equal to expected size based on slope.	High	4-8	10-40	8-12	No	• Bank erosion • Sediment deposition • New channels

Table 18. Management interpretations for the role of live and dead vegetation in maintaining channel structure for streams within three valley types.

Valley Type	Influence of vegetation for moderating bank erosion (adapted from Rosgen and Silvey)	Importance of LWD for creating bed structure (adapted from Anon 1996)	Ratio of floodplain sediment / streambed sediment
V-shaped headwater valley	Medium	Medium	Low
Glaciated headwater valley	Very high	High	Very high
Broad valley	High	Very high	High

This knowledge was summarized into a qualitative sediment budget for streams in each of the three valley types (Figure 34, Figure 35 and Figure 36).

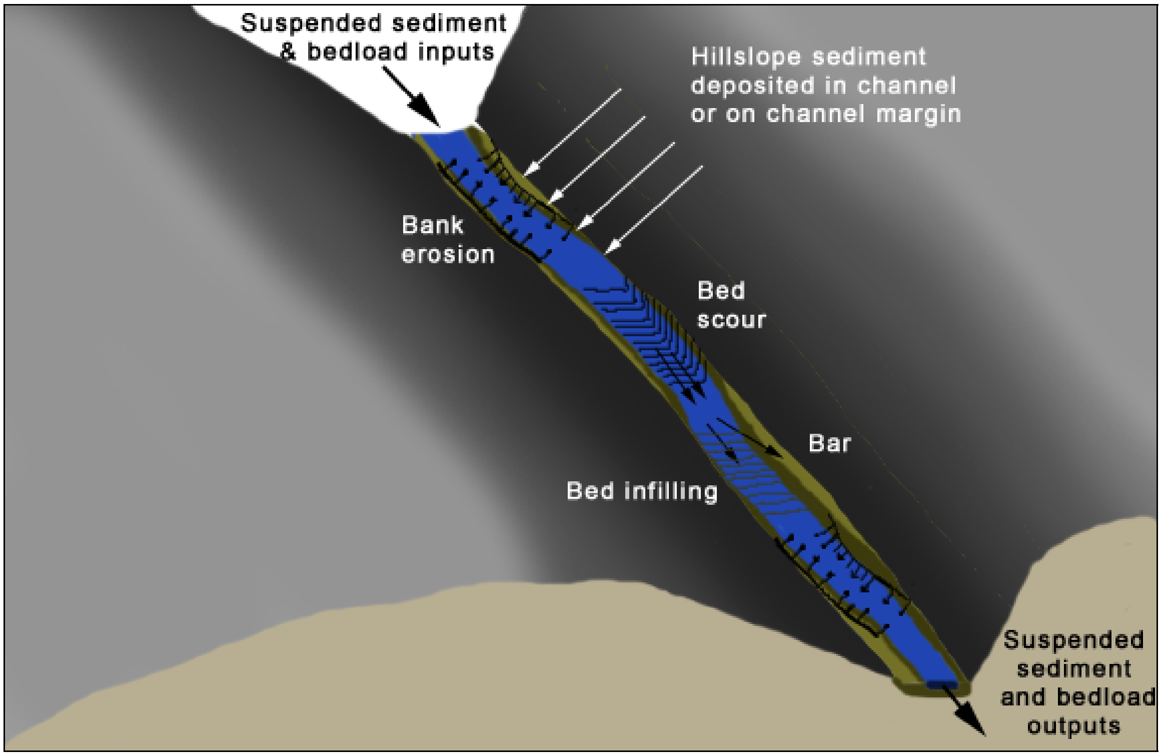


Figure 34. Components of a sediment budget for a stream within a V-shaped valley with exchanges between hillslopes, channel and narrow floodplain. Adapted from (Reid and Dunne, 2003).

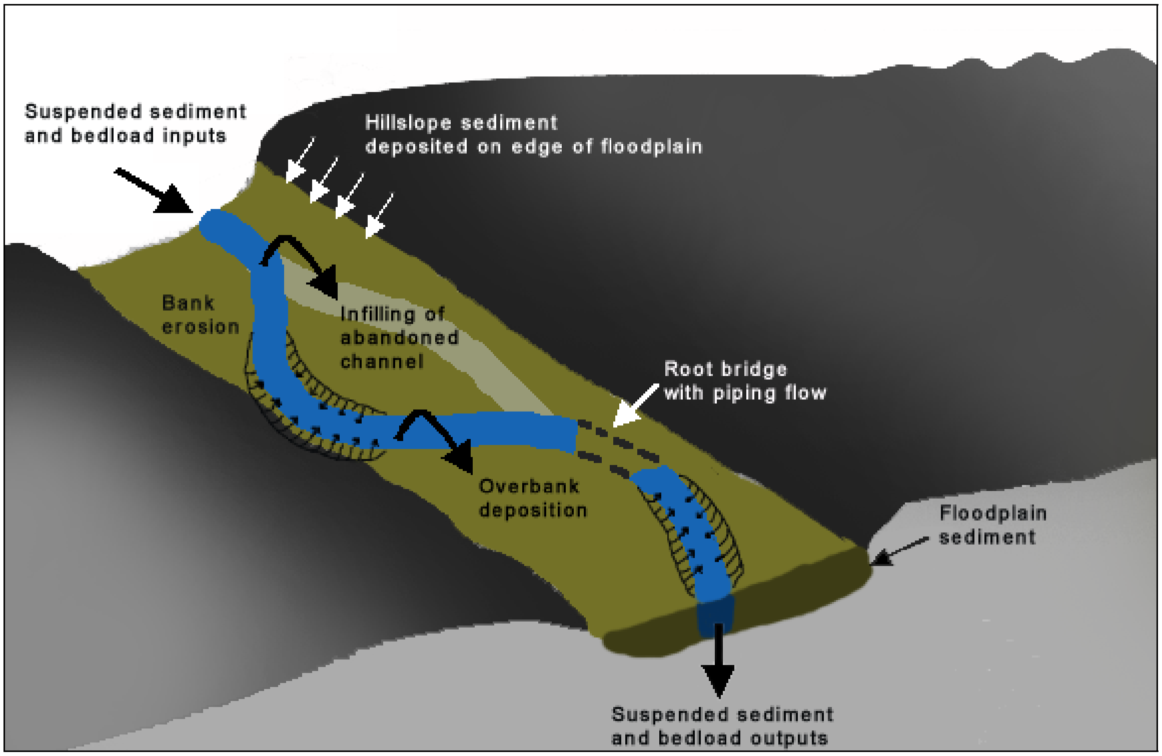


Figure 35. Components of a sediment budget for a stream within a glaciated headwater valley with exchanges between hillslopes, channel and floodplain. Adapted from (Reid and Dunne, 2003).

