LANCASTER

Chapter 17

SPATIAL AND TEMPORAL EVOLUTION OF SMALL COASTAL GRAVEL-BED STREAMS: INFLUENCE OF FOREST MANAGEMENT ON CHANNEL MORPHOLOGY AND FISH HABITATS

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ABSTRACT

Spatial and temporal response of stream channels to natural and forest-management-related disturbance was studied in 12 watersheds, including 34 internal sub-basins, in the Queen Charlotte Islands of British Columbia, Canada. These coastal watersheds have a range of logging histories and the channels have experienced natural landslide impacts spanning more than a century. Longitudinal surveys covered almost 44 km of channel, including 1193 and 1547 channel widths in forested and logged watersheds, respectively.

A direct link exists between landslide occurrence and channel morphology. Landslides initiate large woody debris (LWD) jams in these streams. Logging on steep hillslopes accelerates landslide frequency, with a corresponding increase in the number of recently formed debris jams. Specific morphological changes occur upstream and downstream of the jams, impacting fish spawning, egg incubation and rearing habitats. Streams associated with these young jams are characterized by extensive riffles, shallow pools, less stable bars and an increased frequency, extent and duration of dry channel beds; all contribute to fish habitat degradation.

Influence of debris jams on channel morphology changes over time as jams deteriorate. Channel morphology is radically altered during the first decade following landslide inputs but begins to resemble undisturbed conditions after approximately 35 years. Complex and diverse channels are typical after 50 years. Historical forest management of coastal watersheds

Klingeman, P.C., R.L. Beschta, P.D. Komar, + J.B. Bradley, eds., Water Resources Publications, LLC, Highlands Ranch, CO *has led to a shift in the age distribution of LWD jams. Future management must ensure that any shift in landslide frequency, and therefore debris jam age distribution, be minimized to maintain channel and fish habitat integrity.*

17.1 INTRODUCTION

A central goal of forest and watershed management in British Columbia has been to minimize changes in sediment and debris production and delivery to streams, avoid changes to runoff patterns, and eliminate direct disturbance of channel banks and beds. To accomplish this, harvesting plans are designed to avoid landslide- and erosion-prone terrain, limit harvest rates, ensure high standards of road building and maintenance, and prohibit tree-falling and yarding adjacent to streams (Anon, 1995). However, past practices were not as carefully applied and serious environmental impacts on stream channels and aquatic ecosystems have been widespread (Tripp, 1994).

The long-term response and recovery (on the order of a century) of small streams to past forest management disturbances has seldom been determined by previous studies. Most studies have concentrated on identifying specific channel impacts and their logging related causes and have generally speculated at the temporal duration of the impact. Sullivan *et al.* (1987) reviewed channel recovery rates and processes in four research areas of the United States. They summarize many of the studies conducted in Northern California, Central Idaho, Western Oregon Cascades, but all of these rivers are relatively large compared to the small streams in coastal British Columbia. They show that in most cases the channel bed aggrades, bank stability is reduced as the channel widens, and pools are infilled in response to increased sediment inputs due to landslides. The time required for the recovery of streams to pre-disturbance conditions varied from 5 to over 60 years. The recovery time depends upon sediment input characteristics (e.g., location along the stream system, amount and particle size distribution, the form and structure of the riparian zone). Therefore, streams respond in specific ways to both natural and logging related sediment inputs and the recovery response time of a stream system can be variable.

In addition to changing sedimentation and hydrological characteristics of a watershed, logging has been shown to have a pronounced influence on the introduction and storage of large woody debris (LWD) to streams. The influence of LWD **pieces** on channel morphology has been investigated for more than two decades (cf. Thomson, 1991). LWD is an integral component of stream ecology (Hartman & Scrivener, 1990) and influences both physical and biological characteristics of small and moderate sized streams (channels with widths less than or equal to the length of in-stream debris). In comparison, little has been written about the importance of LWD accumulations (log jams) on channel morphology.

There is a direct and critical link between stream channel morphology and in-stream fish habitats. Pacific salmon, trout and char (salmonids) use stream environments for specific phases of their life cycle. Special conditions are needed for successful spawning, the development and hatching of eggs, and the growth and survival of their young (Toews & Brownlee, 1981). Salmonids spawn in riffles composed of clean, stable gravel with well-oxygenated flows. Certain species require stable pools to rear in for periods of time ranging from months to years (young fish use pools hiding from predators, feeding, and growth before migrating to the sea). Young salmonids (fry and juveniles) may also require access along the stream channel into tributaries and side-channels. Returning adults require an unobstructed migration path between the ocean and the stream spawning grounds.

This chapter identifies and describes the long-term response of stream channels to increased sediment loadings due to both natural factors and forest management practices in small coastal streams on the Queen Charlotte Islands (see Hogan *et al.* in press for a review of channel morphology and fish/forestry interactions in coastal British Columbia). The small streams are generally steep and highly influenced by hillslope processes. They have a range of natural disturbances histories, with hillslope failure events documented back to the 1820s and impacts from logging that began 40 years ago. The main focus is on LWD jam characteristics (origin, function, longevity) because they are a major factor controlling the long term evolution of channel morphology and fish habitats. The studies considered herein rely on extensive longitudinal surveys of channels.

17.2 ENVIRONMENTAL SETTING AND DATA COLLECTION

17.2.1 Watershed Selection

The Queen Charlotte Islands are located approximately 80 km west of Prince Rupert in north coastal British Columbia (Figure 17.1). The islands are characterized by abundant salmon-producing streams (Northcote *et al.* 1984), large areas of steep terrain underlain by highly erodible bedrock (Alley & Thomson, 1978), and several soil types prone to mass movement (Wilford & Schwab, 1982). The incidence of slope failure is also high because the islands have a predominately wet climate and experience frequent seismic activity. Average annual precipitation exceeds 3,600 mm along the west coast, but Williams (1968) estimates this may reach 7,000 mm on coastal mountain ranges. The seismic activity is due to the location of the Queen Charlotte faultline separating the Juan de Fuca/Explorer and America plates (Sutherland Brown, 1968; Church, in press)

An extensive channel evaluation began in 1988 to explore the temporal and spatial relations between stream channel morphology and forestry activities. Channel surveys were undertaken over longitudinal profile lengths of 2,740 channel widths (W_b) (a total of 43.7 km) in 12 watersheds on the Queen Charlotte Islands (Figure 17.1); 1,193 and 1,547 W_b were in forested and logged watersheds, respectively. Generally, watersheds were selected for analysis by their range of biophysical and land-use characteristics (Table 17.1). Four of the watersheds have intact old-growth forests (one of which has only a relatively small portion logged) while the remainder have experienced various levels and methods of logging over the last 50 years. The older logging

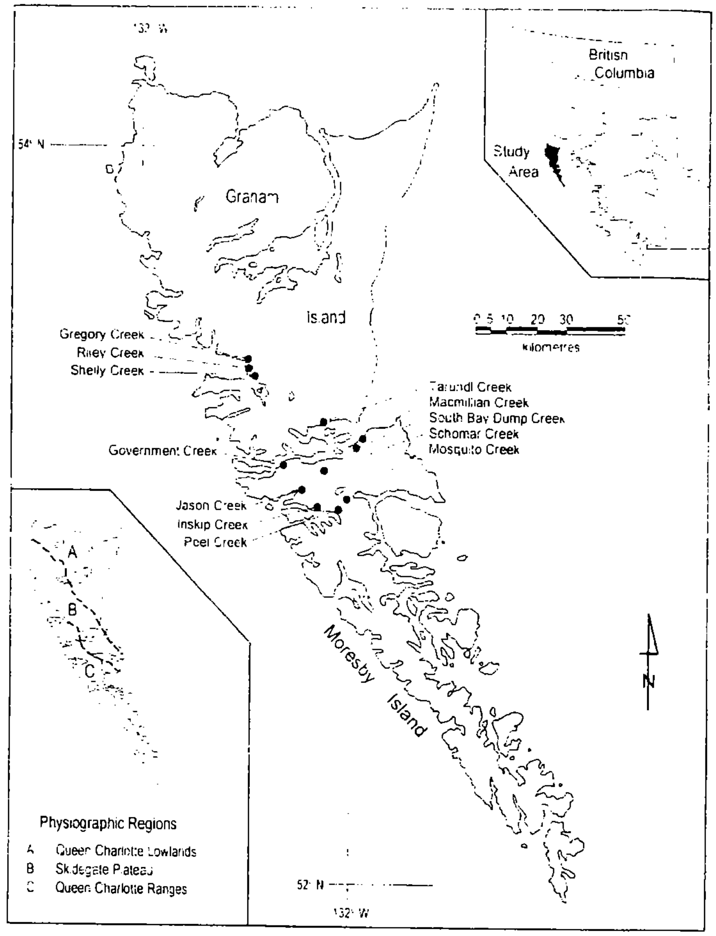


Figure 17.1. Location map of the Queen Charlotte Islands, British Columbia.

methods, involving large clear-cuts and high-lead yarding systems, usually included cutting to the stream bank; buffers along the stream banks were not common in British Columbia prior to 1988.

Where appropriate, watersheds were divided into sub-basins based on the aerial photographic interpretation of consistent channel reach characteristics (e.g., valley flat-channel relations, homogeneous channel pattern, and discharge (Kellerhals *et al.* 1976)). The characteristics of each sub-basin (34 in total) are shown in Table 17.2. Sub-basins have been grouped using a multivariate procedure developed by Cheong (1992). This procedure calculates a dissimilarity matrix among sub-basins (based on 14 morphologic and morphometric parameters) that can be analyzed by cluster analysis. Assuming that the expected response of a watershed to disturbance is determined in part by certain fundamental aspects of basin morphology and morphometry, basins deemed 'similar' by Cheong's method of analysis are expected to develop similar channel morphologies.

Table 17.1. General characteristics of selected Queen Charlotte Islands watersheds.

Creek	Basin Area (km^2)	% Steep Land	% Valley Flat	Relative Relief (m)	Precipitation (mm/year)	Physiography	Geology		% Basin logged	Years since logging		Logging Method	Logging to Channel Bank
							Dominant	Subdominant		started	stopped		
Vancouver Island													
Carnation	11.2	39	6	800	>2100	ECP	Bo		45	1976	1981	Cable yarding	Yes
Queen Charlotte Islands													
Government	16.5	24	15	490	>3600	QCR	K	BI+SC/KU	0				
Gregory	35	24	2	850	>3600	SP	Y	S+M	2	15	9	High Leads	Yes
Inskip	10.3	70	1	1050	>3600	QCR	K	BI+SC/KU	0				
Jason	9.3	57	6	840	>3600	QCR	K	BI+SC/KU	0				
MacMillan	6	25	0	655	>3600	SP	H	HO	77	46	8	High Leads	Yes
Mosquito	17.6	55	15	1140	>3600	QCR	K		65	45	25	Skid & High Leads	Yes
Peel	11.2	71	1	1050	>3600	QCR	K	M+BI	15	30-40	30-40	High Leads	Yes
Riley	27.6	29	12	870	>3600	SP	Y	CS+M	12	14	9	High Leads	Yes
Schomar	7.3	25	4	655	>3600	QCR	Y		36	26	15	High Leads	Yes
Shelly	5.2	56	0	750	>3600	SP	Y	S+CS	17	19	18	High Leads	Yes
SBD	3.7	16	0	655	>3600	SP	HO	H	82	30	10	High Leads	Yes
Tarundl	10.9	18	0	990	>3600	SP	C	BI+SC	37	27	9	High Leads	Yes

Notes:

Physiography: SP=Skidegate Plateau; QCR=Queen Chorlotte Ranges; ECP=Estevan Coastal Plain. For more details see Sutherland Brown (1968) and Holland (1976).

