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EFFECTS OF LARGE WOODY DEBRIS ON SURFACE STRUCTURE AND AQUATIC HABITAT IN FORESTED STREAMS, SOUTHERN INTERIOR BRITISH COLUMBIA, CANADA

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ABSTRACT

It is well known that large woody debris (LWD) plays an important functional role in aquatic organisms' life. However, the influence of LWD on channel morphology and aquatic environments at watershed levels is still unclear. The relationships between wood and surface structure and aquatic habitat in 35 first through fifth order streams of southern interior British Columbia were investigated. Study streams in the channel networks of the study watersheds were classified into four size categories based on stream order and bankfull width: Stream size I: bankfull width was less than 3 m, Stream size II: 3–5 m, Stream size III: 5–7 m, Stream size IV: larger than 7 m. We found the number of functional pieces increased with stream size and wood surface area in stream sizes I, II and III (24, 28 and 25 $m^2/100\,m^2$, respectively) was significantly higher than that in stream size IV ($12\,m^2/100\,m^2$). The contribution of wood pieces to pool formation was 75% and 85% in stream sizes II and III, respectively, which was significantly higher than those in stream size I (50%) and size IV (25%). Between 21% and 25% of wood pieces were associated with storing sediment, and between 20% and 29% of pieces were involved in channel bank stability in all study streams. Due to long-term interactions, LWD in the intermediate sized streams (Size II and III) exhibited much effect on channel surface structure and aquatic habitats in the studied watersheds. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS: woody debris; channel morphology; forested watershed; stream habitat; ratio of riffle to pool; substrate composition

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INTRODUCTION

In-stream woody debris was once viewed as a wasted resource to be neglected, and rather than habitat and materials that contributed to the biological diversity and aquatic organisms (Bilby and Likens, 1980; Harmon *et al*., 1986; Piegay and Gurnell, 1997; Diez *et al*., 2001). As a result, woody debris was often removed from the aquatic environment for navigation, flood control and improved fish passage. The practice of clearing woody debris from forested streams resulted in a great decrease of organic matter and nutrients, and a considerable decline of aquatic diversity and habitat (Bilby and Likens, 1980; Hogan, 1987). The situation did not change until the 1980s when a great amount of research demonstrated the critical role played by woody debris in stream ecosystems and aquatic environments.

A great amount of research has been carried out to examine large woody debris (LWD) abundance, characteristics and dynamics and to evaluate the function performed by LWD in channel morphology, fish habitat and nutrient cycling (Andrus *et al*., 1988; Carlson *et al*., 1990; Robison and Beschta, 1990; Bilby and Ward, 1991; Fausch and Northcote, 1992; Beechie and Sibley, 1997; Jackson and Sturm, 2002; May and Gresswell, 2003; Mossop and Bradford, 2004; Kreutzweiser *et al*., 2005). While most of the studies were focused on coastal areas, little information is available regarding LWD features and functions in forested watersheds of the British Columbia

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interior (Chen *et al*., 2005, 2006). With the differences in climate, geographical characteristics, soil properties, vegetation composition and management practices, it is reasonable to expect that role played by LWD on structural morphology and aquatic environment of streams is quite different between the coast and interior regions. In addition, many investigations of LWD characteristics were carried out at the reach level on either small or large streams. However, it was generally believed that small streams behave differently from larger streams (Jackson and Sturm, 2002). Furthermore, the results of LWD properties derived from studies at reach level cannot completely reflect the spatial distribution and variation of LWD through the channel networks of the watersheds because of the spatial heterogeneity. Consequently, it was not appropriate to make riparian forest management decisions at watershed scale based on the application of research at reach level.

Several studies revealed that the structural and functional role of LWD characteristics depend upon the stream channel size (Bilby and Ward, 1989; Robison and Beschta, 1990; Beechie and Sibley, 1997; Piegay and Gurnell, 1997). As channel size increased, mean woody debris size usually increased, but the frequency of occurrence of woody pieces decreased (Bilby and Ward, 1989; Chen *et al*., 2006). Small channels usually contained abundant LWD, while LWD frequency decreased in larger streams because of the high transport capacity. The influence of LWD on channel morphology was found to be strongest in smaller sized, low gradient streams (Beschta and Platts, 1986). May and Gresswell (2003) reported a difference of LWD redistribution and functioning in small and large sized streams because of different fluvial process influences. Turnover times of LWD (the ratio between LWD standing stock and input rates) were also found to be different with the different stream sizes (Diez *et al*., 2001). Recent research in British Columbia interior watersheds demonstrated that characteristics of in-stream LWD (size, volume, biomass and carbon content) varied greatly at the watershed level (Chen *et al*., 2005, 2006). Average diameter, length, volume and biomass of individual pieces increased as a function of increasing channel bankfull width, but LWD density (piece per 100 m^2 of the stream area) decreased with an increase in bankfull width in southern central interior British Columbia stream networks.

In this study, we examined the relationships between LWD characteristics and channel morphological features in forest watersheds in the southern interior of British Columbia. In particular, we were interested in exploring the impacts of LWD size, amount and position on surface structures and aquatic habitats at watershed scale. The specific objectives of this research were: (1) to quantitatively describe the structural features of LWD pieces through the channel networks at a forested watershed scale, (2) to examine the relationships between LWD characteristics and surface structures and aquatic habitat features and (3) to assess the role of LWD pieces in channel morphology in different stream sizes. Understanding these questions will provide critical information for designing watershed-based riparian management strategies. In British Columbia, various riparian buffer protection strategies are proposed. Before any of these strategies can be implemented, sufficient research must be conducted to examine various watershed processes including LWD and its interaction with riparian vegetation along stream networks.

