

Carnation Creek and Queen Charlotte Islands Fish/Forestry Workshop: Applying 20 Years of Coastal Research to Management Solutions



BRITISH
COLUMBIA

Ministry of Forests
Research Program

**Carnation Creek and Queen Charlotte Islands
Fish/Forestry Workshop: Applying 20 Years
of Coast Research to Management Solutions**

Dan L. Hogan, Peter J. Tschaplinski,
and Stephen Chatwin
(editors)



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CONTENTS

List of Contributors	iii
Introductory Comments for FFIP/Carnation Creek Workshop	
David Wilford	1
Introduction to Day 1: Focus on Research	
Michael Brownlee	3
Introduction: Workshop Outline and Experimental Design	
C. Peter Lewis	5
The Landscape of the Pacific Northwest	
Michael Church	13
An Introduction to the Ecological Complexity of Salmonid Life History Strategies and of Forest Harvesting Impacts in Coastal British Columbia	
J. Charles Scrivener, Peter J. Tschaplinski, and J. Stevenson Macdonald	23
Focus on Forestry-fisheries Problems: Lessons Learned from Reviewing Applications of the Coastal Fisheries-Forestry Guidelines	
D. Tripp and D. Hogan	29
Watershed Hydrology	
Eugene D. Hetherington	33
Landslides on the Queen Charlotte Islands: Processes, Rates, and Climatic Events	
Jim W. Schwab	41
Gully Processes in Coastal British Columbia: The Role of Woody Debris	
M.J. Bovis, T.H. Millard, and M.E. Oden	49
Stream Channel Morphology and Recovery Processes	
D. L. Hogan, S. A. Bird, and S. Rice	77
Evolution of Fish Habitat Structure and Diversity at Log Jams in Logged and Unlogged Streams Subject to Mass Wasting	
Derek Tripp	97
Channel Scour and Fill in Coastal Streams	
Judith K. Haschenburger	109
Fine Sediments in Small Streams in Coastal British Columbia: A Review of Research Progress	
Michael Church	119
Changes of Spawning Gravel Characteristics after Forest Harvesting in Queen Charlotte Islands and Carnation Creek Watersheds and the Apparent Impacts on Incubating Salmonid Eggs	
J. Charles Scrivener and Derek B. Tripp	135
Overwintering Habitats and Survival of Juvenile Salmonids in Coastal Streams of British Columbia	
Gordon F. Hartman, Derek B. Tripp, and Tom G. Brown	141

Long-term Patterns in the Abundance of Carnation Creek Salmon, and the Effects of Logging, Climate Variation, and Fishing on Adult Returns	
Peter J. Tschaplinski, J. Charles Scrivener, and L.B. Holtby	155
Watershed Hydrology: Forest Management Implications	
Robert P. Willington	181
Gully Assessment Methods	
D.L. Hogan and T.H. Millard	183
Classification and Assessment of Small Coastal Stream Channels	
D.L. Hogan and S.A. Bird	189
Productivities, Costs, and Site and Stand Impacts of Helicopter-logging in Clearcuts, Patch Cuts, and Single-tree Selection Cuts: Rennell Sound Trials	
Ray Krag	201
Ten Years of Watershed Restoration in Deer Creek, Northwest Cascades of Washington State	
James E. Doyle, Greta Movassaghi, and Roger Nichols	215
The Fish/Forestry Interaction Program Simulation Model (FFIPS)	
D. Marmorek, Ian Parnell, Tim Webb, Michael Z'Graggen, Werner Kurz, and Josh Korman	231
Problems, Prescriptions, and Compliance with the Coastal Fisheries-Forestry Guidelines in a Random Sample of Cutblocks in Coastal British Columbia	
Derek Tripp	245
POSTERS	
The Spatial Variation and Routine Sampling of Spawning Gravels in Small Coastal Streams	
Stephen Rice	257
Debris Avalanches-flows on British Columbia's North Coast	
Jim W. Schwab	259
Landslide Runout Behaviour in the Queen Charlotte Islands	
R.J. Fannin, M.P. Wise, and T.P. Rollerson	261
Landslide Reforestation and Erosion Control in the Queen Charlotte Islands	
William J. Beese	263
River Otter Predation on Juvenile Salmonids in Winter: Preliminary Report of River Otter Scat Collection and Diet Analysis	
J.M.E. Balke, P.J. Tschaplinski, S.J. Crockford, and G. Suther	265
Applications of Photography in Geomorphology: Size Scales and Appropriate Platforms	
Darren Ham and Dan Hogan	267
Terrain Attribute Study: Slope Failure Frequencies Following Logging in Coastal British Columbia	
B. Thomson	271
Quantifying Basin Comparisons in the Queen Charlotte Islands	
Anthony L. Cheong	273
Riparian Area Response to the Development of a Lateral Sediment Wedge	
Stephen A. Bird	275

Introductory Comments for FFIP/Carnation Creek Workshop

DAVID WILFORD

Welcome to the Workshop.

Both the Carnation Creek and Fish/Forestry Interaction Program (FFIP) have advanced our understanding of fish, forestry, and the effects of forestry and fisheries.

It is important that both projects started at opposite ends of the spectrum.

Carnation Creek was driven by research people who wanted to provide the basic, locally generated knowledge for fish/forestry management. To a degree, the program was calm, and it wasn't until a decade after the program started that managers said, "Let's use this information now."

The Fish/Forestry Interaction Program was the silver lining to the dark cloud of Riley Creek. Managers wanted to know yesterday. There was hot, dirty water all over the place. Things were never calm in FFIP, and scientists were pressed to come up with interpretations immediately. There was no time for researchers to quietly mull over their data.

Whatever the differences in their origin and overall project design, there are some important similarities between the two research programs:

1. Continued Management Intent: Fish/forestry research is long term. Most projects can't be done in a week or two. Several years are generally required, and some aspects require decades. This means that budgets have to be there, and this means that managers have to recognize the value of the work and keep it afloat. Both Carnation Creek and FFIP had such support.

The key players over the last 25 years on the Steering Committees have been:

- Bill Young, John Cuthbert, Keith Illingworth and Ted Baker from the B.C. Forest Service;
- Forbes Boyd and John Payne from the Department of Fisheries and Oceans;

- Jim Walker, Ian Robertson and Dave Narvier from Fish and Wildlife of the B.C. Ministry of Environment, Lands and Parks;
- Vern Welburn and Alex Sinclair from the Forest Engineering Research Institute of Canada;
- Grant Ainscough and Dave Handley from MacMillan Bloedel Limited.

Over the next three days we will focus on the Carnation Creek and FFIP researchers who do the work and the operational people who have implemented the results. It is important that we take our hats off to the Steering Committee members. Without their continued support over the past 25 years, we wouldn't be here today.

2. More Effective Guidelines: Knowledge gained from the research has been used in creating more effective management guidelines. Examples include the B.C. Coastal Fisheries-Forestry Guidelines (CFFG) and field guidebooks such as the *Management of Landslide Prone Terrain* handbook. Reviews of field practices such as the "Assessment of the Applications and Effectiveness of the CFFG" have shown that these guidelines are effective when implemented. But implementation has been an issue, so now with the Forest Practices Code, the application of research-based prescriptions will become law. Local research results have long been recognized as necessary for viable prescriptions. Carnation Creek and FFIP are thus one of the cornerstones of forestry/fisheries management.

But, I have two questions:

1. Have operational people applied all of the research results they can? This is a question for researchers to answer.
2. Are researchers covering the scope of issues operational people encounter or foresee? This is a question for researchers to answer.

This workshop is designed to pull research and operational people together to explore these questions. The degree to which we depend on each other is becoming more clear each year.

Back in 1982, at the Carnation Creek 10-year review, operational people may have considered the

research results “nice to know.” Now, with the Forest Practices Code, research results should be considered a “need to know.”

We’ve got 3 days of hard work ahead.

Best Wishes.

Introduction to Day 1: Focus on Research

MICHAEL BROWNLIE

The goal of this workshop is to present the findings from 20 years of fish/forestry interaction research at Carnation Creek on Vancouver Island and 10 years on the Queen Charlotte Islands. This workshop is not, however, just about research results; it is about applying the results to real problems on the ground—it is about resolving everyday operational problems. It is also an opportunity for us to go, as a group, out to the field to see first-hand what the real world holds—both problems and solution.

We have three days to achieve this goal. We will spend the first day reviewing a wide range of research projects and results. The second day will be spent in the field looking at several of the study sites and operational trials. The third day will concentrate on lessons learned and the applications to fisheries and forestry management. An objective of the workshop is to cover each of these three components (research results, field demonstrations and applied management solutions) with an equivalent level of effort.

This morning we begin with four presentations that set the stage for the rest of the workshop. The four preliminary papers are designed to:

1. compare and contrast the different study objectives and research designs used in the FFIP studies;
2. provide an overview perspective of Pacific Northwest landscapes in order to determine the similarity of the two coastal environments (Vancouver Island and the Queen Charlotte Islands);
3. outline the common fish species found in these areas and indicate some of the life history strategies used to cope with in-stream environmental change; and

4. use the results from recently completed environmental audits to provide a backdrop for the types and nature of the research and applied studies carried out in the two fish/forestry interaction programs.

Following the introduction, we will begin with the first of 10 research presentations. These 10 have been specifically selected for two reasons:

1. each paper summarizes numerous individual research studies conducted within one of three watershed process groups (hillslopes, stream channels and fisheries); and
2. each paper indicates the link between watershed processes and, as such, hillslope process research results precede stream channel process research, and that in turn precedes the fish population and habitat research results.

So, the common themes and linkages that will be pursued over the next three days are:

- research-field-applications; and
- hillslope-streams-fish.

The second day, to be spent in the field, will be led by the individuals responsible for the field research. An effort has been made to have the younger researchers, often students, lead these field demonstrations. My colleague, Nancy Wilkins, from the Ministry of Environment, Lands and Parks, will lead us through the third day dealing with management applications.

And with that I would like to introduce our first speaker. Thank you.

Introduction: Workshop Outline and Experimental Design

C. PETER LEWIS

Introduction

Two major fish/forestry interaction programs have been conducted in coastal British Columbia over the last 25 years. The Carnation Creek Experimental Watershed Study, located on the west coast of Vancouver Island, began in 1970 and is currently the longest-running program dealing with the impacts of forestry practices on a coastal stream ecosystem in North America.

The second initiative, the Fish/Forestry Interaction Program (FFIP) on the Queen Charlotte Islands, began in 1981. About 30 watersheds were looked at in this program, which focussed on the effects of landslides on channel morphology and fish habitat, as well as on watershed rehabilitation techniques and silvicultural treatments.

These two projects were conducted in similar environments, but each used a different experimental design. The different approaches have provided an opportunity to understand ecological responses both over very long time periods and for diverse geographic conditions and logging histories.

The purpose of this workshop was to integrate the findings from these two fish-forestry interaction programs by:

- presenting research findings from studies in Carnation Creek and on the Queen Charlotte Islands;
- viewing a wide range of forest geoscience and biological research results in the field;
- discussing the operational implications of the research findings; and
- critically reviewing the current state of fish-forestry interaction issues and identifying future research directions.

This paper introduces the two programs, briefly describes their objectives and components, and looks critically at the advantages and disadvantages

of each study design. The conclusion is that while neither program is an ideal example of its design type, both have been immensely valuable to our understanding of fish-forestry interactions and to forest management in British Columbia. Taken together, they have had a cumulative effect—their combined value has been greater than the sum of their individual values.

Experiment or Case Study? Both Carnation Creek and FFIP have been described as experiments. However, the word experiment has been used freely—many would say too freely—in the environmental sciences to describe almost any research program for which a set of observations has been planned in advance. The implications of a real experiment can be substantial and differ in both kind and significance from the alternative, a case study. The definitions below are abstracted from Church (1981):

Experiment

- carefully designed to critically evaluate a conceptual model or generalization (e.g., logging-induced mass wasting in steep coastal watersheds significantly reduces fish populations);
- requires that a set of specific tests be developed to provide a clear choice among competing models (e.g., one test in a set could be a comparison of landslide frequencies in logged and unlogged basins);
- control is critical: treatment effects must be conclusively isolated from external variability; the landslide frequency comparison must be among biophysically similar basins.

Case Study

- sequential monitoring of changes to understand variability and develop—not test—conceptual models;
- makes no attempt to exert experimental control.

An experiment, then, provides conclusive testing, while a case study provides understanding. The case study may be scientifically and operationally valuable but it should not be the end of the road.

Carnation Creek

Carnation Creek (Figs. 1–2) drains into Barkley Sound on the west side of Vancouver Island (Scrivener 1987). It produces coho and chum salmon and steelhead and cutthroat trout. The Carnation watershed is in the Coastal Western Hemlock Biogeoclimatic Zone and is small (basin area 11 km²), with no lakes. The local climate is per-humid (2100–4800 mm annual precipitation) and the hydrograph rainfall-dominated (95% of the annual precipitation falls as rain). Monthly streamflows are highly variable, ranging from 0.025 m³s⁻¹ in summer to 33 m³s⁻¹ during winter freshet. Peak flows up to 64 m³s⁻¹ have been measured.

The basin is characterized by irregular topography, with a wide valley flat downstream, confined channels in the mid-valley, and steep valley walls with bluffs and rock outcrops in headwater areas. The bedrock is primarily volcanic with thin, coarse-textured soils that are well drained in most non-alluvial locations.

Project Objectives The Carnation Creek project began because of serious conflicts between approaches to the management of fisheries and forest resources in the late 1960s (Narver and Chamberlin 1976). In 1970, little relevant information was available from British Columbia or from cedar-hemlock watersheds anywhere in the Pacific Northwest. Funding restricted activities to a single watershed, with annual monitoring of summer fish populations at four other locations in Barkley Sound (Scrivener 1987).

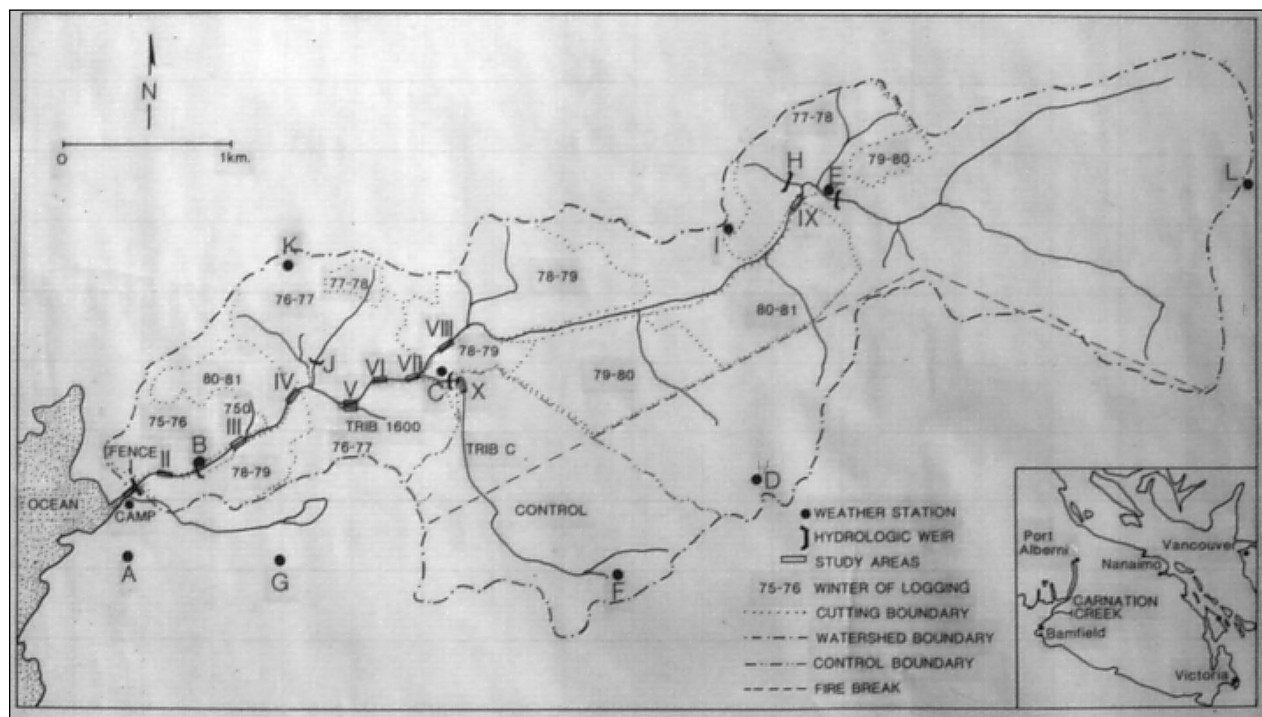


FIGURE 1 Map of the Carnation Creek Watershed.



FIGURE 2 *Carnation Creek: View downstream after logging.*

The objectives of the project were to:

- understand the workings of undisturbed coastal rainforest-salmonid stream ecosystems;
- explain the impacts of clearcut logging on stream environments and salmonid fishes; and
- enable the development of sound, practical integrated resource management guidelines.

Study Components The intent of the study was to show how attributes measured in the stream are related to stream productivity and to processes that originate upslope (Narver and Chamberlin 1976). Components have included (Scrivener 1987):

- hydrometeorology
 - weather records from 10 stations
 - surface and ground water levels
- soil and vegetation disturbance and recovery
 - cutblock surveys before and after logging and after burning
- channel sediment movement
 - suspended sediment movement at B-weir (Fig. 1)
 - gravel and sand transport by direct measurement at B-weir
 - annual changes of pools and streambanks in study sections
 - particle size distributions
 - large organic debris
 - scour and deposition rates (freeze-cores)
- energy gains and losses
 - water temperatures
 - dead leaves and needles (>12 tons/year)
- biological processes
 - periphyton biomass (attached algae)
 - stream invertebrates

- fish: adults, fry/smolt leaving, juveniles, use of tributaries

Study Design After the classification of Hall et al. (1978), the Carnation study design was labelled “intensive pre-post treatment,” involving a single basin only (Hogan and Chatwin 1992). Biological and physical features were intensively monitored for 5 years before logging began (1971–1976). This was followed by a timber harvest phase that ended in 1981, by which time 41% of the basin had been logged. Little harvesting took place between 1981 and 1986, the formal post-logging phase, but subsequent harvesting increased the total logged area to 61% of basin area by the end of 1993.

The initial experimental design focussed on the impacts of streamside logging, not on upland impacts. Three streamside treatments (Fig. 1) were used during the logging phase (Scrivener 1987):

- leave strip: downstream 1300 m; variable width leave strip with deciduous and merchantable trees;
- intense: next 900 m upstream; all merchantable timber yarded away and through the stream; streambanks and large debris damaged; and
- careful: farthest upstream; minor vegetation left; little cross-stream yarding; alder felled and burned.

Advantages and Disadvantages The Carnation Creek approach (Hogan and Chatwin 1992) has had very significant benefits. The study design has provided:

- over 20 years of complete salmonid life cycle that, for example, enabled Scrivener (1991) to develop a predictive model that distinguishes among overwintering, marine, and climatic factors contributing to chum production;
- detailed, spatially and temporally intensive, physical data sets which, among many possible applications, may allow determination of rates of recovery after disturbance;
- over 180 publications by 1989;
- a broad set of pre-treatment data that can be used in after-the-fact post-treatment projects; and—perhaps most significantly—
- an understanding of long-term environmental interactions that has been invaluable in the development of the Coastal Fisheries-Forestry Guidelines and the subsequent Forest Practices Code of British Columbia.

There is another side, however. Both the Carnation design and the way in which it was

implemented also have some disadvantages and weaknesses. These include:

- a focus on one watershed only, with no external control (the lack of conclusive data on Carnation's biophysical similarity to other basins has led to some questioning of the broad applicability of research results);
- the concentration on streamside treatments (no real consideration was given to upstream impacts; other features of the watershed have since been demonstrated to be important, especially the canyon and large sediment source immediately upstream of the "careful" treatment reach;
- location of the "undisturbed" reach downstream from the "intense" treatment, again a reflection of the lack of appreciation of upstream impacts at the time the study began;
- atypical logging practices, both because those logging practices have changed and improved over time and because, in contrast to most other logged coastal basins, no roads or bridges were constructed on the Carnation Creek floodplain; and
- renewed logging following the formal post-logging phase, which has greatly complicated examination of long-term watershed and channel recovery.

The net effect is that the Carnation Creek Watershed Study cannot be considered an experiment in the sense described by Church (1981). Specific hypotheses were not sufficiently inclusive and the critical experimental controls were not present in the design applied at Carnation Creek. Carnation, by itself, is most properly labelled a "case study"—a particularly valuable and long-term case study, but a case study nonetheless.