Geology:
- HO=Honna (conglomerate, sandstone)
- H=Hadia (clastic sedimentaries)
- S=Sandilands (orgillite, siltstone, tuff, sandstone)
- Y=Yakoun (shale, siltstone, sandstone, conglomerate, volcanics);
- K=Karmunsten (mafic volcanic flows, flow breccia, pillow flows, limestone)
- C=Cretaceous shale (shale, siltstone, sandstone)
- BI=Burnaby Island (diorite, monzodiorite, equigranular, quartz)
- SC=San Christoval Plytonic (diorite, monzodiorite, equigranular, quartz)
- KU=Kunga Group (argillite, siltstone, sandstone, tuff)
- M=Masset (volcanics, aphyric, mafic to felsic flows, pyroclastic)
- CS=Cretaceous Sandstone (sandstone, conglomerate, shale)
- Bo=Bonanza (Jurrasic volcanics)

Table 17.2. Typical terrain characteristics of five watershed types used to compare forested and logged streams.

Sub-basin	Watershed					Reach		
	Total area (km^2)	Steepland area (%)	Valley flat area (%)	Gradient (%)	Relative relief (m)	W_b (m)	LWD (m^3/m^2)	Gradient (m/m)
GROUP A								
Government Main	16.5	25	15	29	490	32.3	0.108	0.006
Gregory Upper Main	31.3	24	2	29	830	31.7	0.070	0.013
Gregory Lower Main	35.0	24	2	30	850	31.7	0.054	0.011
Riley Lower	27.6	28	12	18	870	26.7	0.064	0.009
$\bar{X}$	**27.6**	**25**	**8**	**27**	**760**	**30.6**	**0.074**	**0.010**
s	**7.9**	**2**	**7**	**6**	**180**	**2.6**	**0.024**	**0.003**
GROUP B								
Government NB	7.0	19	10	27	490	20.7	0.157	0.017
Government Upper Main	6.7	30	19	30	490	18.5	0.111	0.014
Gregory NB	7.7	0	0	23	520	13.6	0.037	0.027
Mosquito Main	17.8	54	13	46	1120	25.8	0.036	0.009
Mosquito Lower Tributary	14.0	66	7	49	1090	16.1	0.073	0.022
Riley Headwaters	6.0	30	3	33	560	17.7	0.025	0.013
Schomar Upper	6.2	26	0	34	560	15.7	0.037	0.029
Schomar Lower	7.3	25	4	33	620	15.9	0.021	0.015
Tarundl	10.9	18	0	27	990	15.8	0.107	0.018
Gregory Lower SB	17.3	33	3	32	760	14.7	0.026	0.018
Riley Middle	15.0	30	5	32	690	26.5	0.063	0.015
Gregory Upper SB	13.9	35	4	31	620	17.1	0.106	0.018
Riley Upper	11.9	32	2	35	640	17.6	0.069	0.024
$\bar{X}$	**10.9**	**31**	**5**	**33**	**710**	**18.1**	**0.067**	**0.018**
s	**4.4**	**16**	**6**	**7**	**220**	**4.0**	**0.042**	**0.006**
GROUP C								
Government NB East Fork	4.2	29	2	30	470	18.1	0.105	0.025
MacMillan	6.0	25	0	31	660	10.3	0.030	0.056
Inskip Main	10.3	70	1	52	1050	30.9	0.054	0.019
Jason Lower	9.3	57	6	47	840	21.8	0.069	0.011
Peel	11.2	71	1	54	1050	15.6	0.072	0.028
Jason Upper	7.3	62	1	49	800	22.3	0.060	0.018
Mosquito Upper	9.8	50	13	44	1090	35.7	0.104	0.018
Mosquito Back Channel	8.4	58	5	44	1080	26.0	0.007	0.014
$\bar{X}$	**8.3**	**53**	**4**	**44**	**880**	**22.6**	**0.063**	**0.024**
s	**2.4**	**17**	**4**	**9**	**230**	**8.2**	**0.034**	**0.014**
GROUP D								
Inskip NB	5.0	54	0	52	950	18.5	0.118	0.058
Inskip SB	5.0	84	2	53	1010	19.3	0.238	0.046
Mosquito Upper Tributary	5.4	81	11	60	1080	13.2	0.066	0.023
South Bay Dump	3.7	16	0	34	660	13.5	0.034	0.030
Shelly Lower	5.2	56	0	49	750	11.6	0.029	0.037
Shelly Upper	4.6	59	0	45	700	13.4	0.066	0.050
$\bar{X}$	**4.8**	**58**	**2**	**49**	**860**	**14.9**	**0.092**	**0.041**
s	**0.6**	**24**	**4**	**9**	**180**	**3.2**	**0.078**	**0.013**
GROUP E								
Government NB North Fork	1.7	0	12	27	440	11.7	0.177	0.059
Riley Tributary 5	1.1	36	0	32	38[illegible]	9.4	0.081	0.083
Riley Tributary 6	1.3	31	0	35	4[illegible]	10.3	0.238	0.073
$\bar{X}$	**1.4**	**22**	**4**	**31**	**400**	**10.5**	**0.165**	**0.072**
s	**0.3**	**20**	**7**	**4**	**30**	**1.2**	**0.079**	**0.012**

Five watershed groups were identified. Typical sub-basin characteristics of each group are summarized in Table 17.2. Assuming small steep basins are relatively sensitive to adjustments on surrounding hillslopes, channel response to landslides and forestry activities is expected to increase accordingly from Group A through E. Overall, basin and valley flat area decreases from Group A through E, while steepland area and gradient increases.

17.2.2 Field Methods

Detailed longitudinal profiles were surveyed with an automatic level, stadia rod, and surveyors hip chain. Several measurements were made at set intervals along the channel (details included in Hogan, 1989). The survey interval of one bankfull channel width was selected objectively from regional drainage basin area-channel width relations for forested and non-mass wasted watersheds (Hogan, 1986). Water surface, bar top, and bank top elevations were determined at each W_b interval, as well as the b-axis of the largest surface stone visible on the bed.

All LWD (including jams, steps and individual pieces) were categorized at each survey interval according to piece size and shape (length, mean diameter and condition of root wad), position in the channel (orientation and vertical position), and function (bed and bank sediment trapping or scouring). A LWD jam is defined as a major accumulation of debris (either currently or over the last decades where remnants are still evident) that alters(ed) the channel morphology and downstream sediment transport. The age, volume and location of each jam was also recorded. Jam age was determined from the ages of nurse trees and bar/bank vegetation using a standard increment tree bore.

All morphological features (e.g., pools, glides, riffles and runs) were surveyed along the longitudinal profile; morphological breaks were included in addition to the set interval survey point. These were identified in the field by their topographic, sedimentological, and hydraulic characteristics as defined by Keller and Melhorn (1973) and Sullivan (1986). Bankfull, wetted, and valley floor widths were measured at the five W_b interval. General changes in riparian vegetation size and species were noted.

17.3 THE CONNECTION BETWEEN HILLSLOPES AND STREAM CHANNELS

17.3.1 Forestry Activities and Landslides

Forestry activities can influence the amount, timing and nature of sediment and water moving through a stream system. As a result, channel morphology can be altered and this in turn can lead to habitat degradation. The impacts of forestry activities have been studied intensively over the last several decades (e.g., Salo & Cundy, 1987: Hartman & Scrivener, 1990; Chatwin *et al.*, in press). In general, logging and related activities have led to increased levels of sediment entering channels. Excess loads of coarse-textured materials tend to promote bed aggradation leading to expanded bars and riffles, in-filled pools, and bank erosion. The gravel composition of riffles can become less suitable for egg incubation due to increased proportions of fine sediments (<1 mm) within the gravels. Egg-to-fry survival rates can also be reduced because enlarged riffles are less stable and more prone to deep scouring, down to the level of egg deposition. Logging debris left along streams can block main-stem and side-channel access. A complete description of impacts on fish habitat associated with logging and mass wasting on the Queen Charlotte Islands is given by Tripp and Poulin (1986 a,b; 1992).

The Queen Charlotte Islands have vast tracts of valuable commercial timber which, for over half a century, has made logging an important economic resource. The Coastal Western Hemlock biogeoclimatic forests consist of western hemlock, Sitka spruce, amabilis fir and western red cedar, each of which are harvested extensively. Unfortunately, the inherent instability of the steep Queen Charlotte Islands hillslopes has been increased locally by logging (Schwab, 1983; Rood, 1984; Gimbarzevsky, 1986). Rood (1984) emphasizes the relative importance of mass wasting as the dominant geomorphic process in steep areas and documents a 34-fold increase in the frequency of mass wasting occurrences in logged areas. His results also indicate there is 43 times more sediment, derived from hillslopes, entering stream channels in logged areas compared to forested locations.

Mass wasting events on the Queen Charlotte Islands occur episodically through time. There is ample evidence of historical landslides in the island landscape (Figure 17.2). Gimbarzevsky (1986) inventoried almost 9,000 landslides from a series of aerial photographs, beginning in 1939, on the Queen Charlotte Islands. Schwab (in press) sampled 970 of these landslides and determined their date of occurrence by dendro-chronological field surveys. His results (Figure 17.3a) show that almost 85% of the total volume of sediment and debris derived from the landslides and delivered to stream channels was generated in seven large events occurring in the last two centuries (1810 to 1991). Of these, the largest events (in decreasing order of magnitude) occurred in 1917, 1891, 1875, 1978, and 1935; only the 1978 event post-dates the onset of logging.

The landslides documented by Schwab (in press) occurred during years that experienced severe rainstorms. The combined federal Atmospheric Environment Service records (Figure 17.3b), beginning in 1887, show large storms in 1891, 1917, 1935, 1952, and 1978. Septer and Schwab (1995) provide a complete history of each storm. The 1891 storm lasted three days and deposited 305 mm of rainfall in the first 24 hours (debris slides were documented to have killed 49 Native Indians on the mainland north coast east of the Queen Charlotte Islands). There were five major multiple-day storms in 1935 and at least three in 1917 along the north coast. The October 29–November 1, 1978 storm caused an estimated 1,000 landslides on the Queen Charlotte Islands alone (Schwab, 1983), due mainly to short-duration intense rainfall (120 mm/12 hr.) and logging practices (particularly road building and harvesting on steep terrain).