METHODS

Study sites

This study was carried out in forested watersheds in the southern interior of British Columbia, located within an approximate 100 km radius of the City of Kelowna (43°10′N, 79°55′W) (Figure 1). The study area included watersheds in the Engelmann Spruce-Subalpine Fir (ESSF) and the Montane Spruce (MS) biogeoclimateic zones (Meidinger and Pojar, 1991). The study sites had elevations ranging from 700 to 1750 m, with 75% of the total area having a gradient of less than 15%. The soil in the study area can be characterized as podzolic with Humo-Ferric Podzols developed from moderately to well-drained parent materials. Humus forms are generally Mors (Hemimors, Hemihumimors and Humimors), ranging from 3 to 10 cm in thickness.

Generally speaking, the study area has a relatively cool, moist and continental climate. Growing seasons are moderately short and warm and winters are long and cold. Mean annual temperatures in this area range from −2 to 4.0°C. Mean monthly temperatures are below 0°C for about 5 months of the year, and above 10°C for about 3 months of the year. Annual precipitation is highly variable in the study area and ranges from 400–500 mm in the drier portions to 2200 mm in the wetter areas. Most (50–70%) of the precipitation falls as snow (Meidinger and

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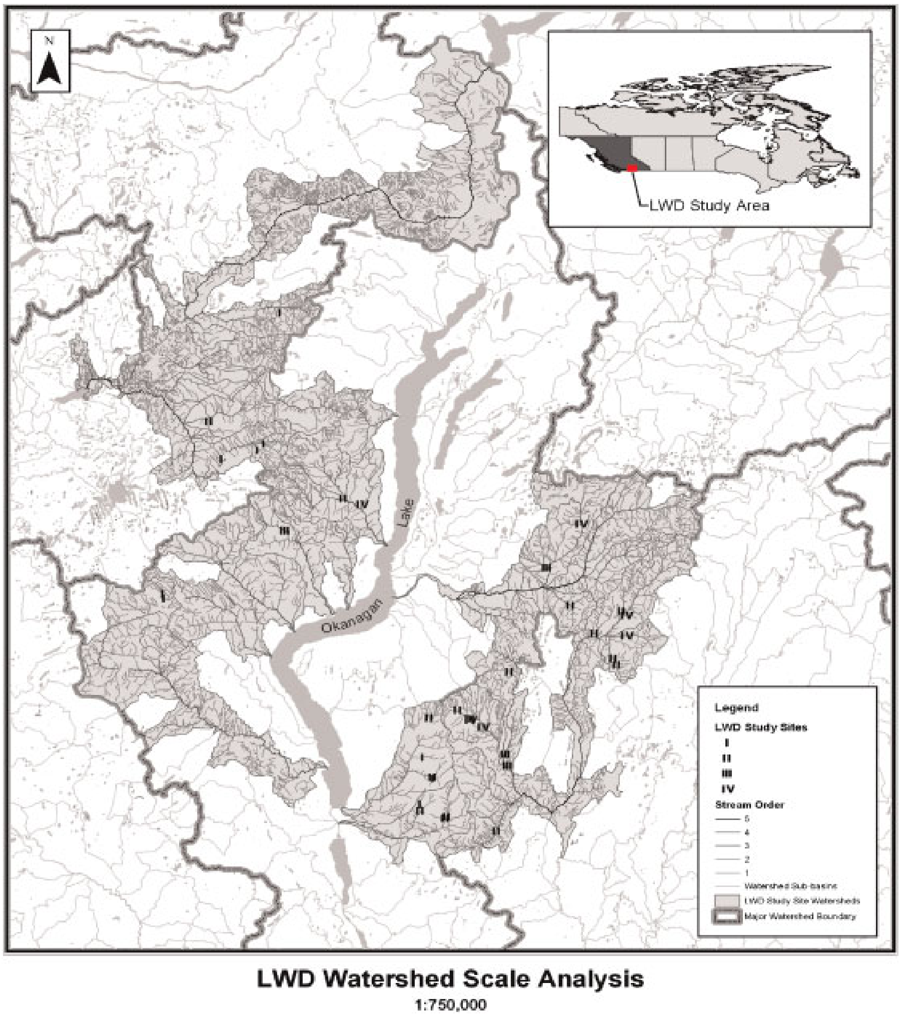

Figure 1. Location of study sites for the LWD survey. I, II, III and IV represent the stream size I, II, III and IV, representatively. Inset map of the contiguous Canada shows the location of British Columbia and research area. This figure is available in colour online at www.interscience.wiley.com/journal/rra

Pojar, 1991). Peak stream discharges occur primarily in the spring between April and June, mostly from melting snowpacks situated above 1200 m.

In the study watersheds, Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), hybird white spruce (*Picea glauca* and *P. engelmannii*) and lodgepole pine (*Pinus contorta*) are the dominant tree species. Other minor tree species include Douglas-fir (*Pseudotsuga menziesii*) and western red cedar (*Thuja plicata*). A special feature of the study watersheds were the extensive, young and maturing stands of lodgepole pine that had formed following wildfire. In wet environments, maturing stands contained mixtures of lodgepole pine and hybird white spruce. Subalpine fir and hybird white spruce were the dominant, shade-tolerant, climax trees.

Sampling design

Stream order is defined as a measure of the relative location of streams in a watershed. Usually first-order streams are perennial streams. When two first-order streams come together, they become a second-order stream. When two

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second-order streams come together, they form a third-order stream. As stream orders increase, streams gradually increase their width and depth. The amount of water they discharge also increases.

