Large woody debris in bull trout (*Salvelinus confluentus*) spawning streams of logged and wilderness watersheds in northwest Montana

F. Richard Hauer, Geoffrey C. Poole, John T. Gangemi, and Colden V. Baxter

Abstract: We measured large woody debris (LWD) in 20 known bull trout (*Salvelinus confluentus*) spawning stream reaches from logged and wilderness watersheds in northwestern Montana. Mean bankfull width of stream reaches was 14.1 m ranging from 3.9 to 36.7 m. Streams were large enough to move LWD and form aggregates. We determined the characteristics of individual pieces of LWD that were interactive with the stream channel. Large, short pieces of LWD attached to the stream bank were the most likely to be positioned perpendicular to stream flow, while large, long pieces either tended to be parallel to the flow or, when attached, were most apt to extend across the channel thalweg. Observations indicated that the majority of pools were formed as scour pools by either very large LWD pieces that were perpendicular to the stream or multipiece LWD aggregates. Among reaches in wilderness watersheds, ratios of large to small LWD, attached to unattached LWD, and with and without rootwads were relatively consistent. However, among reaches with logging in the watershed, these ratios varied substantially. These results suggest that logging can alter the complex balance of delivery, storage, and transport of LWD in northern Rocky Mountain streams, and therefore, the likely substantive change in stream habitats.

Résumé : Nous avons mesuré les gros débris ligneux (GDL) dans 20 tronçons de cours d'eau servant de frayères à l'omble à tête plate dans des bassins exploités par l'industrie forestière et des bassins sauvages du nord-ouest du Montana. La largeur moyenne des tronçons à pleins bords était de 14,1 m, avec une fourchette de 3,9 m à 36,7 m. Les cours d'eau étaient assez larges pour que les GDL se déplacent et forment des agrégats. Nous avons déterminé les caractéristiques des morceaux de GDL qui interagissaient avec le chenal. Les morceaux gros et courts attachés à la berge étaient les plus susceptibles de se positionner perpendiculairement au courant, tandis que les morceaux gros et longs se plaçaient parallèlement au courant ou, s'ils étaient attachés, étaient les plus susceptibles de se placer en travers du thalweg du chenal. Les observations ont montré que la majorité des fosses sont le résultat de l'affouillement causé soit par de très gros morceaux de GDL perpendiculaires au courant, soit par des agrégats composés de plusieurs morceaux de GDL. Parmi les tronçons des bassins sauvages, les rapports des gros aux petits GDL, des GDL attachés aux GDL non attachés, des GDL avec et sans attaches racinaires, étaient relativement constants, alors qu'ils variaient considérablement parmi les tronçons des bassins soumis à l'exploitation forestière. Ces résultats permettent de penser que l'exploitation forestière peut altérer l'équilibre complexe de l'apport, de l'installation et du transport des GDL dans les cours d'eau du nord des Montagnes Rocheuses, et donc occasionner des modifications potentiellement importantes des habitats lotiques.

[Traduit par la Rédaction]

Introduction

Large woody debris (LWD) plays numerous roles in the structure and function of stream ecosystems (Gregory et al. 1991). Riparian forests contribute LWD to a channel network, directly affecting both large- and small-scale stream morphology, hydrologic processes, and stream biota (Abbe and Montgomery 1996; Bisson and Montgomery 1996). Large wood accumulations influence the dissipation of stream energy and thus the ability of the stream to transport material. For example, LWD has been associated with channel avulsion, floodplain formation, and island development (Abbe and Montgomery 1996; Nanson and Knighton 1996). LWD also plays an important role in localized modification of streambed morphology (Bisson et al. 1987; Ralph et al. 1994) and pool frequency and channel geometry (Beschta and Platts 1986; Fausch and Northcote 1992; Richmond and Fausch 1995). The orientation and position of LWD in streams affect storage of organic and inorganic matter (Bilby and Ward 1989; Nakamura and Swanson 1993). Likewise, wood serves as trophic support of stream biota by providing organic matter for stream invertebrates and substratum for attachment and growth (Angermeier and Karr 1984; Benke et al. 1985; Hauer and Benke 1991).

The factors that directly affect introduction, stability, or character of stream LWD have a potentially significant influence on native fish populations that utilize streams for spawning, rearing, or growth and completion of life histories

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F.R. Hauer,[1] G.C. Poole,[2] J.T. Gangemi, and C.V. Baxter. Flathead Lake Biological Station, University of Montana, 311 BioStation Lane, Polson, MT 59860-9659, U.S.A.

[1]Author to whom all correspondence should be addressed. e-mail: rhauer@selway.umt.edu
[2]Present address: U.S. EPA, OEA-095, 1200 6th Avenue, Seattle, WA 98101, U.S.A.

(Andrus et al. 1988). Stream characteristics affected by LWD and its implications on salmonid populations have been the focus of numerous studies (e.g., Marcus et al. 1990; Ralph et al. 1994; Riley and Fausch 1995). A species of particular concern is the bull trout (*Salvelinus confluentus*), which has been in decline throughout the Pacific Northwest and was recently (1998) listed as a threatened species under the U.S Endangered Species Act. Numerous explanations for its decline have been offered, including habitat degradation (Fraley and Shepard 1989), overharvest (Rieman and McIntyre 1996), and displacement by exotic species (Leary et al. 1993).

Despite a generally ubiquitous trend of decline, the bull trout populations of the Flathead Basin in northwest Montana were considered relatively healthy, until recently. Strong spawning populations from Flathead Lake, Swan Lake, and Hungry Horse Reservoir have been an important part of the native fish fauna and an important sport fishery. In the past several years, however, the frequency of bull trout spawning in tributaries of the North and Middle forks of the Flathead River (i.e., the Flathead Lake population) has seriously declined (Rieman and Myers 1997). Overfishing, competitive interactions, predation of juveniles, food web alterations in Flathead Lake, and loss of habitat for spawning and rearing have all been suggested as causes for this decline. It is likely, however, that no single factor can be isolated as the overriding ecological bottleneck. Rather, all these factors influence the Flathead Lake population. For example, inundation of spawning gravels with fine sediments or changes in channel form and complexity may be major factors affecting the decline in bull trout spawning in the tributary drainages of the North and Middle forks of the Flathead River (Weaver and Fraley 1991). Low frequencies of spawning in some of the tributaries of the Swan River have been associated with the presence of logging roads (Baxter et al. 1999). Although the mechanisms that may be leading to the observed decline in bull trout are unclear, either on the landscape or in specific streams, hydrologic and vegetative changes associated with land use clearly play an important role. We suggest that a significant part of that role may be the result of change in the frequency, character, and distribution of in-stream LWD.