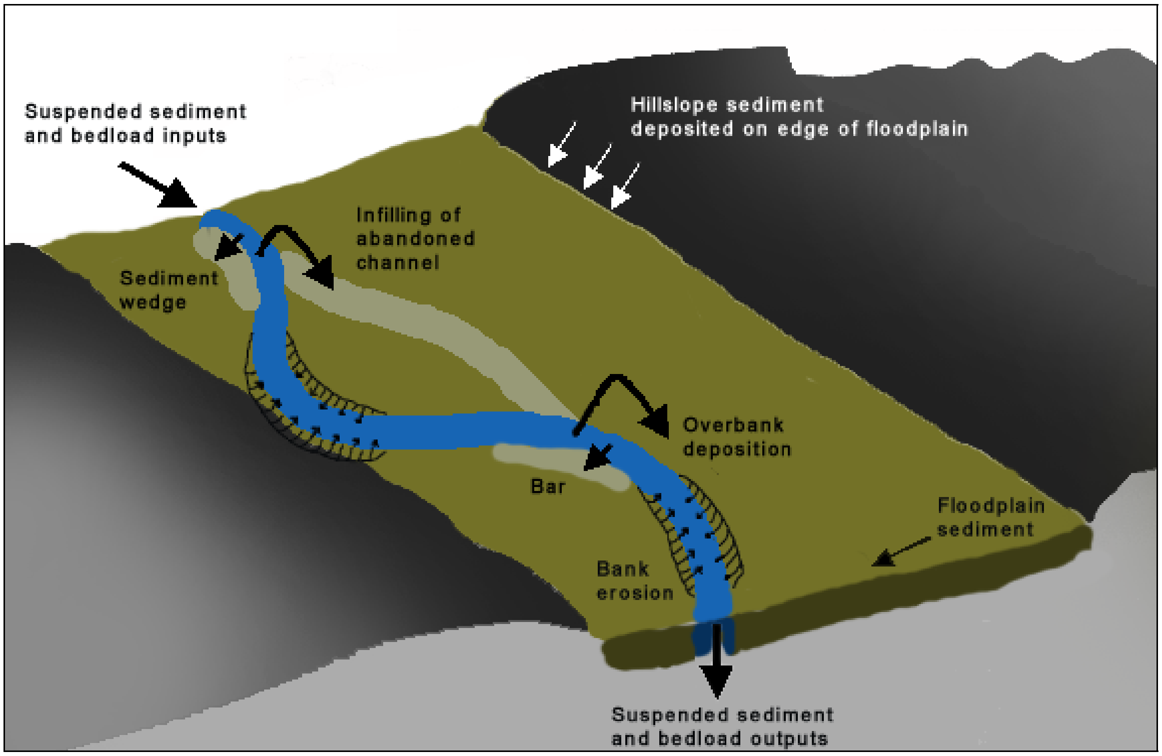


Figure 36. Components of a sediment budget for a stream within a broad valley with exchanges between hillslopes, channel and floodplain. Adapted from (Reid and Dunne, 2003).

Chapter 4. Large Woody Debris Input Sources, Storage, Function And Distribution

1. Introduction

The goal of this chapter was to describe four aspects of large woody debris (LWD) within the small streams of the Dogrib Fire portion of the Sundre Forest Products FMA. The four aspects included LWD quantities, input processes, functions and linkages to forest management through Alberta Vegetation Inventory data for the study area.

2. Methods

The study had a field component coupled with an air photo interpretation component. We selected this approach so analysis of data from labor-intensive field surveys at a small number of sites could be supplemented with air photo interpreted data from a larger number of sites.

Aerial photography (70mm diapositive film) was captured in the fall of 2002 at 20 reaches. To achieve a ground coverage 90m in width, target photo scale was set at 1:1,800 (see Appendix 5 for methods). The number of photo pairs for each reach ranged between 10 and 33 while actual photo coverage distances ranged between 170 and 725m (Table 19). While photo overlap between successive pairs was higher than anticipated (Table 19), cost of film for the project was incidental in comparison to helicopter and support personnel.

Table 19. Summary of air photo coverage for Dogrib stream reaches.

Reach number	# of photo pairs	Coverage length (m)	Average distance between photo centers (m)
1	33	725	22
2	23	500	22
3	29	300	10
4	10	170	17
5	17	400	24
6	33	590	18
7	15	260	17
8	19	360	19
11	19	460	24
12	19	300	16
13	21	440	21
15	14	375	27
17	33	705	21
18	16	380	24
21	15	270	18
22	25	475	19
24	23	450	20
25	21	450	21
26	16	365	23
Average	21	420	20

Due to road crossings and timber salvage, not all photo pairs met the criteria for an undisturbed stand (Chapter 2 Section 3). Therefore to identify individual photos for field inventory, we selected the first photo pair in the flight line for each reach that met criteria for an undisturbed stand (see Appendix 6 with scanned candidate images from 18 reaches). For LWD field inventory sites, we randomly selected a subset of 8 reaches representing the various stream size class and slope class combinations. Field methods were based on existing procedures (Schuett-Hames et al., 1999) and are detailed in Appendix 7). For air photo interpretation, we developed a database to store all interpreted measures. The database had two main tables, the first to store information about each individual photo pair and the second to store information on each piece of LWD (Appendix 8). An experienced photo interpreter completed the measurements using an instrument called a stereo comparator. The device provides a 10 times magnification and at 1:1,800 scale has an effective resolution for ground distances of 0.1m. Interpretation methods are described in Appendix 8.

3. Results and Discussion

3.1. In-Channel LWD Volume

In-channel LWD volumes from field surveys at eight locations are summarized in Table 20. The volumes are presented in two formats: volume per surface area of channel and volume per reach length standardized by the average cross-sectional area. The first format is intended for forest managers who also evaluate standing timber volume in m^3/ha. The second format is intended to promote a comparison with a similar LWD study in British Columbia (Bird, 2002) and therefore uses the standard BC measure.

Table 20. Field measures of stream channel and in-channel LWD from sections of channel represented on individual air photos.

Reach ID	Photo Number	Channel Length	W_b (m)	d (m)	LWD spacing (#W_b/piece)	In-channel LWD volume (m^3/ha)	In-channel LWD volume (m^2/m^2)
1	14	94.6	1.43	0.23	1.4	302.7	0.129197
3	27	119.0	5.58	0.19	0.2	150.2	0.078230
5	11	125.5	2.20	0.22	0.9	371.4	0.168824
6	33	107.3	5.17	0.33	1.6	14.5	0.004444
7	6	96.8	2.31	0.36	1.2	142.8	0.039515
11	12	51.0	1.50	0.14	0.7	910.0	0.640873
12	2	149.0	1.94	0.18	1.2	378.0	0.205442
15	5	115.3	4.25	0.43	2.1	36.1	0.008490

From a review of percent relative bias from various air photo interpreted measures (Table 21), I determined that the best model for predicting field- measured in-channel LWD volumes from air photo interpreted measures would be developed using LWD length, bankfull width and stream length. Due to the high measures of relative bias, piece diameter and number of pieces were not candidates for modelling actual in-channel LWD volumes. The high bias for these two variables may be attributed to a number of factors. The photo scale and interpretation equipment resulted in an effective photo interpretation resolution of approximately 0.1 m, which is large relative to the average LWD diameter of near 0.2 m. Given the time of the year, shadows were also a factor when measuring diameter. Smaller pieces of wood that were well integrated into the streambed or hidden under streambanks or ice were also not readily apparent to the interpreter. These trends in bias suggest that while smaller wood represents a large number of the pieces, whole trees and larger pieces of wood that were readily apparent to the interpreter, represent most of the LWD length and volume.

Table 21. Percent relative bias of air photo interpretive measures of channel and in-channel LWD.