In the present study, a total of 35 first to fifth order streams were sampled during the months of July to October in 2003 and 2004. A topographic map with a scale of 1: 50 000 and forest maps with scales of 1: 30 000 and 1: 50 000 were used to identify the stream order and stream-side forest stand compositions and ages. All of the study sites were randomly selected based on vehicle accessibility and the following criteria: (1) the streams were located in areas of intact mature riparian forests (>80 years), (2) the stream side forests were not disturbed by human activities, such as harvesting, road building, (3) the riparian areas were not logged. Therefore, the results from this study are expected to provide a baseline of LWD characteristics in intact mature riparian forests in the southern interior of British Columbia.

In order to evaluate the relationships between LWD features and channel morphological characteristics at watershed level, all study streams were divided into one of four stream size categories based on channel bankfull width: (1) stream size I: bankfull width less than 3 m, (2) stream size II: bankfull width 3–5 m, (3) stream size III: bankfull width 5–7 m and (4) stream size IV: bankfull width greater than 7 m. GIS forest and fire maps were employed to select watersheds or streams which met our criteria. Geomorphologic characteristics of each study site are given in Table I.

Channel feature surveys

For each site, a representative reach with a total length of 150 m was selected. The 150 m reach was further divided evenly into ten sections (i.e.15 m intervals). At each section, bankfull width, bankfull depth, wetted width, wetted depth, stream gradient and left and right bank slopes were measured at the channel profile perpendicular to the streamflow (Kaufmann and Robison, 1998). The b-axis of 12 particles on the streambed was measured at each section. The stream sections were characterized as to relative proportion of sand (<0.2 cm), gravel (0.2–6.4 cm), cobbles (6.4–25.6 cm), boulders (25.6–100 cm) and very large boulders (>100 cm) (Diez *et al*., 2001). Along the study reach, the wetted depth at the stream thalweg (at the time of measure) was measured at 1 m intervals with the identification of riffle, glide and pool at that place.

LWD surveys

LWD was defined in the present study as pieces >1 m in length and >0.1 m in diameter at the small end. LWD pieces located at least partially within or above the bankfull width of the channel were assessed. The orientation, degree of submersion within the bankfull width, decay state, function and stability of each LWD piece was recorded along the study reach. The small and large end diameters within bankfull width, the length within the bankfull width and the total length of each LWD piece were measured. The surface area and volume of each LWD piece were calculated based on the assumption of cylindrical shapes. Total LWD surface area and volume within the bankfull width were calculated by totaling the piece surface area and volumes in each of the 150 m study reaches. Surface area and volume per unit channel area (m^2/m^2 and m^3/m^2, respectively) were calculated by dividing the total study reach LWD surface area and volume by channel area (i.e.$A = \sum(15 \times W_i)$, where A is channel area, 15 is the section length and W_i is the bankfull width in i section).

Each piece of LWD was grouped into two orientation categories based on the predominant orientation of the piece to the direction of streamflow: (1) perpendicular or close to perpendicular to streamflow (60–120°/240–300°) and (2) parallel or close to parallel to streamflow (any other angle). Each piece was also assigned to one of four submergence categories depending on its position within or above the bankfull height of the channel: (1) lower half of height, (2) upper half of height, (3) above bankfull and channel cross-section and (4) any combination of the above three positions.

Three decay classes were used to describe the stage of decomposition of each piece of LWD: Class 1, the debris had intact bark or at least >50% remaining, wood hard with original colour, branches or twigs present; Class 2, the debris had trace of bark (<50% of the bark remaining), no twigs observed and wood had some surface abrasion; and Class 3, the debris had dark colour, no bark and twigs observed, wood soft throughout with holes and openings. The stability of each piece was recorded as one of the following stability categories: (1) greater than bankfull width, (2) anchored or buried in the stream channel banks, (3) braced by other pieces and (4) loose in channel.

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Table I. Geomorphologic characteristics of the 35 study sites in the south interior of British Columbia