Although LWD plays an important role among streams in forested watersheds of the Pacific Northwest Coastal and Cascade Mountains (e.g., Nakamura and Swanson 1993; Ralph et al. 1994) and in the central Rocky Mountains (e.g., Fausch and Northcote 1992; Richmond and Fausch 1995), little information is available regarding the character or function of LWD in forested streams of the northern Rocky Mountains. The processes that have been documented among Washington and Oregon streams or streams in Colorado might not be seamlessly applicable in western Montana. Differences in climatic regime, landscape geomorphology, hydrologic regime, and the size, density, and longevity of dominant riparian species among these regions will have direct bearing on the interactive relationship between stream structure and function and LWD.

Regardless of the potential causes of bull trout population declines or the current cumulative effects impinging on the health and long-term viability of bull trout populations in western Montana, the maintenance of productive spawning and rearing habitat will be critical to the long-term sustainability or recovery of bull trout (see Fausch and Northcote 1992). As the recent changes in the food web of Flathead Lake come to some new quasi-equilibrium, with its cascading effects on higher trophic levels (Spencer et al. 1991), population restoration for bull trout will be strongly affected by reproductive success and juvenile survivorship. LWD may play a critical role in maintaining appropriate stream habitat and thus affect the long-term sustainability of bull trout populations in the Flathead Basin.

The purpose of this study is to describe the characteristics and selected functions of LWD among an array of historical bull trout spawning streams in the Flathead Basin. Although in several instances, redds occurred within a study reach, it was not our intention to specifically locate bull trout redds or covariation of redds and LWD. We selected streams from each of the four major tributaries in the drainage: the North and Middle forks of the Flathead River (Flathead Lake bull trout population), the South Fork of the Flathead River (Hungry Horse Reservoir population), and the Swan River drainage (Swan Lake population). We also chose streams that represented different types and levels of land use. Streams in the North Fork and Swan River include tributary drainages with extensive logging and riparian clearcuts. Streams in the Middle and South forks were within Glacier National Park or designated wilderness, respectively. The primary objectives of the research were to (*i*) characterize LWD in known bull trout spawning streams of the Flathead Basin, (*ii*) examine relationships of LWD size, position, and orientation across an array of stream sizes, (*iii*) examine the role of LWD in affecting local-scale bedform and stream morphology, and (*iv*) examine the potential effect of land use and (or) riparian logging on the size frequency structure, orientation, and decay relationships of LWD.

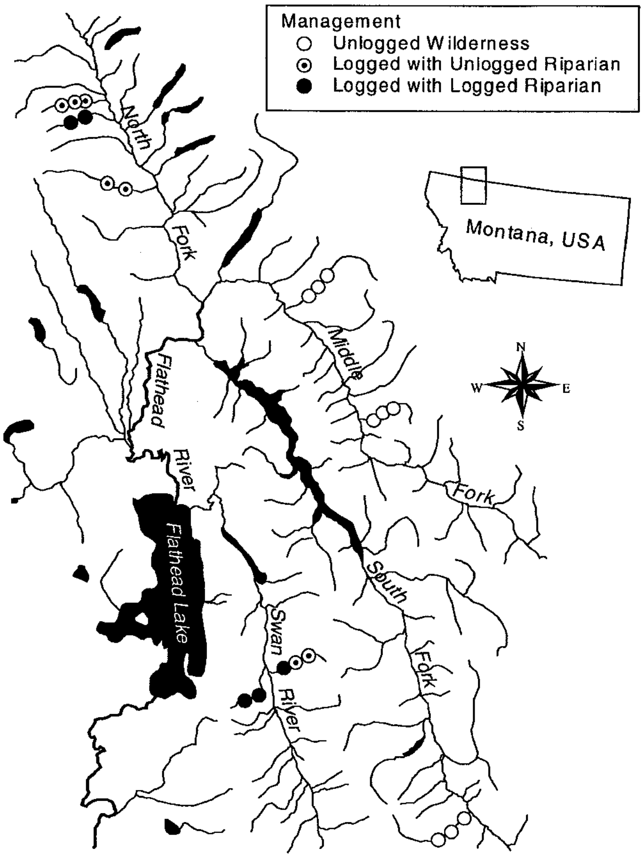
Materials and methods

Study area

This study was conducted in the Flathead Basin, a 22 241-km^2 drainage in northwestern Montana and southeastern British Columbia, along the west slope of the Continental Divide and within the belt series of the northern Rocky Mountains (Fig. 1). Sedimentary bedrock from the late Paleogene to the Proterozoic underlies the region and has been affected by low-grade metamorphosis. These mountain ranges are part of the Rocky Mountain Belt Supergroup and consist of argillites, siltites, and carbonates with a maximum stratigraphic thickness of 5200 m (Whipple et al. 1984). Colluvium and glacial till mantle the heavily forested valleys. During the height of the last major glaciation, about 20 000 years ago, the Flathead Basin was covered by glacial ice. The main glacial advance flowed from the cordilleran ice sheet down the Rocky Mountain Trench. Smaller valley glaciers flowed from the Livingston, Whitefish, Swan, Flathead, and Mission ranges to merge along the valley floors, forming trunk glaciers as much as 1000 m thick. Alluvial valley segments of tributary drainages formed with faulting and local accumulations of valley fill from alluvial and glacial sources.

Twenty stream reaches were selected from a stratified random design for study from eight streams distributed around the basin (Fig. 1). All reaches were in third- or fourth-order segments. We consulted the Montana Department of Fish, Wildlife, and Parks

Fig. 1. Map of the Flathead Basin and northern Continental Divide region of northwest Montana showing the names of major river drainages and study stream reaches in unlogged wilderness watersheds (open circles), logged watersheds with unlogged riparian (encircled dots), and logged watersheds with logged riparian (solid circles).



and selected study reaches within known bull trout spawning tributaries. We selected study streams within watersheds that had a land use history of either logging or wilderness management. Additionally, we selected specific study reaches within streams based on prevalent streamside management within the watershed. In some cases, as in Red Meadow Creek, the selected reaches flowed through riparian clearcuts, which occur commonly along that stream's length. Among other streams, such as Ole Creek in Glacier National Park, the riparian zone along the study reach was in an unaltered condition.

The substratum of each study reach was similar, generally composed of gravel and cobble, although occasionally, larger boulders (50–100 cm) were also present. The drainage area above the study reaches varied from 23 290 ha on Young's Creek to 1610 ha on Red Meadow Creek (Table 1).