Queen Charlotte Islands: Fish/Forestry Interaction Program

Many areas of the Queen Charlotte Islands (Fig. 3) are characterized by steep slopes and shallow, unconsolidated surficial materials that are subject to severe natural mass wasting (Fig. 4). (Gimbarzevsky's [1988] aerial photograph-based regional inventory identified more than 8000 individual debris slides, avalanches, and flows and torrents.) At the same time, the Islands contain significant fish resources and some of Canada's most productive forest land because of the mild climate, high rainfall, and lack of summer drought (Poulin 1984). The Charlottes

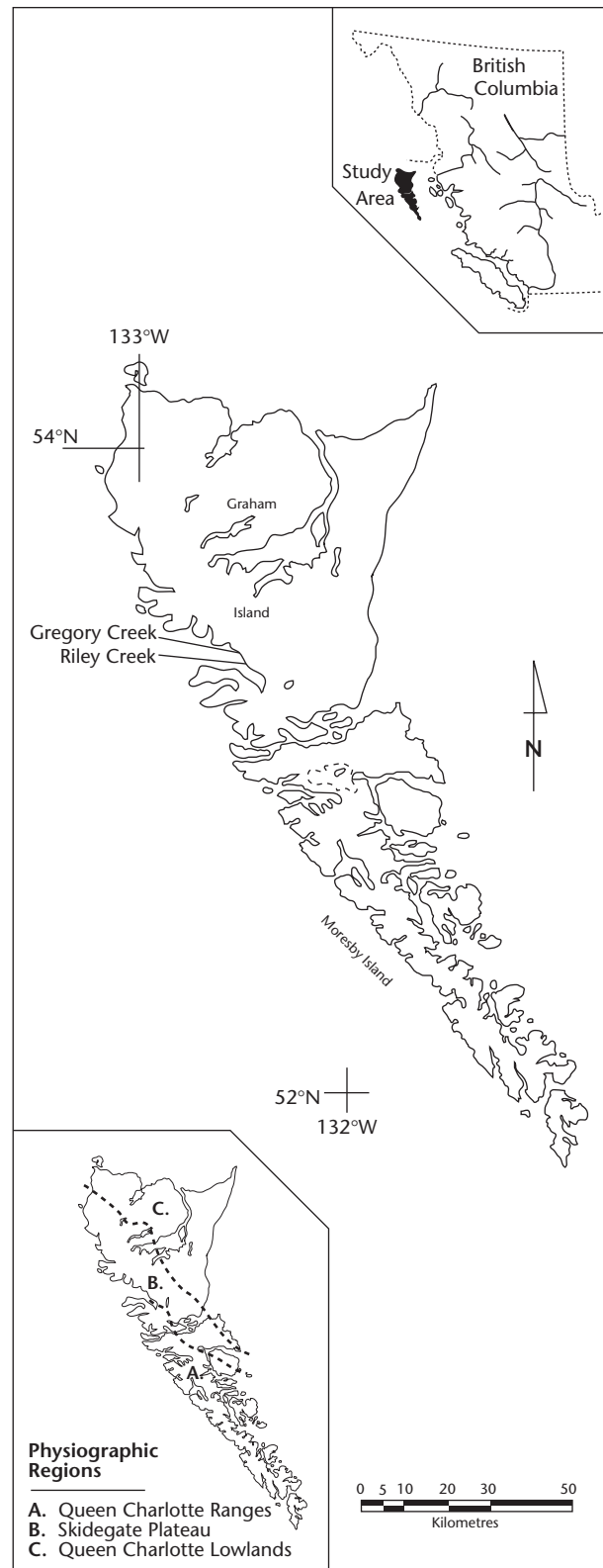


FIGURE 3 Map of the Queen Charlotte Islands.



FIGURE 4 *The “natural” Charlottes.*

exemplify, even exaggerate, what is known throughout the Pacific Northwest: that active logging, valued fisheries, and steep, unstable slopes are a recipe for conflict.

Fish/forestry problems accelerated on the Islands in the late 1960s when most low relief terrain had been logged and forestry operations moved on to the less stable slopes (Fig. 5). A series of events in



FIGURE 5 *Forest harvesting on steep slopes.*

the late 1970s focussed national attention on the Charlottes. A major storm in 1978 triggered landslides throughout the Islands. The next year, these new slides on the west coast led to a major confrontation at Riley Creek (Fig. 6) between government fisheries staff and loggers. The public outcry was widespread. Steep-slope logging was blamed for accelerating natural landslide rates and causing major damage to salmon-spawning streams.



FIGURE 6 *Landslides at Riley Creek, 1979.*

Project Objectives The Fish/Forestry Interaction Program was government’s reaction to public concern (Poulin 1984). Following from a task force recommendation of the need for research, FFIP had several objectives:

- to document the extent and severity of mass wasting on the Queen Charlotte Islands and assess impacts;
- to investigate stream and forest site rehabilitation feasibility;
- to assess alternative silvicultural treatments; and
- to investigate alternative logging methods.

Many answers were known but not accepted. There was a need to achieve “buy-in” as well as understanding.

FFIP has been supported by the B.C. Ministries of Forests and Environment, the Canada Department of Fisheries and Oceans, the Canadian Forestry Service, and the Forest Engineering Research Institute of Canada (FERIC). Phase 1 began in 1981 and ended in 1986, culminating in a major workshop at Sandspit on the Queen Charlotte Islands in October 1986. Output from the program

included numerous reports and publications, and a set of policy recommendations was provided for senior management in the Ministry of Forests. A 5-year Phase 2 FFIP was recommended, starting in 1988 and focussing on information transfer, field demonstrations, monitoring, and selected new or continued research.

Study Components The FFIP approach has involved comparisons among many logged (treated) and forested (untreated) watersheds, in contrast to the long-term, detailed, single basin investigations undertaken at Carnation Creek. Components in the program have included:

- location, extent, and severity of landslides
 - landslide frequencies, points of initiation, and size?
 - how reliable are available methods for predicting slope stability?
- similarity measures for watersheds
 - is there an operationally efficient and effective method for comparing watersheds for research and management purposes?
- effects of landslides on stream channels
 - sources of sediment in the channels?
 - response of channels to mass wasting inputs, including downstream propagation and recovery?
- role of gullies in unstable terrain
 - effect of logging debris and logging debris clean-out in gullies?
 - how should gullies be classified and managed?
- effects of landslides on fish and fish habitat
 - effects of mass wasting on salmonid spawning and overwintering habitats and on juvenile fish populations and habitats?
- effects of landslides on forest productivity
- logging and silvicultural techniques
 - factors in logging-related landslides and how can they best be managed?
 - advantages and disadvantages of alternative silvicultural systems?
 - is logging of unstable terrain by helicopter feasible and beneficial?
- restoration/rehabilitation
 - operational trial of a watershed rehabilitation planning methodology
 - placement and evaluation of log and other structures in streams
- information transfer
 - publication of *A Guide for Management of Landslide-Prone Terrain in the Pacific Northwest* (Chatwin et al. 1991)

Study Design The Queen Charlotte Islands FFIP is an example of the “extensive post-treatment” design in the classification of Hall et al. (1978). The approach involved:

- studies in a broad range of watersheds, both unlogged and previously logged;
- multiple basin case studies;
- opportunity-based prescriptive projects; and
- some “real” experiments.

Component studies that met or attempted to meet the criteria for a true experiment as laid out by Church (1981) include:

- Hogan’s early work on stream channels in paired basins (Hogan 1986);
- recent Hogan channel recovery work (Hogan et al., this volume);
- investigations by Bovis and others of the role of woody debris in gully erosion (Bovis et al., this volume); and
- the Rennell Sound helicopter logging impact study.

Advantages and Disadvantages Like Carnation Creek, the FFIP design has both positive and negative aspects. Among the advantages:

- more comfort with extrapolation because of the wide temporal and spatial perspective offered by a multi-basin program;
- a potential for shorter study lengths in situations where differences between basins can be used to infer changes through time;
- the ability to include opportunity-based work, such as creating and taking advantage of forest harvesting initiatives to test preventative techniques and rehabilitative measures; and
- roughly 40 publications generated over a relatively short period of time.

On the negative side, FFIP suffers because:

- minimal pre-treatment data are available;
- treatment variability must be isolated from natural variability—something that can be difficult to impossible to achieve in some circumstances (e.g., isolation of habitat effects from the many other factors that affect anadromous fish population numbers over the short term);
- many component studies do not include rigorous watershed similarity testing and do not meet the standards for a well-formed experiment; and
- logging practices examined may be obsolete or non-typical; many of the studies consider logging that took place as much as 50 years ago.

The net effect is that FFIP is a heterogeneous mixture of study designs, some rigorous and some not, which contributes significantly to a conceptual model of the impacts of logging-induced mass wasting on fish production. The program on its own, however, does not provide the critical predictions needed for full model testing. Nor, for most components, does it enable quantitative prediction of impacts.

Carnation Creek plus FFIP: "Cumulative Effects"

Both the Carnation Creek Experimental Watershed Study and the Fish/Forestry Interaction Program on the Queen Charlotte Islands have played critical roles in the development of forest management regulations, guidelines, and practices in British Columbia and elsewhere in the Pacific Northwest. Together, their impact and value add up to more than the sum of their individual contributions. Long-term results in Carnation Creek confirm that FFIP findings are realistic and add a deeper and more realistic understanding of the processes and responses behind those findings. The results of FFIP, on the other hand, provide justification for the extrapolation of Carnation findings to other coastal basins. The two programs have had a synergistic, or cumulative effect.

We have seen, though, that neither program is an ideal example of a true experimental design type. This means that results must be viewed with realistic skepticism and that extrapolations will continue to be dangerous and subject to controversy. Nor is quantitative prediction possible at this point in time. Conclusive experiments are yet to come in the years ahead.

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The Landscape of the Pacific Northwest

MICHAEL CHURCH

Introduction

The “Pacific Northwest” is a nebulous place: it denotes different geographies to different people. Broadly, it is that region within which the climate of the northeast Pacific Ocean laps onto the North American continent. Because we are concerned with the forests of the northwest coast of North America, the Pacific Northwest will be defined in this paper as the region occupied by the massive coniferous forest characteristic of this coast. By this definition, the region stretches from 61°N at Cook Inlet, Alaska, through 20° of latitude to Eureka, California (Fig. 1).

Tectonic History

The contemporary environment of this region began to develop about 10 million years ago when the Coast Mountains of British Columbia and the Cascades to the south began their most recent phase of uplift, a consequence of tectonics on the leading edge of the continent. The tectonic regime is controlled by the relative motion of the Pacific, Juan de Fuca/Explorer, and America plates (Fig. 2), which meet in a triple junction off the north coast of Vancouver Island. The Pacific plate is moving north relative to the continent along the Queen Charlotte-Fairweather fault system at about 6 cm a⁻¹ (Keen and Hyndman 1979). To the south, the spreading rate on the Juan de Fuca and Explorer ridges is 4–6 cm a⁻¹ and at least part of this motion is taken up by subduction of the Juan de Fuca plate under the continent. The continental margin is, then, seismically and volcanically active. But, whereas the locus of activity lies offshore—along the Queen Charlotte fault—in most of British Columbia, activity moves onshore over subducting margins in the Cascade province and southern Alaska (Fig. 2). The most impressive physiographic evidence of subduction is the presence of lines of continental stratovolcanos in the Cascades from northern California to southernmost British Columbia, and

in the Wrangell arc, extending from the St. Elias Mountains along the Alaskan coast. In between, basaltic volcanic centres, indicative of deeper-seated vulcanism, occur in the Anahim and Stikine belts of British Columbia (Fig. 2).

Uplift in the Coast Mountains of British Columbia within the last 10 million years has been up to 4 km; that is, up to 0.5 mm/year (Parrish 1983: see Figure 2). While the northern part of the ranges experienced greater uplift in the earlier part of the period, the southern Coast Mountains have experienced uplift rates of greater than 0.5 mm/year in the latter half of the period. Over half of the uplift is probably due to isostatic compensation of erosion during the period; the balance is due to primary tectonic uplift. Contemporaneous tectonic uplift, evidenced by major earthquakes, averages about 2 mm a⁻¹ along the outer coast of British Columbia and several millimetres a⁻¹ in the St. Elias-Alaskan coast region. There also remains significant isostatic adjustment in heavily glaciated regions of southwestern Yukon Territory and southern Alaska. The importance for us of this tectonic history is that the development of the biota of the Pacific Northwest occurred within the same 10-million-year period and probably was conditioned by it.

Glaciation

Glaciers formed in southern Alaska more than 9 million years ago (Denton and Armstrong 1969). Complete Cordilleran glaciation within the last 3 million years (Clague et al. 1989) has strongly sculpted the valleys and mountains in Canada and Alaska. The effects are particularly conspicuous on the Pacific Coast, which is highly dissected and indented by fjords extending as much as 150 km inland. Local relief near the axis of the Coast Mountains is as much as 2500 m, with additional submarine relief of up to 750 m (Mathews 1989). The fjords and terrestrial valleys, which generally represent the structurally controlled, pre-glacial

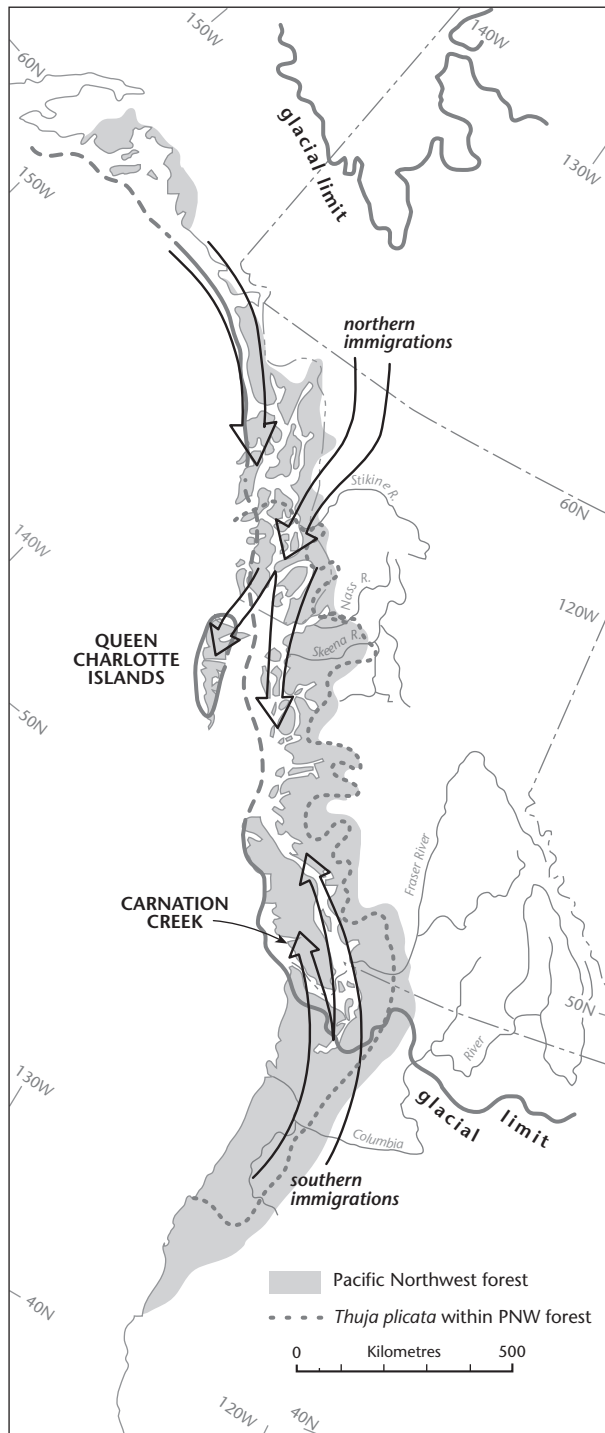


FIGURE 1 Distribution of the Pacific Northwest coast forest. Also shown, the limit of Pleistocene Cordilleran glaciation and the pattern of post-glacial human immigration into the region (highly generalized).

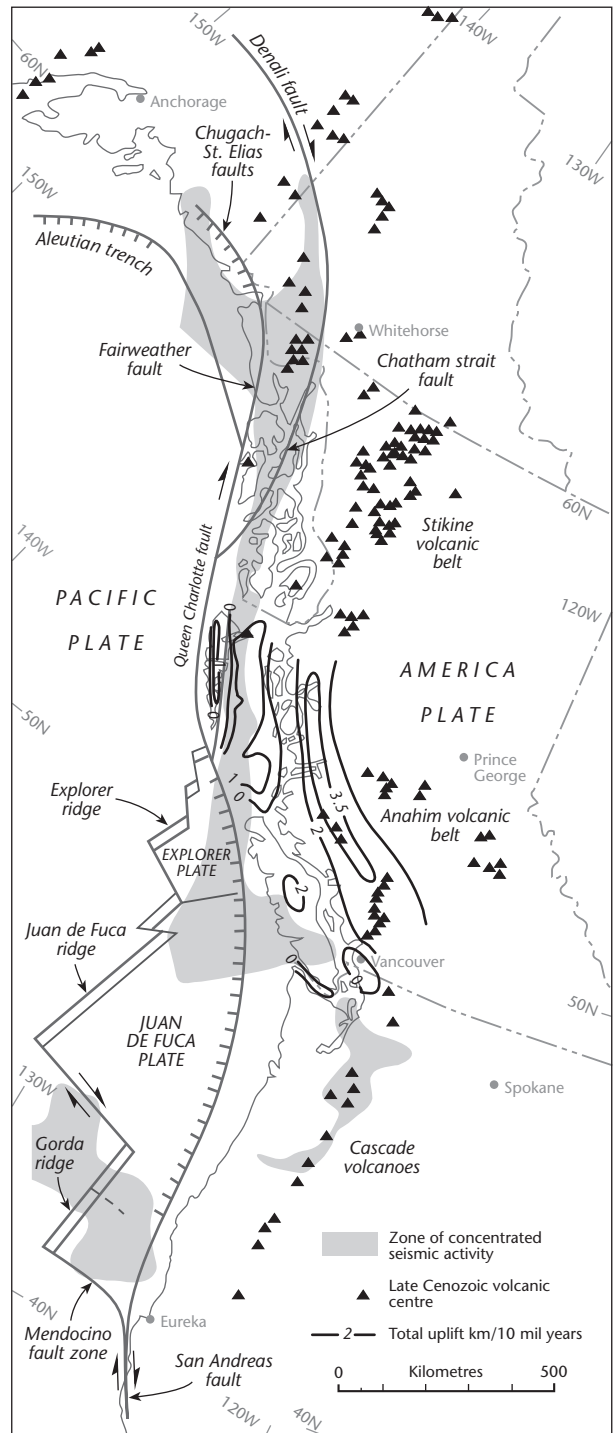


FIGURE 2 Tectonic setting of the Pacific Northwest. Data adapted from various chapters in Gabrielse and Yorath (1992).

drainage lines, exhibit remarkably steep, glacially eroded slopes. Deglaciation has abandoned sediments that are not stable in this steep landscape.

A consequence of Cordilleran glaciation was substantial isostatic depression of the land surface under the weight of ice. The delayed recovery following removal of the ice permitted the sea to flood coastal valleys (Fig. 3), so that highly erodible marine silts occupy many sites near sea level today (Clague 1981). Farther inland, late glacial ice-dammed lakes permitted the accumulation of similarly erodible lacustrine silts in many valleys.

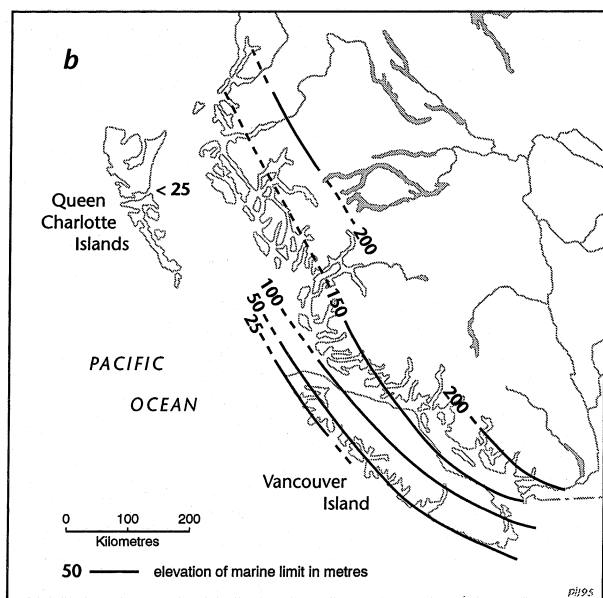
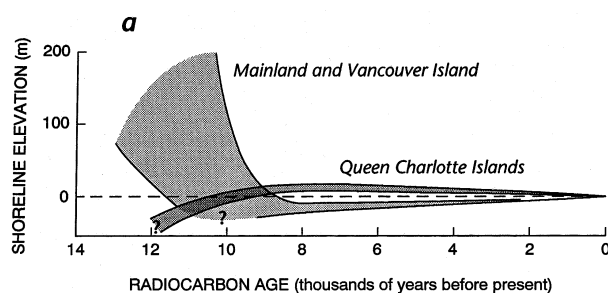


FIGURE 3 (a) Patterns of post-glacial sea level change on the British Columbia coast. (b) Generalized distribution of post-glacial marine incursion and deposits (Clague 1981).