Stream name	Size	Order	Elev. m	Grad. %	Width m	Depth m	L-slope degrees	R-slope degrees
Nicola Creek	I	1	1380	2.2	1.6	0.4	15.1	20.0
Bobcat Creek	I	1	1659	4.2	2.0	0.4	6.5	3.2
Municipal Creek (1)	I	1	1587	6.8	2.0	0.4	11.6	16.6
Dome (1)	I	1	1504	1.1	2.1	0.5	9.3	12.8
Sunset Main CP671	I	1	1471	2.5	2.1	0.4	13.8	13.5
Reed Creek	I	1	1712	5.4	2.4	0.5	28.3	37.0
Cotton Creek (1)	I	1	1451	10.3	2.4	0.3	17.5	16.4
Sunset Main CP672	I	1	1331	4.2	2.5	0.4	26.5	29.5
Dome (2)	I	1	1510	7.8	2.8	0.6	26.2	23.7
Wilkinson Creek	II	2	1583	5.4	3.2	0.5	34.1	22.3
Sterling Creek	II	1	1321	5.1	3.4	0.4	30.7	15.6
Municipal Creek (2)	II	2	1580	5.7	3.4	0.6	24.2	26.4
Terrace Creek	II	3	858	2.8	3.4	0.4	11.0	8.9
Beak Creek	II	1	1354	14.3	3.5	0.5	ND	ND
240 Creek	II	2	1596	3.7	3.5	0.4	17.1	25.1
Ellis Creek (1)	II	2	1405	5.3	3.8	0.7	7.6	7.1
Ellis Creek (2)	II	2	1382	5.5	3.8	0.6	10.2	16.0
North Ellis Creek	II	3	1540	6.3	4.1	0.7	14.4	15.7
Joe Rich Creek	II	3	939	1.8	4.2	0.5	7.5	4.7
Lower Kettle	II	3	1357	3.3	4.2	0.5	16.1	22.5
Upper West Kettle	II	2	1418	1.7	4.5	0.6	6.5	7.5
Upper West Kettle (2)	II	2	1452	4.0	4.8	0.6	20.3	16.0
Upper West Kettle (1)	II	2	1512	2.2	4.9	0.6	4.7	8.8
Saunier Creek	II	3	1107	2.6	4.9	0.7	18.5	7.1
North Ellis Creek (2)	III	3	919	5.2	5.6	0.7	16.6	23.1
Wilkinson Creek 3	III	4	1507	2.7	5.7	0.7	15.5	16.5
Sterling Creek (2)	III	4	1038	1.3	6.2	0.6	14.5	17.6
Sterling Creek (1)	III	4	1005	3.1	6.4	0.6	7.6	8.7
Power Creek	III	3	1147	3.9	6.8	0.7	13.1	16.5
North Ellis Creek (1)	IV	4	1195	1.8	8.0	0.7	12.9	13.2
Bald Range Creek	IV	4	738	4.6	8.1	1.0	4.5	6.7
Upper West Kettle (3)	IV	3	1434	3.1	8.1	0.9	16.5	22.1
Wilkinson Creek (1)	IV	5	1348	4.3	9.4	0.7	17.4	12.5
Wilkinson Creek (2)	IV	4	1504	3.7	11.2	0.9	9.5	8.4
Upper West Kettle (4)	IV	5	1414	2.1	15.1	0.8	5.1	34.1

Size, stream size; Order, natural stream order; Elev., site elevation (m); Grad., mean stream gradient (%); Width, mean stream channel bankfull width (m); Depth, mean stream channel bankfull depth (m); L-slope, mean left stream bank slope (^{0}); R-slope, mean right stream bank slope (^{0}). ND means no data for that variable.

Each LWD piece was also identified as being either functional or non-functional. Functional LWD was defined as any piece that created pools, stored sediment, maintained bank stability, trapped smaller woody debris pieces (<10 cm in diameter), created steps or braced other LWD pieces either individually or in jams. Non-functional LWD were any pieces that did not provide any of the functions identified above. It is worth noting that each LWD piece may have multiple functions. For instance, one piece may function both in trapping small woody debris and creating pools. Thus, the identification of the function category of each LWD piece in the study was dependant on the primary observable feature of the piece in the stream.

A general qualitative definition of pools was used in this study: Still water, low velocity, smooth, glassy surface, usually deep compared to other parts of the channel. Pools are low points in the channel profile (Kaufmann and Robison, 1998). The elements that formed pools were also identified. These elements included LWD, rootwad, boulder/bedrock and fluvial processes that were not readily identifiable.

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Data analysis

Stream order varied from 1st order to 5th order streams within the studied watersheds. Based on site selection criteria, we randomly selected streams at each stream order for the study. Data of stream order and bankfull width were then used to set up the four stream size categories. Mean values of LWD density, volume and biomass among different stream channel sizes were tested for differences by LSMeans multiple range tests. Statistical analyses were performed using the analysis of variance (ANOVA) by SAS statistical software (SAS Institute Inc., 1999). We considered test results with significance levels (p values) of <0.05 to be significant. Regression analysis between LWD properties and geomorphologic features of study sites followed the least-squares method.

RESULTS

LWD loading and function in different sized streams

On average, more than half of the LWD, expressed either by number pieces or by volume, was identified as functional LWD (creating pools, bank stabilization, storing sediment, trapping small woody debris) within the four stream sizes (Figure 2). Furthermore, the percentage of functional LWD increased with the increase of stream channel size. For example, the percentage of functional LWD by volume was approximately 55% in stream size I, rose to 68% in stream size II and further increased to about 84% in stream sizes III and IV, meaning the larger the stream size, the more LWD was involved in creation of stream habitat. The maximum percentage of functional LWD occurred in stream size III although no significant differences were found in terms of percentage of functional LWD expressed either by number or by volume between stream sizes III and IV.

Among the functional LWD categories, most pieces served to stabilize stream banks and/or store sediment in stream sizes I, II and III, whereas in stream size IV, most of the functional LWD pieces served to trap small woody debris (Table II). No significant differences were found in terms of the proportion of LWD pieces that functioned in bank stabilization and sediment storage among the four stream size categories ($p > 0.05$). The percentage of LWD that functioned in the role of trapping small woody debris was significantly higher in stream size IV than in stream sizes I and II ($p < 0.05$). The proportion of LWD pieces that formed pools increased from stream size I to stream sizes II and III, and then decreased in the stream size IV.

Among the study stream sizes, LWD surface area was the highest in stream size II (28 m^2/100 m^2), followed by stream sizes III (25 m^2/100 m^2) and I (24 m^2/100 m^2), all of which were significantly higher than stream size IV (12 m^2/100 m^2) (Figure 3).