Stream channel

Stream cross-sectional profiles, sinuosity, and gradient were measured at each stream reach using an Abney level, a Sonin® electronic distance measurer, and a leveling rod. Eleven transects (A–K) were taken across each stream reach at 10-m intervals covering a total reach length of 100 m. Each transect consisted of channel profiles measured perpendicular to the stream thalweg and to the top of the bankfull channel on both sides of the stream. Typically, 8–12 measures were taken to develop the cross-sectional profile at each transect. The profile data included all major breaks in elevation, the wetted channel width, water depth at the thalweg (at the time of measure), and height of the average bankfull channel. The change in bed height and water depth between each transect profile was measured using the Abney level, electronic distance measurer, and leveling rod. The 10-m intervals between each transect were identified as a stream section and referenced to the downstream transect.

LWD measurements

Measures of LWD were made within each 10-m stream section between each transect. LWD was defined as logs ≥10 cm in diameter and ≥1 m in length. Although there are no standard criteria established as to the minimum size that constitutes LWD, the criteria used here are the same as used in research at other locations (Andrus et al. 1988; Fausch and Northcote 1992; Richmond and Fausch 1995). Each piece of wood meeting the LWD criteria was measured if any part occurred within or was suspended above the bankfull stream channel. The diameter was measured at each end of the LWD piece with a 1-m caliper. The length of each piece was measured with the electronic distance measurer if the length was >2 m or with the caliper for shorter pieces. Piece volume was calculated as a tapered cylinder (Lienkaemper and Swanson 1987). All large rootwads were considered LWD regardless of length. Stumped rootwads with a length <1 m were common among streams with logged riparian areas. Volume of rootwads was estimated by measuring the diameter of the root structure across the dominant mass as one end of the cylinder, the bole of the tree stump above the root structure as the other end of the cylinder, and the distance between these measurements as the tapered cylinder length. The position and orientation of LWD to the channel were determined for each LWD piece. Piece position was recorded as one of three possibilities: (*i*) no contact with either bank, (*ii*) contacting either the left or right bank, or (*iii*) contacting both banks. In addition to simply contacting a bank, many pieces were strongly "attached" to one or, rarely, both banks. We classified an LWD piece as being attached if either or both ends were anchored into the stream bank.

Orientation of LWD is known to affect stream flow and bed morphology (Robison and Beschta 1990). Likewise, stream power affects piece orientation because hydraulic forces move unattached ends in a downstream direction (Nakamura and Swanson 1994). Piece orientation was divided into three categories: (*i*) at an about 0° angle (parallel) to the channel, (*ii*) at an about 45° angle to the channel, and (*iii*) at an about 90° angle (perpendicular) to the channel. We also noted whether an LWD piece had a rootwad attached to the bole, since this plays an important function in the attachment, orientation, and distribution dynamics of the piece.

The relative age of each piece was assessed using a modification of the Grette (1985) decay classification procedure, which divided LWD into four decay classes: (1) bark and branches attached, (2) bark and branches missing; wood solid with evidence of decay restricted to the outer perimeter, (3) wood showing significant signs of decay to at least depths of 5–10 cm, and (4) wood soft and decayed nearly or completely to the center of the piece. We later combined categories 3 and 4 for our analysis because of the infrequency of observing type 4 decay class LWD. We believe that the scarcity of decay class 4 wood is due to the rapidity of final decay and disappearance once a piece undergoes a transition from decay class 3 to class 4.

Data analyses

We conducted a variety of statistical analyses including χ^2, correlation analysis, ANOVA, and MANOVA using the statistical analysis software SPSS for Windows by SPSS, Inc. We considered test results to be significant at $\alpha = 0.95$.

Table 1. River drainage, stream name, watershed area above study reaches, number of pieces in aggregates or not in aggregates, and other characteristics of LWD.

Flathead River drainage	Stream Name	Drainage area (ha)	Reach and logging condition	LWD aggregate (no.)	LWD nonaggregate (no.)	LWD volume (m^3)	LWD attachment	
							Attached	Unattached
Middle Fork	Ole Creek	10 295	A[a]	0	13	8.8	5	8
			B[a]	18	11	7.4	17	12
			C[a]	0	32	30.8	7	25
	Nyack Creek	22 005	A[a]	0	7	0.4	1	6
			B[a]	0	5	3.0	2	3
North Fork	Red Meadow Creek	1 612	A[c]	10	41	35.9	35	16
			B[c]	53	70	73.3	95	28
	Whale Creek	9 836	A[b]	0	56	14.3	26	30
			B[b]	0	87	19.4	37	50
			C[b]	39	52	58.9	59	32
	Coal Creek	12 113	A[b]	51	72	33.3	57	66
			B[b]	11	25	19.8	19	17
South Fork	Young's Creek	23 289	A[a]	145	39	73.2	90	94
			B[a]	49	28	18.6	49	28
			C[a]	0	37	10.1	17	20
Swan River	Jim Creek	3 705	A[c]	71	46	65.2	72	45
			B[c]	0	46	10.9	35	11
	Goat Creek	5 602	A[b]	16	45	18.1	31	30
			B[b]	35	35	20.4	49	21
			C[c]	27	48	56.7	54	21

Note: Diameter class: 1 = 10–19 cm; 2 = 20–29 cm; 3 = 30–39 cm; 4 = 40 cm.
[a]Reach in unlogged wilderness watershed.
[b]Reach in logged watershed with unlogged riparian.
[c]Reach in logged watershed with logged riparian.

Results and discussion

General characteristics of study reaches

Mean (±SD) bankfull widths among all stream reaches combined were 14.2 ± 6.6 m with a range of 3.9–36.7 m across all transects. Study reaches were variable, both between and within streams. Stream gradients among all reaches were moderate (mean 1.0%, maximum 2.6%) but again highly variable. The thalweg bed elevation of some downstream transects was higher than that of upstream transects, clearly illustrating streambed complexity.

Five of the 20 study reaches had one or more side channels. In cases where side channels were present, there was always one dominant channel. The side channels were always small with only minor flow. Side channels in two stream reaches contained a high density of LWD and likely were abandoned main channels.

Thalweg stream depths across all transects ranged from a minimum of 0.15 m in Ole Creek reach A to a maximum of 1.33 m in Young's Creek reach C. An examination of the relationship between drainage area and stream depth showed a significantly, positive correlation (p = 0.016) with stream maximum depths; however, neither mean nor minimum stream depth was significantly correlated with basin size (Fig. 2).