In the Cascades of Washington and Oregon states, and in northern California, glaciation was very much more restricted. Here, alpine glaciation occurred in the high mountains; elsewhere, however, much older, more deeply weathered surfaces persist. Nonetheless, the sedimentary and volcanic rocks of much of this region are relatively highly erodible, so that substantial slope instability is found in these mountains as well. The different Quaternary histories of the northern and southern portions of the Pacific Northwest mean that caution must be exercised in comparing experience of soil and slope stability between the two. (Figure 1 shows the southern limit of general Cordilleran ice inundation.)

Much of the glacial sediment was evacuated from steep, headwater drainage basins relatively quickly, so that contemporary natural rates of erosion are not high (Fig. 4). However, a major episode of "paraglacial" sedimentation continues in the main mountain valleys (Church and Slaymaker 1989) as sediment flushed out of small upland basins thousands of years ago is resorted and moved onward by the rivers.

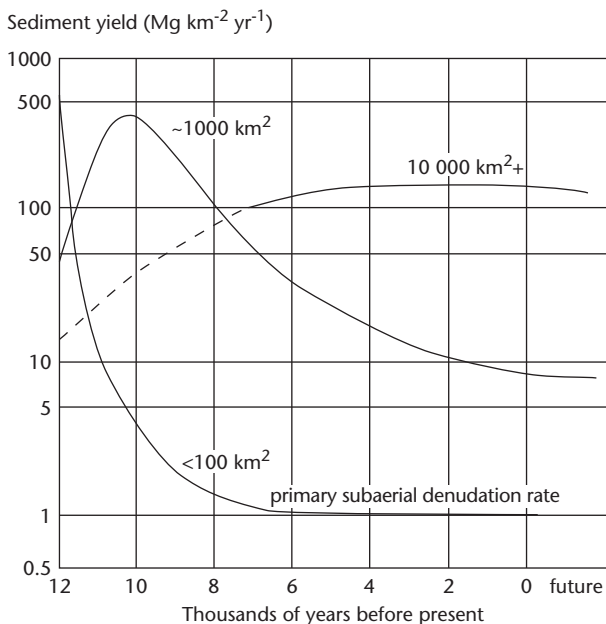


FIGURE 4 Temporal pattern of paraglacial sediment yield at non-glaciated upland and valley sites in coastal British Columbia and Alaska. Values are order of magnitude estimates based on the contemporary spatial pattern of sediment yield (Church and Slaymaker 1989).

The result today of the tectonic and Quaternary glacial history is a vertically zoned geomorphological landscape (Fig. 5). The highest summits remain subject to glacial or periglacial regimes, with frost weathering the major evident process on exposed rock. Episodic mass wasting—including debris slides and flows on open slopes and in gullies, and rock-falls and rock avalanches originating on higher, steeper faces—dominates mountain slopes. More continuous fluvial processes sort the relatively coarse glacial and mass-wasted material in the valleys. In steep mountain valleys with restricted or no valley flat, the slope regime of mass wasting delivers material directly to the streams. However, in the larger glacial troughs, slopes may be mainly decoupled from the main river, so far as the transfer of coarse material goes. The consequence is the build-up of moderately sorted sediments on lower valley sides and in tributary valleys in the form of colluvial footslopes, debris cones, and alluvial fans. The major rivers evacuate Quaternary sediments mobilized from their banks and the fine, wash-load component of material mobilized upslope.

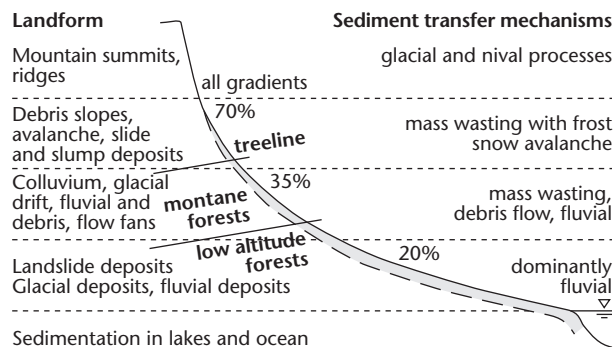


FIGURE 5 Generalized geomorphological zonation of the Pacific Northwest landscape (after Ryder 1981).

Hydroclimate

A key element of the contemporary landscape is water. Water moves sediments and nutrients. It is the connecting link through all parts of the ecosystem. Facing the north Pacific Ocean, and presenting a high barrier to the westerly atmospheric circulation, the region is very wet. Windward slopes in the

region receive greater than 1 m of precipitation per year; many locations receive greater than 3 m, and extremes on upper mountain slopes may be higher than 6 m. Because of the strong control of topography on orographic enhancement of precipitation, substantial local variations occur. Although the effect is well known, there are insufficient gauges—virtually none at higher elevations—to permit construction of a map that reveals these variations systematically. The major regional precipitation gradient is from the coast inland.

Precipitation is concentrated in the winter half-year when cyclogenesis is very active in the North Pacific and Gulf of Alaska. The most damaging floods occur in mid- to late autumn as the result of heavy rain and rain on snow, with the largest flows tending to occur later in the year farther south. Fifty percent or more of the annual precipitation falls as snow, except near sea level on the coast. A high proportion of winter rain and melted snow runs off. In the southern part of the region and inland, relatively little of the summer precipitation runs off, but on the coasts and farther north, an increasing proportion does so. The result is runoff ratios that vary from 40% to more than 80% in outer coast basins.

Maximum specific runoff becomes larger in small basins (Fig. 6). This is a consequence of the concentration of maximum precipitation amounts in relatively small areas. An analysis by Melone (1985) shows an apparent upper limit for 24-hour runoff of about $5 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$ in basins of less than 200 km^2 area, but it is unclear whether this is the result of a limit scale for precipitation cells within large storms, or whether it merely reflects the relative lack of observations on small streams within the mountains. It is clear that the ratio of maximum instantaneous runoff to maximum daily runoff continues to increase in very small basins as a result of the very restricted spatial and temporal scales of extreme precipitation.

Extreme precipitation causes erosion. On mountain slopes erosion takes the form of debris slides in unsaturated or partly saturated soil on open hill-sides, and slides or debris flows in gullies. Because of the spatially vagrant occurrence of extreme water input, and because of the need for there to be a supply of weathered, moveable debris, events in individual headward tributaries may be fairly rare. Recurrence intervals of between 30 and several hundred years are suspected for major events (or for

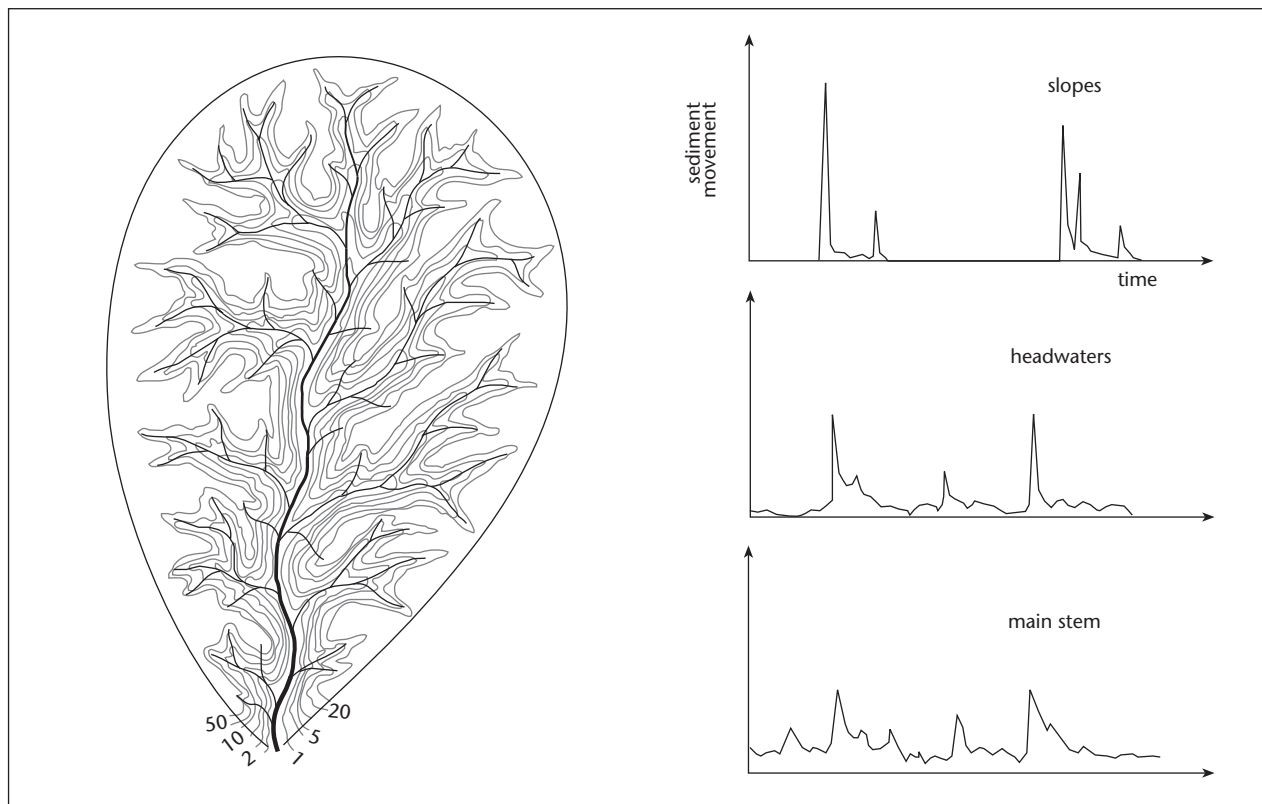


FIGURE 6 *Relation of maximum specific runoff to drainage area in the Coast Mountains of British Columbia (after Melone 1985).*

a series of debris-exhausting events). Because drainage basins collect water and sediment flows from many headwaters, events become more frequent, but less dramatic, as one moves down the system (Fig. 7). Major rivers move sediment regularly and with some predictability, at least in the synoptic time scale, by purely fluvial means. However, the highly contingent nature of events on mountain slopes makes it impossible to plan land use activities there that altogether avoid hazards associated with slope failures.

On the other hand, it certainly is easy to aggravate mountain slope instability. The normal stability of steep slopes depends on drainage mechanisms that move water through the relatively coarse glacial and colluvial materials mainly in the subsurface. This is achieved by the infiltration of even intense storm precipitation into the highly permeable forest soils and by storm flow working its way through a network of soil macropores which consist of root channels, animal burrows, highly

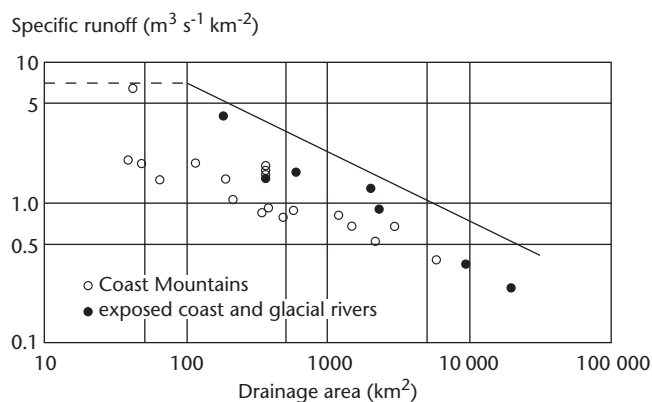


FIGURE 7 *Schematic diagram of the return period for geomorphologically effective events in a mountain drainage basin. Isolines are labelled in years. Typical time sequences and magnitude-frequency graphs for upland/mass wasting-dominated and lowland/fluvially-dominated sediment transfer processes.*

porous, granular soils, and eroded pipes (Cheng et al. 1975). The greatest concentration of drainage tends to occur at the base of the weathered soil or at the surface of compact glacial till or bedrock, and these sites become failure planes when high water pressures develop. Maintaining soil and slope stability in this landscape depends critically on not impeding this drainage mechanism.

The Forest

The forest has developed with the geology. Twenty million years ago the Pacific Northwest forests included oak, beech, sycamore, hickory, and elm (see review in Waring and Franklin, 1979). Conifers of modern genera were present at upland sites in Alaska (Wolfe and Leopold 1967). By late Miocene time (<10 million years ago), coniferous forests occupied large areas on the uplands, but the deciduous lowland forests persisted (cf. Martin and Rouse 1966, on Queen Charlottes flora). By the end of the Pliocene Epoch (ca. 2 million years ago), the flora was essentially modern.

The apparently steady development of coniferous dominance over about 10 million years is ascribed by palaeobotanists to deteriorating temperatures, with a severe decline in summer temperatures occurring in the late Miocene Epoch (Wolfe and Leopold 1967). This probably was related, at least in part, to increasing altitude accompanying tectonic activity. At lower elevations, the increasingly extreme seasonal precipitation regime—also related ultimately to tectonics through the effect of the rising mountain barrier on the atmospheric general circulation—may also have been important.

Conifers possess a number of advantages for survival in the seasonally wet/dry and thermally moderate climate of the Pacific Northwest. They have the ability to photosynthesize outside the main growing season, which is more or less drought restricted (Fig. 8), depending on location. Their high sapwood volume gives them a high moisture storage capacity with which they can protect themselves against seasonal drought. They are also effective at nutrient scavenging and nutrient retention. Nutrient scavenging is promoted by the trees' ability to be physiologically active during late autumn and early spring nutrient flushes; nutrient retention gives the trees a competitive advantage on the heavily leached, nutrient-poor podzol soils.

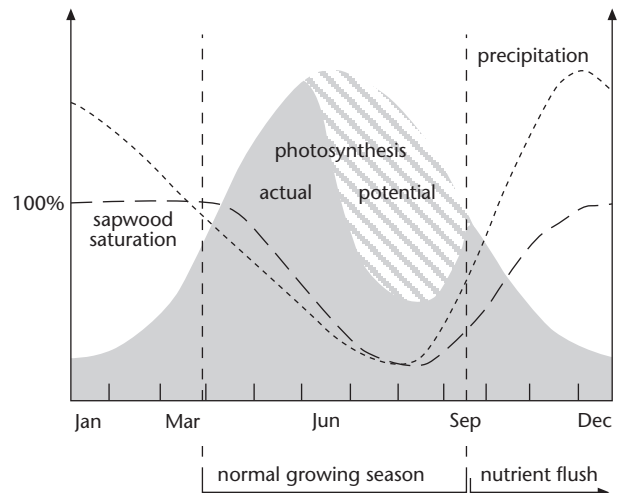


FIGURE 8 Some aspects of the water balance of coniferous trees in Pacific Northwest forests (constructed in part from data in Waring and Franklin 1979).

Exceptional features of the forest are the massive size of the dominant trees and the sheer extent of conifer dominance. Size is not the consequence of superior productivity (the net primary productivity of these trees is not exceptional), but of survival to a remarkable age. Net primary productivity in these forests, on the order of 10–15 tonnes/ha per year, is about half to two-thirds of the values found in tropical and subtropical forests. However, the dominant trees may live for 400 to over 1000 years, so the biomass of the natural forest is very high. Values range to over 1000 tonnes/ha of which, in old-growth stands, up to 30% may be dead wood. See Grier and Logan (1997) for summary data.

The high old age reached by veteran trees, combined with the patchwork pattern of small openings produced by windthrow, slope failures, and disease, creates a remarkably complex forest structure within which dead wood is a vital component. Structure creates both vertical and lateral differentiation of habitats. Vertically, the upper canopy, mid-canopy, upper and lower understoreys, forest floor, and soil create a well-differentiated range of physical and climatic niches. Laterally, openings, downed wood accumulations, and clumps of trees of various ages provide different sorts of opportunities for other organisms. This leads to a rich variety of ecological

niches and high biodiversity. Nevertheless, much of the living forest fabric is not particularly palatable, and so the incidence of herbivory, secondary production and numbers of terrestrial animals (particularly larger ones) are not notably high. Stream systems, however, nurture large populations of many organisms, including fishes.

The Fish

It is thought that the fishes of the Pacific Northwest forest, notably the salmon, also have evolved with the mountains. They are cold, fast-water fish. The ancestral species, *Eosalmo*, was a small, sedentary, whitefish-like animal, fossils of which are found in British Columbia. By 20 million years ago, salmon had appeared (Stearley and Smith 1994). The ancestral taxon of *Salmo* and *Oncorhynchus* evolved into a cold-water, long-distance migrant and spent a protracted period at sea. It also evolved redd digging and guarding. Cold-water tolerance, anadromy, and redd digging are plausible adaptations to the water quality, high hydraulic stresses, and materials found in mountain streams. By mid-Miocene time (10 million years ago before present), *Oncorhynchus* were very diverse, but glaciation has considerably restricted them.

The short period of stream occupation of the Oncorhynchids is thought to be related, again, to the tectonically determined stream environment. Chum salmon (*O. keta*) spawn in the estuaries of small, steep systems and quickly go to sea. The species that spend a longer period in freshwater, the sockeye and chinook (*O. nerka* and *O. tshawytscha*), dominate the larger, lower gradient rivers that flow through the mountains. Spawning strategies appear to be adapted to the seasonal hydrology of the Pacific Northwest mountains (Montgomery 1994). Most species spawn in steep channels when the probability for scouring flows is declining (in early summer or late autumn), or dig deep redds in larger, flatter channels. High fecundity is a population survival strategy exhibited by Oncorhynchids in face of the hazardous mountain environment. Finally, the swimming ability of the fish, including their jumping ability, is adapted to steep, swift waters. High fecundity and the protracted period spent by the fish in the ocean allow the streams to sustain large populations, even though most of them could not support large numbers of resident, adult fish of the size reached by salmon.

In Holocene time, the Pacific Northwest rivers have been very high salmon producers, and a number of characteristics of the post-glacial landscape have made this possible (Northcote and Larkin 1989). Glacial sediments along the major valleys, and the influx of material from mountain slopes, assure a steady resupply of gravel to the streams. Moderate turbidity in mainstem rivers provides useful cover from predators during migration, while normally clean, clear headwaters provide spawning and rearing habitat. These circumstances reflect the conditions of post-glacial sediment transfers in the region (Fig. 4). Headwater lakes of glacial origin—some of them large—provide a degree of flow regulation along most major rivers, as well as habitat for the sockeye. Melting snow from the uplands, sustained well into summer, supports migration runs over an extended period. On the other hand, the relative isolation of many drainage systems has favoured stock adaptation and genetic drift, so the fishes exhibit a high degree of race distinction.

Glacial history has had a major influence on the distribution of all the fish fauna of the region. Glacial refugia were in the Columbia River system and in Beringia. The post-glacial history of reoccupation of the rivers is reflected in declining species numbers northward, from 52 species in the Columbia system (of a total of 61 native species) to 39 species in the Fraser, 32 species in the Skeena, and only 27 species in the Nass and Stikine (McPhail and Lindsey 1986). In the Stikine, the first Beringian fish appear.

The People

The post-glacial migration of plants, animals and fish into the region was accompanied by the immigration of humans who became highly adapted to the forest resources of the Pacific Northwest region.

People entered both from the south and the north (Fig. 1). The southern immigrants had been subsisting in Washington and Oregon, south of the latest Pleistocene ice in British Columbia. They are now recognized to have been related to the classic Clovis hunter-gatherer tradition of the plains and basins in the Cordillera (review in Matson and Coupland 1995). But on their appearance in Puget Sound and on the British Columbia Inner Coast more than 9000 years ago, they rapidly adapted to exploiting fish—principally salmon—and inshore marine fauna (Borden 1979). These provided much more secure food sources than did hunting. The northern

immigrants appear to have arrived from interior Alaska and Yukon Territory, again almost as soon as they could gain access past remnant Pleistocene ice. These people appear to have adapted rapidly to the coastal environment. They quickly moved southward on the sea, learning to exploit its resources as they went.