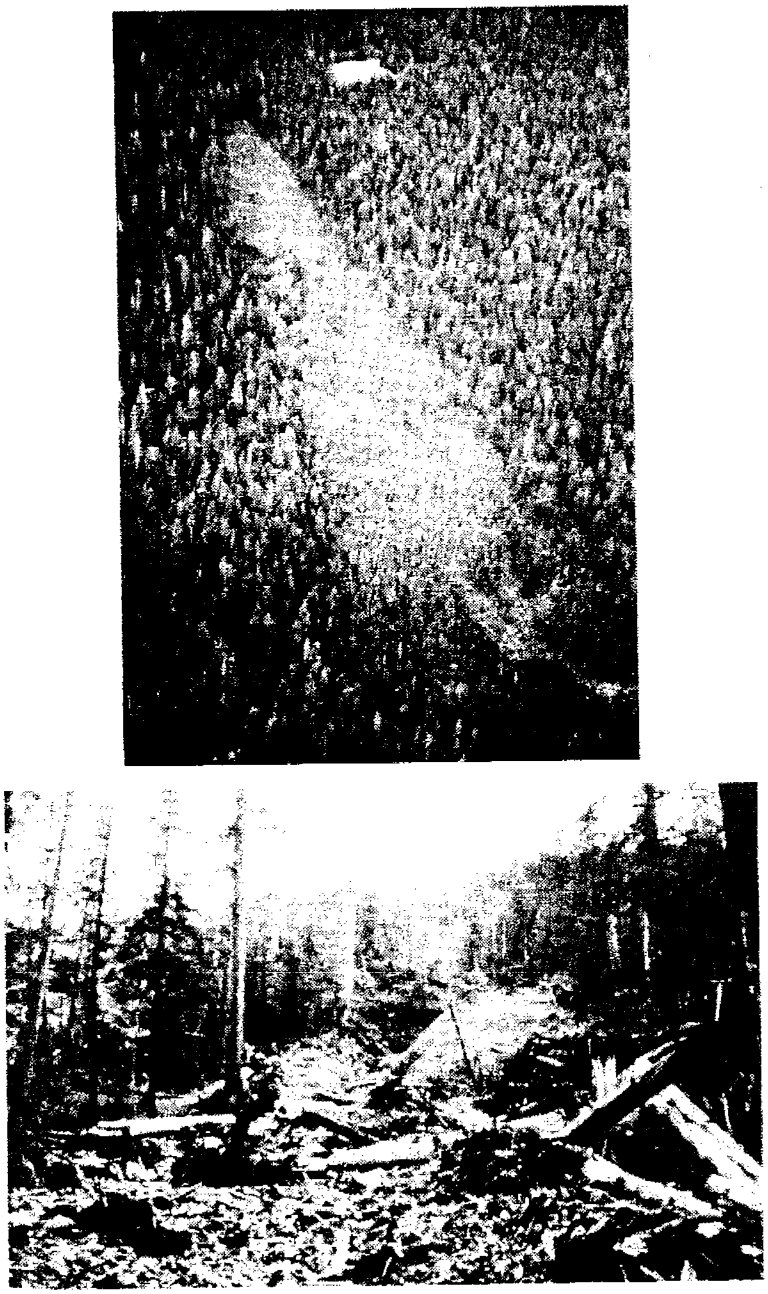
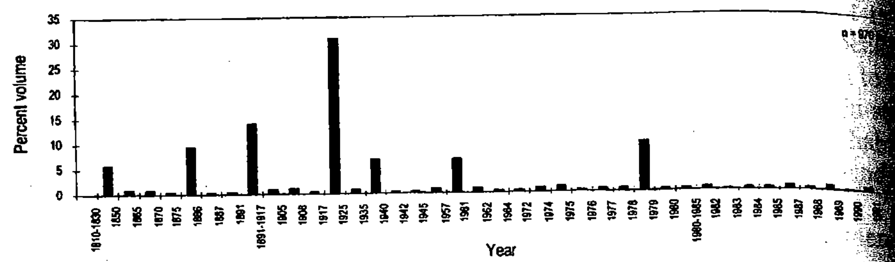


Figure 17.2. **Examples of landslides and debris delivery to stream channels.**
A) Old landslide track on Queen Charlotte Islands.
B) Sediment and debris delivered directly into stream (coupled hillslope and stream). LWD jam formed at terminus of debris flow.

a) **Landslide events occurring in Queen Charlotte Islands from 1810 to 1991 (from Schwab, in press).**



a) **Annual maximum 24 hour precipitation records for selected station (aggregate record: Port Simpson 1887–1909; Masset 1910–1914; Queen Charlotte City 1915–1948; Sandspit 1949–1962; Tasu 1963–1972; Sewell Inlet 1973–1989).**

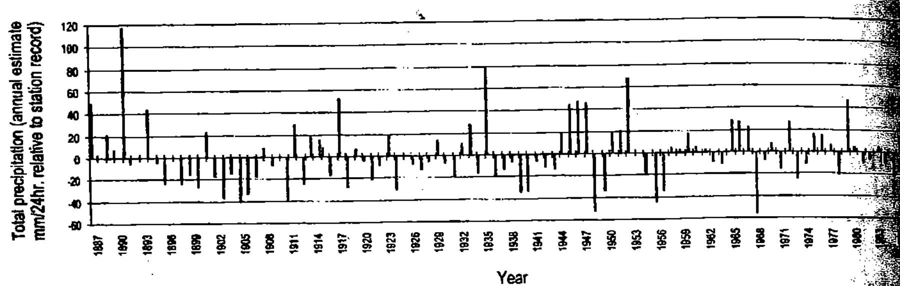


Figure 17.3. Historical landslide and precipitation records.

17.3.2 Landslides and LWD Jam Formation

LWD jams are formed in coastal streams by several mechanisms. The m important factors seem related to watershed attributes, particularly the lin between hillslopes and stream channels. Channelized debris flows (torre introduce large amounts of sediment and debris to the channel (Figure 17 In watersheds with hillslopes connected directly to the stream system (cou streams) and with limited valley flat extent, jams are formed primarily a terminus of debris flows that enter the channel. A significant relation betw the terminus of a debris flow and the occurrence of a LWD jam has identified in the Queen Charlotte Islands (Hogan & Bird, in prep.); in cou streams much of the volume of debris in the jam is derived from upslope upstream with relatively minor amounts derived from the proximal rip zone.

In uncoupled watersheds (buffered streams) where debris flows originate on steep hillslopes do not reach the stream, LWD jams originate ted debris that becomes anchored at some point along the channel. Approximately equal amounts of debris in the jam is derived from upstream and the proximal riparian zone. The riparian vegetation is produced as a result of bank erosion initiated by the formation of the jam; once the jam forms it has a tendency to grow by addition of wood from overbank areas.

Longitudinal channel surveys within the 34 sub-basins identified 620 LWD jams, including 238 and 382 LWD jams in forested and logged watersheds, respectively. The frequency of LWD jams through time (Figure 17.4) indicates that the rate of LWD jam creation has been episodic over the last century. The distribution is bi-modal, with the first peak centered over the turn of the 20th century and the second in the 1970s. Based on landslide histories provided by Schwab (in press) and the corresponding meteorological histories provided by Septer and Schwab (1995), episodes of jam initiation correspond to landslide events trigged by severe rainstorms. The first peak on the histogram identifies an episode of LWD jam formation corresponding to storms that occurred in 1891 and 1917, while the second peak identifies another episode of LWD jam formation corresponding to storms that occurred in 1964, 1974, and 1978.

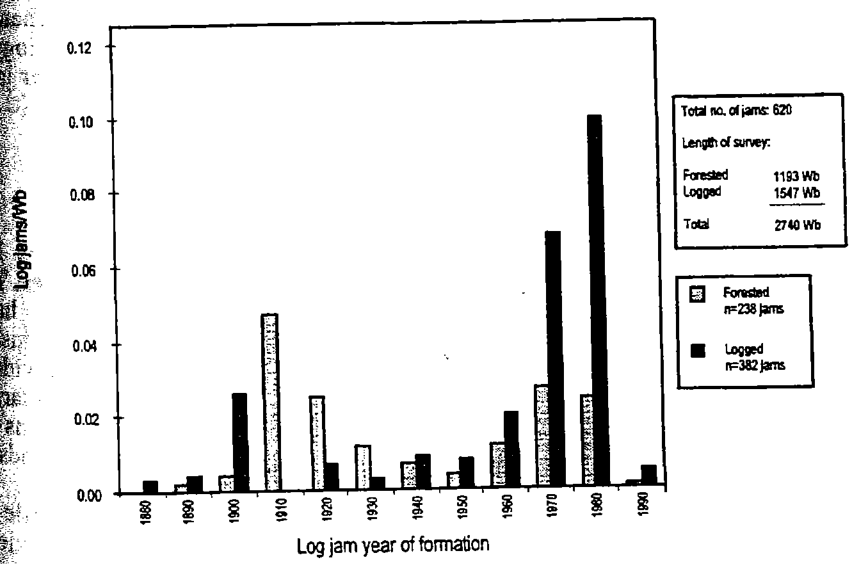


Figure 17.4. LWD jam age distributions for forested and logged watershed streams.

Both episodes of LWD jam formation were evident in all watersheds regardless of land use. However, the frequency of LWD jam formation through time was mutually dependent on both watershed type (Groups A through E, Table 17.2) and land use ($\chi^2 = 64.3$, $\chi^2_{0.05,8} = 15.5$; reject Ho). Generally, the relative frequency of young jams increased as the watershed became smaller and steeper. In relatively large watersheds with predominately buffered stream channels, mass wasting events rarely impact the channel. Consequently, relatively few new LWD jams are created during episodes of wate[r] disturbance. As the connection between the hillslope and the stream cha[nnel] becomes stronger, mass wasting events create LWD jams at an increasing [rate], often destroying old LWD jams in the process. As the channel grad[ient] becomes increasingly steep, the rate of jam production with an increa[sing] connection to the hillslope may reach a critical point. For example, channe[ls in] watershed Group E have an average gradient of 0.072 m/m. During a de[bris] flow from upslope source areas, the entire channel is scoured as the de[bris] passes completely through to the stream mouth. LWD jams that exist be[fore] such an event can be completely destroyed.