General characterization of LWD

A total of 1320 pieces of LWD were counted and measured among all study reaches. The number of pieces and volume of LWD across all reaches were highly variable (Table 1). For example, reach A on Young's Creek had 184 pieces, while, in contrast, reach B on Nyack Creek had only five pieces of LWD.

Across all stream reaches, the size of the LWD was also extremely variable. About 70% of all LWD was in the smaller two diameter classes (10–19 cm: >35%; 20–29 cm: >30%) (Fig. 3A) and >50% of the LWD was between 1 and 4 m in length (Fig. 3B). Size frequency of diameter measures and tree length measures demonstrated a decreasing exponential curve with increasing piece size. Together, <50% of the LWD across all stream reaches consisted of pieces >30 cm in diameter and >4 m in length. However, as in other studies (e.g., Abbe and Montgomery 1996), we found that the larger LWD pieces played the primary role in streambed configuration and the formation of aggregates (see data analysis below). LWD pieces that had been moved by the stream into large debris jams, or aggregates, often spanned the stream channel and were extremely stable, owing to their mass and configuration with the stream banks and the LWD pieces within the jam.

Other studies have found that LWD attachment to one or both banks and (or) the presence of the tree's rootwad are important factors influencing the stability (i.e., the resistance to being moved during flood) and orientation of the LWD piece (Beschta and Platts 1986; Richmond and Fausch 1995). Among nonaggregated LWD, we found attachment to one or both banks and the number of pieces that had rootwads to be highly variable, commensurate with the high variation in LWD occurrence between stream reaches (Table 1). However, we did find statistically significant relation-

0° by diameter class				45° by diameter class				90° by diameter class				Rootwad	
1	2	3	4	1	2	3	4	1	2	3	4	With	Without
1	0	1	0	2	3	1	4	1	0	0	0	6	7
4	3	0	1	4	3	2	3	4	2	1	2	2	27
4	6	3	4	3	4	1	1	1	1	0	4	7	25
2	0	0	0	3	1	0	0	0	0	0	0	0	7
2	1	1	0	0	0	0	0	0	0	0	1	1	4
2	4	5	4	3	3	2	4	3	10	3	8	9	42
3	7	1	4	5	18	9	12	8	15	13	28	8	115
13	19	3	1	10	2	2	2	4	0	0	0	1	55
19	14	6	3	18	13	6	1	2	3	2	0	0	87
13	14	14	5	11	13	3	1	5	7	0	5	17	74
33	20	3	4	17	17	6	6	10	6	1	0	4	119
7	2	2	3	5	2	0	1	5	4	3	2	2	34
16	16	8	5	43	29	20	9	12	10	5	9	27	157
11	7	2	1	20	9	3	10	4	4	2	3	15	62
6	4	0	4	9	4	4	0	3	2	0	1	5	32
9	8	2	3	19	19	8	8	7	14	9	11	18	99
7	3	0	2	13	7	1	2	5	0	3	2	2	44
6	7	1	2	6	2	2	1	9	13	4	8	8	53
15	5	3	3	9	7	1	4	7	9	1	6	6	64
4	5	2	4	7	3	4	8	9	9	4	16	20	55

ships between the orientation of the LWD piece, the attachment of the piece to the bank, and both the volume and the length of the LWD piece. Using χ^2 analysis, we found that LWD tends to be significantly shorter among those pieces that are perpendicular to the stream flow (orientation 90°) than among those that are parallel (orientation 0°) to stream flow (Table 2). This is likely due to longer pieces being subject to rotation around an anchor point, such as a bank attachment, during flooding when stream power and floatation of the LWD are at their highest (Nakamura and Swanson 1994). We found a similar significant relationship of increased LWD piece diameter associated with pieces that were perpendicular to the channel compared with those parallel to the channel (Table 2). We also observed that bank attachment often extended a considerable distance onto the bank and back into the riparian vegetation. These pieces were often the most stable and demonstrated resistance to change in orientation.

In addition to girth and length influencing stream LWD position, we also examined the affect of LWD attachment on orientation. A χ^2 analysis revealed that LWD pieces that were perpendicular to the current had a significantly higher frequency of bank attachment (Table 3). We found these features to be particularly important, since perpendicular pieces were the most interactive with the stream channel in that they were often most responsible for change in streambed morphology and complexity (see LWD influence on streambed morphology below). We also examined LWD wood decay (Table 1). We found that among all stream reaches, most LWD was in decay class 2, i.e., most pieces had been stripped of their bark and branches and showed only the earliest signs of rotting at the surface. This finding has the following implications: (*i*) most of the wood has been in the stream for at least several years, long enough to loose the outer bark and limbs, but not so long as to enter advanced decay stages and (*ii*) the paucity of decay classes 3 and 4 suggests that once an LWD piece enters the latter stages of decay, decomposition processes occur rapidly. The latter stages of decay may be strongly enhanced during spring runoff as increased stream power causes decomposing logs to break apart. We did not conduct tests to directly determine the rate of LWD decomposition; however, based on our knowledge of aggregate accumulations at sites that we have visited regularly since the mid-1970's, we know that LWD can remain >20 years with no signs of surface decomposition. Thus, it appears that LWD probably remains in these streams for periods exceeding 50 years (sensu Andrus et al. 1988). To summarize, those pieces that were perpendicular to the flow tended to be attached to the stream bank, large in diameter, and short. This finding corroborates Nakamura and Swanson (1994).

LWD influence on streambed morphology

An important feature of stream habitat structure is the development and stability of streambed morphology. Streams that alternate between riffles, pools, and runs provide complex habitats that support high biodiversity, biomass, and secondary production of aquatic insects and fish. Complex

Fig. 2. Maximum, mean, and minimum thalweg depths among all transects for each stream reach regressed against the drainage area of each watershed above the study area. The maximum thalweg depth to basin area correlation coefficient ($r = 0.51$) is significant at the 0.05 level. Correlations between mean and minimum thalweg depths and basin area were nonsignificant.