The second major resource adaptation, though well known, is less well remarked. After 5000 years before present, the aboriginal cultures of this coast became highly evolved civilizations by any standard, and they depended for a wide range of their cultural goods on one tree: the western redcedar, *Thuja plicata*. From this wood they built seagoing canoes, constructed massive plank houses, carved monumental poles and ceremonial objects, made cooking and storage containers, and wove clothing, rope, and matting. All of these products depended upon the durability and working qualities of cedar.

The western redcedar did not become well established in the post-glacial forest until after 6000 years BP (Hebda and Mathewes 1984). It appears to have been slow to invade in drier, warmer early Holocene times. Between 5000 and 2500 years BP, it became a co-dominant on moist sites in the coastal forests, and the people of the region learned to exploit it to extraordinary effect. The evidence of their activities remains present today in old-growth forests everywhere in the region in the form of “culturally modified” trees.

Summary and Prologue

The salmon and the cedar, products of the long-term natural history of the Pacific Northwest region, were the most significant bases of the distinctive cultures that were developed on this coast in Holocene time. Salmon and cedar are intertwined in other ways as well. The Pacific Northwest is characterized by a particular geological history that has bequeathed to us a steep and geophysically active landscape mantled by soils tenuously stable in the humid climate, a forest of exceptional ecological complexity, both terrestrial and aquatic, and a highly developed cultural history with a special dependence on the forest and the streams. When we work in the forests today to extract timber, we may upset all of these conditions if we are not careful. Our modern commercial quest for cedar and the other softwoods

has the potential to destroy the salmon and most of the other features of the forest.

The purpose of this workshop is to examine progress made in understanding the effects of forest harvest practices on coastal aquatic ecosystems, particularly on the salmon and their habitat. In British Columbia, a large portion of the investment in such studies during the last 25 years has been concentrated in two major programs: the Carnation Creek experimental drainage basin (cf. Hartman and Scrivener 1990) and the federal-provincial Fish/Forestry Interaction Program (FFIP) in the Queen Charlotte Islands. The two programs have been entirely different in their character (see Lewis in this report).

Carnation Creek is a classical longitudinal study, with controls, of the immediate and long-term effects of forest practices at one site. From such studies we gain detailed knowledge of ecosystem function, and how the system is disturbed by the intrusion of logging. The results provide a template for understanding what is happening elsewhere. But one of the important lessons we have learned is the importance of local and contingent effects in determining how the ecosystem develops. Thus, there must be doubt that the results from Carnation Creek can be extrapolated to make quantitative predictions for other sites.

For that, an appreciation of variability in the landscape is required. The synoptic FFIP study (Poulin 1984), in which a large number of stream systems were examined in a similarly wet, west coast environment, goes some way toward providing the context of regional variability in both disturbances and effects. Both studies are situated on the very wet outer coast. The moderate relief (by regional standards) and steep slopes at Carnation Creek, developed on deformed sedimentary and volcanic rocks, falls well within the range of land surface conditions encountered in the Queen Charlotte Islands. The forest at Carnation Creek is similar to that of the Queen Charlottes, and the aquatic ecosystem—a steep channel with an alluvial lowermost reach, hosting coho and chum salmon and cutthroat trout—is typical of those on the Charlottes. These conditions are broadly representative of the entire British Columbia coast. It is appropriate to compare these two study programs, and to apply the conclusion coastwide, appropriate respect being given to the range of local landscape variability.

The papers in this workshop will summarize much that we have learned from these studies, and will point out many things that we do not yet know. They will indicate where we must take fish/forestry interaction studies next. Undoubtedly, the next stage will incorporate a significant modelling component that seeks to fuse the systematic knowledge gained from Carnation Creek, and similar studies, with the knowledge of regional conditions gained in studies like FFIP. Ultimately, all of this work is rooted in the conditions of the landscape. All of the papers in this workshop will begin from one or another of the conditions outlined in this paper.

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An Introduction to the Ecological Complexity of Salmonid Life History Strategies and of Forest Harvesting Impacts in Coastal British Columbia

J. CHARLES SCRIVENER, PETER J. TSCHAPLINSKI, AND J. STEVENSON MACDONALD

Introduction

Coastal watersheds are large producers of forest products and salmonid fishes in British Columbia. Coastal valleys contain all the “good” (3.3%) and the “medium” (33%) industrial forest land of the Vancouver and Prince Rupert forest regions (B.C. Ministry of Forests 1980). Five species of Pacific salmon and two species of trout use the rivers and smaller streams of these forest regions. Two studies of forest harvesting impacts on salmonids were initiated to address concerns relevant to both regions: the Fish/Forestry Interaction Program on the Queen Charlotte Islands in 1978 and the Carnation Creek project on Vancouver Island in 1970.

Streams are used in a different manner by each salmonid species, thus impacts from forest harvesting are expected to affect each species differently. Species such as pink, chum, and sockeye salmon use streams primarily to incubate their eggs (Fig. 1).

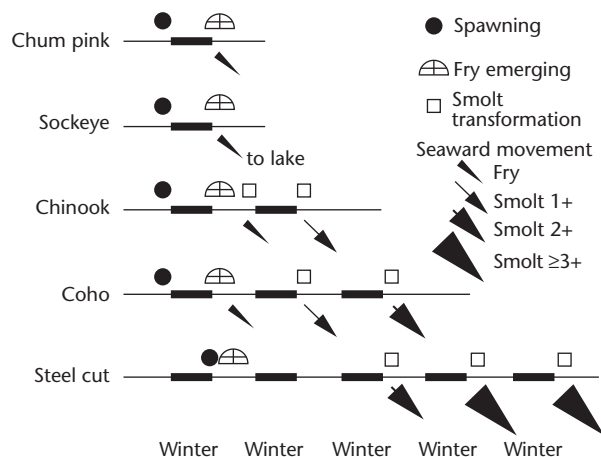


FIGURE 1 A schematic representation of the freshwater life histories of juvenile chum, pink, sockeye, chinook, and coho salmon, and steelhead and cutthroat trout in coastal British Columbia.

They emigrate either to the ocean or to lakes shortly after the fry emerge from the streambed in the spring. Sockeye salmon spawn in tributary streams to their rearing lake or river (Burgner 1991). Chum salmon spawn in the lower reaches of rivers and small coastal streams. Often, these areas are under tidal influence (Thornsteinson et al. 1971; Hartman and Scrivener 1990). Pink salmon usually spawn in large numbers in large rivers (Heard 1991), but they can also spawn in estuaries. When both species use the lower reaches of the same stream for spawning, pink salmon tend to occupy intertidal areas, while chum salmon occupy spawning sites immediately upstream (Helle 1970; Thornsteinson et al. 1971). These species are affected only by impacts to their spawning and incubation environments, but the location of those environments differs for each species.

The other species incubate their eggs and rear for varying periods of time in rivers and streams (Fig. 1). Juvenile chinook salmon either occupy large rivers for 6–12 months (Levings and Lauzier 1991) or move into estuaries within 30–90 days (Healey 1983). In large river systems, they can move progressively downstream; often, some move upstream into non-natal tributaries (Murray and Rosenau 1989; Scrivener et al. 1994). Steelhead trout, the anadromous (sea-run) variety of rainbow trout, occupy the main channel of rivers and streams for 2–3 years before emigrating to the ocean (Fig. 1). Anadromous cutthroat trout frequently spawn in small tributaries with small gravel, and they rear for 2–3 years in the main channel and small tributaries of streams (Hartman and Scrivener 1990). Some rainbow and cutthroat trout remain in freshwater throughout their lives (non-anadromous or “resident” populations). Forest harvesting impacts on spawning and egg incubation environments of stream-dwelling salmonids can be either ameliorated or made worse by impacts occurring in the subsequent freshwater life-stages of each species (Hartman and Scrivener 1990).

Juvenile coho salmon reside for 1–3 years in freshwater before migrating seaward as smolts. Their life histories are complex during the period spent in freshwater. They may use rivers and other large streams in a manner similar to chinook salmon, progressively moving downstream while in freshwater (Cederholm and Reid 1987), but they most frequently inhabit smaller streams and ponds. We have recognized five life history strategies for coho salmon in one small watershed, the 11-km² Carnation Creek system (Fig. 2):

1. they can remain in the main channel for 1 year before emigrating to the ocean;
2. they can reside in main channel for 2 years (rarely for 3) before emigrating;
3. some fish occupy the main channel for the summer but move into ephemeral tributaries and swamps for the winter during the 1- to 3-year period of freshwater residence;
4. they can move downstream into the estuary for the summer and return upstream into estuarine drainages for the winter; or
5. they can occupy the estuary for the summer and then move into the ocean during autumn.

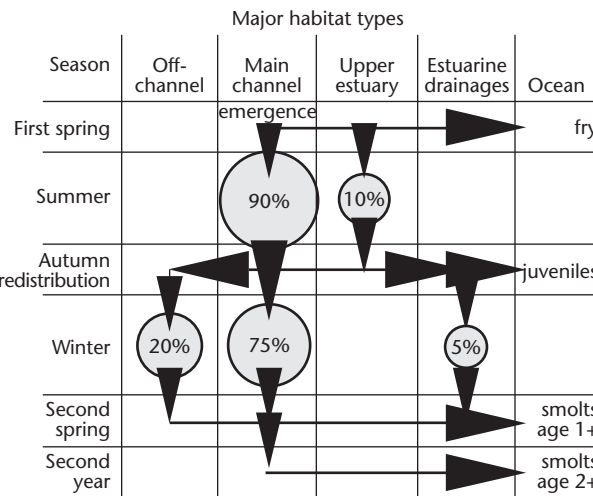


FIGURE 2 Major habitat types and life history strategies that are used by coho salmon in Carnation Creek.

All of these strategies contribute to adult escape-ment and catch (Hartman and Scrivener 1990). The multiple strategies tend to stabilize smolt production, because each environment is affected differently by ecological processes. Stability of production is essential for these small populations. Impacts from forest harvesting would affect each of these strategies differently.

Most forest harvesting impacts on streams fall into three categories. The first group is related to the regrowth of watershed vegetation. These impacts begin immediately after logging and continue until vegetation restabilizes the soils or channels. Examples are: increased stream temperatures when harvesting allows more sunlight into the stream (Fig. 3); changes to the concentration of nutrients and dissolved ions in stream water when soil disturbance (or burning) permits more leaching of soils (Scrivener 1988); increased fine sediments in streams when slope soils, road cuts, road surfaces, and road ditches are exposed to erosion (Fig. 4); and decreased inputs of leaf litter to streams when riparian vegetation is removed (Culp and Davies 1983).

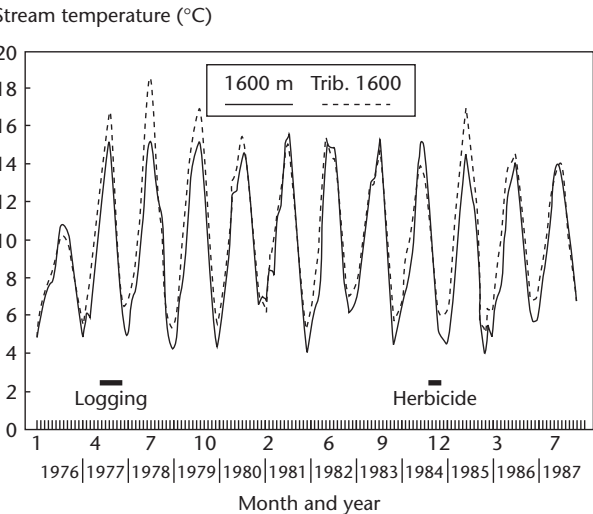


FIGURE 3 Monthly means calculated from daily maximum temperatures from Carnation Creek (1600 m), a fourth-order stream; and one of its first-order tributaries (Tributary 1600) where all riparian vegetation was removed by clearcut logging during 1977 and by aerial application of a herbicide during 1984.

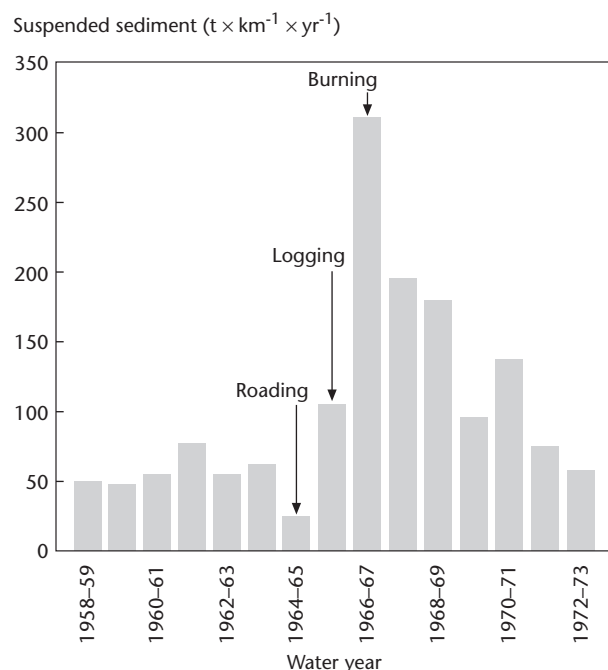


FIGURE 4 Annual rate of suspended sediment transported through the weir during each water year (September to August) of the Alsea watershed study, Oregon (from Beschta 1978).

Organic litter is the major source of energy for aquatic production within forested streams (Hynes 1970). The second group of impacts does not begin immediately, but initiation depends on the occurrence of large flood events with return periods of 5–10 years. Examples of these impacts include: increased occurrences of mass wasting (Swanson et al. 1987); increased erosion and transport of sediment and bedload when stream bank integrity is lost (Fig. 5); changes to fluvial processes and channel morphology when more sediment enters the channel (Hogan 1986; Powell 1988); and changes to the composition of the streambed (Fig. 6). The third group contains very long-term impacts that can appear in 10–20 years, but probably continue throughout the forest rotation. An example is the structural and habitat changes caused by the loss of large woody debris (LWD) in streams (Fig. 7).

Processes that cause these changes have very different time frames in coastal streams. The short-term effects of the first group persist for 3–20 years (Bormann and Likens 1979) and can be beneficial or harmful to aquatic organisms (Hartman and Scrivener 1990; Meehan 1991). The 3- to 5-year

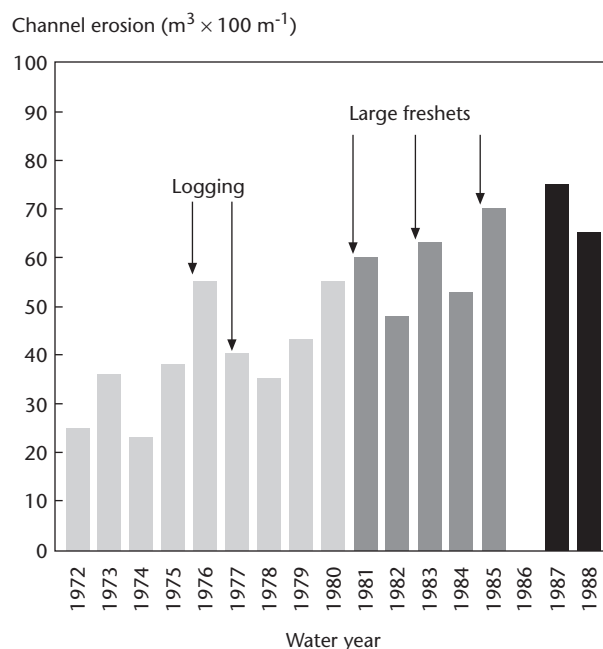


FIGURE 5 Net volumes of sediment eroded or deposited in study section I near the mouth of Carnation Creek as calculated from maps drawn from annual surveys.

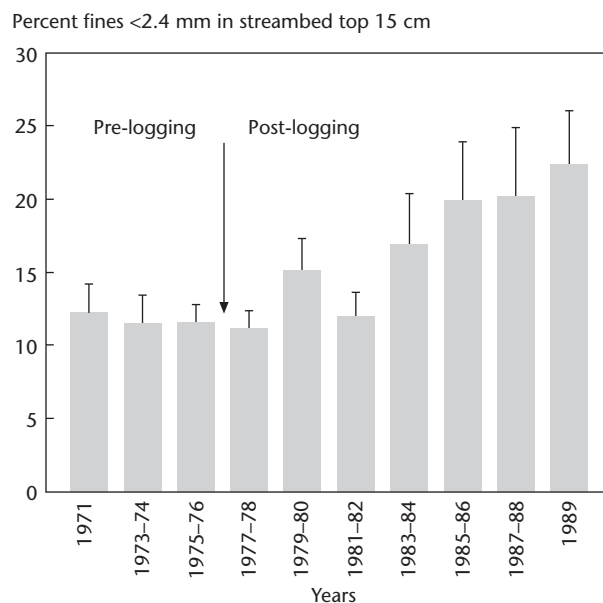


FIGURE 6 Percentage sand size and smaller particles in the top layer of frozen gravel cores from the leave-strip treatment (0–1400 m) of Carnation Creek. Means and confidence limits (95%) were obtained from 6 to 24 freeze-cores of each period.

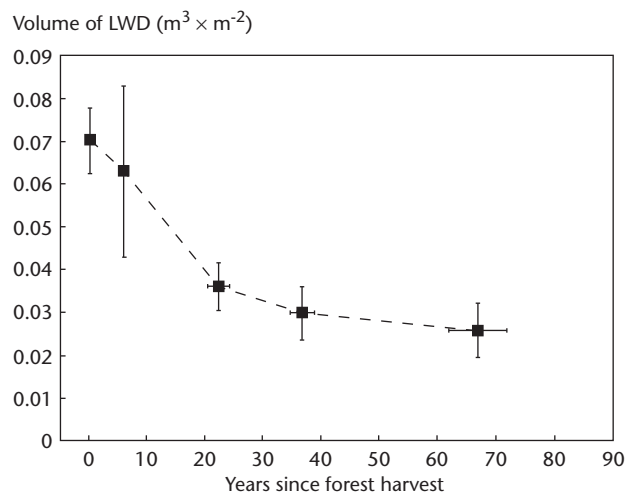


FIGURE 7 Mean volumes of large woody debris (>10 cm diameter.) and standard errors for 53 streams on the west coast of Vancouver Island (Fisheries and Oceans Canada, unpublished data), for 6 streams on the Queen Charlotte Islands (from Hogan 1986), and for 27 streams on the Olympic Peninsula, Washington (Grette 1985; Bisson et al. 1987). The number of streams in each category is also shown.

impacts from increased nutrient concentrations on a stream's primary production is lost as new vegetation begins extracting nutrients from the soil (Hartman and Scrivener 1990). Temperatures of coastal streams increase during winter, spring, and summer after riparian vegetation is removed by clearcut logging or herbicides (Fig. 3). Temperatures decline again when vegetation shades the stream. This occurs within 4 years in first-order streams (Fig. 3) and in ~20 years in fourth-order streams (Beschta et al. 1987). Increased levels of suspended sediment from disturbed soils and roads persist for 6–10 years in coastal watersheds (Fig. 4; Beschta 1978), but can last longer if the roads are still being used and maintained (Cederholm and Reid 1987).

A longer time period is required before the second group of impacts fully manifests itself. Impacts in coastal streams can continue accelerating for a decade (Fig. 5) and may persist for many decades. They tend to have harmful effects on stream productivity. Slope landslides and channel torrents increased in the Queen Charlotte Islands within just a few years after logging had begun (Hogan 1986).

Channel erosion was still accelerating in Carnation Creek a decade after adjacent areas were logged (Fig. 5). Sands and fine gravels from debris torrents and bank erosion were still being transported into spawning gravels 1–2 km downstream, 10 years after logging (Fig. 6; Hartman and Scrivener 1990). Incubation success of salmonid eggs will probably be reduced for decades because of this streambed instability and increased sand (Hartman and Scrivener 1990).