Reach ID	Photo Number	Percent Relative Bias (%)				
		W_b	Channel Length	# Pieces	Total LWD Length	Total LWD Volume
1	14	-43.6	-9.1	-42.6	22.1	-63.2
3	27	-43.1	-5.9	-67.7	-36.3	-70.9
5	11	-27.6	-21.1	-59.4	-38.7	-81.2
6	33	-12.1	-13.3	-7.7	49.8	123.0
7	6	-34.4	-9.1	-66.7	-25.5	-75.7
11	12	1.5	-2.0	-48.9	-23.9	-55.5
12	2	-18.8	-17.4	-70.3	-60.4	-86.2
15	5	-11.1	-11.5	15.4	-8.5	-55.8
Mean		-23.6	-11.2	-43.5	-15.2	-45.7
SD		16.3	6.1	31.3	35.6	69.1

A model of in-channel LWD volume from air-photo interpreted in-channel LWD length (standardized for channel area) was developed (Figure 37). A single outlier was omitted during model development. The intermittent nature of the stream flow, multiple channels due to recent channel disturbance and ice at this site (Reach 1, Photo 14) likely contributed to the occurrence of the outlier, and these factors were not typical of most of the streams within the study area. The model was used to predict in-channel volumes at an additional 11 sites (Table 22). The in-channel LWD volume per channel area was converted to cross-section area by dividing the model output by field measures of the average bankfull depth from each of the 11 reaches.

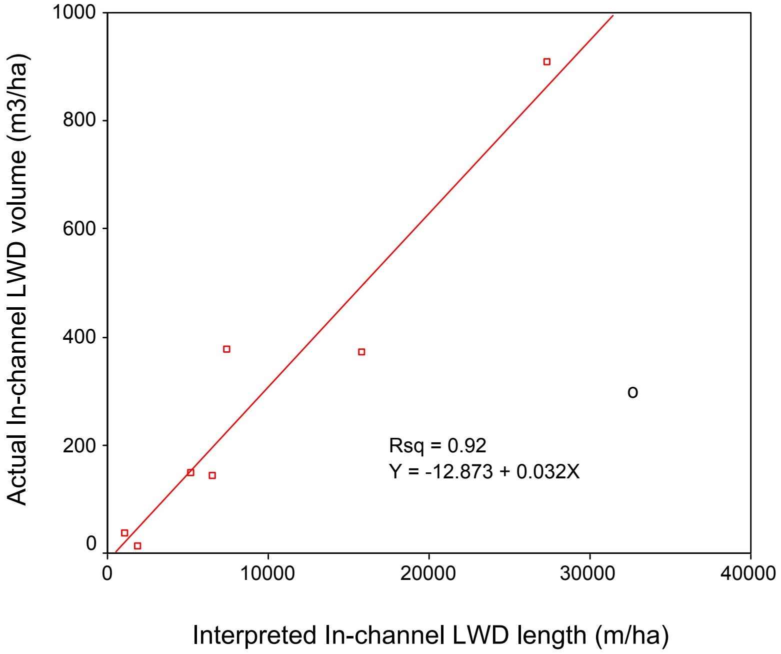


Figure 37. Model for predicting in-channel LWD volume (m^3/ha) from photo-interpreted in-channel LWD length (m/ha) from seven locations. Single outlier omitted from analysis indicated by open circle.

Table 22. Predicted in-channel LWD volume from air-photo interpreted data for 11 locations.

Reach ID	Photo Number	W_b (m)	d (m)	In-channel LWD volume (m^3/ha)	In-channel LWD volume (m^2/m^2)
2	1	1.52	0.13	101.8	0.079849
4	1	1.112	0.10	26.3	0.025716
8	4	0.898	0.10	169.3	0.175160
8	19	0.35	0.10	151.1	0.156320
13	2	2.32	0.12	19.1	0.015949
17	7	0.528	0.21	5.0	0.002456
18	8	1.1	0.18	77.9	0.043280
21	10	1.452	0.27	34.7	0.012972
22	15	1.262	0.16	45.7	0.028576
25	14	1.216	0.16	191.0	0.116660
26	11	3.548	0.15	-4.2	-0.002909

While it was important to compare our findings to other similar studies, none had been completed within Alberta and one had been completed in BC. A common ecological land classification was developed to link components of the BC biogeoclimatic ecosystem classification (BEC) and the Alberta natural subregion classification (Gordon et al., 1997). This study identified that the Upper Foothills (UF) natural subregion was comparable to the Sub-Boreal Spruce (SBS) BEC. Therefore, the LWD volumes from this location in the UF natural subregion were compared with those published for the SBS BEC (Bird, 2002). There was no statistical evidence to indicate that the two mean volumes from the two study areas were different at P=0.05 (Figure 38 and Table 23).

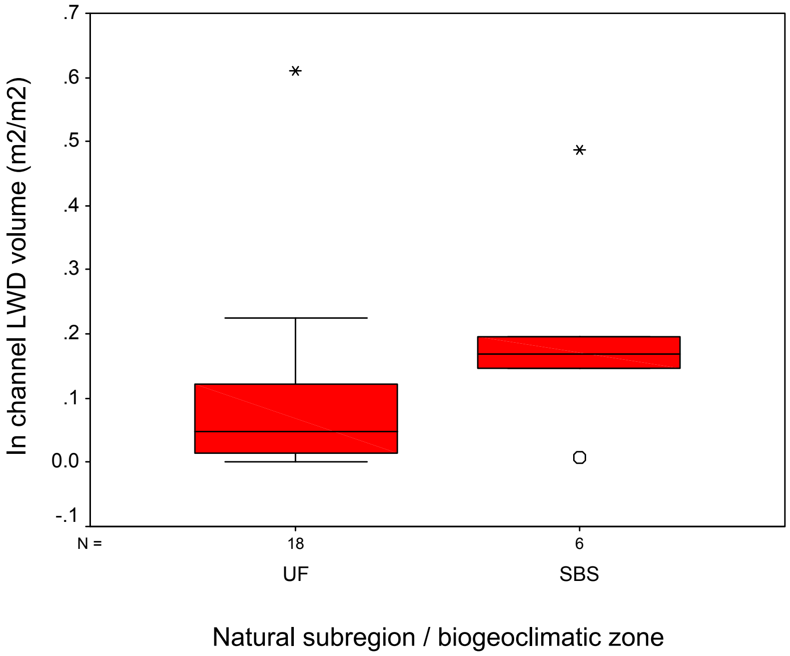


Figure 38. Boxplot for in-channel LWD volume (m2/m2) for the BC Sub-boreal Spruce biogeoclimatic zone (SBS) and the Alberta Upper Foothills natural subregion (UF). Horizontal bars indicate median, boxes indicate 25%-75%, whiskers indicate non-outlier range, open circles and stars represent outliers and extreme values respectively.

Table 23. Descriptive statistics and independent samples t-test with preliminary test for equality of variance: In-channel LWD volume for Sub-Boreal Spruce biogeoclimatic zone and the Upper Foothills natural subregion.

Ecological Zone	n	Mean	Std. Deviation	Part 1: Levene's Test for Equality of Variances		Part 2: t-test for Equality of Means equal variances assumed		
				F	Sig.	T	df	Sig. (2-tailed)
Upper Foothills	18	0.098	0.14	0.015	0.905	--	--	--
Sub-Boreal Spruce	6	0.20	0.16	--	--	-1.399	22	0.176