The influence of land use on LWD jam formation is appare[nt] considering the impact of the 1978 storm. The large number of jams initi[ated] in 1978 was due to the accelerated rate of landslide occurrence in lo[gged] watersheds. The lack of old jams (initiated in 1917) in logged watershe[ds is] likely a result of their replacement by young jams initiated by the [1978] episode.

The frequency of LWD jams per unit length of channel increases sl[ightly] with logging. Longitudinal channel surveys identified 238 jams (0.[..] jams/W_b) and 382 (0.26 jams/W_b) in forested and logged waters[heds], respectively. For streams in forested watersheds, the main anchors of L[WD] jams are generally large root wads, previously existing jams, mid-chan[nel] islands, and bedrock knobs that constrict flow. However, for streams in log[ged] watersheds, most jams develop on-top or immediately upstream of older [jams] and do not, therefore, significantly alter jam frequency.

17.4 THE EVOLUTION OF CHANNEL MORPHOLOGY

Previous research on the influence of LWD on channel morpholog[y has] concentrated on changes in the size, amount and function of LWD pieces. [The] results of such studies have been applied to forest management issues and [have] proven beneficial in solving specific problems, such as the need for strea[m] buffers to provide a continued LWD source. Although the role of indivi[dual] LWD pieces is important and influences morphology, LWD **jams** play a la[rger] role through time and space in controlling channel conditions for stream[s on] the Queen Charlotte Islands. The evolution of channel morphology depen[ds to] a large extent on LWD jams.

LWD jams have an important influence on the longitudinal profi[le of] small coastal streams. This is seen by the extensive sediment accumula[tion] upstream of the debris jams (Figure 17.5). Major sediment wedges are fo[und] upstream of large jams or multiple jams that are closely spaced. Betwe[en] jams the channel has the typical pool-riffle sequence (mean spacing distan[ce] 4.3 W_b), cobble-gravel textured bars and individual LWD pieces, partic[ularly] debris steps, are important. In relative terms, jams seem to have the gr[eatest] influence on the overall channel because they control the largest fe[atures] (extensive sedimentation upstream of jams); the individual piece[s are] important to channel morphology and fish habitat features at a smalle[r scale] (between the jams).

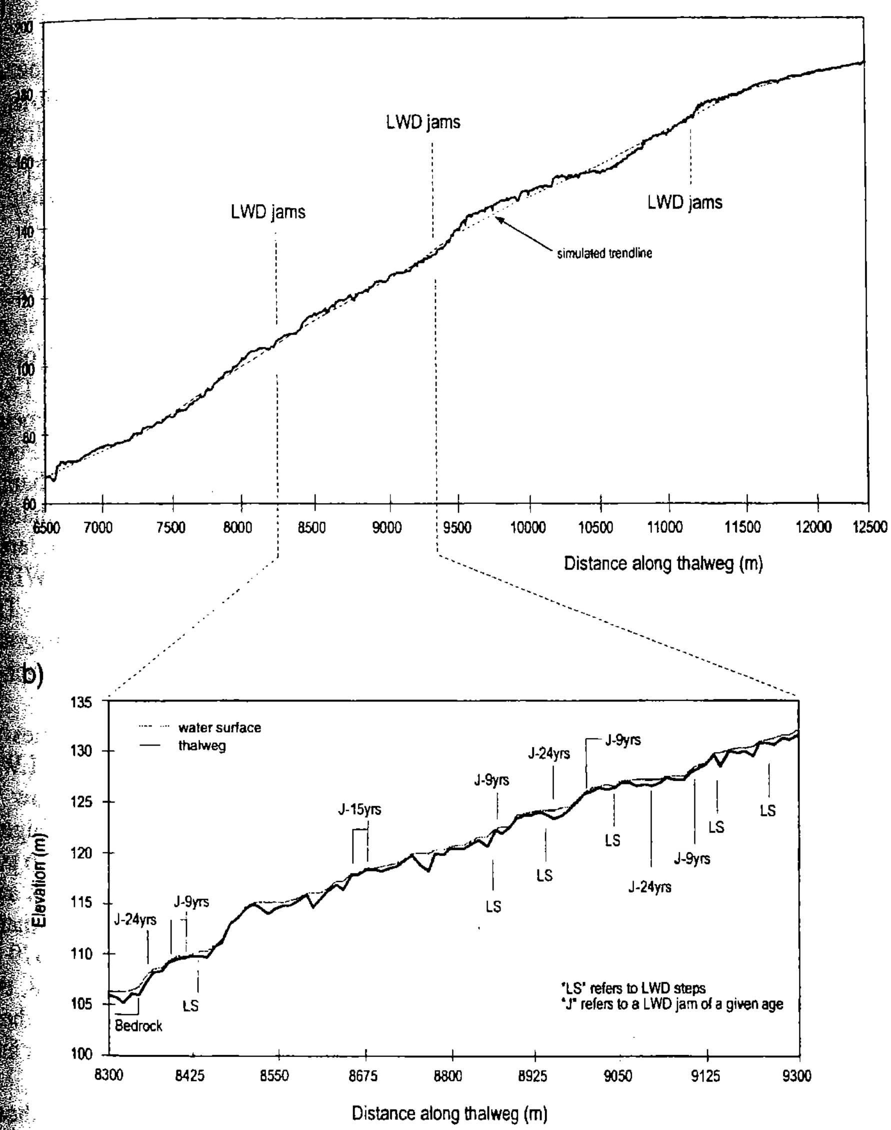


Figure 17.5. **Longitudinal profile of Riley Upper, a logged watershed. stream (from Hogan, 1989).**

A) Entire longitudinal survey (zones lying above smooth line drawn through data points -- smooth line is second order polynomial placed to make visual inspection easier).

B) Detailed profile of selected section from A.

17.4.1 A Model of LWD Jam Evolution

The Queen Charlotte Islands stream studies have shown a characteristic patt of channel changes over time associated with the formation and breakdown LWD jams. Generally, the sequence goes from morphologically dive channels prior to the jam formation, to simple channels during development, and then a progressive change back to complex cha conditions. Many specific channel changes are evident.

Streams in forested watersheds have abundant LWD incorporated their channels. If there are no recently formed jams present, then the stre are characterized by complex and diverse channel features. Figure 17.6 sh an example of a stable, not-recently-disturbed stream channel in a Co Western Hemlock forest (Government Upper Main, Figure 17.1, Table 1 Overall, the channel is diverse, with complex longitudinal and planim forms, and with distinct, well defined pools and riffles (Hogan, 1986). Po primarily lateral scour pools, account for almost 65% of the overall cha area. Considerable variation is also evident in channel width, as the cha alternates between narrow and wide reaches. Banks are commonly und and channel bars consist of cobble, gravel and sand size materials. LW prevalent and frequently spans the channel from bank to bank. predominant orientation of the debris pieces is either perpendicular or diag to the general alignment of the banks. Most of the debris pieces have att root wads.

Debris flows that enter the stream channel deposit large volum sediment and LWD into the channel and reorganize existing pieces of into jams. The development of a LWD jam following a debris flo Carnation Creek on the west coast of Vancouver Island is shown in Fi 17.7. (Annual surveys have documented short-term channel adjustments formation in Carnation Creek -- there are no short-term records of thi available for the Queen Charlotte Islands, but the areas are similar in respects). This jam began to form in 1976 but was greatly enlarged in 19 a result of a large storm. Over the next decade, between 1979 and 198 channel width upstream of the fully developed jam increased 6-fold and was over 2 m of net bed aggradation. All previously existing pools, riffle bars were completely destroyed.

LWD jams are different than other in-channel blockages such as caused by rock slides that create essentially permanent dams. LWD jams to break down over time (Figure 17.8), as debris pieces rot, are brok smaller sizes, and are moved by floods. The longevity of each jam infl its temporal role in controlling channel morphology, as the interrupti sediment transport decreases through time.

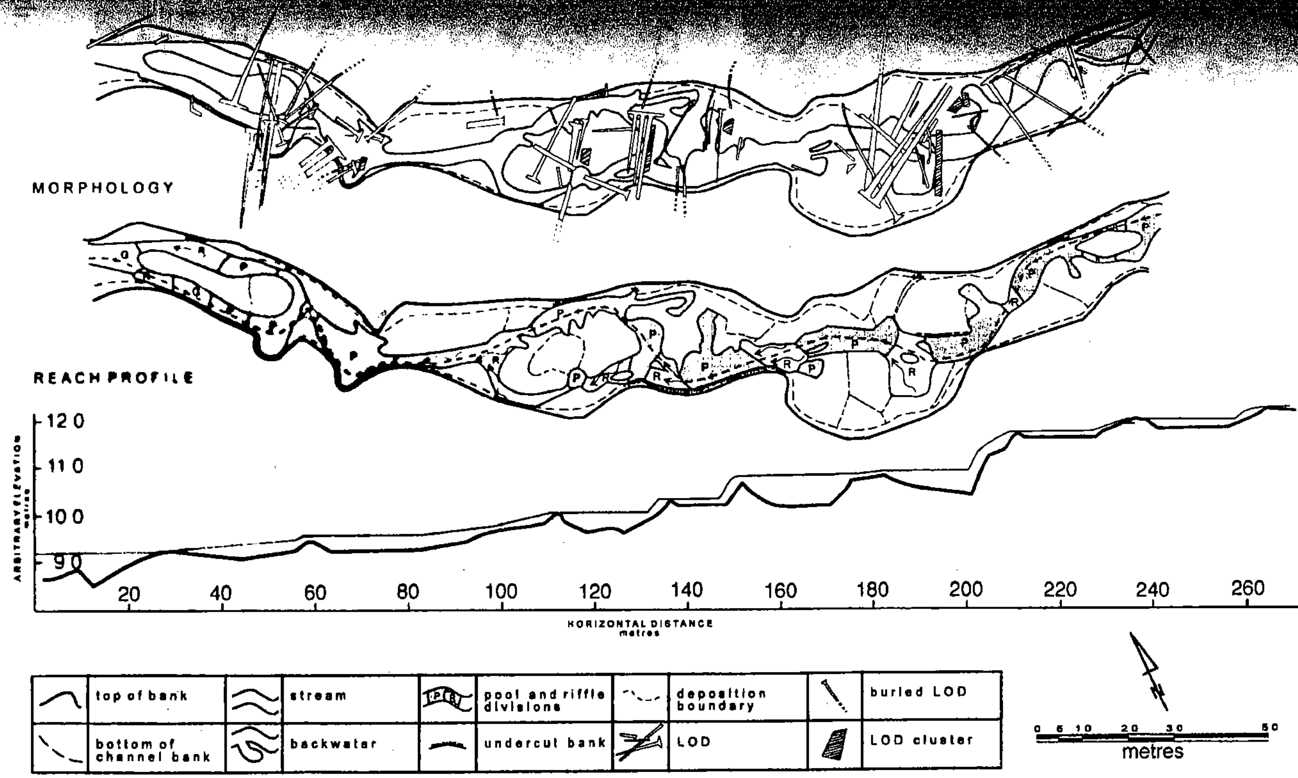


Figure 17.6. Channel morphology, LWD characteristics and longitudinal profile of old-growth Coastal Western Hemlock forested watershed stream (from Hogan, 1986).