Impacts of the third group may not occur for 20 years after logging, but they can persist for centuries in coastal streams. For example, LWD continues to decline 70 years after harvesting in riparian forests (Fig. 7). Hydraulic forces develop zones of scour and deposition around the LWD, and channel topography remains stable as long as the LWD remains (Grette 1985; Hogan and Church 1989). A stable streambed is maintained for incubating salmonid eggs (Scrivener and Brownlee 1989) and aquatic invertebrates (Culp and Davies 1983). Pool area, which provides the rearing habitat for fish, increases with LWD volume in streams 1–7 m, 7–10 m, and 10–20 m wide (Bisson et al. 1987). The effective lifespan of LWD is 100–200 years in coastal streams, because large conifers are preserved in freshwater (Sedell and Luchessa 1982). A continual source of LWD must be available if stream channel habitat is to be maintained. However, red alder (*Alnus rubra*) is the dominant deciduous tree in riparian areas. This species does not support suitable aquatic habitat because it is relatively small, unstable, breaks easily, and decomposes rapidly due to frequent freshets and moderate climate (Bisson et al. 1987). Therefore, 3 centuries may be required before volumes of coniferous LWD return to pre-logging levels in coastal streams (Gregory et al. 1987).

These impacts from forest practices must be considered together with the effects of commercial and sports fisheries, and the ecological processes of climate variability in both freshwater and marine environments if we are to explain the numbers of adult salmonids returning to spawn. Furthermore, forestry impacts must be examined for decades if their role in determining fish production is to be accurately quantified and clearly understood (Hartman and Scrivener 1990). Salmon stocks can be severely depleted when the harmful effects of fishing, climate change, and land use are compounded (Meehan 1991).

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Focus on Forestry-fisheries Problems: Lessons Learned from Reviewing Applications of the Coastal Fisheries-Forestry Guidelines

D. TRIPP and D. HOGAN

Coastal Fisheries-Forestry Guidelines Audits

A common complaint about research is that by the time the studies are complete and the information disseminated, the original problem that initiated the work no longer exists. Studies to explore the influence of different streamside management practices on aquatic ecosystems began over 20 years ago in Carnation Creek. Do we still have streamside management concerns? Have we learned enough already to enable forest harvesting activities while retaining fish habitat integrity? Determination of the influence of forestry on hillslope processes and stream environments was the focus of work begun on the Queen Charlotte Islands over 10 years ago. Have these problems been solved such that forest and fishery management coexist in complete harmony? This presentation will attempt to answer these types of questions, and thereby provide a frame of reference for much of what will be discussed in this workshop.

Recent findings of environmental audits to assess the effectiveness of the 1988 Coastal Fisheries-Forestry Guidelines (CFFG; see Tripp, this volume) were used as a basis for the types of questions being addressed by the Fish/Forestry Interaction Program. The audits provided an opportunity for identifying the type, nature and severity of common, and, very importantly, contemporary stream impacts. This was an opportune situation, because the usefulness of past research has often been limited by the passage of time. Once research results are finalized, the forest industry has frequently found that the past harvesting activities—as considered in the research—are no longer practised. The next claim is that the research findings are no longer applicable.

The environmental audits referred to here are detailed in Tripp (this volume). The audit population included only those cutblocks in coastal

British Columbia with fisheries concerns. These were blocks that encompassed or impinged on Class I or II streams, or blocks that included Class III or IV streams that could affect Class I or II waters downstream. Stream reach classification was based primarily on fish use as defined in the 1988 CFFG. Class I stream reaches included any reaches with anadromous salmonids or better-than-low levels of resident sport fish at any time of the year. Class II streams were reaches with low levels of non-anadromous sport fish. (Class I and Class II streams are now referred to as Class A streams in the 1993 edition of the CFFG.) A Class III stream reach was a reach with resident non-sport fish only; a Class IV stream reach was a reach with no fish, nor any likelihood of fish use in the future. (These streams are now called Class B and C streams, respectively.) The cause of any impacts was identified wherever possible during stream inspections.

Stream Impacts

Approximately half (48.2%) of the stream reaches inspected with fisheries concerns had a major or moderate impact, as defined in Tripp (this volume). The lowest percentage of streams affected was in the Queen Charlotte Islands (23.6%); the highest percentages were in the Kalum, North Coast, Mid-Coast, and Chilliwack forest districts (65–70%).

Differences among districts in the percentage of specific stream reach classes affected tended to be greatest for Class I–II streams, and smallest for Class IV streams (Fig. 1). The best performance on Class I–II streams was on the Queen Charlotte Islands where only 8.3% of the Class I–II reaches inspected were affected. Mid-Coast had the poorest record for avoiding impacts on Class I–II streams (56% of the streams), while Chilliwack had the poorest record on Class III streams (60% of the

streams). No district fared particularly well on Class IV streams, where 56–100% of the streams inspected with moderate to high transport potential had a moderate to major impact.

Salmon (Class I) and other sport fish streams (Class II) were less affected than resident fish (Class III) or non-fish-bearing (Class IV) streams. For all districts and all streams combined, including streams with minor or no impacts, average net stream area affected was 3% on Class I streams, 11% on Class II streams, 16% on Class III streams, and 55% on Class IV streams. Most of the streams affected were the smaller, first-order streams or side channels evident on 1:5000 scale maps. This was particularly true of Class I and II streams, where the difference between

“large” and “small” streams was substantial compared to most Class III or IV streams.

Larger streams were less affected by logging than small streams, partly because larger streams were usually better protected with Streamside Management Zones (which included leave strips, buffer strips, and machine-free zones) and partly because of the conservative nature of the methods used to estimate impacts.

Source of the Stream Impacts

If the amount of work currently being directed at roads is any indication, there is a widespread belief that roads are the main source of fisheries-forestry problems. This may be true in terms of the degradation of plantable sites. It may also be true in terms of the amount of fine sediments introduced to streams. The audits consider only the overall net stream area affected by increases in large woody debris (LWD) and sediment loads, stream bed scouring, and channel scouring. The results clearly indicate that roads were much less of a problem than the harvest operations themselves (e.g., falling, bucking, yarding, and clean-up). Coast-wide, poor harvest practices affected 7.5 times more net stream area (120 000 m²) than poor road practices (16 000 m²).

Post-harvest failures (mainly torrents) were the most significant problem overall, accounting for 39% of the total net stream area affected by all problems combined (Fig. 2). A combination of inappropriate streamside activities (such as over-harvesting, trespasses, machinery or trails in streams, burn piles in streams, stock piling gravel in a stream, or excessive clean-up on streams) accounted for another 20% of the total area affected, all on fish-bearing streams. A lack of clean-up, where clean-up was possible, and poor falling and yarding practices represented another 17% and 11% of the area affected, respectively.

With an average net stream area of 4400 m² affected, inappropriate streamside activities were individually the single most damaging problem. This was followed by post-harvest failures at 2900 m² of net stream area per event. With the exception of poor road deactivation work, individual differences in the amount of stream area affected by all other problems were small, ranging from approximately 350 to 760 m². Although road deactivation work accounted for the least area affected per incident

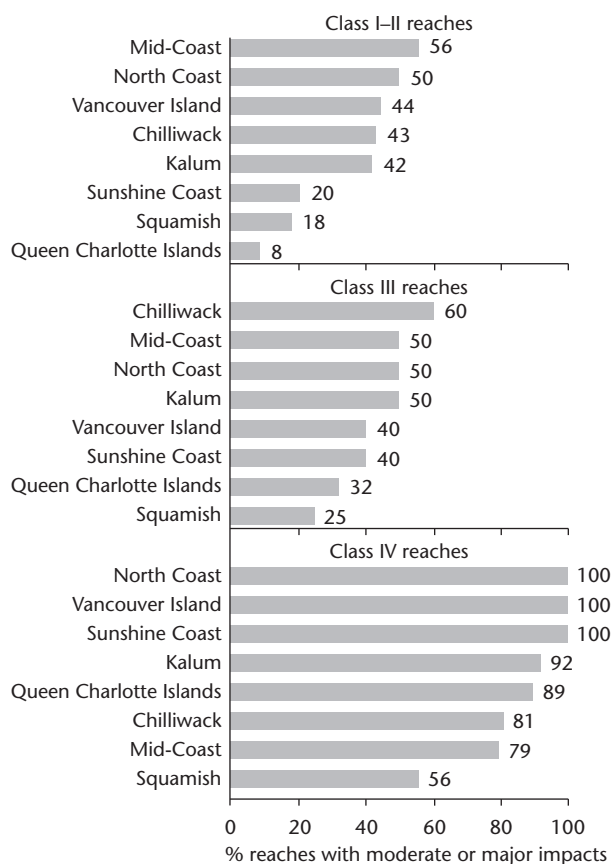


FIGURE 1 Percent of streams with a moderate or major impact, by Forest District and stream class. Class IV streams here refer to reaches with a moderate to high transport potential, and which flow into Class I–III reaches downstream.

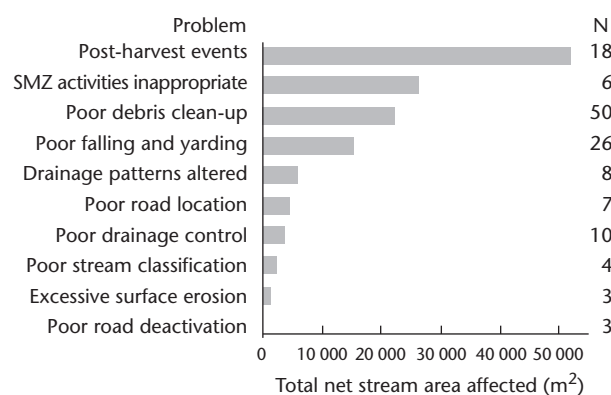


FIGURE 2 *Total net stream area (m²) affected by each of the 10 main problems observed in coastal Forest Districts of British Columbia. Numbers arranged vertically on the right are the number of times each problem was observed. SMZ – Streamside Management Zone.*

(70 m²), this may underestimate the potential for problems, since the only evidence of a problem encountered (large accumulations of fine sediments) was not visible until the next heavy rain.

Lessons and Research Directions

Of the streams inspected in the audits, almost half with fish or of direct concern to fish-bearing streams were affected by logging. Streams most likely to be affected were those that lacked specific prescriptions for some sort of buffer strip or appropriate harvest techniques. Non-fish-bearing streams with a reasonable potential of affecting fish resources downstream were particularly prone to problems. This indicates that upstream or upslope risks are not always recognized or evaluated in a consistent fashion. Simple, reproducible methods to accomplish such assessments are needed. The work reported in this workshop by Schwab, Bovis, Hogan,

and their co-workers relate to both hillslope research and assessment methods.

Roads are regularly assumed to be the main source of the problems. This may well be true in terms of overall site degradation or the loss of plantable sites, but it was clearly harvest operations that caused most of the stream damages observed. Torrent or torrent-like events damaged the most habitat, but inappropriate, if not illegal, activities (such as machinery in streams and trespasses over streams) caused or contributed substantially to some of the greatest individual problems. Ray Krag's work (see Krag in this volume) addresses these issues.

Another important lesson is the need to respect the integrity of streamside management zones and natural drainage patterns throughout the harvesting process, from road construction and harvesting to road deactivation or abandonment. The impacts that sometimes resulted from even small transgressions of this type were often out of proportion to their original significance. There is also a need for a better appreciation in the field of the sediment and debris transport capabilities of all stream systems, and better decisions on how such streams should be logged. The studies reported on in this volume by Hetherington, Haschenburger, Church, and Hogan deal with several of the physical characteristics, while the work reported on by Scrivener, Hartman, and Tschapinski deal with the fisheries aspects.

Clearly, based on the review of current forest practices, significant unresolved forestry-fishery issues remain in coastal British Columbia. This review indicates that altered watershed hydrology, steep and unstable hillslopes and certain riparian and streamside management practices must be considered carefully and new, straightforward and objective assessment methods need to be developed and used. It is hoped that the remainder of this workshop will shed more light on these important watershed management practices.

Watershed Hydrology

EUGENE D. HETHERINGTON

Introduction

In addressing issues of land use impacts on streams and fisheries resources, it is important to remember and understand the role of water and water-related processes. The Fish/Forestry Interaction Program (FFIP) on the Queen Charlotte Islands has been synoptic in nature. Available hydrological information consists primarily of precipitation and streamflow data collected by federal and provincial government agencies. These data were intended to provide general coverage of the area.

In contrast, the Carnation Creek Experimental Watershed Project on Vancouver Island has been intensive in nature. Networks of hydrometeorological stations were established in the watershed to provide detailed information on streamflow and climate. Several additional studies were also carried out to provide a more in-depth understanding of hydrological processes and hydrological impacts of logging.

Hydrology *per se* was not the primary focus of either program. Rather, the streamflow and precipitation data were intended to assist with the interpretation of the results of other studies and observations. The objective of this paper is to summarize the hydrological information and reports relevant to both programs.

Fish/Forestry Interaction Program

FFIP was initiated in 1981 following a series of major winter storms in 1978 that triggered landslides over much of the Queen Charlotte Islands. Prior to the 1978 storms, the issue of hydrological impacts of logging in the Queen Charlottes was already a concern. In a landmark report, Toews and Wilford (1978) provided recommendations for minimizing the impact of forest harvesting on water and aquatic resources on Graham Island. They

reviewed monthly precipitation and temperature data taken from Calder and Taylor (1968) and summarized Water Survey of Canada streamflow data for the Yakoun River. Comparative calculations of clearcut versus forested area snowmelt were also presented to indicate the potential for changes in rain-on-snow runoff.

Schwab (1983) prepared a subsequent report on mass wasting in Rennell Sound. It provides precipitation information on the October–November 1978 rain storm that caused the mass wasting, including a mass curve of Gospel Point station precipitation, an isohyetal map of total storm precipitation for the Queen Charlottes, and a summary table of daily precipitation for existing climatological stations. A maximum of over 400 mm of rain fell in a 5-day period. This storm was estimated to have a 5- to 10-year return period frequency. Schaefer (1979) also reported on meteorological conditions pertaining to this 1978 storm.

Three other reports have focused more specifically on hydrological data for the Queen Charlotte Islands. Trends and fluctuations in precipitation and stream runoff since 1900 have been analyzed by Karanka (1986). Precipitation and runoff characteristics have also been examined in some detail by Hogan and Schwab (1990, 1991).

Precipitation data exist for 8 long-term stations (about 1971–present) of the Atmospheric Environment Service and 44 short-term stations (mostly 1976–1980) of the B.C. Ministry of Environment, Resource Analysis Branch (Hogan and Schwab 1990) (Fig.1). Long-term streamflow data exist for three Water Survey of Canada stations: Yakoun River (since 1962), Pallant Creek (since 1967), and Premier Creek (since 1971). In addition, shorter term streamflow (three sites) and precipitation measurements have been taken as part of the FFIP program (Hogan and Schwab 1990).

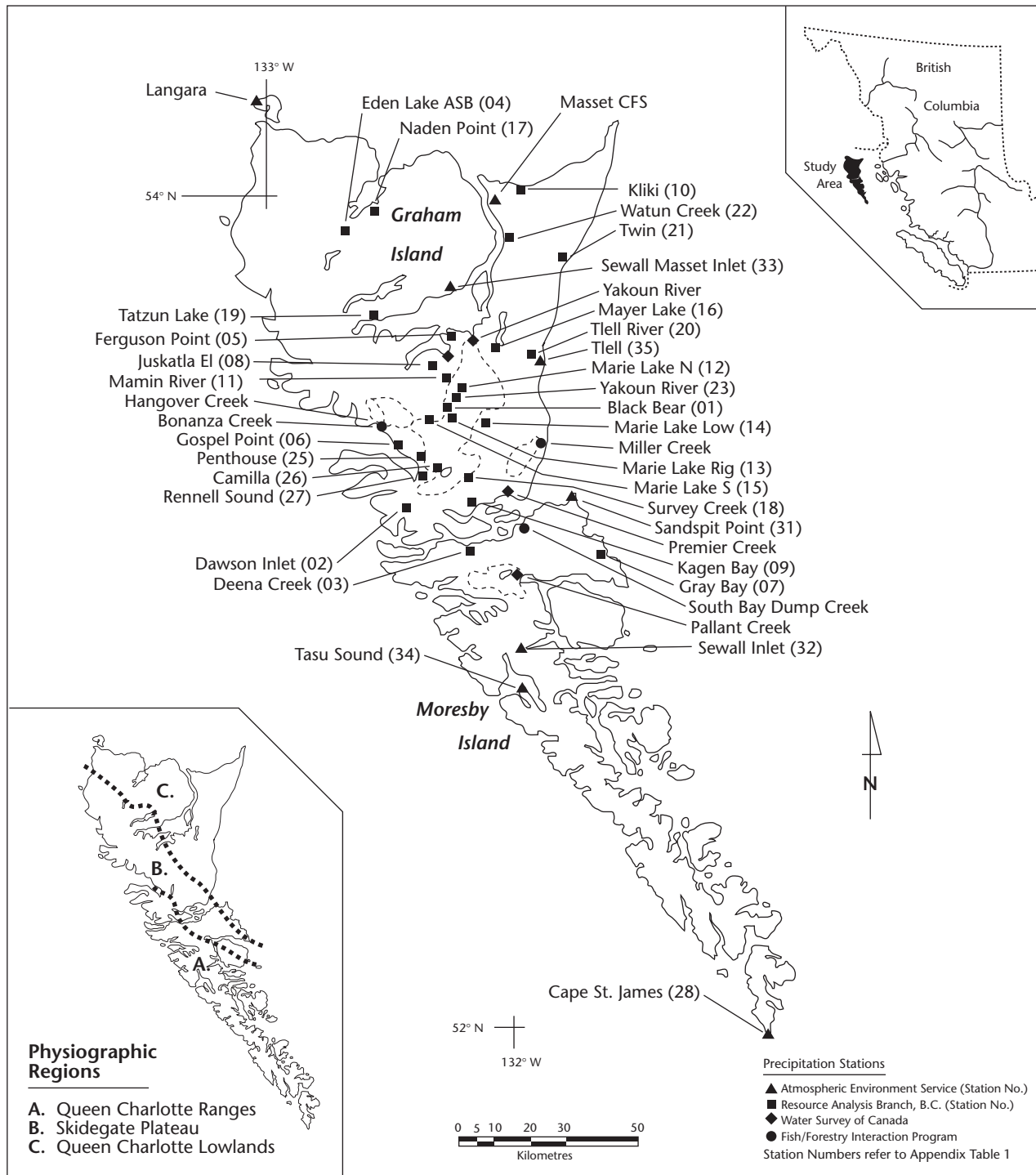


FIGURE 1 Location of hydrometeorological stations on the Queen Charlotte Islands (Hogan and Schwab 1990).

The Hogan and Schwab (1990) report includes return period frequency tables and graphs for both precipitation and streamflow, precipitation-runoff relationships for selected watersheds, and a generalized map of spatial variation of mean annual precipitation. In addition, a regression relationship for estimating mean annual peak flows based on drainage basin area and mean annual precipitation is provided. Maximum mean annual precipitation totals on the Queen Charlottes exceed 4000 mm.

As well, the Hogan and Schwab (1991) report examines meteorological conditions associated with hillslope failures. Antecedent precipitation and rain intensity are related to the occurrence of slope failures.

Streamflow data for the Yakoun River have been evaluated for land use effects (unpublished report by G. Barrett; Dan Hogan, B.C. Ministry of Forests, pers. comm.). No changes were detected that could be attributed to forest harvesting.

Carnation Creek Experimental Watershed Project

Within and immediately adjacent to the Carnation Creek watershed, a basic monitoring network of streamflow and precipitation stations was established (Fig. 2). A comprehensive meteorological station was also set up at site A. Most of the stations were installed in 1971 and 1972. The watershed thus has valuable, relatively long-term records of continuous hydrological data. Shorter term hydrological studies and measurements have also been conducted to evaluate sub-surface water behaviour, rainfall interception, and precipitation distribution.

Preliminary hydrological data analyses were reported in the first Carnation Creek workshop proceedings (Hetherington 1982) and updated in the proceedings of the second workshop (Hetherington 1988). Complementary hydrological information is also contained in the watershed overview bulletin by Hartman and Scrivener (1990). A review and further update is provided in this paper.

Hydrological Processes

The monitoring of several of the components of the hydrological cycle within the Carnation Creek watershed during the past 22 years has provided an important legacy of understanding of coastal watershed hydrology. Some of the more interesting

observations on basic hydrological processes are summarized below. Many of these are not necessarily new but do provide local knowledge on which the applicability of research findings from other areas can be judged.

Topographic Influences on Precipitation The fact that topography has a direct influence on precipitation amounts is well known. Not so well known is the magnitude and variability of this influence in mountainous terrain. These factors have been evaluated for the Carnation Creek watershed in a report under preparation. Most of the precipitation in the watershed occurs as rain, with <5% occurring as snow over most of the area but reaching about 10% at the highest elevations.