How can the wide range of instream LWD volumes observed within the forested reaches be explained? The instream LWD volume variation may relate to riparian vegetation composition patterns and processes that have been described at continental, regional and local scales. At the continental scale, evergreen conifers (Thuja plicata, Abies grandis, Picea engelmanii) and deciduous trees (Populus) dominate the riparian forests of the Rocky Mountains and foothills in the region of 46°N and southward, while deciduous shrubs dominate the wettest sites at more northern latitudes including Jasper National Park at 52°N (Peet, 1988). At the regional scale, within the Upper Foothills natural subregion in southwestern Alberta, the site index for lodgepole pine (Pinus contorta) averaged 16.7 m at 50 years on moderately well drained sites, 12.2 m at 50 years on imperfectly drained sites and was not available on sites with poor soil drainage (Archibald et al., 1996). For white spruce (Picea glauca), site index was 9.8 m at 50 years at the single ecosite on moderately well drained sites, 11.2 m at 50 years on imperfectly drained sites and not reported on sites with poor soil drainage (Archibald et al., 1996). Within the Upper Foothills, moderately well drained sites have low-moderate soil temperature limitations, while imperfectly drained sites have high soil temperature limitations that can limit seedling establishment and growth (Archibald et al., 1996). Therefore within the region, the improved soil moisture and fertility associated with floodplain soils does not necessarily translate to increased tree growth and a variety of productivity rates can be expected. At the local scale, the occurrence of non-forested riparian areas along mid-sized streams was also noted during the ecological land classification completed in the vicinity of the study area and was attributed to a combination of excess soil moisture and cold air drainage (Stelfox, 1981). This pattern of higher standing tree biomass in upland areas verses riparian areas was also observed in transects along headwater streams within the temperate rain forests of southeast Alaska (Alaback and Sidle, 1986). In summary, while riparian areas are generally considered to be highly productive forest sites, within the study area various ecological processes including soil drainage and soil temperature may influence seedling establishment and tree growth and therefore large woody debris production.

3.2. In-channel and floodplain LWD recruitment

Landslides and debris flows were not important processes for debris recruitment within the study area. Recruitment processes were limited to bank erosion and mortality from fire or other causes. From air photo interpretation, we observed that on average, 90% of the in-stream wood originated from trees growing within 7.6 m of the edge of the stream (Table 5 and Figure 39). In another study where a source distance curve was developed in a stream where recruitment processes did not include landslides, similar recruitment patterns were observed with 90% of the wood originated from within 10 m of the stream (Benda et al., 2003).

Table 24. Summary of wood source distance from stream edge for eight different reaches.

Cumulative proportion of wood length	Average distance from stream edge (m)
0	0.0
10	0.7
20	1.3
30	1.8
40	2.3
50	3.1
60	3.9
70	4.9
80	6.2
90	7.6
100	10.2

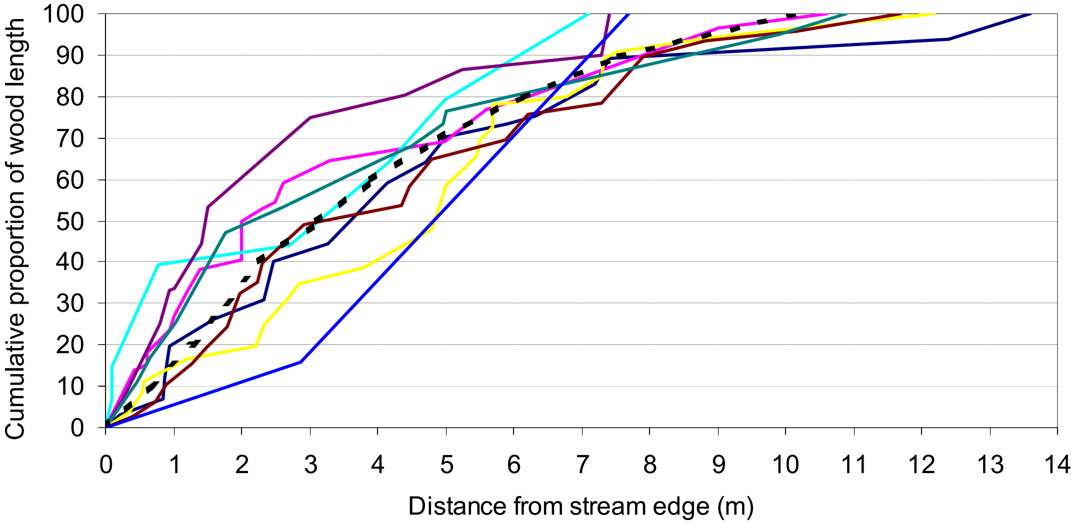


Figure 39. Wood source distances from stream edge based on photo-interpreted measurements for eight reaches. Dashed line indicates average source distance.

On average, 48% of the wood within the floodplain originated from trees growing within the floodplain itself and 90% of the floodplain wood originated from trees growing within 6.6 m of the edge of the floodplain (Table 25 and Figure 40).

Table 25. Summary of wood source distance from floodplain edge for eight different reaches. Summary of wood source distance from floodplain edge for eight different reaches.

Cumulative proportion of wood length	Average distance from floodplain edge (m)
0	0.0
10	0.0
20	0.0
30	0.1
40	0.5
50	0.8
60	1.9
70	3.4
80	4.6
90	6.6
100	8.4

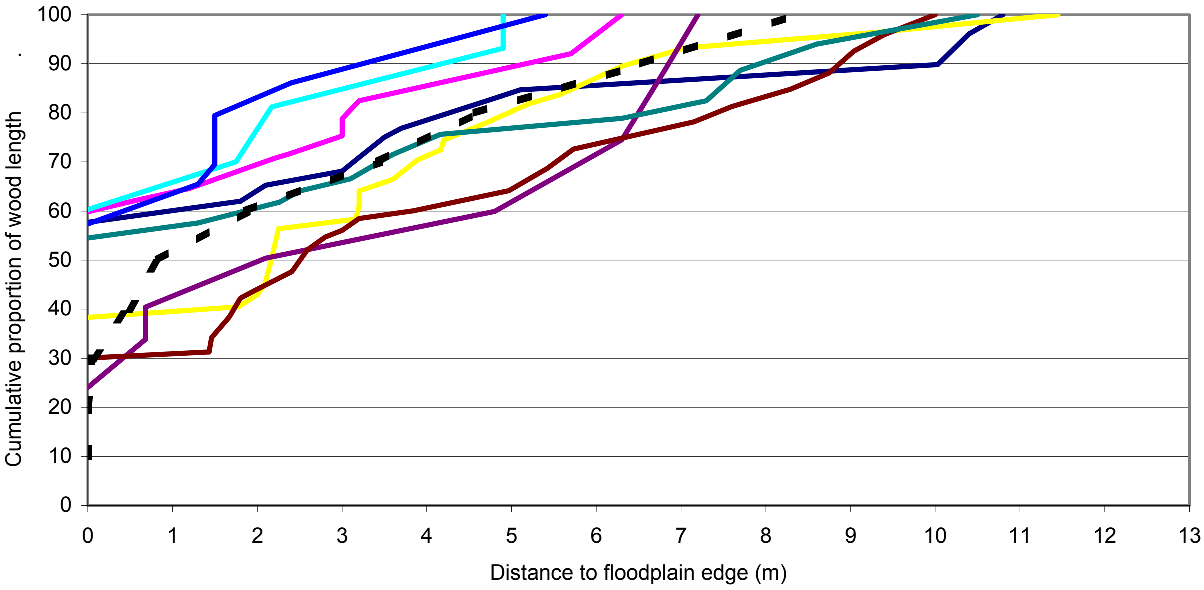


Figure 40. Wood source distances from floodplain edge based on photo-interpreted measurements for eight reaches. Dashed line indicates average source distance.

3.3. LWD function

The reaches selected for this in-stream LWD inventory represent the wide range of channel conditions within the study area (Figure 41) and these conditions have a strong influence on potential functions of LWD. Channel gradient has a strong influence on key LWD functions, including sediment storage (Anonymous, 1996). For example, the step length and stored sediment volume created by 0.2 m high LWD step within a 3 m wide channel vary by a factor of 20 among the range of channel slopes within the study area streams (Table 26). Therefore, channel gradient and size information are important considerations when reviewing these findings pertaining to LWD function.