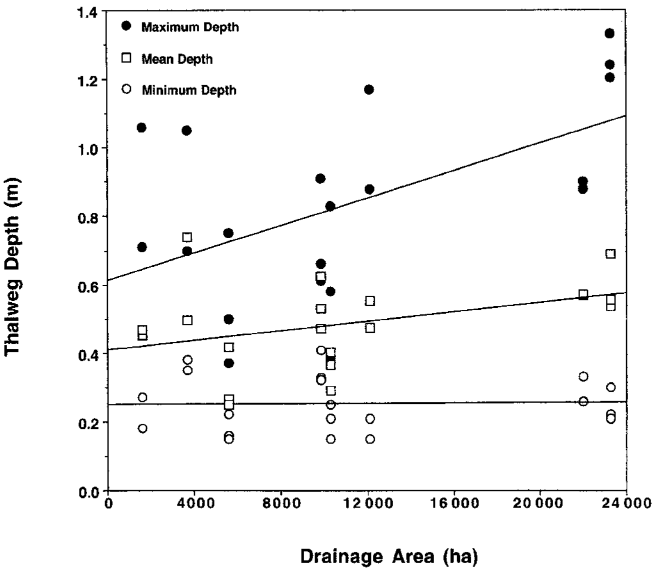
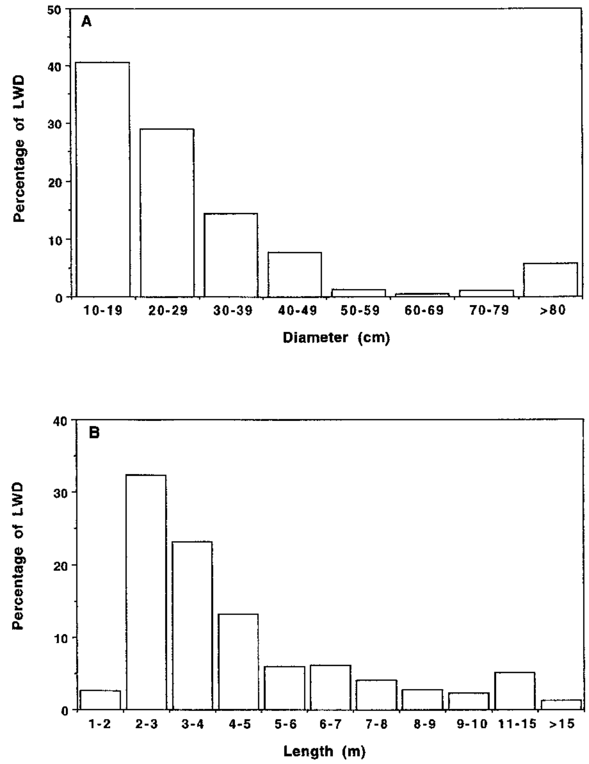


Fig. 3. Percentage of LWD in each of (A) eight bole diameter classes and (B) 11 length classes.



variation in stream habitat and streambed morphology is frequently required for different species to coexist (sensu Connell 1980).

Using correlation analysis, we examined the role of LWD and its influence on streambed morphology. We found that as the number of pieces of LWD and the volume of LWD increased within a stream section, there was a corresponding increase in the bedslope of the section immediately downstream (Fig. 4). The steepest bedslopes were all associated with upstream aggregates, large snags with rootwads, or large-diameter LWD oriented perpendicular to the stream thalweg. Each of these LWD structures performs important bed-forming functions, e.g., the retention of gravel on the upstream side of the structure and (or) the focus of stream flow and thus stream power and scour on the downstream bed material forming pools. Both of these factors lead to the aggradation of upstream gravel and cobble and the downstream degradation of bed material. These correlations between increased LWD piece frequency and volume and bedslope underscore the importance of LWD aggregates in stabilizing bedload, capturing gravel, and promoting pool formation.

Land use influence on LWD

Three of the eight watersheds (eight of 20 study reaches) examined were located within Glacier Park or the Bob Marshall Wilderness. These three watersheds are managed as wilderness and have never been logged or roaded. The other five watersheds are in the North Fork or the Swan River drainages and flow through lands managed for multiple use, but primarily for timber harvest.

We found a tight correlation ($r = 0.99$) between the frequency of large LWD (≥30 cm in diameter) and the frequency of small LWD (<30 cm in diameter) among the reaches draining wilderness areas (Fig. 5). In contrast, among reaches in watersheds with upstream logging, the large to small LWD relationship was poorly correlated ($r = 0.18$). These data suggest that even though variation in number of pieces of LWD among stream reaches may be high, there is a consistent and highly predictable relationship between the frequency of large-diameter trees and small-diameter trees in the LWD pool in wilderness watersheds that was not present in logged watersheds. In addition to the cross-watershed comparison of LWD size ratios, we further compared streams flowing through logged riparian zones with those flowing through unlogged riparian zones, but in logged watersheds. Among the logged watersheds, we found that streams flowing through logged riparian zones tended to have a higher large LWD to small LWD ratio than streams flowing from wilderness areas, while streams flowing from logged watersheds, but with unlogged riparian zones, usually had smaller ratios (Fig. 5).

We also examined the relationship of attachment of LWD to the stream bank. Again, we found that among wilderness watersheds, there was a relatively tight correlation ($r = 0.94$) between the frequency of attached LWD and the frequency of unattached LWD and a poorly correlated relationship ($r = 0.30$) among logged watersheds (Fig. 6). Additionally, we examined the relationship between the frequency of LWD pieces with rootwads and the frequency of those without rootwads. Again, among reaches in wilderness watersheds, there was a high correlation ($r = 0.96$) between LWD pieces with rootwads and those without rootwads, but among logged watersheds, this relationship was poorly correlated ($r = 0.13$) (Fig. 7).

Table 2. Chi square analysis of length and bole diameter versus attachment and orientation characteristics of nonaggregate LWD among all stream study reaches.

	Attachment characteristic			Orientation characteristic			
LWD characteristic	Attached	Unattached	Pearson χ^2	0°	45°	90°	Pearson χ^2
Length <4 m	219	155	0.05 ($p = 0.82$)	108	150	116	38.0 ($p < 0.00$)
Length ≥4 m	184	135		153	121	45	
Diameter <30 cm	236	232	35.4 ($p < 0.00$)	190	191	87	17.7 ($p < 0.00$)
Diameter ≥30 cm	167	58		71	80	74	

Table 3. Chi square analysis of attachment and orientation characteristics of nonaggregate LWD among all stream study reaches.