Mean annual precipitation increases from about 2900 mm at the low elevation station A, near the mouth of Carnation Creek, to 4000 mm at the high elevation station L, in the headwaters area of the watershed. During major individual storm events, amounts recorded at station L have been close to double those measured at station A. Maximum storm rainfall amounts have exceeded 400 mm at station L.

Return period frequency data have been computed for rainfall durations ranging from 15 minutes to 10 days for five continuous recording stations (A, C, E, F, L). Two of these stations (F and L) are at higher elevations (450 m and 665 m, respectively). These results provide rare information on the variation of return period data with elevation.

Rainfall Interception Comparative measurements of rainfall beneath a dense old-growth forest canopy and in an adjacent clearcut have provided quantitative insight into the magnitude and variability of rainfall interception by the forest canopy. This 7-year study was carried out at an elevation of 150 m on a mountain slope near station G.

Preliminary calculations show that the total 7-year precipitation catch beneath the canopy was 21% less than in the open. However, about 30% of the time, precipitation measured in the forest exceeded that measured in the open. This can occur when an already wet forest canopy scours moisture from moving, low level clouds, as well as intercepting vertical rainfall. Some of the intercepted water is evaporated back into the atmosphere and constitutes an "interception" loss to the system. Some of the

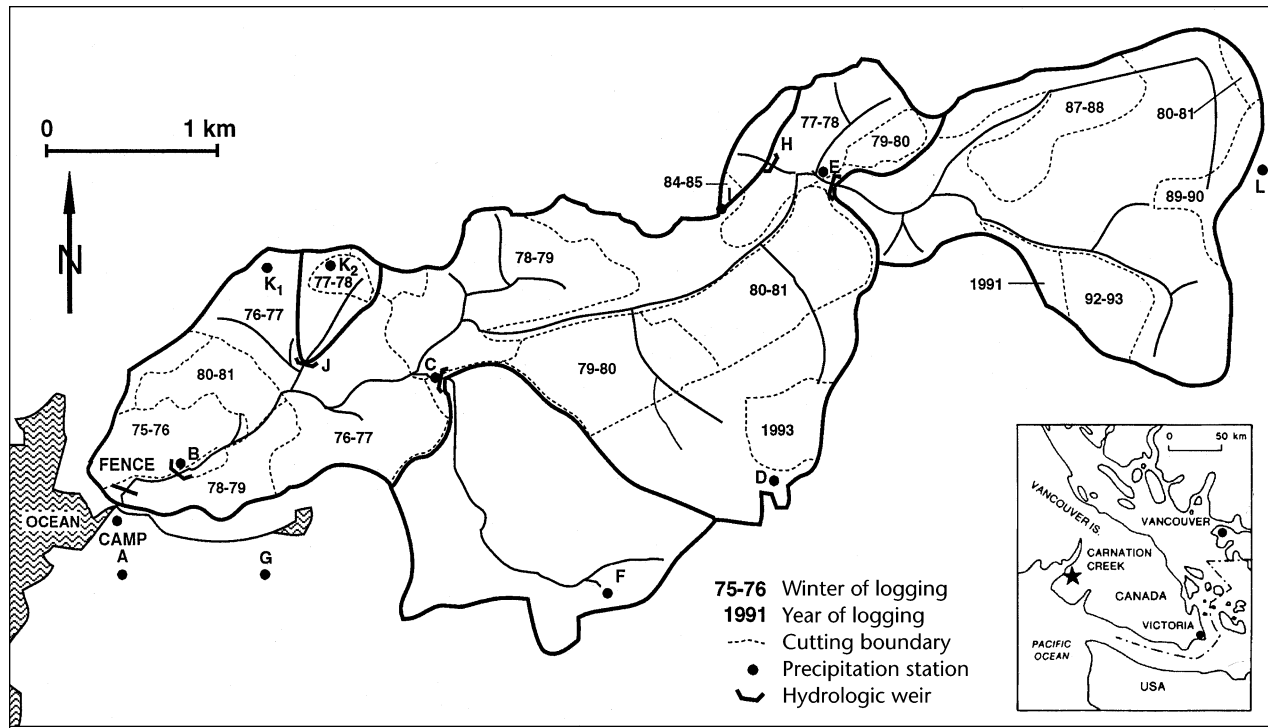


FIGURE 2 Carnation Creek watershed showing location of hydrometeorological stations and clearcut logging boundaries.

extra moisture scoured from clouds, commonly known as “fog-drip,” adds moisture to the system by falling from the canopy to the ground.

For the total time when precipitation in the open exceeded that beneath the forest canopy, interception averaged close to 32%. This result suggests the occurrence of a fog-drip component of at least 11%. However, this figure must be viewed with caution as it represents data for a particularly dense canopy from only one site. Further analysis and interpretation of the data are required.

Evapotranspiration The combination of warm, relatively dry summers and mild but wet and windy winters results in high evapotranspiration (ET) losses in the Carnation Creek watershed. Based on the difference between annual precipitation and annual stream discharge, annual ET from forested areas in the watershed can be estimated to average about 1100 mm. This amount is made up primarily of dry weather (mostly summer) transpiration and wet weather (mostly winter) rainfall interception losses.

Annual transpiration estimates have been derived from an equation proposed by Spittlehouse and Black (1981), based on daily air temperature, relative humidity, and solar radiation data (Hetherington et al. 1995). Annual interception has been estimated using a relationship between interception and daily precipitation derived from the interception study data (Hetherington et al. 1995). These calculations indicate that combined transpiration and interception losses are divided almost equally between the six summer months (April to September) and the six winter months (October to March).

Subsurface Water Behaviour Despite the high evapotranspiration losses, measurements have shown that soils in the Carnation Creek watershed remain moist year round. Because the soils are also shallow (mean depth <1 m), this means that the excess storage capacity for rain water is limited even during the summer months.

These soils are also highly permeable to water. The thick organic forest floor allows even the

highest intensity rains to infiltrate. The subsurface mineral soil is laced with “macrochannels.” A variety of these have been identified, including hollowed out decayed roots, channels along live roots, cracks in the soil, and lenses of very coarse soil. Water tends to move preferentially and rapidly through the soil profile via these macrochannels. In addition, the mineral soil is highly porous, having a porosity or volume of voids amounting to 65–75%.

Subsurface water moves rapidly through the soil to the impermeable bedrock surface and then laterally downslope to stream channels. The water movement is also directed by the topography of the underlying bedrock. This results in seepage zones and development of localized ephemeral surface runoff during rain storms at intervals across the hillslope. A study of subsurface flow rates along the bedrock surface has demonstrated this variability in flow patterns and documented the high rates of flow that occur in these subsurface seepage zones (Hetherington 1995).

During the winter, a subsurface water table develops on the mountain slopes and is sustained by the frequent rains. This water table responds rapidly during rain storms, rising and falling in concert with variations in rainfall intensity (Hetherington 1982). During the summer, the slope water table disappears, whereas the groundwater table in the floodplain remains but slowly drops as the summer progresses.

Floodplain Hydrology A description of the hydrology of the lower Carnation Creek floodplain for the water year September 1984 to September 1985 has been developed (Hetherington 1989). Graphs are included to show comparative relationships between groundwater table fluctuations, precipitation, and Carnation Creek streamflow.

Streamflow As in most coastal watersheds, streamflow is flashy. Major peak flows are often attained in a matter of hours and then decline rapidly as water moves quickly from the slopes to the channels. Because of the low capacity of the soil to store water, a high equivalent percentage of storm rainfall appears as streamflow within one or two days depending on the duration of the rain. Because of limited snowfall in the watershed, most of the runoff in Carnation Creek is from rain only. In many watersheds, rain-on-snow storms cause the largest peak flows.

The length of streamflow records in the Carnation Creek watershed now permit reasonable estimates of the longer return period peak flows. This information can be obtained from the Water Management Branch of the Ministry of Environment, Lands and Parks in Victoria.

Logging Impacts on Water and Soil

Forest harvesting and road construction have measurably affected several components of the water cycle in the Carnation Creek watershed. The changes induced in some of the hydrological processes have resulted in observed changes in subsurface water behaviour, erosion, and streamflow.

Subsurface Water Behaviour In clearcut areas, removal of the forest canopy initially eliminated much of the interception and transpiration losses. This was partially offset by the elimination of the for-drip component of precipitation. One result of this change, as indicated by preliminary analysis of soil moisture measurements, is that the total soil profile in the clearcut was wetter at the end of the summer than in the adjacent forest. The wetter soil condition means that the already limited water storage capacity is further reduced, making more water potentially available for runoff.

Soil disturbance caused by yarding resulted in locally increased groundwater table levels (at peak slope) at three sites. The biggest increases at one site exceeded 20 cm (Hetherington 1982). It is postulated that the surface soil disturbance disrupted entry of rain water into normal subsurface flow pathways and caused the water to move more slowly through the mineral soil. This would result in a transient increased build-up of the groundwater table at that location.

Road construction resulted in three different effects on downslope groundwater tables. At one site below a road, peak storm groundwater tables were reduced by subsurface flow being intercepted at the road and diverted laterally (Hetherington 1982). Further along the same slope where the road was constructed on top of existing soil, no change in peak groundwater tables was detected. At a third location, water flowing down a road surface spilled over onto the slope below. This extra water caused a 22-cm surge in the groundwater table 24 m downslope. This process is believed to have triggered a small landslide the previous year at this location.

In the lower Carnation Creek floodplain, late summer groundwater tables were 30–50 cm higher after harvesting (Hetherington 1982). The increased levels persisted for at least 10 years despite vigorous vegetation regrowth on the floodplain. The changes in groundwater table were due primarily to reduced evapotranspiration losses from the floodplain and sustained higher amounts of subsurface seepage from the adjacent hillslopes where vegetative regrowth has been slower.

Mass Wasting and Surface Erosion Small landslides (debris avalanches) and debris torrents have occurred during major rain storms in both clearcut and undisturbed forested areas. For example, a January-1982 rain-on-snow storm triggered two landslides on stability Class III terrain in a clearcut 4 years after harvesting. Disruption of normal subsurface flow pathways was a cause in both of these landslides, neither of which reached a creek channel. In January 1983, another landslide occurred in the forest on nearby stability Class V terrain. This landslide went directly into Carnation Creek. It appears to have been triggered by windthrow possibly resulting from altered wind turbulence patterns following harvesting of adjacent areas.

A number of mountain slope debris torrents occurred during the January-1982 rain-on-snow storm and also during a January-1984 storm that produced the highest precipitation amounts recorded thus far in the Carnation Creek watershed. These torrents occurred on stability Class III, IV and V slopes, and most were associated with clearcuts. One torrent, in particular, is postulated to have triggered an even bigger torrent in the main channel just above the lower floodplain. A large amount of large woody debris that had been stored in jams in the canyon area was swept out into the floodplain channel and deposited primarily in three major debris jams along the channel.

A map of potential sediment sources (i.e., exposed mineral soil) in the watershed has been produced that indicates a sizable number of such sources (Steve Chatwin, B.C. Ministry of Forests, pers. comm.). Some sediment production was monitored during the early phases of road construction (Ottens and Rudd 1975). Localized ditch enlargement, cutbank sloughing, and road surface rilling are also evident in some parts of the road network. Suspended sediment measurements at the main weir (B) on Carnation Creek, however, show little effect from the

logging (Tassone 1988). While surface erosion has occurred and undoubtedly contributed some sediment to Carnation Creek, it appears that the amounts have been modest despite the apparent large number of potential sources.

Increases in fine sands accumulating in spawning gravels in the lower reaches of Carnation Creek have been measured (Scrivener 1988). The primary sources of this additional sediment are attributed to erosion of disturbed streambanks, movement of material stored in the channel following disruption of in-channel woody debris, and release of sand and gravel from the canyon during the 1984 torrent.

Streamflow Annual water yields or total runoff increased at both H (Hetherington 1982) and J weirs following clearcut harvesting of 90 and 94% of their drainage areas, respectively. Recent analysis has shown that the increases were sustained for at least 12 years. Approximately 80% of the increases occurred during the wet winter months (October to March) and would have resulted primarily from a reduction in the interception losses described above. Inaccuracies in low flow measurements preclude definitive detection of water yield changes for Carnation Creek at B weir.

Late summer low flows at H weir also appeared to increase in the first 2 years after harvesting (Hetherington 1982).

Recent re-evaluation of the stormflow data has confirmed the earlier finding (Hetherington 1982) that rain-only peak flows increased at H weir following harvesting (90%) but not at B weir which had about 40% of its drainage area clearcut. The peak flows at H weir increased for both large and small storms and the increases have persisted for at least 12 years. There is also some evidence to suggest that the peaks occur a little sooner and that total storm runoff has increased.

J weir was installed after road construction but before harvesting. The analyses still indicate that peak flows increased at J weir following the harvesting of about 90% of the drainage area.

For B weir data, there is no clear indication of any changes in rain, only stormflow hydrographs up to 1991.

The occurrence of major rain-on-snow events in the Carnation Creek watershed is a relatively rare event. In fact, only one such event when snow covered the entire watershed has been recorded at Carnation Creek since the project began. In January

1982, about 30 cm of snow at low elevations and probably over 60 cm at higher elevations was present at the start of a major rain storm. The peak flow values for this storm for B, H and J weirs plot well above the post-logging regression lines between peak flows for these stations and the control C weir. While not definitive, this result appears to indicate a definite difference between rain-on-snow versus rain-only runoff response from the clearcut drainages in comparison with the forested watershed. A logical interpretation is that the peak flows from clearcut areas were increased as a result of modification of snow accumulation and melt patterns.

The Hydrological Database

The hydrometeorological data collected in the watershed form an important legacy of the Carnation Creek project. Much of the data were originally compiled and processed at the Pacific Biological Station in Nanaimo. The computer data files and recording charts of unprocessed data were subsequently taken and the data further processed and extracted at the Pacific Forestry Centre in Victoria.

For the period from 1972 to 1990, complete data sets for the various parameters have been developed. All available data have been compiled and extracted from charts where necessary. Where appropriate, missing data have been estimated using various procedures to develop continuous records suitable for further analysis. The exceptions are the basic time series for recorded streamflow data digitized from charts or monitored by data loggers, wind direction data, evaporation pan data, and stream temperature data. Hydrological monitoring has continued since 1990, but the data have mostly been compiled without further checking or processing.

Final computer files have been developed in a consistent format for the following parameters for each of the stations at which the respective data were collected:

- Precipitation: 15-minute periods, hourly, daily, monthly
- Streamflow: as digitized, hourly, daily
- Air temperature: hourly, daily minimum, daily mean
- Relative humidity: hourly, daily
- Solar radiation: daily
- Wind speed: hourly, daily
- Wind direction: hourly

Data exist for evaporation pan measurements (April to October), maximum air temperatures, and stream temperatures, but computer files with the same format as the above parameters remain to be developed.

This comprehensive hydrological database has been used to calibrate the HSPF streamflow simulation model (Hetherington et al. 1995), and could be used to calibrate or develop other models. Such models can be applied to estimate flows in other coastal watersheds and assist in evaluating stream channel conditions. Both the original precipitation and streamflow data and the HSPF model could be used to develop simpler rainfall-runoff relationships for application in other coastal areas.

As already noted, the length of the Carnation Creek precipitation and streamflow records now permits improved estimation of extreme event return period frequency values. With ongoing monitoring in the watershed, these estimates will continue to improve, as will our ability to make comparisons with shorter-term measurements in other coastal watersheds. These comparisons will enable assessment of the short-term data in relation to longer term trends.

Conclusions

In the Queen Charlotte Islands, hydrological monitoring has been synoptic and limited primarily to precipitation and streamflow. In the Carnation Creek watershed, a variety of hydrological parameters have been monitored at a number of sites for varying periods of time. The resulting data and analyses have provided an improved understanding of coastal hydrological processes and quantified the impacts of forest harvesting and road construction on several of these processes. An important hydrological database is now available for use as a management tool. Moreover, the value of this database will increase as long as monitoring is continued in the Carnation Creek watershed.

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Landslides on the Queen Charlotte Islands: Processes, Rates, and Climatic Events

JIM W. SCHWAB

Introduction

Mass wasting constitutes the dominant geomorphic process on the steep mountain slopes of the Queen Charlotte Ranges and Skidegate Plateau. The term “mass wasting” encompasses a variety of processes by which masses of soil rock and debris are transported downslope primarily by gravity.

The principal processes active on the Charlottes are described by Alley and Thomson (1978) and Wilford and Schwab (1982). Based on the classification of Varnes (1978), the processes are debris slides, debris avalanches, debris flows, debris torrents, bedrock slumps and slides, and slump earthflows. The terms mass wasting, mass movement, landslide, failure, and hillslope failure are often used interchangeably in discussions and reports lumping similar types of processes. In this presentation, hillslope failure or slope failure is used to describe the debris slide–avalanche–flow–torrent processes. The classification of Varnes is used when specific process are discussed.

The impact of logging on slope stability is a major concern of the forest industry on the Queen Charlotte Islands and the mountainous terrain of coastal British Columbia. In the mid-1970s, forest managers began to recognize that mass wasting and erosion were a problem in terms of stream habitat destruction and the potential loss of productive forest site. Hence, the first research questions were asked: How big is the problem? What is the cause? How can we solve it?

The initial research was aimed mainly at establishing that mass wasting was a problem, rather than at developing solutions or solving problems related to management in landslide-prone terrain. The first research thus looked at obtaining data on the frequency and yield of mass wasting for various landscape types affected by logging activity. This presentation summarizes the initial research.

Management solutions are discussed in other presentations. Presented here is a short description of mass wasting processes active on the coast, and of debris slide–avalanche–flow–torrent processes.

Mass Wasting Procedures

Many large bedrock slumps and slides have been identified on the Queen Charlotte Islands—most in the deeply weathered Masset volcanics on Graham Island. Many appear to be covered with vigorous forest growth older than 250 years but probably less than 1000 years. Seismic activity is believed to be involved in triggering these large bedrock failures (Alley and Thomson 1978). These failures have moved catastrophically in the past; building structures on them is not necessarily safe if there are signs of active movement. Avoidance is often the best management decision.

Slow earthflows or slump earthflows have been identified on Ramsay Island and in the Rennell Sound area on the Queen Charlotte Islands. The failures appear to be confined in bedrock-controlled gullies filled in with deep clay rich glacial till deposits. These features can be recognized by a slump basin, bowed trees, deep, poorly drained materials, and fresh tension cracks. Failure rate is generally believed to be governed by long-term fluctuations in soil moisture, with trees and vegetation not having much of an anchoring effect. Forestry activities have avoided these identified large earthflows on the Queen Charlotte Islands. Small earthflow sites can be affected by engineering activities by removing the toe of the slope or adding water to the sites.

Sensitive glacial marine deposits are located along coastal fjords along the mid- and north coast of British Columbia. These deposits are found situated up to 200 m above present day sea levels. The high sensitivity of some of these deposits makes the clays

particularly susceptible to earthflows. The clays are often described as quick clays, because they behave as a fluid once disturbed. Large earthflows have occurred in the deposits, with the apparent trigger not known (e.g., Mink Creek near Terrace). Smaller flows have been triggered through construction activities, generally as a result of the loading of materials and vibrating of the equipment (e.g., Kitsault, Kitaktia, and Crow Lagoon). Field recognition of the sensitive glacial marine deposits is important so that the type of engineering activities that may cause failure can be avoided.

Large bedrock failures and earthflows have devastating environmental effects. However, these large events are well beyond our control to manage. Nevertheless, it is important to recognize them when working in landslide-prone terrain—even if it is simply to identify and accurately describe an event or terrain feature when calling a specialist for help.

Debris slides, avalanches, flows, and torrents are the coast-wide geomorphic processes that most affect the forest industry. These slope processes are recognized as long linear tracks in forested terrain. They are either bare or covered in forest vegetation of different age or species. Terrain susceptible to debris slides and flows is generally steep ($>30^\circ$) with shallow soils of low cohesion. The sites can often be identified by the evidence of past failures, including linear strips of vegetation, gullied terrain, old failure head scarps, linear depressions, and fan deposits at the base of slopes. Debris-avalanche-flow-torrent rates are most affected by forest harvesting activities. Management in landslide-prone terrain is possible with the use of a variety of techniques, some of which are presented in Chatwin et al. (1994).