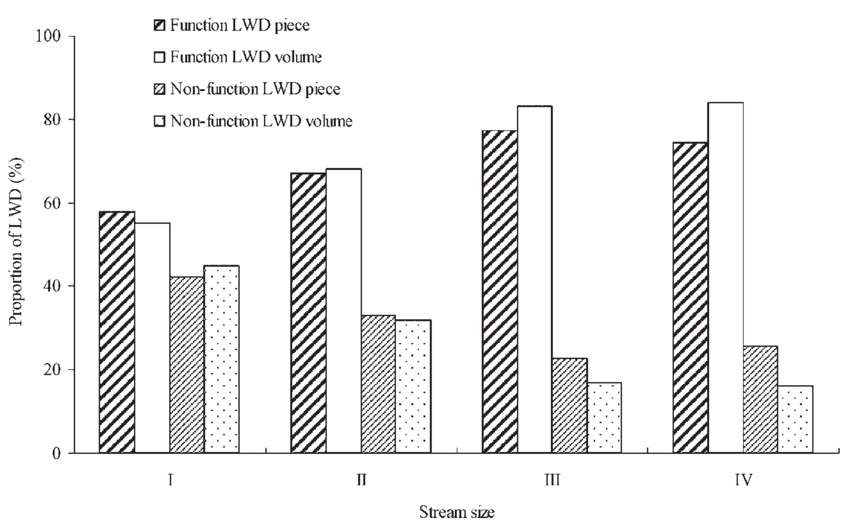

Figure 2. Proportion of functional and non-functional LWD pieces and volume within four stream size categories in forested watersheds in the southern interior of British Columbia. Stream size I: less than 3 m, Stream size II: 3–5 m, Stream size III: 5–7 m, Stream size IV: larger than 7 m

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Table II. Influence of LWD on the morphology of stream channels within four stream size categories in forested watersheds in the southern interior of British Columbia*

Stream size	Functional LWD pieces (%)				Non-functional LWD pieces (%)
	P	B	S	SWD	
I	3	20	24	11	42
II	5	29	23	10	33
III	5	25	25	22	23
IV	1	23	21	30	25

*P, pool formation; B, bank stabilization; S, stores sediment; SWD, trapping small woody debris.
Stream size I: less than 3 m, Stream size II: 3–5 m, Stream size III: 5–7 m, Stream size IV: larger than 7 m.

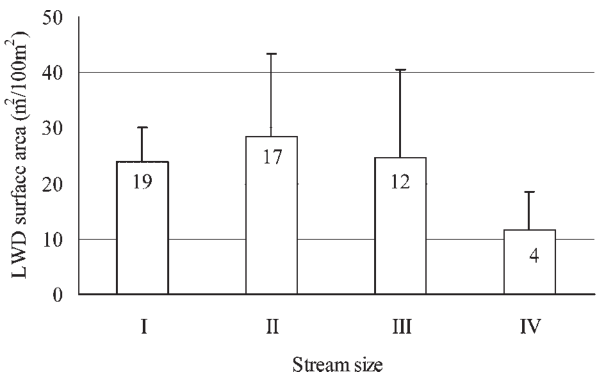

Figure 3. Mean LWD surface area per unit of stream area within four stream size categories in forested watersheds in the southern interior of British Columbia. Number within the bar is the sample size. Error bars correspond to standard errors. Stream size I: less than 3 m, Stream size II: 3–5 m, Stream size III: 5–7 m, Stream size IV: larger than 7 m

LWD orientation, position and stability within various sized streams

Besides LWD loading, the orientation, position and stability of LWD also determine the state of aquatic habitats. The majority of LWD pieces (63%) were perpendicular to the streamflow direction in stream size I, which was significantly higher than those in other stream size categories ($p < 0.05$). Conversely, more than 60% of LWD pieces were parallel to the streamflow direction in stream sizes II, III and IV (Figure 4). The differences in the proportion of LWD pieces parallel to streamflow for stream size I was significantly different from sizes II, III and IV

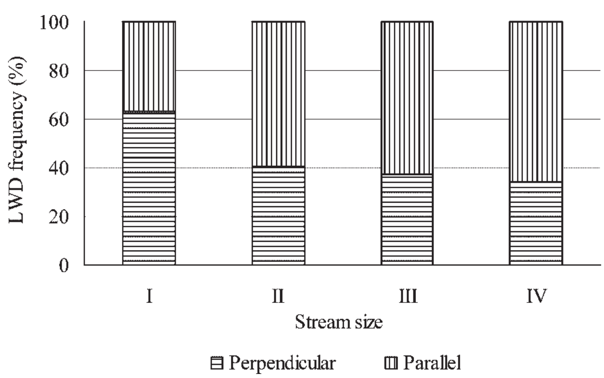

Figure 4. Frequency of LWD piece in two orientation categories (parallel and perpendicular to streamflow) within four stream size categories in forested watersheds in the southern interior of British Columbia. Stream size I: less than 3 m, Stream size II: 3–5 m, Stream size III: 5–7 m, Stream size IV: larger than 7 m

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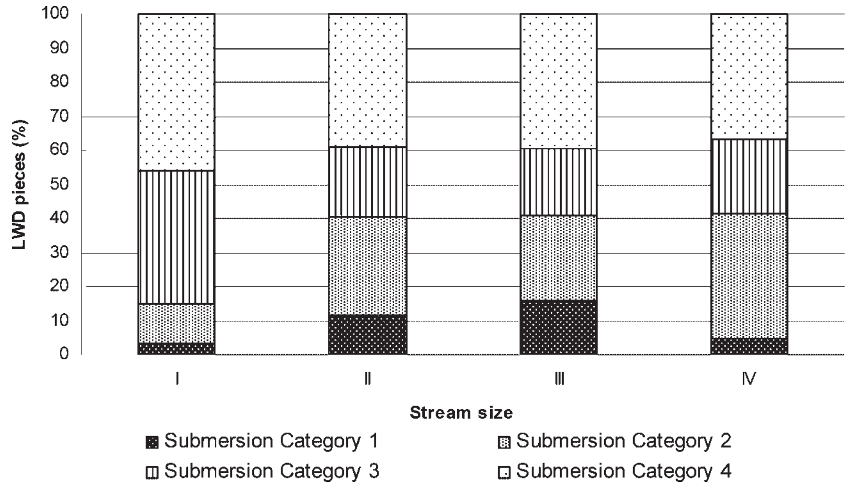

Figure 5. Frequency of LWD piece in four submersion categories within four stream size categories in forested watersheds in the southern interior of British Columbia. Stream size I: less than 3 m, Stream size II: 3–5 m, Stream size III: 5–7 m, Stream size IV: larger than 7 m

($p < 0.05$). Although the frequency of LWD pieces parallel to streamflow increased as the stream size increased, the differences of in the number of pieces parallel to streamflow were not significant among the stream sizes II, III and IV ($p > 0.05$).