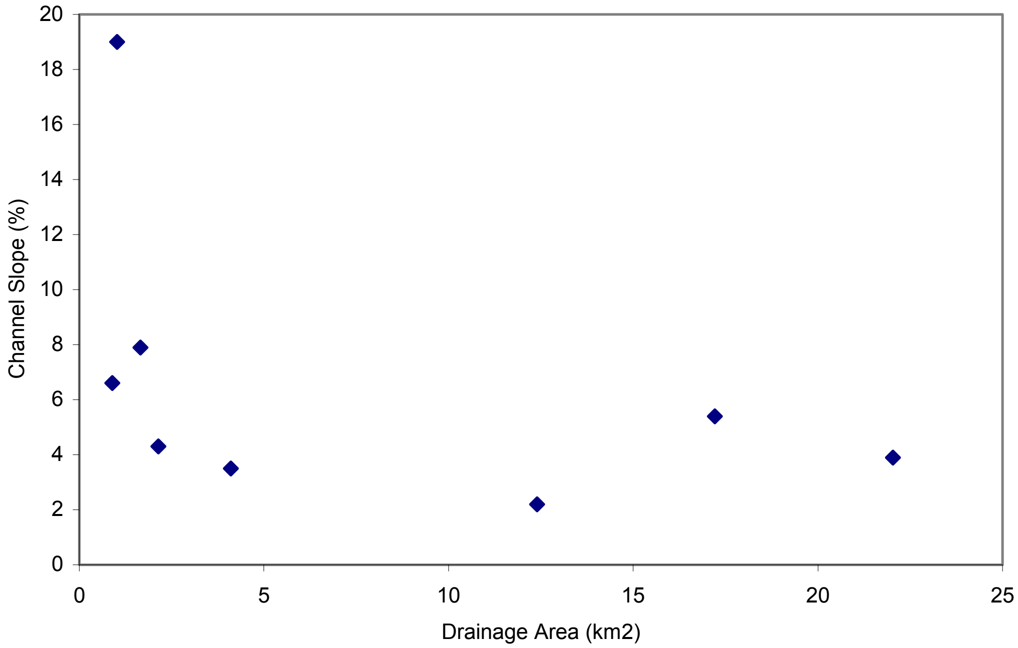


Figure 41. Channel slope and drainage area for eight in-stream LWD inventory reaches.

Table 26. Comparison of predicted step length and sediment volumes stored behind 0.2m diameter LWD step in 3m wide stream of various slopes. Step length (run) = *100/slope. Sediment volume stored = step height * step width * step length / 3 (Gomi et al., 2001).

Channel slope (%)	Step height (m)	Step width (m)	Step length (m)	Sediment volume stored (m^3)
1	0.2	3	20	4
2	0.2	3	10	2
4	0.2	3	5	1
8	0.2	3	2.5	0.5
20	0.2	3	1	0.2

Input mechanism has a strong influence on LWD function. Whereas LWD delivered into a channel by mass wasting may breakup and also interact with water and sediment flows immediately, in my study area this input processes was limited to a single rotation slump representing 1% of the total LWD pieces from all reaches (Table 27). In most cases, charring of the wood made it impossible to determine whether a piece of LWD originated from natural mortality prior to the fire or the fire itself, therefore input mechanism was identified as fire or mortality for 55% of the pieces.

Table 27. Summary of LWD input mechanism for eight inventory reaches.

Reach Number	# pieces / 100m	LWD pieces by input mechanism (%)							
		Wind	Transport	Landslide	Fire	Mortality	Fire or mortality	Bank erosion	Other *
1	49.7	2.1	14.9	0.0	6.4	4.3	63.8	8.5	0.0
3	83.2	0.0	32.3	0.0	3	16.2	42.4	6.1	0.0
5	51.0	0.0	3.1	0.0	0	29.7	51.6	4.7	10.9
6	12.1	7.7	30.8	30.8	7.7	0.0	15.4	7.7	0.0
7	37.2	0.0	16.7	0.0	8.3	0.0	50.0	22.2	2.8
11	92.2	6.4	0.0	0.0	2.1	23.4	66.0	2.1	0.0
12	42.3	1.6	3.2	0.0	7.9	9.5	73.0	4.8	0.0
15	11.3	0.0	7.7	0.0	0	7.7	69.2	15.4	0.0
Total		1.6	14.1	1.0	4.2	14.4	55.2	7.3	2.1

* other includes disease, beaver and chainsaw.

Water transport was the third most important LWD input mechanism. I posed two questions relating to transported LWD. First, is the size of the transported wood related to stream size? Second, does the percentage of water transport LWD pieces increase with stream size? I used linear regression to address both of these questions and no relationships were apparent. Future studies with larger sample sizes may provide more information on these questions.

The location of LWD within the channel also influences function. Reach 6, the largest stream of the study reaches, was located within a steep-walled valley with frequently exposed bedrock that generated a streambed comprised of colluvial material. Given the non-alluvial nature of the bed, this reach was considered an outlier and excluded from the linear regression analysis. Key LWD functions, including sediment storage and pool formation, are largely limited to pieces with direct contact with the stream bed or in the baseflow channel. On average, the proportion of entire LWD pieces within the three channel zones (baseflow channel, bankfull channel and above bankfull channel) was lowest within the baseflow channel and greatest above the bankfull channel (Table 28).

Table 28. Summary of LWD distribution among zones for field survey reaches (sorted by drainage area).

Reach Number	Drainage Area (km^2)	Channel Slope (%)	Bankfull Width (m)	Reach total LWD volume by zone				
				Baseflow channel (%)	Bankfull channel (%)	Above bankfull (%)	Floodplain (%)	Upland (%)
11	0.9	6.6	1.5	9.7	7.9	22.9	49.6	9.9
7	1.0	19.0	2.3	7.5	14.6	36.1	25.2	16.6
1	1.7	7.9	1.4	9.8	10.4	21.2	48.3	10.3
5	2.1	4.3	2.2	9.6	5.1	19.0	66.3	0.0
12	4.1	3.5	1.9	13.5	10.0	15.2	52.8	8.4
3	12.4	2.2	5.6	21.9	22.3	24.8	29.8	1.3
15	17.2	5.4	4.3	29.8	9.5	13.4	47.2	0.0
6	22.0	3.9	5.2	0.9	27.1	20.5	51.5	0.0
Average				11.41	11.88	19.23	41.19	5.17

Is this proportion of LWD within the baseflow channel related to stream size or slope? When considering the remaining seven sample reaches, stream size variables including drainage area and bankfull width were related to proportion of baseflow LWD and stream slope was not related (Table 29 and Figure 42).

Table 29. Model summary for predicting proportion of LWD volume located within baseflow channel from various channel descriptors.