Hillslope Failure Rates

A regional overview of mass wasting on the Queen Charlotte Islands, compiled from 1:50 000 aerial photographs, identified 8240 relatively recent large debris slides-avalanches-flows and torrents (Gimbarzevsky 1983). The frequency of slope failure averages $2.6/\text{km}^2$ for the islands. However, selected map areas in the mountainous terrain show an extreme rate of natural failure (Rennell Sound, $18/\text{km}^2$; Moore Channel, $14/\text{km}^2$; Louise Island $10/\text{km}^2$). Slope failure intensity classes of moderate ($1\text{--}3$ failures/ km^2), severe ($4\text{--}7$ failures/ km^2), and extreme (greater than $8/\text{km}^2$) occupy 24%, 7%, and 1% respectively, of the Queen Charlotte land area.

This implies that approximately one-third of the landscape on the Charlottes is subjected to active hillslope failure processes. The same value could be extended over much of British Columbia's coastal forests land where logging operations take place in mountainous terrain.

The impact of logging operations on slope stability has been studied by the Forest Service, Fish/Forestry Interaction Program (FFIP), and forest companies. A survey of 1978 storm impacts in the 150-km^2 Rennell Sound area (Schwab 1983) revealed 264 mass movements: 113 in forested terrain, 126 in clearcuts, and 25 from roads. These failures tended to be relatively small, mostly in the order of $250\text{--}1000\text{ m}^3$. Debris avalanches from clearcuts caused the largest impact, affecting 4.3% of clearcut terrain. In comparison, debris avalanches disturbed 0.1% of forested slopes and 1.9% of roads. Debris torrents scoured 22.3 km of stream channel, mostly on forested terrain.

A comparison of mass wasting rates revealed a 15-times greater rate of occurrence on man-modified terrain than on forested terrain. Most striking was the relative areal impact of debris avalanches on man-modified terrain, 43 times and 17 times, respectively for clearcuts and roads. Relative to forested terrain, large volumes of material were transported from clearcuts and roads 46 and 41 times, respectively. Also relative to forested terrain, the length of stream scoured by debris torrents was increased by 7 times in clearcuts and by 21 times by roads. The largest volume of material transported during the storm came from clearcuts. Overall, clearcut values tended to be quite high in comparison to those found in similar studies along the west coast of North America.

Rood (1984) assessed the influence of logging by examining frequency and yield calculated for clear-cut and road areas compared to forested terrain in 27 basins encompassing a land area of 350 km^2 on the Queen Charlottes Islands. Based on 1337 landslides, he found that the overall effect of logging had been to increase the landslide frequency by 34 times over a 7.3-year period, the average age of logging on steep lands in the study basins. Forested areas provided a yield of $1.6\text{ m}^3/\text{ha}$ per year. The removal of vegetation produced a yield of $50.7\text{ m}^3/\text{ha}$ per year, a rate increase of 31 times. Larger increases were also associated with roads, where the yield was $144\text{ m}^3/\text{ha}$ per year, and the rate relative to forested terrain was 87 times. Approximately 39% of the total

volume from mass wasting in forested terrain and 47% from logged terrain was delivered to streams. Comparative rates for debris avalanches and flows from clearcut terrain, in the basins studied on the Queen Charlotte Islands, were found to be significantly greater than those reported in similar studies in the Pacific Northwest (Sidle et al. 1985). Roads tended to fit the mid-values found in other studies.

Harvesting and Road Building Causes of Slope Failure

Logging-related slope failures on the Queen Charlottes have been studied by numerous investigators. Published documents include Wilford and Schwab (1982) and Krag et al. (1986). Factors leading to failures in clearcuts are often difficult to determine. At most failure sites, considerable investigative work is required to identify the often subtle conditions that set the stage for failure. Some examples found in Forest Service investigations into the cause of failures:

- a yarding road that redirected and channelized surface water onto sensitive sites;
- poor deflection during yarding, which resulted in scalped soils and pulled and overturned stumps in the vicinity of the failure head scarp;
- trees felled downslope onto sensitive terrain, dislodging stumps and roots and possibly causing changes in soil structure;
- debris, left as a jam in a watercourse, which redirected streamflow onto unstable terrain;
- debris jams in a gully which broke during high flows, contributing to a torrent;
- windthrow along a cutblock boundary, situated on shallow organic soils at a gully headwall, which triggered a debris slide; and
- root decay that resulted in the loss in strength of a root mat or web bridging a sensitive soil.

The FFIP-sponsored study carried out by Krag et al. (1986) documents 31 slope failures with causes related to road construction practices. That study, as has others, found that most road-related slope failures are caused by: 1) overloading of the slope with fill or sidecast materials; 2) inadequate road drainage; or 3) a combination of slope overloading and inadequate drainage. These factors in road-related failures occur on steep slopes, in gully headwall areas, and on wet unstable soils.

In general, road engineering and construction practices contribute to stability problems in steep terrain through: 1) the poor recognition of unstable terrain during layout; and 2) the poor recognition of road drainage requirements in road construction plans. Insufficient maintenance of road drainage structures, particularly on inactive roads, was considered by Krag et al. (1986) to be the most significant factor in road-related failures. Road maintenance of drainage structures and the deactivation of inactive roads no longer used for logging activity are believed to reduce the incidence of road-related failures.

Improved forest management practices on the Queen Charlotte Islands have resulted in reduced rates of failures. However, the forest industry in general has done a poor job of documenting how a greater awareness of slope stability problems has improved practices and management on landslide-prone terrain. The factors contributing to failures, when recognized, can be dealt with during the development planning of harvesting operations, the use of appropriate harvesting systems, and the use of appropriate road-building design and construction. Over a 4-year period, Sauder and Welburn (1987) observed yarding operations on sites considered unstable. A comparison of failure rates to Rood's (1984) study showed a reduced rate of failure frequency. They attributed the reduced rates to: yarding system usage change, improved layout, and terrain specialist involvement in the identification of sensitive areas that should not be logged. Schwab (1988) looked at the area of land disturbed by mass wasting in clearcuts in the Rennell Sound area. For every 100 ha of unstable terrain logged (Class IV and V), 25 ha of land was disturbed downslope from mass wasting originating in the unstable terrain (Fig. 1). Where slope stability was recognized as a problem before harvesting began, a management decision was made to avoid the clearly identified potential failure zones. The result was a substantial reduction in the land area disturbed by failures (20.5 ha unstable; 1.5 ha disturbed by slides).

Rainfall and Threshold Limits

Heavy rainfall events are regularly associated with debris slides—avalanches—flows and torrents on the Queen Charlotte Islands. Hogan and Schwab (1991) examined rainfall characteristics before and during verified slope failures. Temporal frequency of slope

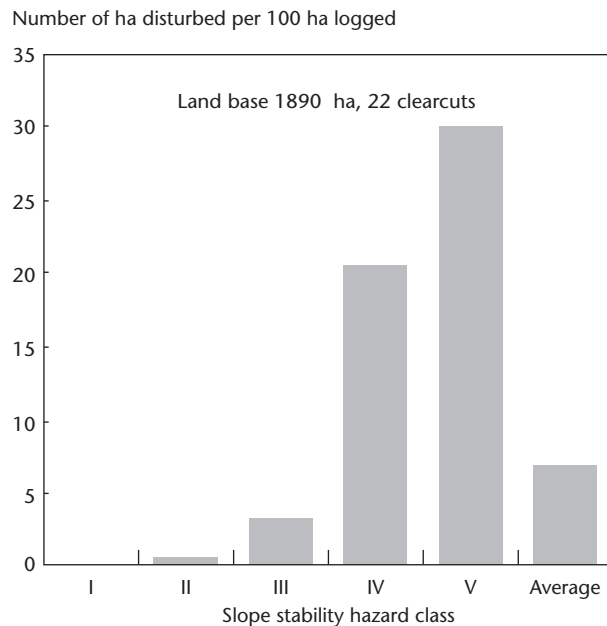


FIGURE 1 *Land area disturbed by failures originating from within mapped slope stability hazard classes (Schwab 1988).*

failures was compared to precipitation trends for antecedent time scales ranging from years to days. Over the longer temporal scale, they found a positive correlation between annual moisture conditions and reported hillslope failure frequency. Over the shorter time scale, they found that only those months immediately preceding the slope failure appeared to be important in conditioning hillslopes for failure. Daily antecedent conditions were found to influence how important variable amounts of short-term precipitation would be in triggering a slope failure. Their data showed that under wet antecedent daily conditions, slope failures could occur if precipitation amounts exceeded 22 mm in a 24-hour period. Under dry conditions, more precipitation was required (29 mm/24 hr) to trigger slope failures.

Limiting curves prepared for the wet and dry conditions show that when the precipitation event exceeds 2 days, then the antecedent conditions resemble wet conditions. Storms with recurrent intervals of greater than 2 years were sufficient to trigger failures regardless of antecedent moisture status. From a forest management perspective,

precipitation levels required to trigger slope failures are exceeded regularly, though the threshold values are exceeded most frequently during winter months. Thus, the low magnitude or moderate storm (with a 2- to 10-year return period) must be taken into consideration when planning harvesting operations in areas of potentially unstable terrain.

Often the first response to the values presented by Hogan and Schwab is that they are too low. But we must remember that they describe minimum values above which failures can occur. In situations where roads channel water onto unstable slopes, even lower values can trigger a failure. For the most part, we believe our coastal soils can drain a lot more water under natural conditions, possibly 50 mm in a 24-hour period. We therefore usually accept much higher rainfall before stating that caution must be taken. The limits presented in Chatwin et al. (1994) generally define the critical limits of rainfall safety shutdown for forestry operations working downslope or on potentially unstable terrain: 75 mm, 100 mm, 150 mm, and 200 mm for 12-hour, 24-hour, 48-hour, and 72-hour periods, respectively. However, to completely understand precipitation threshold, we need more than the limited climatological data currently available. We must collect precipitation data on a real time basis in order to adequately define critical limits for operation safety shutdown requirements.

Historical Hillslope Failures

The 1978 storm of the Queen Charlotte Islands is thought by many to be a significant event that produced considerable rates of failures from clearcuts and roads, but caused only few failures in forested terrain. Historic events, however, have caused many large hillslope failures over the last few hundred years. The landscape in mountainous terrain on the Queen Charlottes is scarred with large debris slides—avalanches—flows and torrents. These landslides are readily recognized on air photographs as linear strips of different age classes of vegetation. This observation prompted Schwab (1983) and Rood (1984) to suggest that the 1978 storm was of insufficient magnitude to cause extensive mass wasting in forested terrain.

Schwab,¹ in selected areas along the British Columbia north coast and Queen Charlotte Islands,

1 Research project EP 782.07. Historical documentation of mass wasting in North Coastal British Columbia. J.W. Schwab, Forest Sciences Section, B.C. Forest Service, Smithers, BC.

has determined ages through increment core analysis of large debris slides–avalanches–flows and torrents back to the early 1800s (large bedrock landslides of much older ages have also been identified, but are not included in the data base). Verification of storm events determined from the landslide increment core analysis is provided in a catalogue of information on storms and floods prepared by Septer and Schwab (1995). Most of the debris–avalanche–flow volume transported occurred during major events. In the Riley and Gregory creek watersheds, the years 1875, 1891, 1917, 1935, and 1978 transported, respectively, 1.6%, 2.9%, 13.3%, 2.1%, and 9.6% of the volume. In comparison, Beresford Creek watershed experienced major events in 1875, 1891, 1917, and 1935, respectively, transporting 16.5%, 10.8%, 36.2%, and 9.5% of the failure volume. Interestingly, the Beresford Creek area did not experience hillslope failures during the 1978 storm. This may be a reflection of the fact that no forestry activity had occurred in the watershed or that the storm track missed the area. In any case, four major storms since 1875 have transported 73% of the volume in the Beresford Creek watershed.

A similar relationship holds for the study areas covering Graham Island and the area in the vicinity of Prince Rupert (Fig. 2). Six storms over the last 180 years have transported 77% of the volume from debris slides–avalanches–flows and torrents: 9.6%, 14.1%, 31.1%, 6.5%, 6.4%, and 9.2%, respectively, for the years 1875, 1891, 1917, 1935, 1957, and 1978. Precipitation trends explored by Karanka (1986) identified locus of warm wet conditions that shift north and south depending on the prevailing storm tract off the Pacific. Periods of above-normal autumn and winter rainfall and temperature, but below-normal snowfall occurred from 1924/25 to 1945/46, 1958/59 to 1963/64, and 1974/75 to 1983/84. Periods of below-normal rainfall and temperature and above-normal snowfall occurred from 1946/47 to 1956/57 and 1964/65 to 1974/75. A comparison of the hillslope failure dates to the trends presented by Karanka suggest that, in recent years, the storm events that have triggered a large frequency of the failures may follow the trend (1935 and 1978 storms). However, the 1957 storm does not lie within a period of above-normal rainfall. Considerably more work is required to examine the

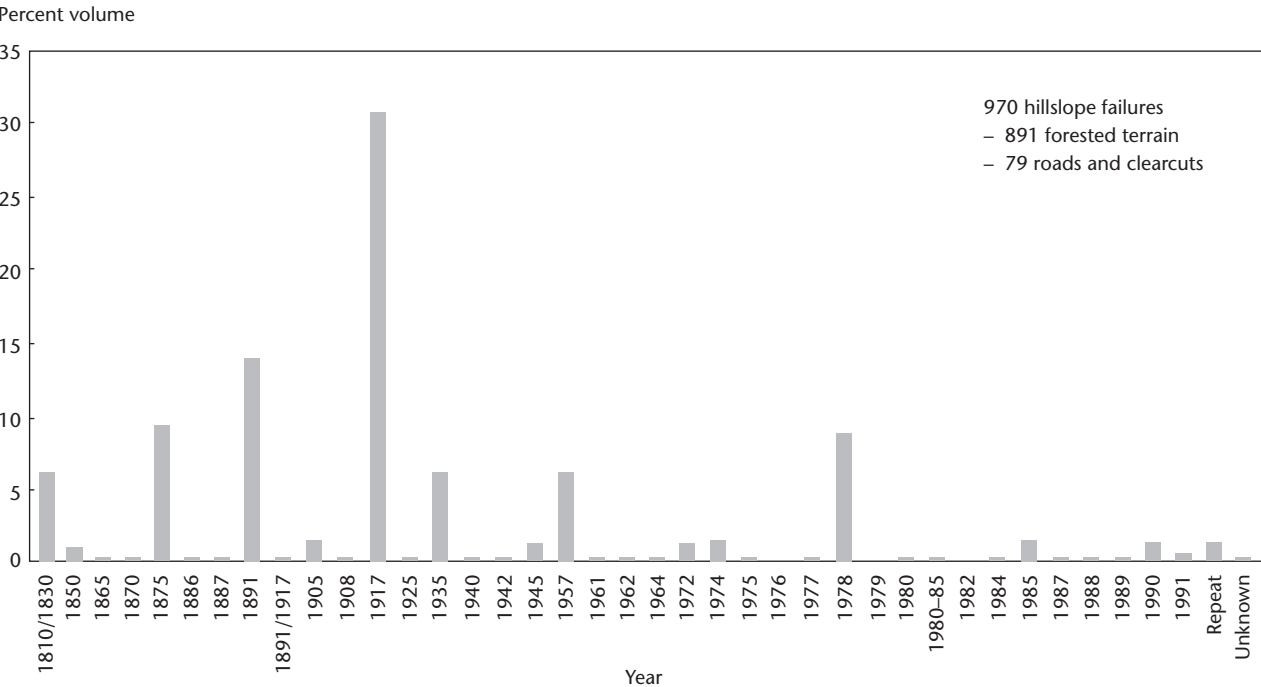


FIGURE 2 Percent volume transported per year by debris slides–avalanches–flows and torrents for the study areas on Graham Island and in the Prince Rupert area. Values are based on known, determined, and estimated failure dates, as shown.

relationship between failure dates and possible precipitation trends back into the mid-1880s.

The strongest earthquake felt in Canada occurred just off the coast of Graham Island on August 22, 1949. The earthquake had a magnitude of 8.0 on the Richter scale and an intensity of IX on the Mercalli scale. Debris–avalanches–flows observed in the Cave Haines, Hanna Koot, and Beresford Creek watersheds, located 15–50 km from the epicentre of the earthquake, were believed to have occurred during the earthquake (Alley and Thomson 1978). However, the dates determined through increment core analysis for failures in these watersheds do not tie to the 1949 earthquake (closest dates being 1945 and 1957). Soil moisture conditions, considering the time of year (late August), were probably relatively dry, and therefore not conducive to debris–avalanches–flows. This adds credence to our belief that the dominant trigger for debris–slides–avalanches–flows and torrents on the Queen Charlotte Islands is intense precipitation.

Summary

- Mass wasting constitutes the dominant geomorphic process in the mountainous terrain of north coastal British Columbia and the Queen Charlotte Islands. We recognize that different landslide processes occur on the landscape, and that not all landslides can be attributed to land management activities. However, debris slides–avalanches–flows and torrents are affected by such activities.
- Slope failure rates are increased when inappropriate land management activities are performed in landslide-prone terrain. The application of appropriate management practices and road construction techniques can greatly reduce the incidence of landslides.
- This historical documentation of slope failure ages suggests that forest management activity on the British Columbia north coast and the Queen Charlotte Islands has yet to experience the “Big Storm” similar to the 1917-event that triggered a large number of debris slides–avalanches–flows and torrents throughout the region.

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Gully Processes in Coastal British Columbia: The Role of Woody Debris

M.J. BOVIS, T.H. MILLARD, AND M.E. ODEN

Introduction

The Gully Management Problem in Coastal British Columbia Large tracts of forested terrain in coastal British Columbia are dissected by gullies. These steep channels are typically less than 1 km in length and 3–30 m in depth, and have a V-shaped cross-sectional form. Because of their steepness and instability, gullies are important sources of both sediment and large woody debris (LWD) for downstream areas in coastal British Columbia (Chatwin et al. 1994). Much of this material is delivered by debris flows, triggered by relatively small debris slides on steep, unstable gully walls.

It is now widely acknowledged that logging activities have greatly increased the delivery rate of both sediment and LWD from gullies, principally by increasing the frequency and magnitude of gully debris flows. The result in many cases has been unacceptably high debris loadings to downstream areas (Wilford and Schwab 1983; Rood 1984; Roberts and Church 1986). The need for better forest management practices in gullies prompted the B.C. Ministry of Forests to develop the Gully Assessment Procedures (Hogan and Millard, this volume). The procedures are designed to assess the likelihood of debris slides, debris flows, and fluvial transport of sediment and woody debris occurring, and recommend the best practicable strategies to minimize gully instability. It is generally recommended that excess woody debris produced by logging operations be removed if the potential for either water transport of debris or debris flow is deemed significant. Indeed, post-harvest clearance of LWD is now common practice in coastal gullies. However, despite the acknowledged importance of woody debris in the sediment dynamics of gullies, there are very few quantitative data on the real-time in-gully interactions between sediment and coarse woody debris. This study reports data on the effects

of woody debris in both logged and unlogged gully channels, including observations on the effects of woody debris removal from gully channels following timber harvest.

Overview of Processes in Forested Gullies Gullies have long been recognized as distinct landforms during routine terrain mapping in British Columbia (Howes and Kenk 1988), but it is only in the past 15 years that their geomorphic significance have been fully appreciated (Wilford and Schwab 1983; Rood 1984, 1990; Krag et al. 1986; Howes 1987; Buchanan and Savigny 1990; Millard 1993; Chatwin et al. 1994; Oden 1994). Some of this awareness stems from work conducted earlier in forested terrain in other parts of the Western Cordillera (e.g., Swanston and Swanson 1976; Dietrich and Dunne 1978; Swanson et al. 1982).

Gullies combine features of both hillslopes and stream channels, and therefore a wide variety of processes tend to occur within them. Hillslope processes include debris slides and debris flows, creep and ravel, and significant fluvial transport of sediment and LWD. All of these processes are affected by timber harvesting to varying degrees. The rate of supply of LWD is usually greatly increased by the breakage of trees during tree falling, and by trimming and log-bucking. This debris slides down steep gully sidewalls and becomes concentrated along the gully channel (Fig. 1). Coupled with increased LWD production is a greater sediment supply by debris slides from steep gully walls. These small landslides increase in frequency following harvest because of yarding disturbance to sidewalls and through root decay leading to loss of soil strength over time (Sidle et al. 1985). Debris-slide scars, in turn, promote accelerated fine sediment production by surface erosion and ravelling. In summary, an acceleration in the supply rate of both LWD and sediment tends to occur following harvest.



FIGURE 1 Typical logged gullies in lower Macmillan Creek, north Moresby Island. Gullies are classed as “slash-full,” but have not yet produced debris flows.