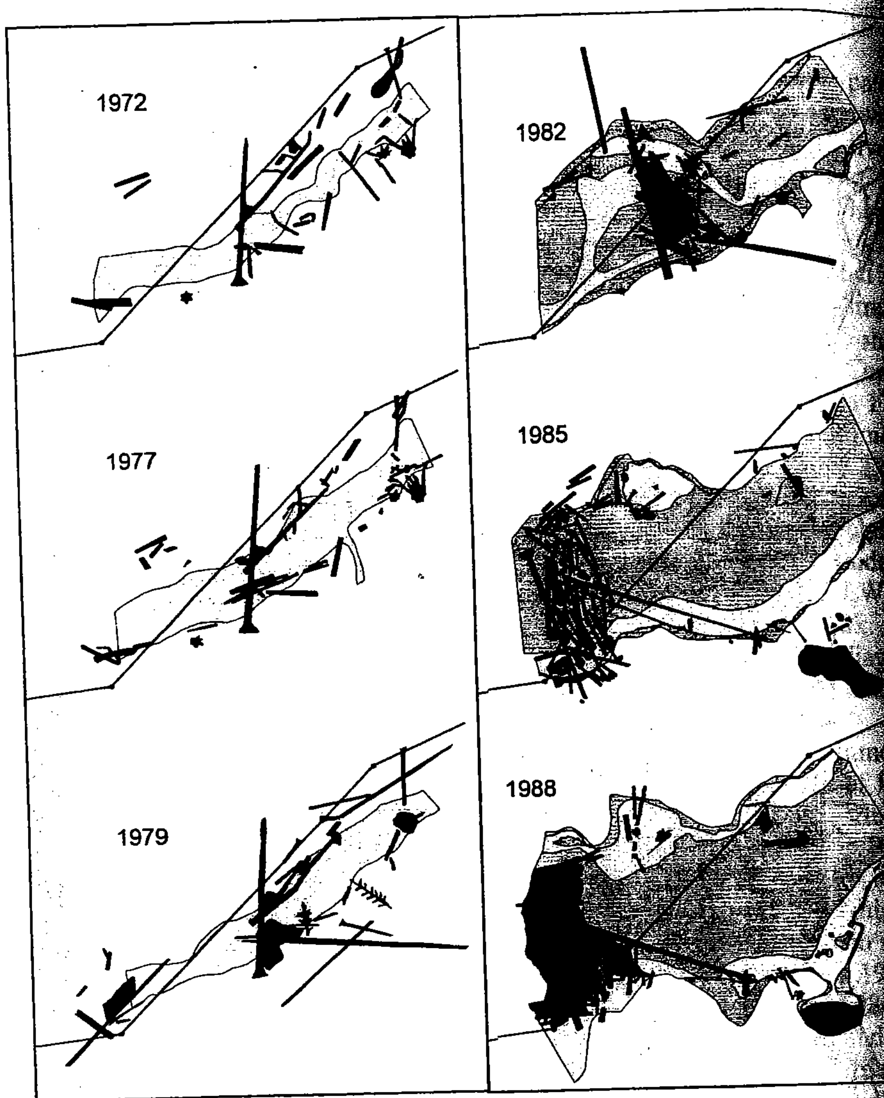


Figure 17.7. **Examples of jam formation in logged coastal strea[illegible] (Carnation Creek on Vancouver Island, B. C. -- use[illegible] because annual surveys available). Note that survey hu[illegible] and lines are in the same location on each map. (Se[illegible] Figure 17.8a for photograph of jam taken in 1987.)**

Figure 17.9 shows a cobble-gravel bed channel with two disti[illegible] different sections upstream and downstream of a LWD jam. The debris lo[illegible] in the middle of the channel is of two ages and origins. The large debris o[illegible] of the debris cluster is a result of recent blow-down (logs mapped as abov[illegible] channel bed and with attached root wads located in the overbank zone).

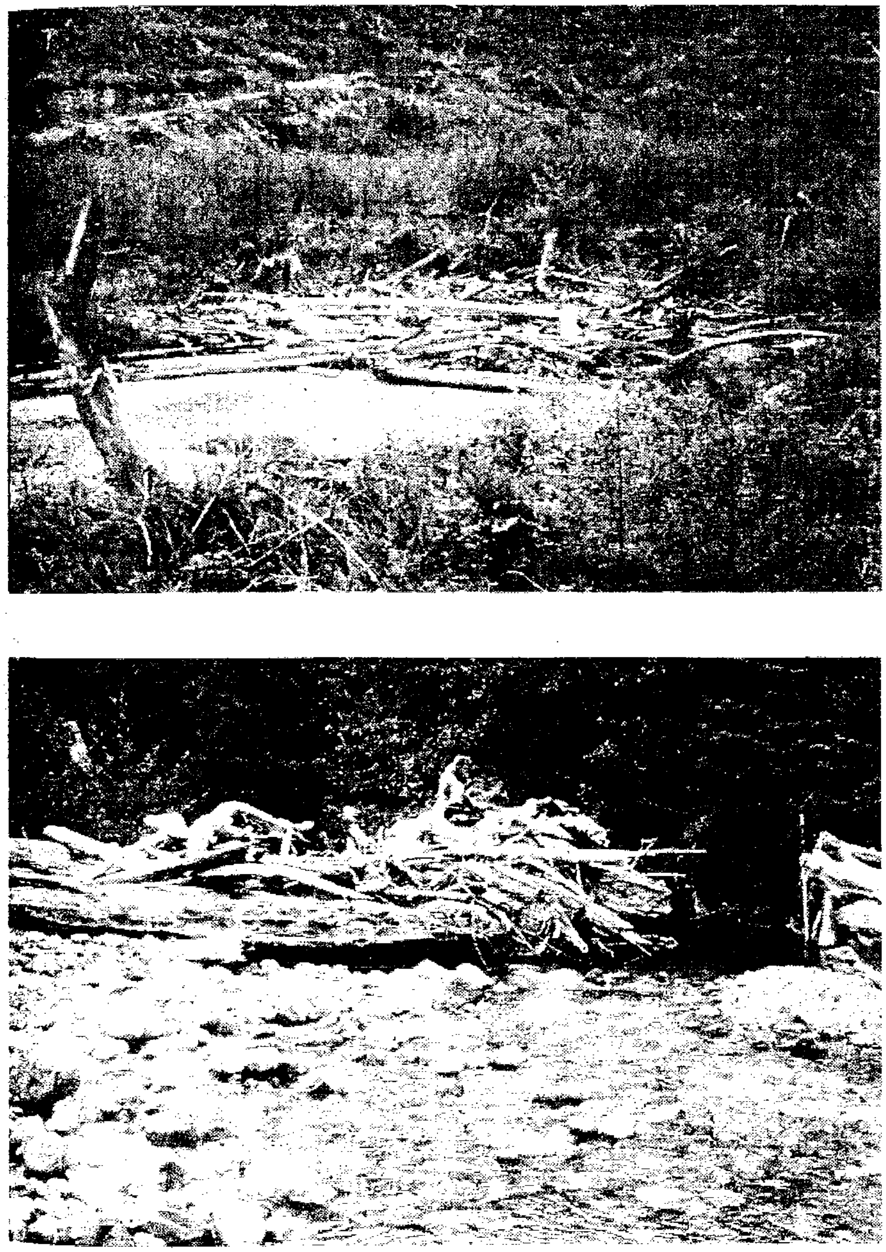


Figure 17.8. LWD jams of different ages.

A) Recently formed jam with extensive sediment wedge upstream of intact debris that effectively stops sediment transfer downstream.

B) Moderately old jam (25 years since formation) showing evidence of downcutting of sediment wedge as jam deteriorates (no longer spans channel).

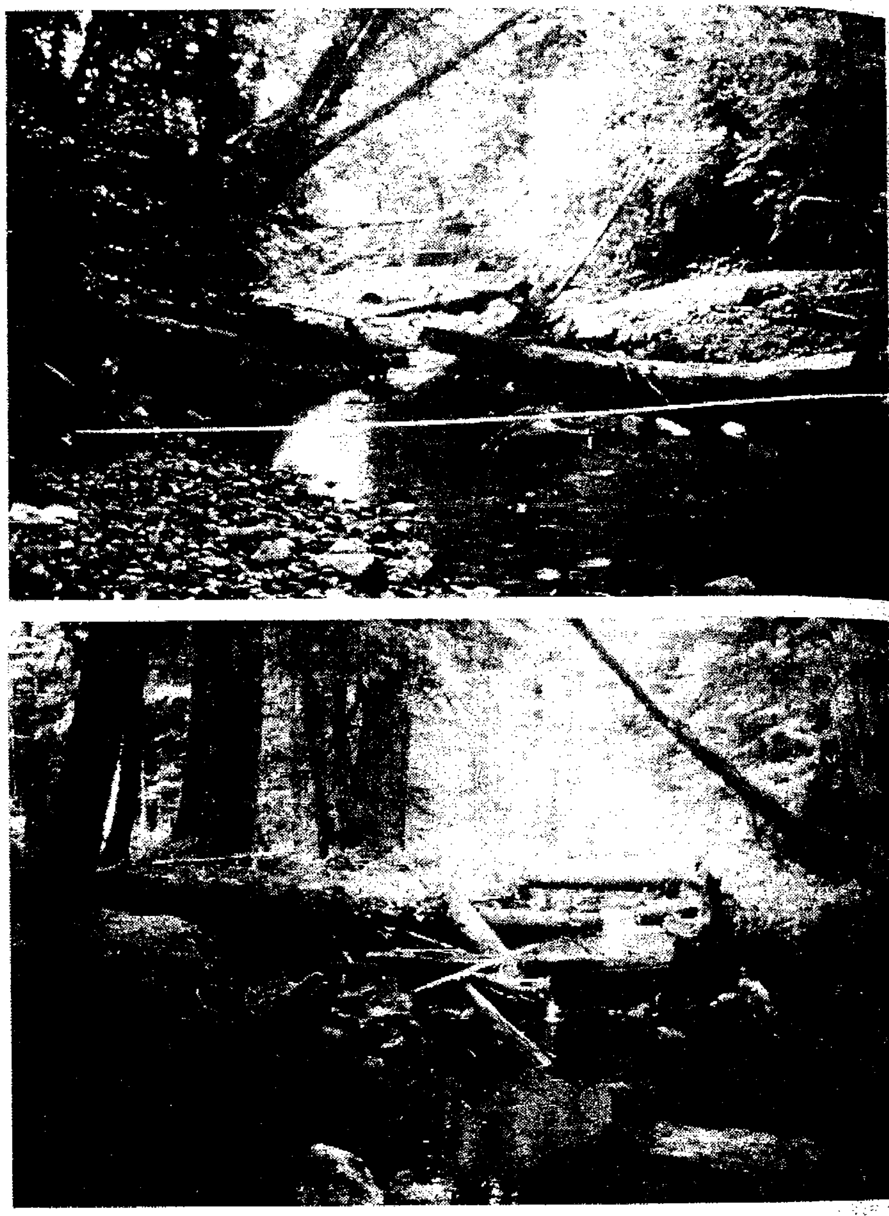


Figure 17.8. LWD jams of different ages. (Continued.)