LWD pieces which were completely situated within the lower half of the bankfull height of the channel and were lying along the streambed (submersion category 1) accounted for a very small proportion of LWD in both stream sizes I and IV (3% and 5%, respectively) (Figure 5), which was significantly lower than that in stream sizes II and III ($p = 0.04$ and $p = 0.02$, respectively). It means that more LWD pieces touched the streambed and streamflow in II and III streams than in I and IV streams. The percentage of pieces in submersion category 2 (LWD is situated in upper half of bankfull height) was significantly lower in stream size I than in stream sizes II, III and IV ($p < 0.05$). In other words, more than 40% of LWD pieces were within the bankfull height in stream sizes II, III and IV, while the corresponding value was about 15% in stream size I. The percentage of LWD that bridged the stream banks (submersion category 3) was about 40% in stream size I, which was approximately twice as much as stream sizes II, III and IV.

Approximately 40% of LWD pieces were longer than channel bankfull width (defined as stability category 1) in stream size I, which was significantly higher than in stream sizes II, III and IV) (Table III). In particular, in IV sized streams, a very small proportion of pieces were greater than the channel bankfull width (5%). However, more than 40% of pieces were braced by other pieces (stability category 2) in IV sized streams. The percentage of LWD pieces which were anchored or buried in the channel banks (stability category 3) was over 40% in all four stream sizes, and

Table III. Percentage of LWD within each stability category within four stream size sizes in forested watersheds in the southern interior of British Columbia*

Stream size	LWD stability (%)			
	1	2	3	4
I	39	45	10	6
II	15	56	18	11
III	18	40	28	14
IV	5	41	42	12

*Stability Category 1: greater than bankfull width, Stability Category 2: anchored or buried in the stream channel banks, Stability Category 3: braced by other pieces, Stability Category 4: loose in channel.
Stream size I: less than 3 m, Stream size II: 3–5 m, Stream size III: 5–7 m, Stream size IV: larger than 7 m.

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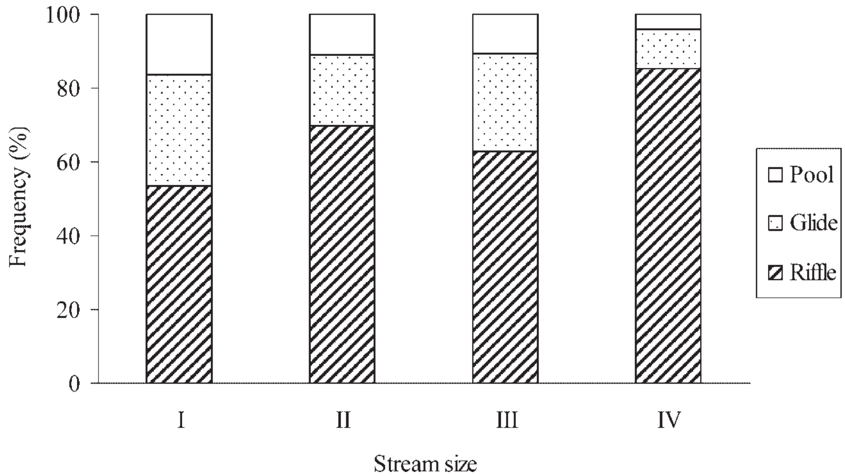

Figure 6. Relative distribution of riffles, glides and pools within four stream size categories in forested watersheds in the southern interior of British Columbia. Stream size I: less than 3 m, Stream size II: 3–5 m, Stream size III: 5–7 m, Stream size IV: larger than 7 m

no significant differences were found in terms of this stability category between the streams. LWD pieces that were loose in the channel accounted for small proportion of the total pieces. Approximately 6% and 10–15% of the total LWD was loose in the channel in I sized streams and in II, III and III sized streams, respectively.

Aquatic habitat features within the stream networks

In general, pools accounted for a small proportion of the total channel habitat features (riffle, glide and pool) in the study stream systems (Figure 6). On average, the percentage of riffles, glides and pools was approximately 50%, 30% and 20%, respectively in stream size I, 70%, 20% and 10% in stream sizes II and III, and 85%, 10% and 5% in stream size IV. No statistical differences were found among the four stream size categories in terms of the frequency of riffles, except between stream sizes I and IV ($p = 0.005$). Pool frequency significantly differs between stream sizes I and II ($p = 0.031$), and I and IV ($p = 0.02$).