Attachment	Orientation characteristic			
characteristic	0°	45°	90°	Pearson χ^2
Attached	127	156	120	27.5 ($p < 0.00$)
Unattached	134	115	41	

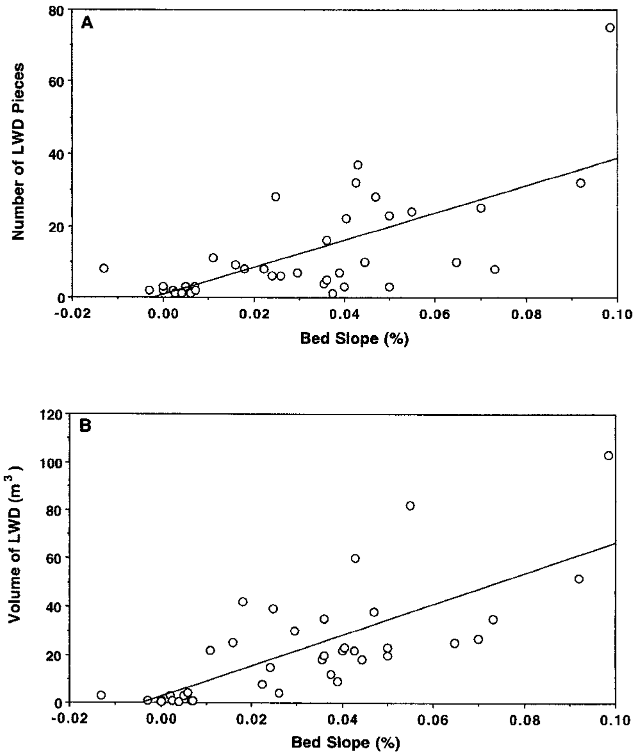
Among all watersheds, there was high variance in the frequency of LWD. Furthermore, LWD is not evenly distributed at the stream reach (100 m) spatial scale. However, the ratio of large to small LWD, the ratio of attached to unattached LWD, and the ratio of LWD with and without rootwads were relatively consistent across stream reaches in wilderness areas. However, among stream reaches in logged watersheds, these relationships were highly variable. These data suggest that logging or associated land use activities within a watershed may result in an alteration in the balance of delivery, storage, and transport of stream LWD, which in turn would have strong implications regarding effects on material transport and stream habitats.

It would require additional, focused study to determine the cause and effect relationship between size, attachment, and rootwad frequencies of stream LWD and specific logging practices. However, regardless of whether increased variance in size frequency is the result of direct actions that alter LWD input to the stream (e.g., cutting of large-diameter riparian trees) or indirect forces (e.g., postlogging blowdown), they may contribute to LWD characteristics that depart from relationships among streams in unlogged watersheds. Such departures may result in substantive habitat alteration and adverse effects on species dependent on habitats affected by stream LWD structure and function, such as pool size and frequency, surface/ground water exchange, and complex channel morphology.

Implications for watershed and streamside management

We found a close association between LWD and streambed morphology. For example, the steepest bedslopes were all associated with upstream aggregates of LWD. Among nonaggregated LWD, we found large pieces attached to stream banks and oriented perpendicular to the thalweg to be more closely associated with pool formation than parallel or unattached pieces. Among LWD pieces that were oriented perpendicular to stream flow and crossed the stream thalweg, there was a statistically significant higher frequency of long pieces (i.e., ≥4 m in length), a nearly significant proportion of large pieces (i.e., ≥30 cm in diameter), and a statistically significant higher frequency of LWD pieces attached to the stream bank (Table 4). These field observations suggest that LWD pieces that are perpendicular to the stream channel and engage the stream thalweg are the primary influence promoting pool formation. Field measurements further indicate that of the perpendicular LWD pieces, large-diameter pieces that are long and attached to the stream bank are the most stable (e.g., best able to resist reorientation and movement once in the channel). Grette (1985) and Richmond and Fausch (1995) also reported a significant positive relationship between LWD and the abundance of pools, as well as the importance of relatively few, stable LWD pieces that accounted for most of the pool formation.

Fig. 4. (A) Number of LWD pieces and (B) volume of LWD in the upstream 10-m stream section and the corresponding downstream bedslope.



Wohl et al. (1993) reported that stream depth, gradient, stream power, and the resistance of bed and bank materials to erosion were important determinants of pool size. We observed a similar relationship in which the streams of the larger drainages had the deepest pools, even though drainage size had no significant effect on mean or minimum thalweg

Fig. 5. Frequency of large-diameter (≤30 cm) versus small-diameter (<30 cm) LWD among study stream reaches in wilderness watersheds (solid circles) and in logged watersheds (open circles). Arrows denote study stream reaches with logged riparian areas. The trend line is for wilderness watersheds. Correlation coefficients are given in the text.

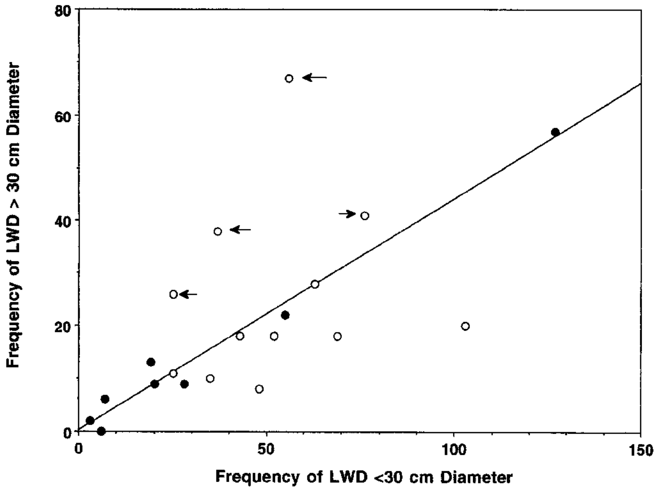


Fig. 6. Frequency of unattached versus attached LWD among study stream reaches in wilderness watersheds (solid circles) and in logged watersheds (open circles). The trend line is for wilderness watersheds. Correlation coefficients are given in the text.

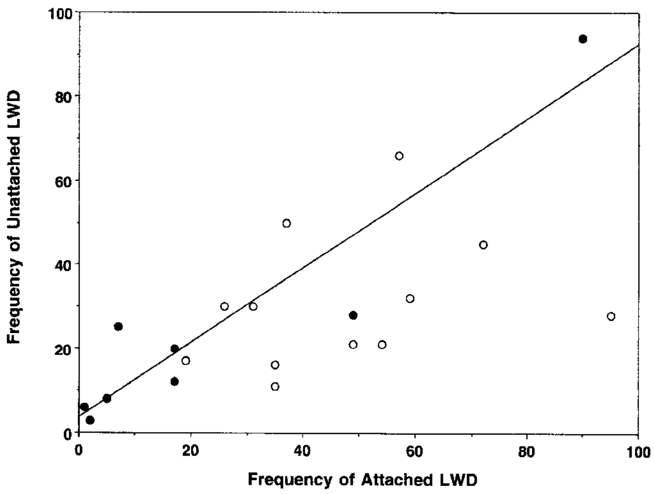


Fig. 7. Frequency of LWD with rootwad versus without rootwad among study stream reaches in wilderness watersheds (solid circles) and in logged watersheds (open circles). The trend line is for wilderness watersheds. Correlation coefficients are given in the text.