C) Old jam (50 years since formation) that has minimal contemporary influence on sediment trapping and scouring.

D) Very old jam (300+ years since formation) with complex channel conditions (deep pools, log steps, under-cut banks, stable bars and back channels, etc.).

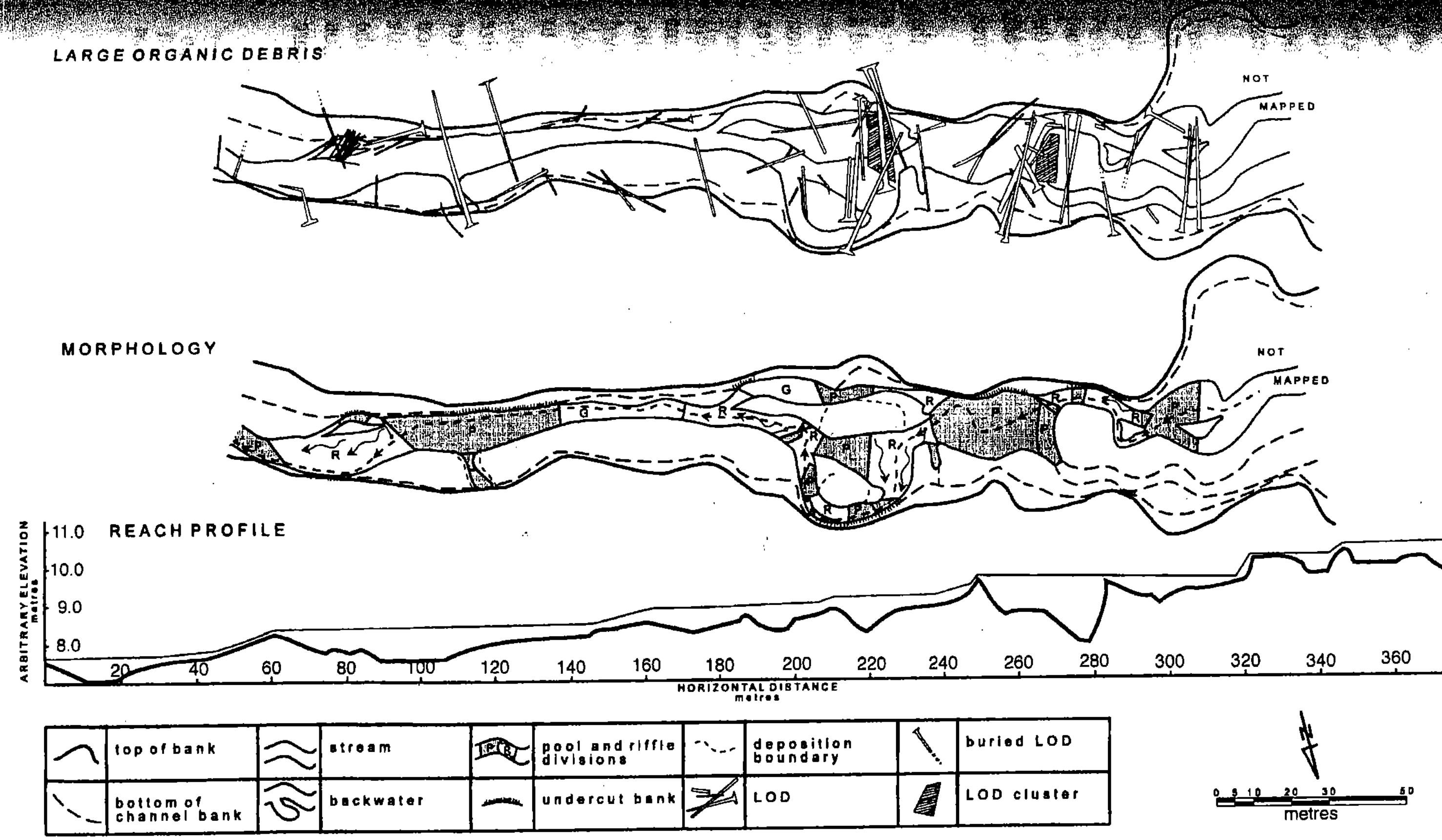


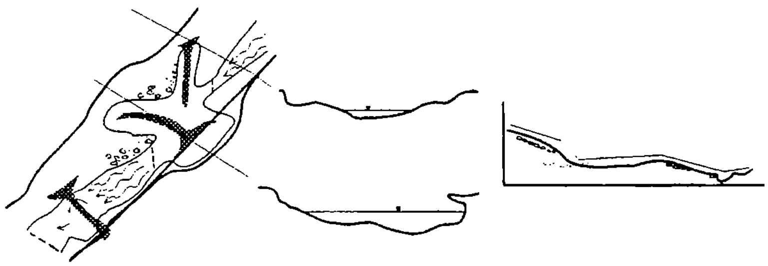
Figure 17.9. Channel morphology map showing old (45–50 years) LWD jam (map legend included in Figure 17.6). (from Hogan, 1986).

Because this material is above the bed it currently has very little influence on bed and bank sediment scour or deposition. Beneath the blown-down wood is an old debris jam. Nurse trees growing on in-stream debris had ages ranging from 32 to 45 years indicating that the jams had been in place for several decades; the vegetated, undercut and stable banks and islands attest to their ages. The remains of logs are also incorporated into the fluvial sediments making up the channel banks.

The downstream zone (Figure 17.9), extending from 0 to 180 m, has a single channel with long, well defined pools and riffles, gravel textured side-channel bars and diagonally oriented LWD pieces that cause lateral and under-scour pools. Upstream of 180 m, the channel expands laterally, doubling in width, has multiple channels with mid-channel bars and vegetated islands. Pool and riffle shapes are very different in the upstream section compared to downstream, with increased lateral and vertical variability. Examples of old and very old log jams (50+ years since jam formation) are given in Figures 17.8c and 17.8d.

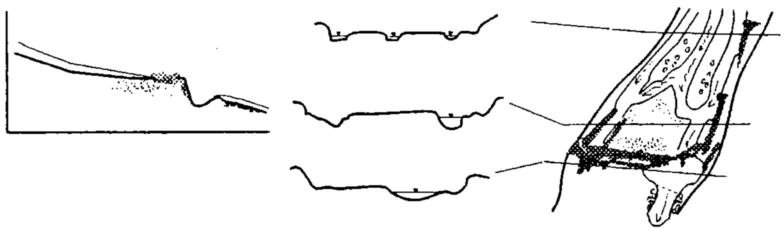
LWD age and channel morphology are intricately linked, therefore, a shift in LWD jam age distribution documented in Figure 17.4 will lead to a corresponding shift in expected channel morphology. Hogan (1989) proposed a model of temporal and spatial adjustments of channel morphology in response to the development LWD jams (Figure 17.10). Initially, prior to the formation of a LWD jam (Figure 17.10a), the channels are morphologically complex with many of the features shown in Figure 17.2. After the jam has been established, the channel undergoes fundamental changes; the most severe changes occur during the first decade (Figure 17.10b). Recently-formed jams form effective sediment traps that cause bank erosion and increased widths, reduced gradients and finer sediment textures upstream of the jam due to aggradation. During the second and third decades the jam begins to deteriorate, becoming a less effective sediment trap, and the sediment supply to downstream zones increase. As a result, the upstream wedge is down-cut, preferred channels are established and riparian vegetation begins to colonize the bar and bank surfaces (Figure 17.10c and 17.10d). Typically, after approximately 30 years the channel begins to resemble pre-jam formation conditions (Figure 17.10e and 17.10f). After 50 years there is very little evidence of the original jam (e.g., Figure 17.9). Remnants remain along the channel margin, and individual LWD pieces remain along the bed and function as indicated previously. Many of the debris steps evident in Figure 17.9 are actually the final remains of ancient jams.

(a) No direct evidence of a LWD jam



The channelis complex, with diversemorphology (e.g., high width, depth and sediment texture variability). LWD is diagonal to flows, and lateral scour pools and diagonal riffles dominate. Banks are undercut and small LWD steps are frequent.

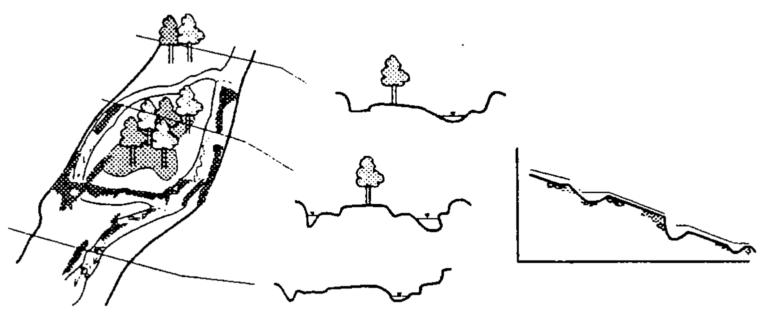
(b) Less than 10 years since LWD jam formation



Upstream
The channel is fine-textured and braided. Riffles and glides dominate with few pools. Undercutting of banks is minimal.

Downstream
The channel is single thread and coarse-textured. Riffles dominate with few pools. LWD lies parallel to the banks. Banks are over-hanging, not undercut.

(c) 10 to 20 years since LWD jam formation

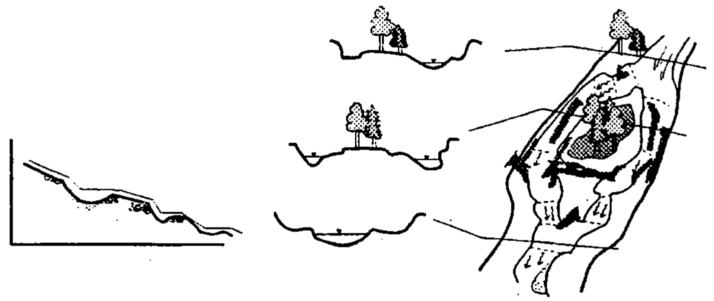


Upstream
The number of channels is reduced,while the sinously and gradient are increased. Bed texture is coarser as fine sediment is removed. Pools are associated with LWD.

Downstream
A single main channel dominates with mid-channels bar development. Bed sediment texture is reduced and pools are associated with LWD.