The percentage of LWD pieces involved in pool formation varied with stream sizes. Almost all pools were created by LWD pieces in intermediate sized streams (Table IV). The percentage of pools formed by LWD was about 75% and 85% in stream sizes II and III, respectively. Approximately 50% of pools were created by LWD in stream size I and about 25% of pools were created by pieces in stream sizes IV. No significant differences were found in the percentage of LWD forming pools between stream sizes I, II and III, but the differences between sizes II and III and stream size IV were significant ($p < 0.05$). Almost all pools were created by boulders or bedrock in

Table IV. Percentage of LWD pieces involved in pool formation within four stream size categories in forested watersheds in the southern interior of British Columbia*

Stream size	Pool form (%)				
	W	F	S	B	R
I	51	32	6	10	0
II	74	7	1	11	5
III	85	3	0	4	8
IV	25	0	0	73	2

*W, large woody debris; F, fluvial; S, small woody debris; B, boulder or bedrock; R, rootwad.
Stream size I: less than 3 m, Stream size II: 3–5 m, Stream size III: 5–7 m, Stream size IV: larger than 7 m.

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Table V. Distribution of streambed substrate composition within four stream size categories in forested watersheds in the southern interior of British Columbia*

Stream size	Streambed substrate categories (%)				
	Sand	Gravel	Cobble	Boulder	Large boulder
I	25 ± 14	26 ± 14	38 ± 16	11 ± 11	0.0 ± 0.0
II	14 ± 15	14 ± 11	58 ± 18	14 ± 13	0.0 ± 0.0
III	20 ± 22	14 ± 14	47.8 ± 20	18 ± 10	0.2 ± 0.4
IV	4 ± 7	4 ± 8	60.7 ± 13	31 ± 14	0.3 ± 0.5

*Value: mean ± standard deviation; Sand: <0.2 cm; gravel: 0.2–6.4 cm; cobble: 6.4–25.6 cm; boulder: 25.6–100 cm; large boulder: >100 cm.
Stream size I: less than 3 m, Stream size II: 3–5 m, Stream size III: 5–7 m, Stream size IV: larger than 7 m.

stream size IV (73%), which significantly differs from those in stream sizes I, II and III ($p < 0.05$). In small streams, fluvial processes were the second most important factor in pool formation, which was statistically higher than those in intermediate and large streams ($p < 0.05$) (Table IV).

LWD and streambed substrate composition

Table V shows the substrate size composition in study stream systems. For all four stream size categories, the dominant substrate in the channel beds was the cobble group (range of 38–61%). Large boulders were seldom found in any of the study streams, especially in the stream sizes I and II. In stream size I, the percentage of sand and gravel particles in the total substrate was approximately 50%. The corresponding values were approximately 30% for stream sizes II and III, and <10% in stream size IV. Larger particles dominated in the large sized streams. More than 90% of particles were cobbles and boulders in stream size IV, and the corresponding values decreased to 70% and 50% in II and III sized streams and I sized streams, respectively. When compared to I, II and III sized streams, IV sized streams had a significantly lower percentage of sand and gravel, but had a significantly higher percentage of cobbles and boulders ($p < 0.05$).

DISCUSSION

LWD patterns in the watersheds

The accumulation and distribution of woody pieces in the stream channel network of a watershed are controlled by many factors including climate, geography, topography, hydrology and vegetation, as well as natural and human

Table VI. LWD features and impact on channel morphology in different sized streams in the southern interior of British Columbia*

LWD feature	Stream size			
	I	II	III	IV
Interact streambed	+	+++	++++	++
Perpendicular	++++	+++	++	+
LWD size	+	++	+++	++++
Functional LWD	+	++	++++	+++
Total pieces	++	+++	++++	+
Affecting pool	++	+++	++++	+

*Level of impact: + very weak; ++ weak; +++ significant; ++++ very significant.
Stream size I: less than 3 m, Stream size II: 3–5 m, Stream size III: 5–7 m, Stream size IV: larger than 7 m.

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disturbance. Such patterns of accumulation and distribution of woody debris along the stream networks determine the roles played by the woody debris. Our findings show that the frequency of functional LWD piece and volume increased with an increase of stream size in the study sites. These findings suggested that the potential functional ability possessed by LWD on aquatic environment was increased as stream size increased. Stream size and LWD length and orientation are attributed to the functional LWD distribution pattern in the watershed level. In generally, streams size increases as stream orders increase. Woody debris may more easily enter into the streams with the stream size increases. As a result, more woody debris is expected to be involved in various functional categories in high stream order.

Channel size plays an important role in the spatial distribution of LWD in the stream network (Chen *et al*., 2006). On the other hand, the structural features of LWD in different sized streams have different functional effects on stream morphology and aquatic environment through the channel networks. Our results confirm the relationships of LWD and channel size in terms of the structure and function in the stream systems (Bilby and Ward, 1989; Jackson and Sturm, 2002).

The major contrast in terms of LWD orientation among the small (size I), intermediate (sizes II and III) and large (size IV) sized streams was that the large proportion of LWD oriented parallel to streamflow in intermediate and large sized streams, whereas the majority of the LWD was oriented perpendicular to streamflow in the small sized streams. The high percentage of LWD in a perpendicular orientation in stream size I reflects the fact that most of the LWD that entered the studied streams was naturally oriented perpendicular to streamflow regardless of stream size in the study region. However, for small streams, the LWD is proportional greater than the bankfull width and most of the LWD is situated above the bankfull height and is therefore not subjected to stream flow. As a consequence, most of LWD piece does not rotate during normal flow in small streams.

In contrast to small streams, most pieces in the intermediate and large sized streams were found to be oriented parallel to the streamflow (Figure 4). Since the ratio of the average length of LWD to the bankfull width was small in these streams, pieces were more readily moved by streamflow in intermediate and large streams. In addition, the relatively higher proportion of LWD located below the bankfull height of the channel (Figure 5) reveals that most of the LWD is subjected to stream flow. Therefore, it is reasonable to deduce that most of LWD has been moved and rotated in the intermediate and large sized streams. Furthermore, LWD situated below the bankfull height plays an important role in stream systems because it can enter the channel bottom where it diverts flow and affects erosion and deposition (Mutz, 2000).