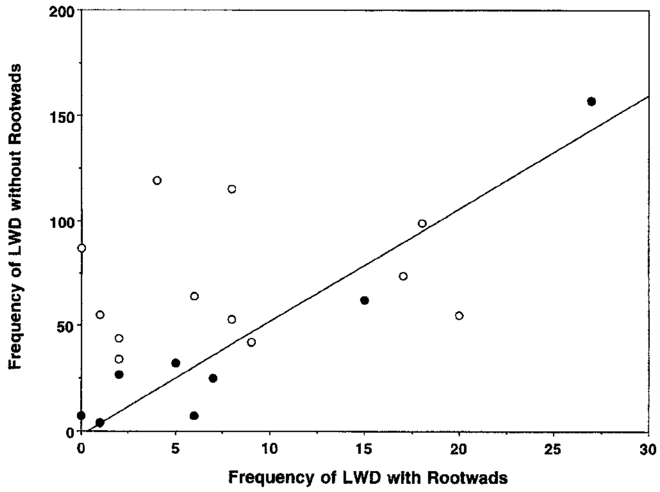


Table 4. Chi square analysis of length, bole diameter, and attachment characteristics of nonaggregate LWD crossing the stream channel and engaging the stream thalweg versus LWD within the bankfull channel but not engaging the stream thalweg.

	Crossing characteristic		
LWD characteristic	Across thalweg	Not across thalweg	Pearson χ^2
Length <4 m	40	321	6.64 (p = 0.01)
Length ≥4 m	56	254	
Diameter <30 cm	57	396	3.38 (p = 0.07)
Diameter ≥30 cm	39	179	
Attached	66	324	5.20 (p = 0.02)
Unattached	30	251	

depth. Other researchers have suggested that for large streams and rivers, LWD generally has a limited effect on gradient, stream power, maximum stream width, and maximum bankfull depth (Andrus et al. 1988; Evans et al. 1993). Our results support this suggestion, since within the largest watershed streams, such as Young's Creek, pool-forming LWD pieces occurred almost exclusively as aggregates (Table 1). In other words, as a stream gets larger, exemplified by Young's Creek in our study, stream power becomes sufficient to move virtually all wood that enters the channel. However, this does not mean that as stream size increases, LWD becomes of little consequence but rather that the role of LWD may change as aggregates interact with the dynamics of flood waters affecting anabranching and (or) avulsion behavior (e.g., Nanson and Knighton 1996).

Robison and Beschta (1990) and Richmond and Fausch (1995) showed that changing relationships between LWD and stream flow influenced pool types and that the majority of pools were formed by LWD spanning the channel perpendicular to flow. Richmond and Fausch (1995) found plunge and dammed pools to be the most prevalent pool type in the small subalpine streams of Colorado. Bilby and Ward (1989) found a similar pool type in smaller streams (<7 m wide) in southwestern Washington, but mainly scour pools in large streams (Bilby and Ward 1991). We observed similar situations among streams in the Flathead Basin where pools in the smaller streams (e.g., Goat Creek, Red Meadow Creek) were primarily associated with plunging or dammed water around LWD and with scour pools around aggregates in the largest streams (e.g., Young's Creek, Coal Creek).

In forested watersheds, LWD is an essential component in the formation of stream morphology and provides habitat for aquatic insects and fish. However, the relationship between stream size and power and the position and role played by LWD in the modification of bedform and channel development is a changing one. It is apparent from this study that large-diameter, shorter pieces of LWD attached to the stream bank have a higher frequency of perpendicular orientation and that larger, longer pieces attached to the bank tend to interact with the channel, as represented by those logs that cross the thalweg. Thus, a greater degree of pool-forming interaction with stream flows is represented by large, long pieces of LWD attached to the stream bank. Likewise, as the stream size increases, a concurrent increase in the size of LWD comprising an aggregate is needed to remain stable and interactive with the channel. Thus, the interaction of stream power, bed characteristics, and LWD piece diameter, length, and position largely determines the structure and function of stream LWD. The distribution of LWD among size classes, and attachment and orientation categories appears relatively consistent across streams in unlogged watersheds but becomes less predictable in streams that have been influenced by logging. A detailed investigation into the specifics of various logging histories would be necessary to determine how specific site prescriptions affect the outcome of LWD relationships associated with forest streams.

The implications of this study for forest managers are twofold: (*i*) with riparian logging comes increased unpredictability in the frequency of size, attachment, and stability of the LWD and (*ii*) maintaining the appropriate ratios of size frequency, orientation, and bank attachment, as well as rate of delivery, storage, and transport of LWD to streams, is essential to maintaining historic LWD characteristics and dynamics. Our data suggest that exclusion of logging from riparian zones may be necessary to maintain natural stream morphology and habitat features. Likewise, careful upland management is also necessary to prevent cumulative effects that result in altered water flow regimes and sediment delivery regimes. While not specifically evaluated in this study, in general, it appears that patterns of upland logging over space *and* time may have cumulative effects that could additionally alter the balance of LWD delivery, storage, and transport in fluvial systems. These issues will be critical for forest managers attempting to prevent future detrimental environmental change or setting restoration goals for degraded bull trout spawning streams (cf. Reeves et al. 1991).

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References

Abbe, T.B., and Montgomery, D.R. 1996. Large woody debris jams, channel hydraulics and habitat formation in large rivers. Regul. Rivers, **12**: 201–221.

Andrus, C.W., Long, B.A., and Froehlich, H.A. 1988. Woody debris and its contribution to pool formation in a coastal stream 50 years after logging. Can. J. Fish. Aquat. Sci. **45**: 2080–2086.

Angermeier, P.L., and Karr, J.R. 1984. Relationship between woody debris and fish habitat in a small warmwater stream. Trans. Am. Fish. Soc. **113**: 716–726.

Baxter, C.V., Frissell, C.A., and Hauer, F.R. 1999. Geomorphology, logging roads and the distribution of bull trout (*Salvelinus confluentus*) spawning in a forested river basin: implications for management and conservation. Trans. Am. Fish. Soc.