Model Variable	n	Model R^2	Sig.
Drainage area (km^2)	7	0.985	0.000
Bankfull width (m)	7	0.652	0.028
Channel slope (%)	7	0.215	0.295

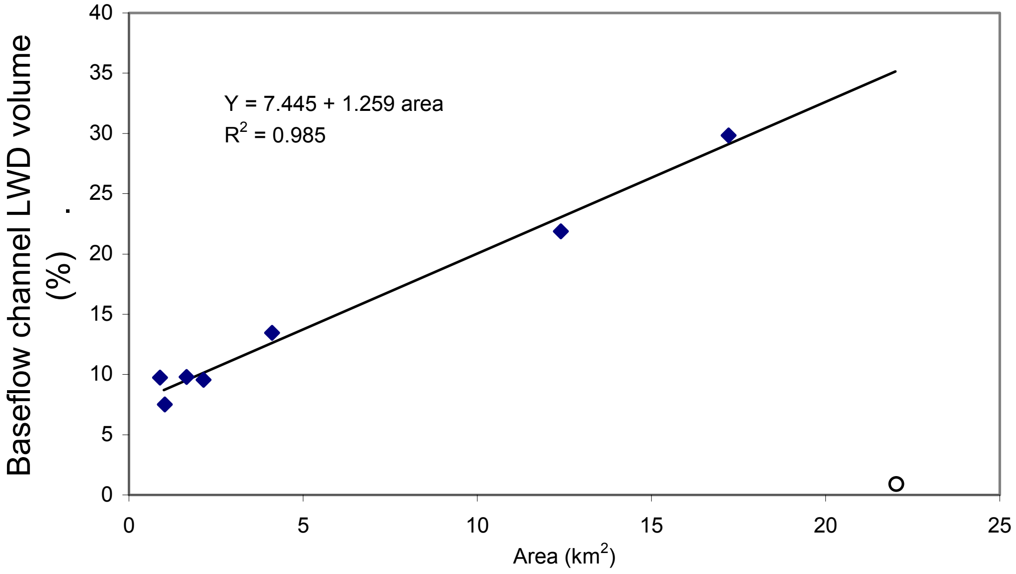


Figure 42. Proportion of total LWD volume within baseflow channel predicted from drainage area. Open circle indicates a single outlier in the data set.

3.4. Floodplain versus In-stream Wood

In this section, I address the following questions that relate to timber management within the riparian zone:

1. How much coarse woody debris is stored on the floodplain of the various sites?
2. What is the range of standing tree volumes within the in-stream recruitment zone at the various sites?
3. What is the range in fall-down rates between the sites?
4. Can we combine measures of standing tree volume and coarse woody debris within the floodplain (surrogate site index indicator) to predict the amount of in-stream wood?

At the eight field-reference reaches, the total length of coarse woody debris on the floodplain from air photo interpretation ranged between 0 and 9110.3 m/ha, while the average volume of standing wood ranged between 23.0 and 107.2 m^3/ha (Table 30). The ratio ranged between 0 and 396.2 with an average of 79.2 (Table 30). These findings suggest that both the productive capacity of the riparian zone and the fall down rates are highly variable between reaches.

Table 30. Air photo-interpreted future in-stream LWD source amounts including length of coarse woody debris (CWD) from floodplain line intersect transects and standing volume from 10 m diameter plots (0.01 ha) bordering streambank.

Reach	Floodplain CWD length (m/ha)	Average recruitment zone standing volume (m^3/ha)	Ratio
1	2617.8	86.9	30.1
3	4786.6	49.2	97.2
5	2661.0	33.3	80.0
6	1878.0	37.8	49.7
7	1750.3	38.1	46.0
11	9110.3	23.0	396.2
12	1422.5	107.2	13.3
15	0.0	32.0	0.0
Average	2691.83	45.28	79.17

While neither stand volume nor floodplain CWD length were useful individual predictors of field-measured LWD, the combination of the two variables provided a reasonable model (Table 31).

Table 31. Summary of linear regression models to predict field-measured in-stream LWD from air photo-interpreted riparian variables including standing volume from 10 m diameter plots (0.01 ha) bordering streambank and length of coarse woody debris (CWD) from floodplain line intersect transects (n=8).

Model	Constant	B1	B2	R^2	Sig.
1. Stand volume (m^3/ha)	310.87	-0.445		0.002	0.914
2. Floodplain CWD length (m/ha)	-102.87		0.039	0.233	0.233
3. Stand volume + floodplain CWD length	-101.16	2.219	0.091	0.716	0.043

3.5. Linking reach-scale patterns in LWD to watersheds using Alberta Vegetation Inventory (AVI)

In the previous section, I established a linkage between quantities of instream LWD volume and standing downed wood in the adjacent stand. These findings warranted further investigation into linkages between instream LWD quantities and forest stand characteristics including volume and stand age. Using Alberta Vegetation Inventory collected prior to the Dogrib Fire, I identified both the total gross volume and stand origin date for the forest stands adjacent to 17 air photo interpreted reaches. Total gross volume included volume of standing live and dead coniferous and deciduous trees. Using stepwise regression, these stand volume estimates provided a reasonable predictor of instream LWD volume at 16 of these locations (Figure 43).

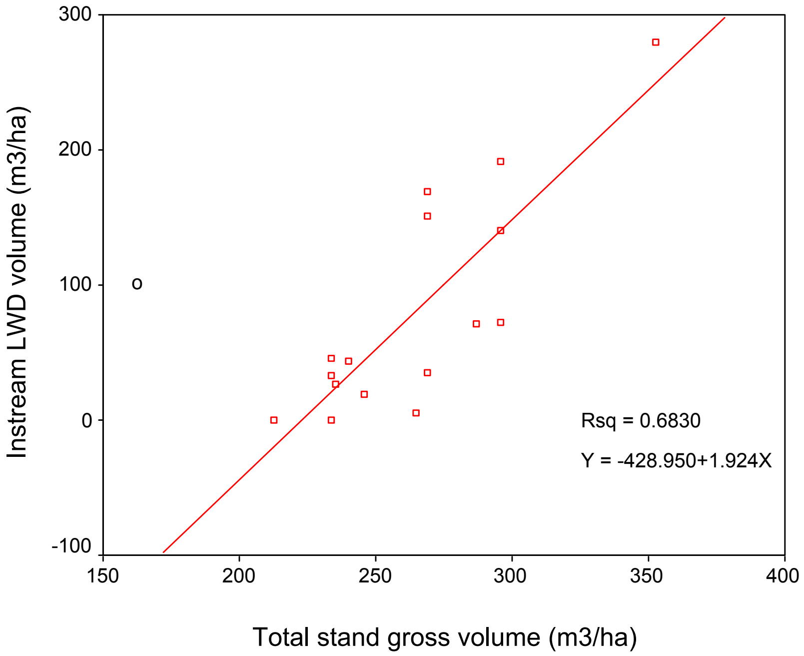


Figure 43. Instream LWD volume (derived from air photo measures) predicted from Alberta Vegetation Inventory total stand gross volume. Open circle indicates a single outlier in the data set.

While there was no evidence for individual use of stand origin year to predict instream LWD volume (Figure 44), there was weak evidence for interaction of total stand volume and stand origin year when predicting instream LWD volume (Table 32).

Table 32. Instream LWD volume model summary.