In stream networks in forest watersheds, LWD is constantly delivered from lower order streams (upstream) to higher order streams (downstream). Also, spatial heterogeneity needs to be considered when designing riparian management strategies to provide suitable LWD loading in forested watersheds. Such spatial variation of LWD loading will result in different distribution patterns of carbon and other nutrients, and thus form a variety of riparian and aquatic habitats through the channel network. As a consequence, the approach which is based solely on the application of research from the stream reach level or riparian stand level may not be appropriate for sustainable forest ecosystem management at the watershed scale (Jackson and Sturm, 2002).

LWD impacts on morphological features

We found that LWD played a greater role in forming pools in intermediate sized streams than in either small or large sized streams. Although the number of pieces was the highest in small streams, only a very small percentage of the total LWD pieces (3%) was situated in the streambed and directly impacted stream flow. Most pieces were not directly connected to the streambed in small sized streams. The number of functional LWD pieces was also small in these streams. Addition, because of the limited transport capacity, woody debris is usually abundant in headwater streams or lower order streams. As a result, the LWD impact on aquatic habitat in small sized streams is limited. The influence of LWD on aquatic habitat in large sized streams was also limited primarily because of the small number of LWD pieces and the high transport capacity of these streams.

Pools, riffles and glides are important components of channel habitat for fish and other aquatic biological organisms. They are also morphological features that reflect the distribution and dynamic of sediment supply to the stream network of the watersheds. The ratio of pools to riffles showed that there were fewer pools than riffles in all

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study stream sizes. Also, the frequency of riffles usually increases with the increase of stream size, while the frequency of pools decreases as the stream size increases (Jackson and Sturm, 2002). In our field survey, it was difficult to determine whether or not a stream unit was a pool in low flow conditions. Jackson and Sturm (2002) indicated that the definition of a pool is based upon fish habitat and may not be appropriate in non-fish bearing headwater streams. When using the standard requirement of a minimum residual pool depth of 10 cm, they could not find a pool in their survey of small channels. Therefore the methods used to define the pool in practice become an important factor in affecting the final results.

The contribution of LWD to pool formation in steam sizes II and III was 75% and 85%, respectively. These values were significantly higher than those in stream sizes I (50%) and stream size IV (25%). The results were consistent with other studies in the Pacific north-west in which the influence of LWD on pool formation ranged from 48% to 75% (Andrus *et al*., 1988; Montgomery *et al*., 1995; Richmond and Fausch, 1995; Beechie and Sibley, 1997). In this study, boulders or bedrock were primary factors in the pool formation in large streams (stream size IV) and they contributed about 73% of the total pool formation. The fluvial factor was the second largest contributor to pool formation in the small streams (stream size I) next to LWD, which significantly differed from those in the other three stream size categories.

In the study, effect of LWD piece on channel morphology is greater in intermediate sized streams (stream size II and III) than in small and large sized steams (stream sizes I and IV). Other researchers have pointed out that LWD generally has a limited effect on gradient, stream waterpower, maximum stream width and maximum bankfull depth (Andrus *et al*., 1988; Hauer *et al*., 1999). This is partially true because that as a stream gets larger, stream waterpower becomes sufficient to move virtually all wood that enters the channel (Hauer *et al*., 1999).

No obvious effects were found between LWD number and volume and streambed substrate composition within the study watersheds except the effects of LWD number and volume on boulder percentage. It suggested that the distribution of streambed substrate was mainly controlled by geological and hydraulic processes.

Management implications

During the past decades, management policies and regulations have been made relying only on data from larger streams (Jackson and Sturm, 2002). Watershed management strategies were also made from the data and information derived from reach scale. In this study, we found that structural characteristics of LWD piece vary with stream size, which result in different functional features of LWD through the channel network in the forested watersheds. Therefore, results from specific reach scale studies have limited applicability for developing forest management strategies for the whole ecosystems. LWD features and impacts on channel morphology for different sized streams in the southern interior of British Columbia are listed in Table VI.

Information on spatial distribution of LWD amount and size with changing stream sizes could be used in sustainable forest management strategies. In-stream LWD loading and its influence on aquatic habitats depends on stream size within a watershed. As a consequence, the strategies and management practices for LWD in sustainable forest ecosystem management should be made based on the heterogeneity of LWD at spatial scales. Our study shows various behaviours of in-stream LWD piece and its impacts on stream habitats along the stream networks:

(1) In the small sized streams (bankfull width less than 3 m), there are the highest proportion of non-functional pieces (>40%) and highest proportion of pieces perpendicular to the stream flow (>60%) and bridged to the stream bankfull width; a very small percentage of LWD (<3%) touched the stream flow; half of LWD was involved in the creation of pool habitat;

(2) In the intermediate sized streams (bankfull width between 3 and 7 m), there are high proportion of functional LWD pieces (>70%) and pieces parallel to stream flow (>60%); highest proportion of LWD touching the stream flow (>15%) and involved in the pool creation (>80%); half of pieces are anchored or buried;

(3) In the large sized streams (bankfull width larger than 7 m), there are high proportion of functional pieces (>70%) and parallel pieces (>60%); low proportion of LWD touching the stream flow (5%) but the having the high proportion of LWD toughed the flow when the flow is high (40%); 30% of LWD is functioned as to prevent the movement of small woody debris; lowest proportion of pieces is involved in the creation of pool.

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