Benke, A.C., Henry, R.L., III, Gillespie, D.M., and Hunter, R.J. 1985. Importance of snag habitat for animal production in southeastern streams. Fisheries (Bethesda), **10**: 8–13.

Beschta, R.L., and Platts, W.S. 1986. Morphological features of small streams: significance and function. Water Resour. Bull. **22**: 369–379.

Bilby, R.E., and Ward, J.W. 1989. Changes in characteristics and function of woody debris with increasing size of streams in western Washington. Trans. Am. Fish. Soc. **118**: 368–378.

Bilby, R.E., and Ward, J.W. 1991. Characteristics and function of large woody debris in streams draining old-growth, clear-cut, and second-growth forests in southwestern Washington. Can. J. Fish. Aquat. Sci. **48**: 2499–2508.

Bisson, P.A., and Montgomery, D.R. 1996. Valley segments, stream reaches, and channel units. *In* Methods in stream ecology. *Edited by* F.R. Hauer and G.A. Lamberti. Academic Press, New York. pp. 23–52.

Bisson, P.A., Bilby, R.E., Bryant, M.D., Dolloff, C.A., Grette, G.B., House, R.A., Murphy, M.L., Koski, K V., and Sedell, J.R. 1987. Large woody debris in forested streams in the Pacific Northwest: past, present, and future. *In* Proceedings of the Symposium on Forest Hydrology and Watershed Management. *Edited by* E.O. Salo and T.W. Cundy. Publ. 167. International Association of Hydrologic Sciences, Wallingford, Oxfordshire. pp. 191–198.

Connell, J.H. 1980. Diversity and the coevolution of competitors, or the ghost of competition past. Oikos, **35**: 131–138.

Evans, B.F., Townsend, C.R., and Crowl, T.A. 1993. Distribution and abundance of coarse woody debris in some southern New Zealand streams from contrasting forest catchments. N.Z. J. Mar. Freshwater Res. **27**: 227–239.

Fausch, K.D., and Northcote, T.G. 1992. Large woody debris and salmonid habitat in a small coastal British Columbia stream. Can. J. Fish. Aquat. Sci. **49**: 682–693.

Fraley, J., and Shepard, B. 1989. Life history, ecology and population status of migratory bull trout (*Salvelinus confluentus*) in the Flathead Lake and River system, Montana. Northwest Sci. **63**: 133–143.

Gregory, S.V., Swanson, F.J., McKee, W.A., and Cummins, K.W. 1991. An ecosystem perspective of riparian zones. BioScience, **41**: 540–551.

Grette, G.B. 1985. The role of large organic debris in juvenile salmonid rearing habitat in small streams. M.S. thesis, University of Washington, Seattle, Wash.

Hauer, F.R., and Benke, A.C. 1991. Rapid growth of snag-dwelling chironomids in a blackwater river: the influence of temperature and discharge. J. North Am. Benthol. Soc. **10**: 154–164.

Leary, R.F., Allendorf, F.W., and Forbes, S.H. 1993. Conservation genetics of bull trout in the Columbia and Klamath River drainages. Conserv. Biol. **7**: 856–865.

Lienkaemper, G.W., and Swanson, F.J. 1987. Dynamics of large woody debris in stream in old-growth Douglas-fir forests. Can. J. For. Res. **17**: 150–156.

Marcus, M.D., Noel, L.E., and Young, M.K. 1990. Rating salmonid habitat research needs in the central Rocky Mountains. Fisheries (Bethesda), **15**: 14–18.

Nakamura, F., and Swanson, F.J. 1993. Effects of coarse woody debris on morphology and sediment storage of a mountain stream system in western Oregon. Earth Surf. Processes Landforms, **18**: 43–61.

Nakamura, F., and Swanson, F.J. 1994. Distribution of coarse woody debris in a mountain stream, western Cascade Range, Oregon. Can. J. For. Res. **24**: 2395–2403.

Nanson, G.C., and Knighton, A.D. 1996. Anabranching rivers: their cause, character and classification. Earth Surf. Processes Landforms, **21**: 217–239.

Ralph, S.C., Poole, G.C., Conquest, L.L., and Naiman, J.R. 1994. Stream channel morphology and woody debris in logged and unlogged basins of western Washington. Can. J. Fish. Aquat. Sci. **51**: 37–51.

Reeves, G.H., Hall, J.D., Roelofs, T.D., Hickman, T.L., and Baker, C.O. 1991. Rehabilitating and modifying stream habitats. Am. Fish. Soc. Spec. Publ. **19**: 519–557.

Richmond, A.D., and Fausch, K.D. 1995. Character and function of large woody debris in subalpine Rocky Mountain streams in northern Colorado. Can. J. Fish. Aquat. Sci. **52**: 1789–1802.

Rieman, B.E., and McIntyre, J.D. 1996. Spatial and temporal variability in bull trout redd counts. N. Am. J. Fish. Manage. **16**: 132–141.

Rieman, B.E., and Myers, D.L. 1997. Use of redd counts to detect trends in bull trout (*Salvelinus confluentus*) populations. Conserv. Biol. **11**: 1015–1018.

Riley, S.C., and Fausch, K.D. 1995. Trout population response to habitat enhancement in six northern Colorado streams. Can. J. Fish. Aquat. Sci. **52**: 34–53.

Robison, E.G., and Beschta, R.L. 1990. Coarse woody debris and channel morphology interactions for undisturbed streams in southeast Alaska, U.S.A. Earth Surf. Processes Landforms, **15**: 149–156.

Spencer, C.N., McClelland, B.R., and Stanford, J.A. 1991. Shrimp stocking, salmon collapse and eagle displacement: cascading interactions in the food web of a large aquatic ecosystem. BioScience, **41**: 14–21.

Weaver, T.M., and Fraley, J. 1991. Fisheries habitat and fish populations. Flathead basin forest practices, water quality and fisheries cooperative program. Flathead Basin Commission, Kalispell, Mont.

Whipple, J.W., Connor, J.J., Raup, O.B., and McGimsey, R.G. 1984. Preliminary report on the stratigraphy of the Belt Supergroup, Glacier National Park and the adjacent Whitefish Range, Montana. *In* Northwestern Montana and adjacent Canada. *Edited by* J.D. McBride and P.B. Garrison. Mont. Geol. Soc. Field Conf. Guideb. Montana Geological Society, Billings, Mont. pp. 33–50.

Wohl, E.E., Vincent, K.R., and Merritts, D.J. 1993. Pool and riffle characteristics in relation to channel gradient. Geomorphology, **6**: 99–110.