Model Summary	Model variables	Variable coefficient	Coefficient sig.
Model Form: $y= a + b_1x_1 + b_2x_2$	Constant	1293.859	0.161
Model R^2: 0.757	Stand age	-0.933	0.068
Model Sig.: 0.000	Total stand volume	1.898	0.000

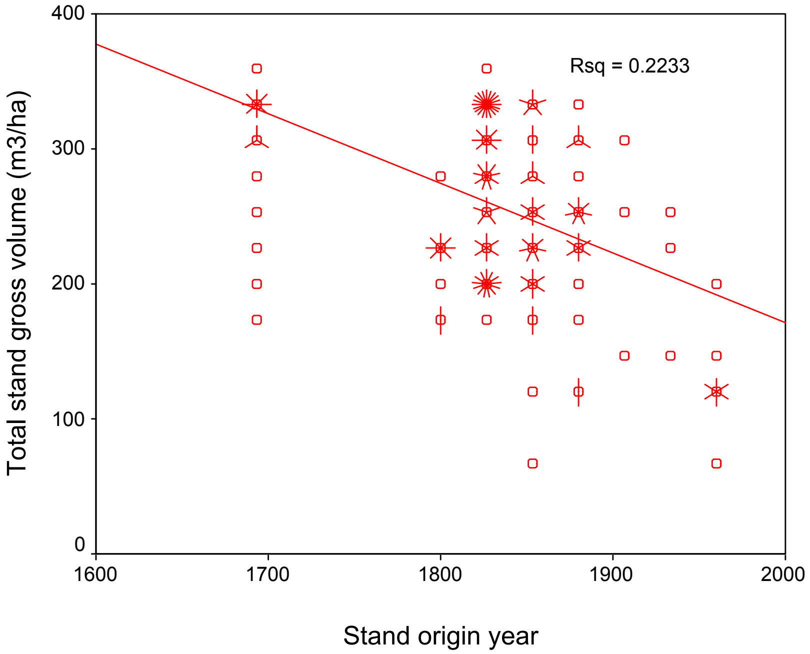


Figure 44. Total stand gross volume from all AVI polygons bordering streams within the study area verses stand origin date.

By applying this model to all stream reaches with AVI data from adjacent stands, I mapped the predicted instream LWD for all study area streams (Figure 45). By further applying the model for percentage of LWD volume within the baseflow channel based on drainage area (Figure 42), I mapped the predicted baseflow channel LWD volume (the LWD most likely to influence channel structure), for all study area streams (Figure 46).

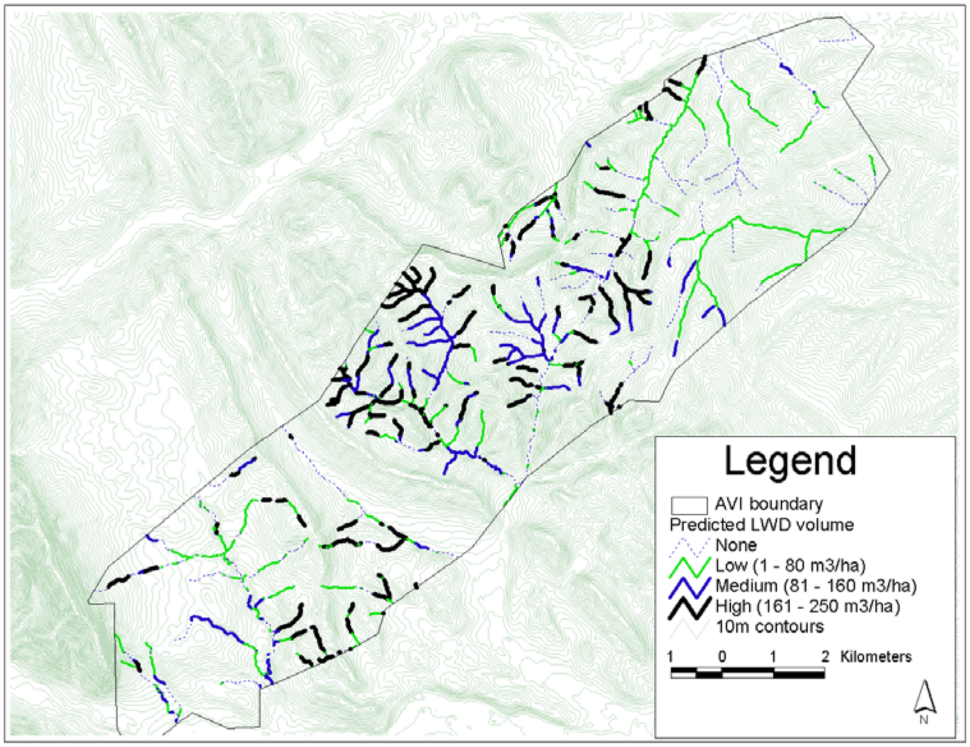


Figure 45. Map of predicted instream LWD volume by category within study area streams.

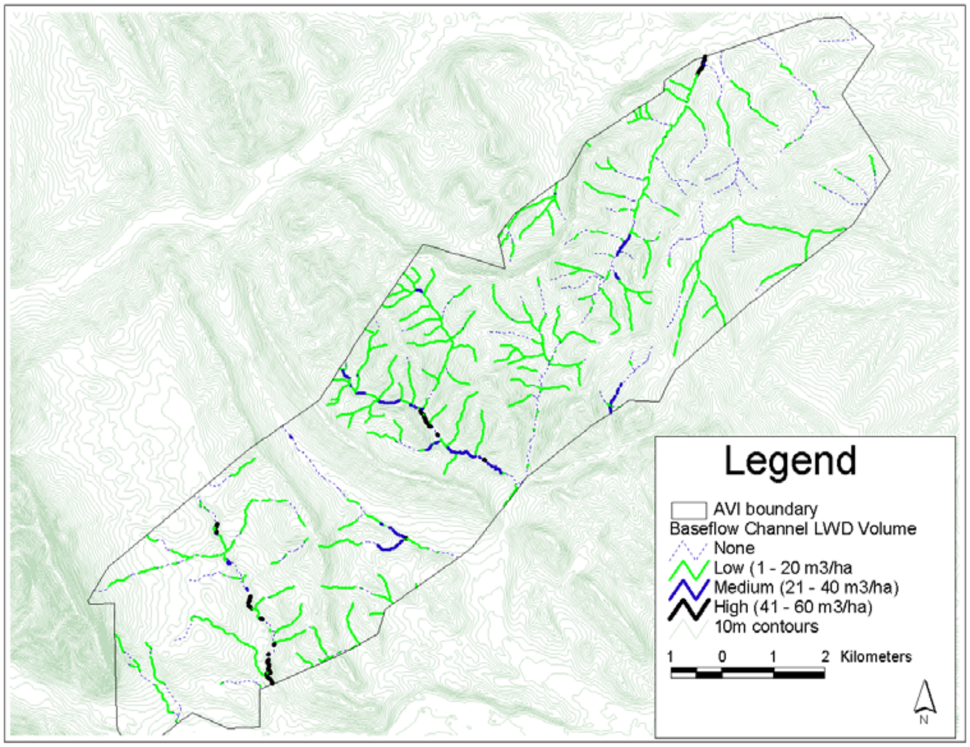


Figure 46. Map of predicted baseflow channel LWD volume by category within study area streams.

4. Conclusions

The successful management of riparian areas to meet both timber supply and fish habitat conservation objectives entails setting goals to maintain a long-term supply of instream LWD (Boyer et al, 2003). By organizing this LWD study at various scales, we were able to improve knowledge of LWD within small Foothills streams and establish linkages to stand and landscape level forest management. At the stand level, greater stream size translated to increased efficiency of processing wood inputs into functional wood within the baseflow channel. At the stand level, the LWD recruitment zone represents an important ecological boundary with direct applications for establishing management boundaries. At the landscape level, connections between instream LWD volume and AVI stand volume may facilitate management that considers the natural spatial variation of instream LWD across a wide area.

Chapter 5. Conclusions and Recommendations

Pressures to change riparian management strategies originate as we try to achieve timber supply and terrestrial biodiversity management goals. However, more active management of riparian areas necessitates that we consider other values associated with riparian areas. In particular, managers may consider setting goals for the maintenance of water quality (sediment outputs) and fish habitat (instream LWD supply). This study improved the understanding of sediment and LWD processes within the riparian areas of small Foothills streams and it also created a foundation from which a complete sediment budget and LWD budget can be built (Table 33). Additional work is required to develop and validate landscape models to predict changes in sediment output and instream LWD storage. With additional development and testing, the channel assessment procedure adopted for use in this study will serve as an important site indicator tool for use in an adaptive riparian management process. Once developed, these tools should assist in the development, evaluation and monitoring of existing and alternative riparian management strategies.