Figure 17.10. Response of channel morphology to LWD jam formation and deterioration. (from Hogan, 1989).

d) 20 to 30 years since LWD jam formation



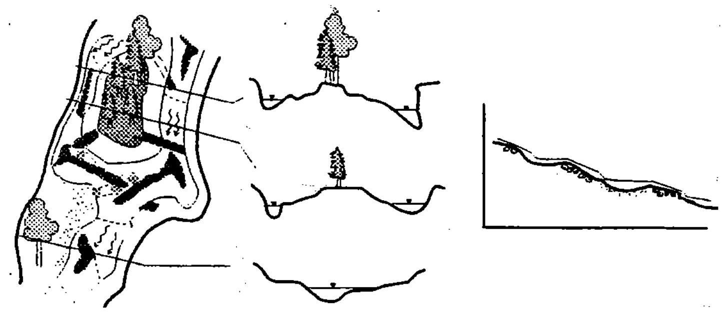
Upstream

One or two main channels dominate and bed sediment is coarser. Pools become more extensive and riffles less extensive, while overall channel gradient increases.

Downstream

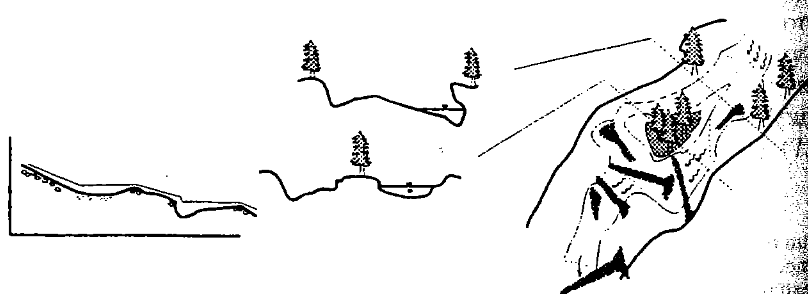
One or two main channels dominate and sediment is finer. Pools become more exten and riffles less extensive.

e) 30 to 50 years since LWD jam formation



Downcutting continues through the remnants of the wedge. pool and riffle extents are rel equal. Pool-types are diverse and stable; diagonal riffles dominate. Previously buried L exhumed and functioning (traps and scours sediment).

f) More than 50 years since LWD jam formation



Channel morphology is complex, with diverse bed forms and side-channel developme overall morphology resembles a channel with "no direct evidence of a LSW jam".

Figure 17.10. Continued.

17.4.2 The Temporal Influence of LWD Jams on Channel Morphology

Field examples of channel changes associated with debris longevity are shown in Figure 17.11. Debris jam locations and ages are shown in the longitudinal profiles for comparison of specific features associated with the various ages. In all cases there is substantial channel aggradation upstream of the recently formed, young LWD jams. For example, at the 3,400 m distance (Figure 17.11a), the bank top and bar top surface graphs merge indicating that the channel bed is at the same elevation as the bank top; the channel has completely filled with sediment and the bar tops are elevated to the height of the bank tops. Degradation of the channel bed is also evident downstream of the young jams (3,350–3,400 m). As LWD jams age, more sediment is excavated and the bed upstream of the jam downcuts and eroded sediment is transferred downstream. For example, there is relatively little filling between 2,800 and 3,000 m and from 3,150 to 3,350 m although there are two large older jams present in these zones.

The volume of LWD in a jam also decreases with time (Figure 17.11b) as individual pieces rot or are broken into smaller pieces and removed by higher flows. As jams are reduced in size, the orientation of the remaining LWD shifts from perpendicular to parallel relative to the stream bank (Figure 17.11c). This shift in orientation decreases the sediment trapping ability of the debris, increasing the effectiveness of bed and bank scour through time.

Changes in channel width and sediment texture are also related to LWD jam age (Figure 17.11d and 17.11e). In general, where the channel walls are not confined by bedrock there is an increase in channel width associated with the newer jams. Coinciding with the new jam, wider channel, and upstream aggradation is a reduction in sediment size. In most instances the sediment is finer immediately upstream of the jam and considerably coarser downstream. However, as LWD jams break apart, the width increases and sediment sorting characteristics of young jams become progressively inconspicuous.

LWD jams are spatially prevalent. Considering all surveyed channels, the median spacing is 2.85 and 2.30 W_b in forested and logged streams, respectively (Figure 17.12a). However, in the field, only the recently formed jams are obvious and their spacing distance is much greater than for the total of all ages. For instance, in Riley Creek approximately 50% of the young jams are spaced further than 14 W_b apart (Figure 17.12b).

17.4.3 The Spatial Influence of Forest Management on Channel Evolution

LWD jams are fundamental structural elements in the small coastal streams investigated in the Queen Charlotte Islands (Hogan, 1987). The recently formed jams alter channel morphology to the point that in-stream fish habitats are essentially destroyed. However, in the course of 50 years the same LWD jam creates complex, diverse morphologies that are highly productive fish habitats. Therefore, the shift from an even distribution of young, moderate and old LWD jams, to predominately young LWD jams, constitutes a critical impact.

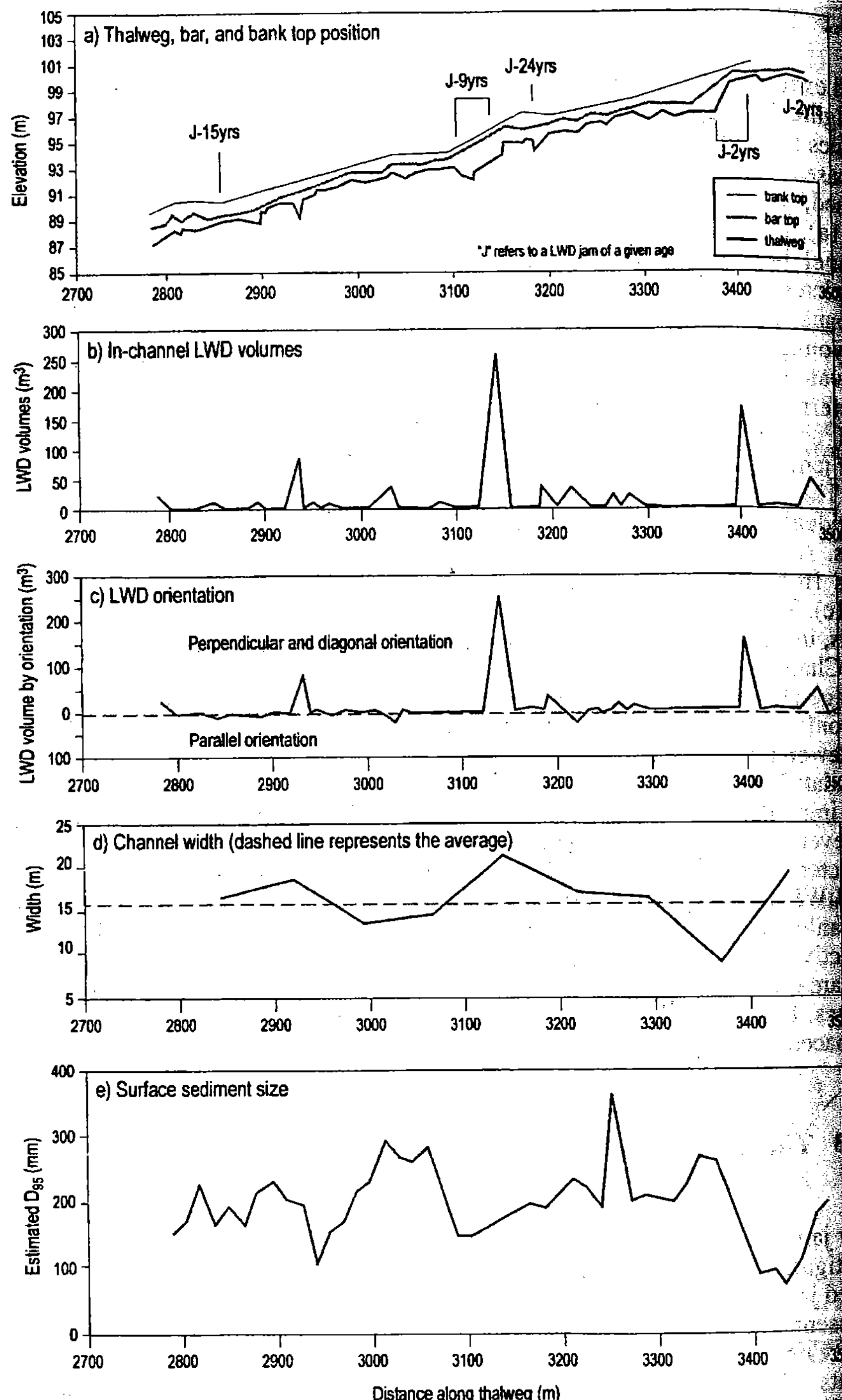
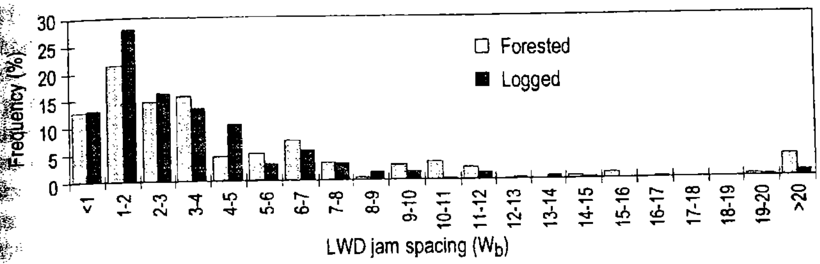


Figure 17.11. Channel changes associated with LWD jam longevity (from Hogan, 1989).

A) **LWD jams in forested and logged streams.**



Forested: n=178 jams, median spacing=2.86 (W_b)
Logged: n=328 jams, median spacing=2.30 (W_b)

B) **Recently formed LWD jams.**

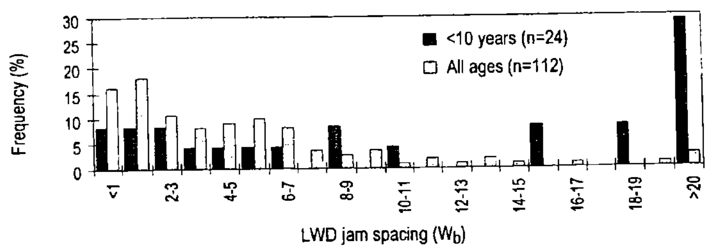


Figure 17.12. Spacing of LWD jams.