Table 33. A budget framework and associated tools for management of timber, sediment and LWD.

	Inputs	Storage	Outputs
1. Timber	tree growth	standing trees	• timber harvest • fire • insects • decay
Tools	• growth & yield models, • ecosite classification	AVI maps with timber volume	• Detailed Forest Management Plan • Annual Allowable Cut
2. Sediment	sediment transport	• landforms, channel forms, lwd	water quality: • suspended sediment • bedload
Tools	reach and watershed process model	Alberta based floodplain and channel assessment	• reach and watershed process model • field measurement
3. Wood	tree fall	Fish habitat: • floodplain • channel	• decay • transport
Tools	adapted growth and yield model	• AVI maps • field inventory	wood decay model

Literature Cited

Alaback, P. and Sidle, R.C., 1986. Biomass, structure, and nutrients of riparian vegetation on a small watershed on Chichagof Island, Southeast Alaska. In: D.L. Correll (Editor), Watershed Research Perspectives. USDA Forest Service, Smithsonian Environmental Research Center, pp. 135-165.

Alberta Pacific Forest Industries Inc., 1999. Detailed Forest Management Plan, Boyle, Alberta.

Alberta Sustainable Resource Development - Public Lands and Forests Division, 1994. Alberta timber harvest planning and operating ground rules. Publication No. Ref. 71. 0-86499-919-4, Alberta Environmental Protection.

Andison, D.W., 2000. Landscape-level fire activity on foothills and mountain landscapes of Alberta. Report No. 2.

Andison, D.W. and McCleary, K., 2002. Disturbance in riparian zones on foothills and mountain landscapes of Alberta, Alberta Foothills Disturbance Ecology Reserach Series, Report Number 3.

Anonymous, 1996. Channel assessment procedure field guidebook. Ministry of Forests and BC Environment.

Archibald, J.H., Klappstein, G.D. and Corns, I.G.W., 1996. Field guide to the ecosites of southwestern Alberta. Special Report 8, Natural Resources Canada, Canadian Forest Service, Northwest Region, Northern Forestry Centre, Edmonton, Alberta.

Benda, L. et al., 2003. Wood recruitment processes and wood budgeting. In: S. Gregory, K. Boyer and A. Gurnell (Editors), International conference on wood in world rivers, American Fisheries Society Symposium 37. The ecology and management of wood in world rivers. American Fisheries Society, Oregon State University, Corvallis, Oregon, pp. 49-74.

Bird, S.A., 2002. Stream channels, large woody debris and biogeoclimatic zones in managed watersheds, redefined one-year deliverables, Report submitted to Dan Hogan, Research Branch, Ministry of Forests, UBC, Vancouver, British Columbia.

Bott, R., Murphy, P. and Udell, R., 2003. Learning from the forest: a fifty-year journey towards sustainable forest management. Fifth House Ltd., Calgary, Alberta, 242 pp.

Boyer, K.L., Berg, D.R. and Gregory, S.V., 2003. Riparian management for wood in rivers. In: S.V. Gregory, K. Boyer and A. Gurnell (Editors), The ecology and management of wood in world rivers, American Fisheries Society, Symposium 37, Bethesda, Maryland, pp. 407-420.

Dumanski, J., Macyk, T.M., Veauvy, C.F. and Lindsay, J.D., 1972. Soil survey and land evaluation of the Hinton-Edson area, Alberta. Alberta Institute of Pedology Report No. S-72-31, Soils Division, Research Council of Alberta, Edmonton, Alberta.

Fisheries and Oceans Canada, 2001. Habitat enforcement bulletin. No. 10, Fish Habitat Management, Conservation and Protection.

Gadd, B., 1995. Handbook of the Canadian Rockies. Corax Press, Jasper, Alberta, 831 pages pp.

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

Gordon, S., Bentz, J., O'Leary, D. and Clish, D., 1997. Common ecological land classification and associated attribute database for the Yellowhead ecosystem, GEOWEST Environmental Consultants Ltd. Edmonton, Alberta, under contract to Foothills Model Forest, Hinton, Alberta, for Yellowhead Ecosytem Working Group.

Hinton Wood Products - A Division of West Fraser Mills Ltd., 1999. Detailed Forest Management Plan, Hinton, Alberta.

Lee, P. and Smyth, C., 2003. Riparian forest management: paradigms for ecological management and practices in Alberta. Northern Watershed Project Final Report No. 1, Report produced by the Alberta Research Council (Vegreville, Alberta) and the Alberta Conservation Association (Edmonton, Alberta) for the Northern Watershed Project Stakeholder Committee.

MacDonald, L. and Huffman, E.L., 2004. Post-fire soil water repellency: persistence and soil moisture thresholds. Soil Science Society of America Journal, 68: 1729-1734.

MacDonald, L.H. and Stednick, J.D., 2003. Forests and water: a state-of-the-art review for Colorado. CRWRRI Completion Report No. 196, University of Colorado, Colorado Water Resources Research Institute, Fort Collins, Colorado.

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

Naiman, R.J., Decamps, H. and Pollock, M., 1993. The role of riparian corridors in maintaining regional biodiversity. Ecological Applications, 3(2): 209-212.

Peet, R.K., 1988. Forests of the Rocky Mountains. In: M.G. Barbour and W.D. Billings (Editors), North American Terrestrial Vegetation. Cambridge University Press, New York, pp. 63-101.

Platts, W.S. et al., 1987. Methods for evaluating riparian habitats with applications to management. General Technical Report INT-221, Intermountain Research Station, USDA Forest Service, Ogden, Utah.

Reid, L.M. and Dunne, T., 2003. Sediment budgets as an organizing framework in fluvial geomorphology. In: G.M. Kondolf and H. Piegay (Editors), Tools in fluvial geomorphology. John Wiley and Sons Ltd., West Sussex, England, pp. 463-500.

Rosgen, D. and Silvey, H.L., 1998. Field guide for stream classification. Wildland Hydrology Books, Pagosa Springs, Colorado, 193 pp.

Rosgen, D.L., 1994. A classification of natural rivers. Catena, 22: 169-199.

Schuett-Hames, D., Pleus, A.E., Ward, J., Fox, M. and Light, J., 1999. TFW Monitoring Program method manual for the large woody debris survey. TFW-AM9-99-004. DNR #106., Prepared for the Washington State Dept. of Natural Resources under the Timber, Fish and Wildlife Agreement.

Slaymaker, O., 2003. The sediment budget as conceptual framework and management tool. Hydrobiologia, 494: 71-82.

Stelfox, H.A., 1981. Ecological Land Classification Red Deer - James. ENR Report Number: T/11-No.8, Alberta Energy and Natural Resources, Resource Evaluation and Planning Division, Edmonton, Alberta.

Strong, W.L., 1992. Ecoregions and ecodistricts of Alberta., Edmonton, Alberta.

Sullivan, K., Lisle, T.E., Dolloff, C.A., Grant, G.E. and Reid, L.M., 1987. Stream channels: the link between forests and fishes. In: E.O. Salo and T.W. Cundy (Editors), Streamside management: forestry and fisheries interactions. University of Washington Institute of Forest Resources, University of Washington, pp. 39-97.

Waters, T.F., 1995. Sediment in streams: sources, biological effects and control. American Fisheries Society Monograph 7. American Fisheries Society, Bethesda, Maryland, 251 pp.