Two episodes of LWD jam formation have occurred in the Queen Charlotte Islands in the last century (Figure 17.4). The jam-forming magnitude of the first episode (storms in 1891 and 1917) is fairly similar in both forested and logged watersheds (peak rate of LWD jam formation is 0.0047 and 0.0026 jams/W_b/yr in forested and logged watersheds, respectively) as the episode pre-dates logging (i.e. the "logged" watersheds were unlogged at the time). However, the magnitude of the second episode (1964, 1974 and 1978 storms) is significantly greater in the logged watersheds (peak rate of LWD jam formation is 0.0027 and 0.0099 jams/W_b/yr in forested and logged watersheds, respectively). Although both forested and logged watersheds have similar distributions of old jams, logged watersheds have more new jams. Given the distribution of LWD jam frequency through time (Figure 17.4), a contemporary inspection of a stream in the Queen Charlotte Islands would likely reveal old and young channel characteristics (Figure 17.10a and b) equally distributed through space in forested watersheds. In logged watersheds, however, young channel characteristics would be found nearly four times as often as the old morphologies.

An analysis of pool and riffle spacing characteristics was designed to test these broad changes in channel morphology between forested and logged stream channels. The influence of altering the distribution of LWD jam ages on pool and riffle characteristics is considered for two reasons. First, pools and riffles are important components of channel morphology that integrate sediment supply and transport characteristics as influenced by LWD jams. Thus, pools and riffles in a stable and undisturbed channel are likely to attain a

characteristic spacing and differences in pool-riffle spacings may reflect le[vels]
of channel disturbance. Second, pools and riffles represent critical
habitats, so alteration of pool-riffle characteristics can represent a los[s of]
habitat.

Operational definitions used to distinguish each channel feature are gi[ven]
in Figure 17.13a. Riffle-pool (R/P–R/P) spacings are not intended to meas[ure]
the rhythmic spacings of riffles and pools; rather R/P–R/P simply measures
distance between stable alluvial channel-units. The relation between pool-
pool (P–P) spacing and channel width at bankfull stage for logged and fore[sted]
sub-basins is shown in Figure 17.13b. Despite a shift in LWD jam age in
logged channels, the overall trend and variability between forested and log[ged]
channels are similar. The proportion of pools, relative to all other chan[nel]
units, between forested and logged channels do not change and consti[tute]

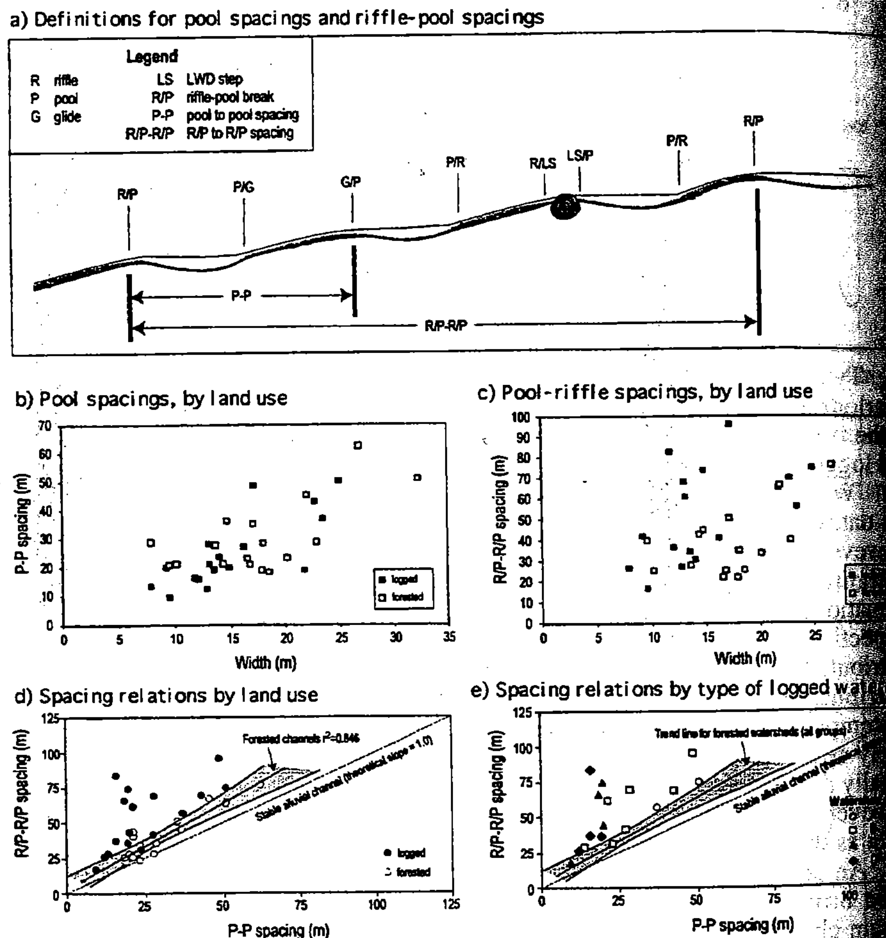


Figure 17.13. Pool and riffle characteristics based on pool spacing (pool-to-pool) and riffle-pool spacings (riffle/pool-to-riffle/pool breaks), for two land uses (forested and logged) and by logged watershed type.

nearly half of the total channel length (Figure 17.14). Given that the spatial distribution of pools has not been influenced by logging and the subsequent shift in LWD jam age, P–P spacing alone is not a sensitive measure of channel disturbance.

Similarly, Figure 17.13c presents the relation between riffle-pool to riffle-pool (R/P–R/P) spacing and channel width at bankfull stage for logged and forested sub-basins (R/P–R/P spacing measures the distance separating those pools only initiated immediately downstream of a riffle (Figure 17.13a). This measure is an indicator of the departure of a forest stream from a stable, alluvial state. For example, as glides and cascades become more prominent (an indicator of channel disturbance), the distance between stable riffle-pools will increase. Additionally, as LWD (in both pieces and jams) becomes more prominent in the channel (a non-alluvial control of channel morphology), the distance between stable riffle-pools will again increase. However, as with P–P spacings, there appears to be no significant difference between R/P–R/P spacings in forested and logged watersheds. The relative proportion of stable pools and riffles, in both forested and logged channels (70 and 72%, respectively; Figure 17.14), represent similarly high values indistinguishable

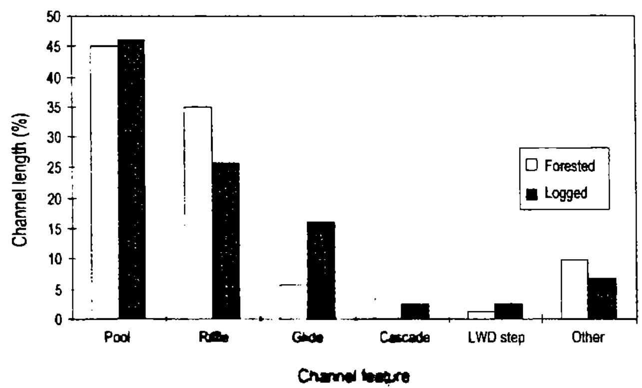


Figure 17.14. Proportions of channel features in forested and logged watershed streams.

by this analysis. The relative proportion of alluvial channel units (pools, riffles, glides, and cascades combined), in both forested and logged channels (89 and 91%, respectively; Table 17.2), again represent high values indistinguishable by this analysis. In general, the spacing of bedforms in relation to channel width does not appear sensitive to changes in channel morphology induced by logging.

In a truly stable alluvial channel (e.g., a "hypothetical" channel consisting entirely of pools and riffles), the spacing measures P–P and R/P–R/P converge to a single value. Figure 17.13c shows the relation between P–P and R/P–R/P for both forested and logged channels. Considering the forested channels alone, a increase in R/P–R/P is observed with P–P ($r^2 = 0.85$). Although the slope of the line is significantly greater than 1.0 (a departure from an absolute stable alluvial channel), the significant relation indicates the background level of disturbance associated with forested watersheds in the Queen Charlotte Islands. This suggests that although channels in forested watersheds do experience disturbance, channel morphology has adjusted to both magnitude and frequency of these events over the past century. In compa[illegible] logged channels (with the exception of two sub-basins) plot outside and a[illegible] the 95% confidence interval which indicates a significant level of cha[illegible] disturbance not present in the forested channels. The lack of a consis[illegible] relation between P/P and R/P–R/P in logged watershed channels suggests [illegible] the magnitude of disturbance was not uniformly distributed among sub-ba[illegible] Considering sub-basin groups (Table 17.2), the average deviation of [illegible] observed values of R/P–R/P, as predicted by the stable forested chan[illegible] generally increases by hillslope connection (8.9, 17.8, 24.8 and 21.8 [illegible] Groups A, B, C, and D, respectively).

17.5 CONCLUSIONS AND MANAGEMENT IMPLICATIONS

Much of the channel diversity that characterizes coastal streams is a resul[illegible] LWD jam formation and longevity. Over the long term, on the order of ha[illegible] century, the complex channels and riparian zones that develop as a LWD [illegible] deteriorates are highly productive fish habitats. However, habitat conditio[illegible] are inhospitable for fish during the early phases of channel adjustment to [illegible] formation. Spawning areas (riffles) are buried (upstream of the jam) or ero[illegible] (downstream of the jam), rearing pools are in-filled and egg incubat[illegible] environments are smothered with fine textured sediments. Therefore, [illegible] interference with the natural evolution of stream channels, by shifting [illegible] relative frequency of recently formed jams, constitutes a fundamen[illegible] environmental impact.

In an old growth forested watershed, the natural rate of LWD [illegible] formation is very low. Therefore, in the forested stream there will be a w[illegible] range of jam ages and no one age will dominate the morphology. Althou[illegible] some age classes will be more prevalent because of the episodic nature [illegible] landslides, the range of ages produces a diverse mosaic of channel patterns [illegible] have rich habitat attributes. In the logged watershed, the rate of LWD [illegible] formation is accelerated. The nature of entire channel systems can be alt[illegible] because the steep headwater streams receive proportionally more jam form[illegible] events but the influence of these are transferred downstream into larger, low[illegible] gradient streams.

A troublesome legacy of past forest management practices in steep te[illegible] is the severity of the environmental damage produced by relatively l[illegible] magnitude high-frequency storm events. Although the 1978 storm on [illegible] Queen Charlotte Islands was not as intense as events occurring earlier in [illegible] century, far more landslides occurred during 1978 than in earlier storms o[illegible] same or greater magnitude. Previous studies have confirmed that logging [illegible] unstable slopes accelerates the already high rate of landslide activity al[illegible] much of coastal British Columbia. This leads to a corresponding increase [illegible] recently formed LWD jams with all of the associated channel morphology [illegible] fish habitat changes. New management initiatives, particularly the Bri[illegible] Columbia Forest Practices Code, will strive to minimize future environme[illegible] impacts in streams. However, the current recovery of stream channels to [illegible] pre-logging conditions is dependent on the time required -- approximately [illegible] years -- for a diverse array of LWD jam-ages to establish.