Much of this increased debris load is stored along the gully channel, since water flow depths in gullies are probably less than 0.2 m. Large pieces of woody debris retard the flow and tend to promote sediment deposition. Although some reworking of the LWD and sediment load stored along a gully channel can occur by fluvial transport during periods of high runoff, only a debris flow is capable of removing all of the stored material as a single catastrophic event. Most gully debris flows are triggered by debris slides that start on steep gully walls during winter rainstorms (Krag et al. 1986; Fannin and Rollerson 1993). Debris flows usually run the full length of a gully, since channels are steep (15–30°) as well as confined. The total volume of material moved by a debris flow usually depends more on entrainment of material from a gully channel than on the volume of the original debris slide triggering the flow. This fact was first widely publicized by Swanson and Swanson (1976) in the context of forested gullies. Because of sediment entrainment along the gully channel, a small debris slide of about 100 m³ can produce a debris flow totalling several thousand cubic metres (Fannin and Rollerson 1993). Entrainment of the surcharge debris load produced by logging operations accounts for the large volume of many debris flows that scour the clearcut sections of gullies.

After the passage of a debris flow, a gully channel is usually scoured to bedrock or to less erodible material such as basal till, and the process of debris

recharge must begin anew. Sediment supply to a gully is usually large directly following a debris flow, since the sidewalls are scoured and undercut by the passage of the flow, which increases the area of bare soil. Since the gully is also temporarily devoid of woody debris, finer sediment derived from erosion of scoured gully walls is readily removed by fluvial transport. Eventually, the input of fresh LWD creates obstructions along the channel, which become new sediment storage sites. Woody debris is therefore an important regulator of sediment movement and storage, and is one of the main factors controlling the magnitude of future debris flows. For this reason, the control of LWD in gullies, both during and after timber harvest, is an important issue having long-term implications for sediment management in coastal British Columbia. Gully processes were the central focus of this study.

Study Objectives To evaluate the possible benefits of LWD removal from gullies following timber harvest, data on the rates of sediment production, storage, and delivery were gathered from gullies in both logged and unlogged terrain. This study reports results from two separate investigations conducted in the period 1990–1993.

The *process study* was designed to measure real-time differences in sediment production, storage, and delivery in both logged and unlogged gullies. Gullies were studied in two geologically distinct environments—the Queen Charlotte Islands and the southern Coast Mountains—to assess the influence of logging and terrain factors in gully processes. The main objectives of the process study were to:

1. compare the temporal patterns of sediment storage and discharge in gullies fully loaded with logging debris, with those in gullies cleared of logging debris following harvest;
2. make recommendations concerning various strategies for LWD management in logged gullies; and
3. investigate variations in sediment output from gullies over a range of geologic conditions.

Examples of the main types of gullies investigated in the process study are illustrated in Figure 2.

A second component, the *synoptic study*, was designed to complement the process study by investigating differences in debris recharge rates between logged and unlogged gullies over periods of several

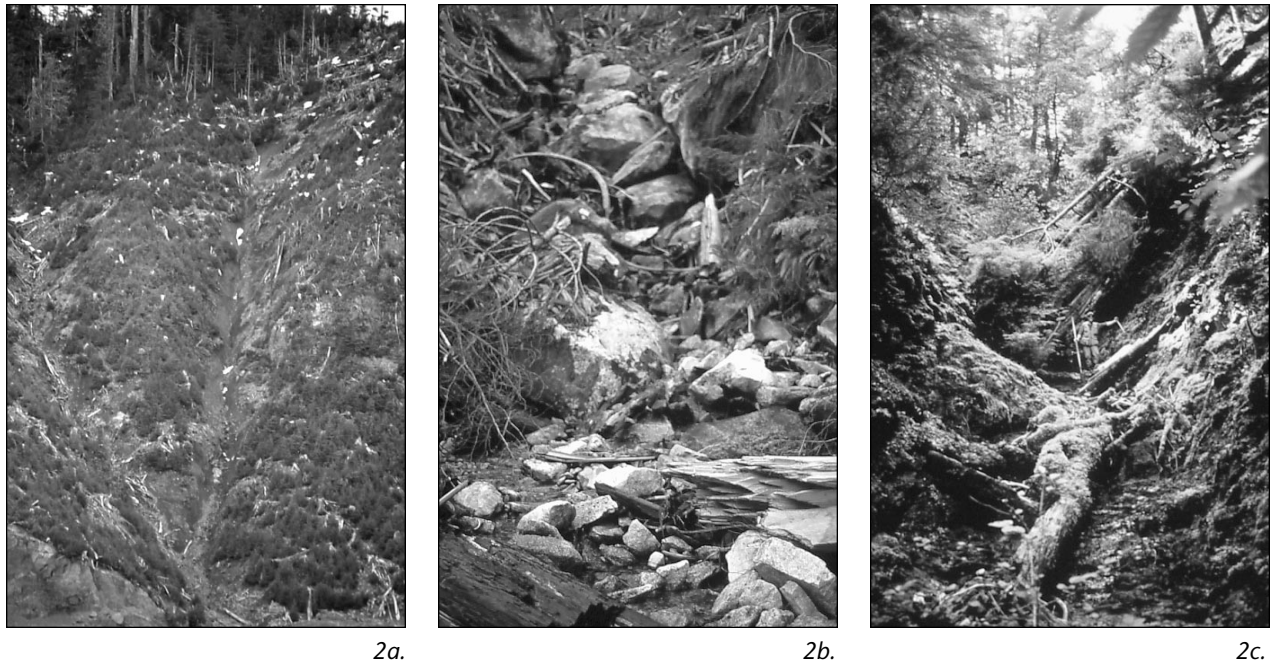


FIGURE 2 Photographs of representative gullies in the three main treatment groups:
 (a) Logged slash-full gully M2 (left) and logged tormented gully M1 (right), in upper Macmillan Creek. Note the contrast in woody debris loadings and the highly scoured sidewalls of the recently tormented gully.
 (b) Logged slash-clear gully C10, Coquitlam basin. Note that channel is scoured clear of fine sediment following removal of woody debris.
 (c) Unlogged, old-growth gully in Gregory Creek, Rennell Sound area showing typical large woody debris accumulation.

decades. Gullies were studied in the Rennell Sound area of southwestern Graham Island, Queen Charlotte Islands. The main objectives of the synoptic study were to:

1. estimate the volumes of debris stored in logged and unlogged gullies in the period since the last documented debris flow;
2. estimate from (1) the recharge rates of clastic and woody debris in logged and unlogged gullies over periods of several decades; and
3. consider the effects of converting old-growth to second-growth forests on debris recharge rates in gullies.

Study Areas

Process Study Field Areas Study areas were selected in the Queen Charlotte Islands and the southern Coast Mountains to ensure that research findings could be extended to a large area of coastal British Columbia. Macmillan and Deena creek basins on

north Moresby Island were considered typical of the weak sedimentary and volcanic rocks that underlie large areas of gullied terrain on the Queen Charlotte Islands (Fig. 3). Macmillan Creek is a 6.2-km² basin containing more than 20 steep gullies discharging directly into the main stem channel (Fig. 4). Approximately two-thirds of the basin was logged during the 1970s and, since then, at least four significant debris flows have occurred, all associated with gullies. The basin is underlain below about 300 m by shales and friable sandstones of the Cretaceous Haida Formation, and above that level by conglomerates and sandstones of the Cretaceous Honna Formation (Sutherland-Brown 1968). Exposures along gully channels indicate that much of the basin is mantled with compact basal till, capped with about 1–2 m of unconsolidated colluvium derived from till and bedrock weathering. Given the lack of a floodplain along Macmillan Creek, debris fans are generally absent from the mouths of the gullies.

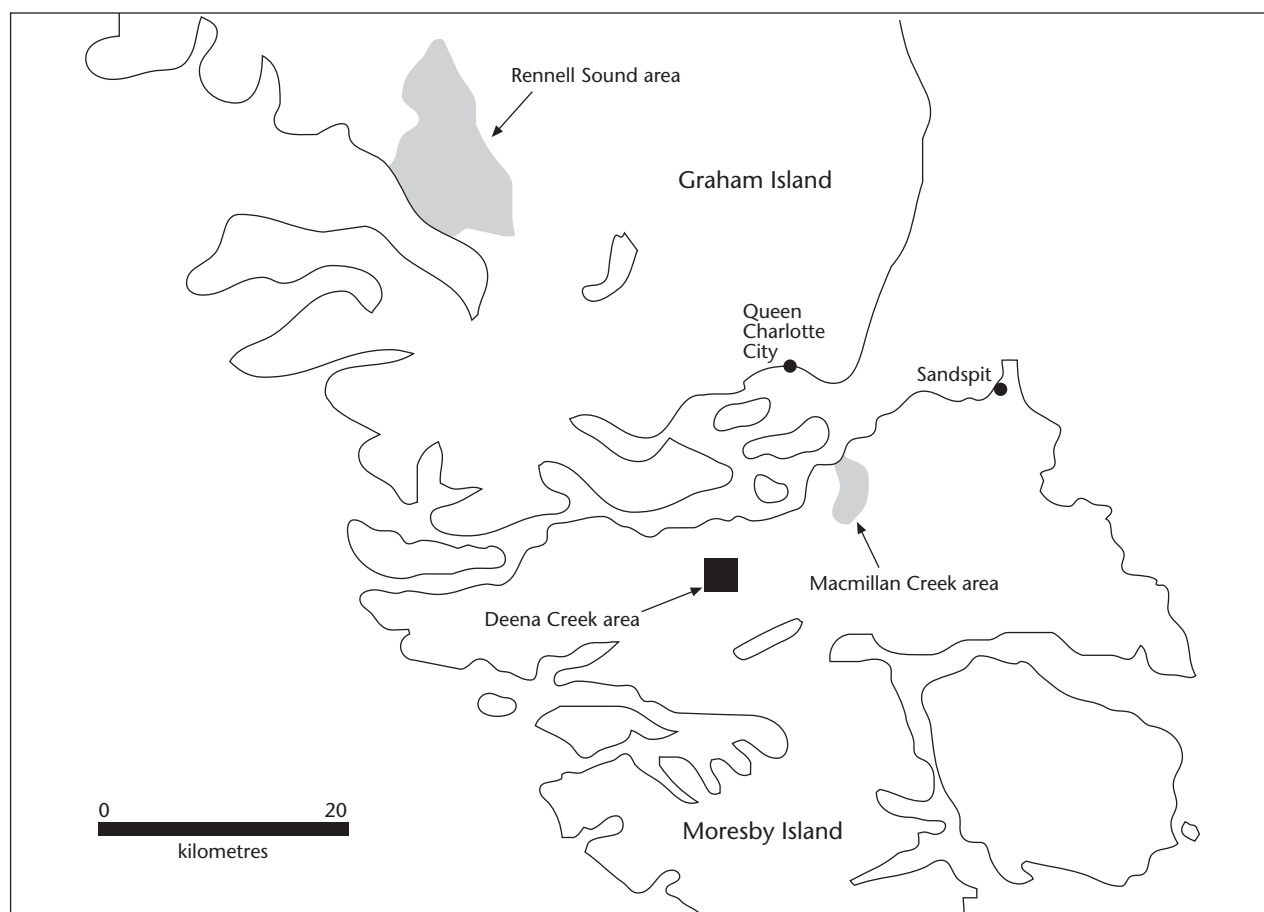


FIGURE 3 *Locations of study areas within Queen Charlotte Islands.*

Six gullies were selected for monitoring on the south flank of middle Deena Creek: two unlogged gullies (D3, D4) and two slash-full gullies (D1, D2) in upper Shomar Creek, and two slash-clear gullies (D5, D6) in the headwaters of a nearby unnamed basin (Fig. 5). Most of the Deena map area was logged in the late 1980s and early 1990s, and during this period at least two large debris flows originated in clearcut gullies (Fig. 5). The terrain is similar to that in Macmillan basin and is characterized by steep gullies discharging directly into main-stem streams. However, there are geologic differences between the two basins; the northeastern half of the Figure 5 map area is underlain by andesitic volcanic units of the Jurassic Yakoun Formation (Sutherland-Brown 1968), which weathers to a more clay-rich debris than that found in Macmillan basin. The southwestern half of the area is underlain by carbonates and argillites of the Jurassic-to-Triassic Kunga Group. A clayey till of

generally unknown thickness mantles most slopes. Climatically, the Deena Creek study area is probably similar to Macmillan Creek in that the general aspect of both areas is northerly and most of the instrumented gullies are located between 350 and 450 m above sea level.

Coquitlam basin, located 15 km northeast of Vancouver, is typical of the till-mantled, crystalline intrusive-rock terrain of the southern Coast Mountains (Fig. 6). The monitored gullies are located on the northwest side of upper Cedar Creek basin, underlain by coarse-grained intrusives (gabbro to quartz-diorite) generally massive and resistant to erosion (Roddick 1965). Gullies often follow zones of finely fractured rock, some of which may be fault lines. Much of the topography is mantled with basal till, 1–5 m thick, though many knob-shaped bosses of crystalline rock crop out in the upper and mid-slope sections. Colluvial material

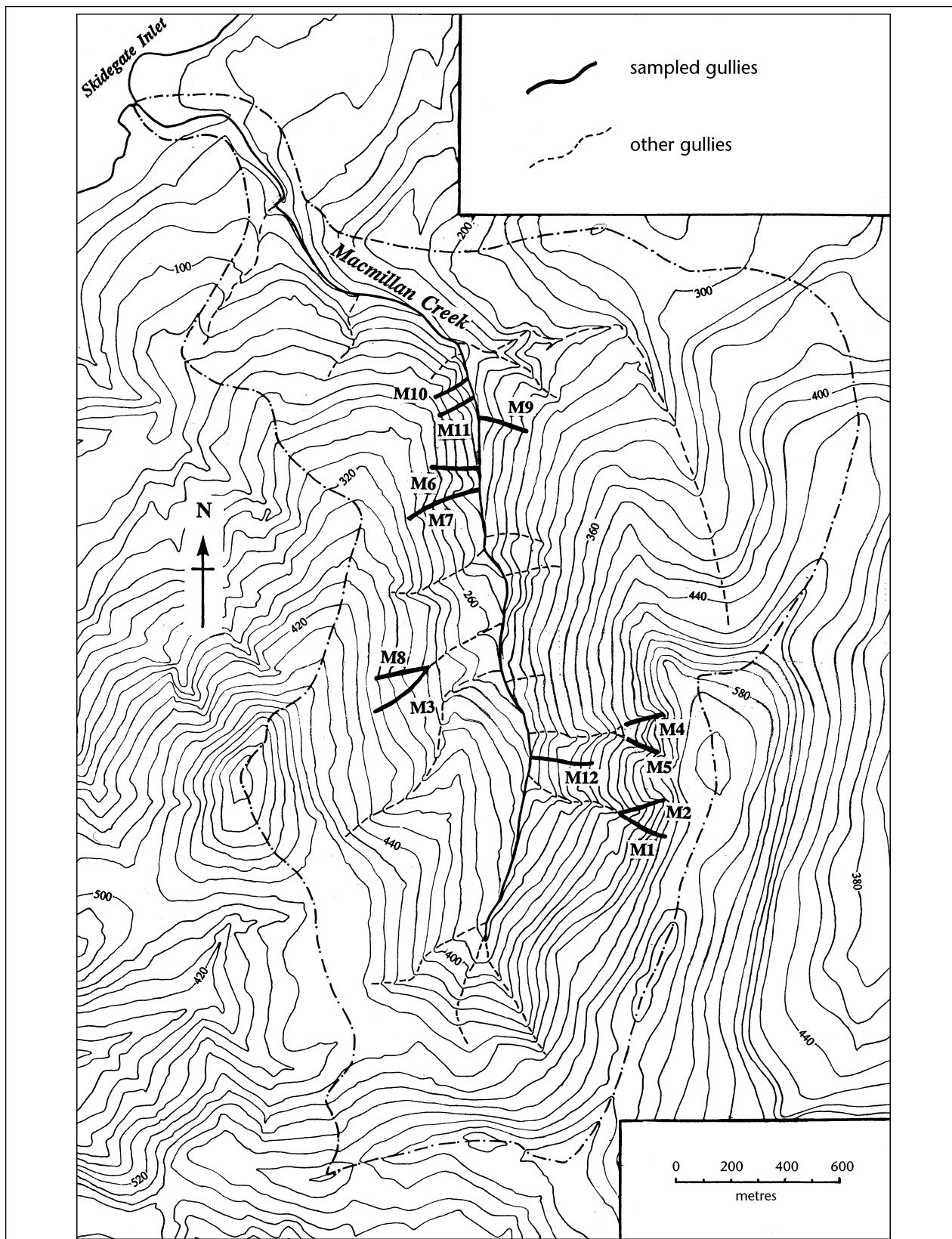


FIGURE 4 Macmillan basin study area, north Moresby Island, Queen Charlotte Islands.

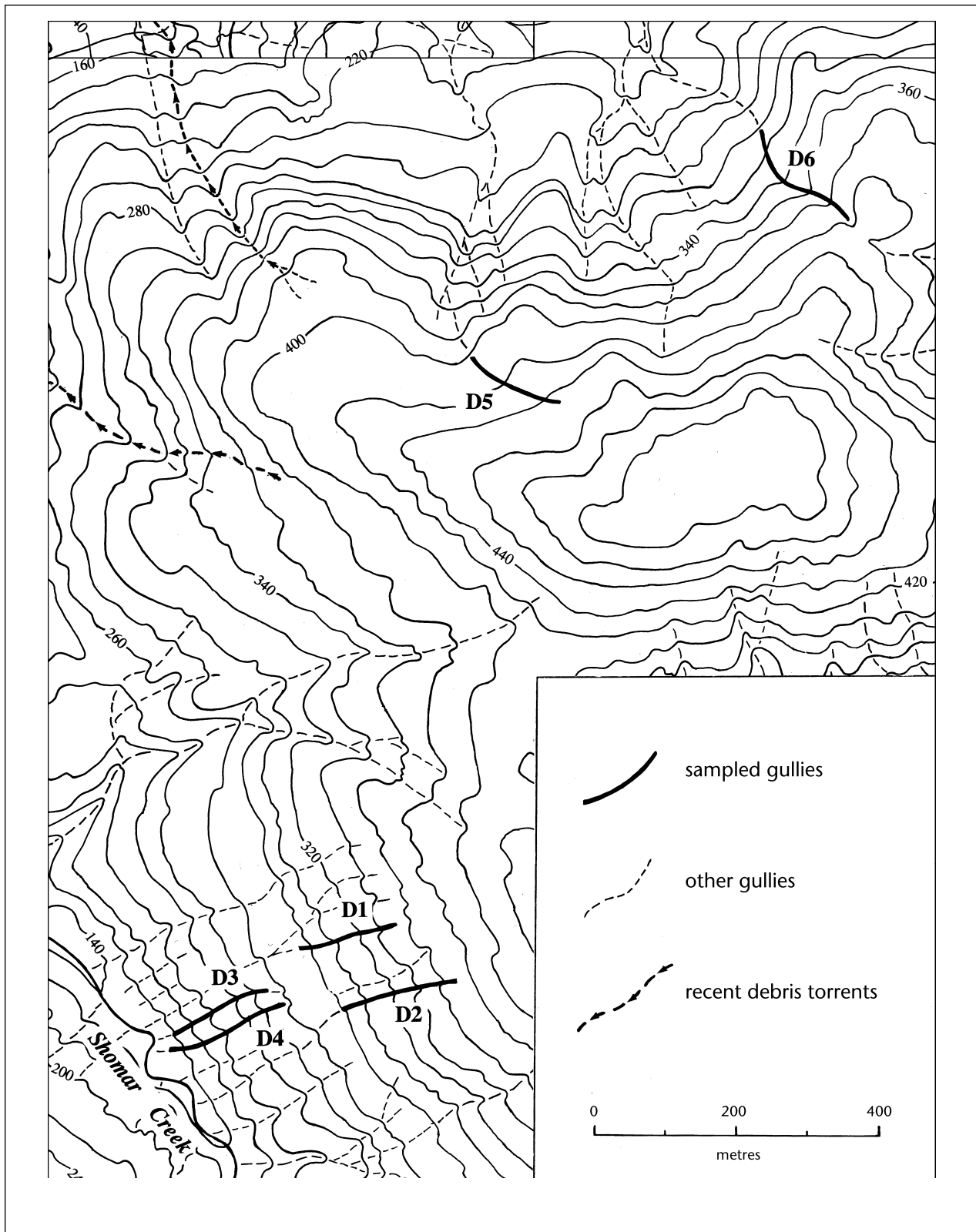


FIGURE 5 Deena Creek study area.

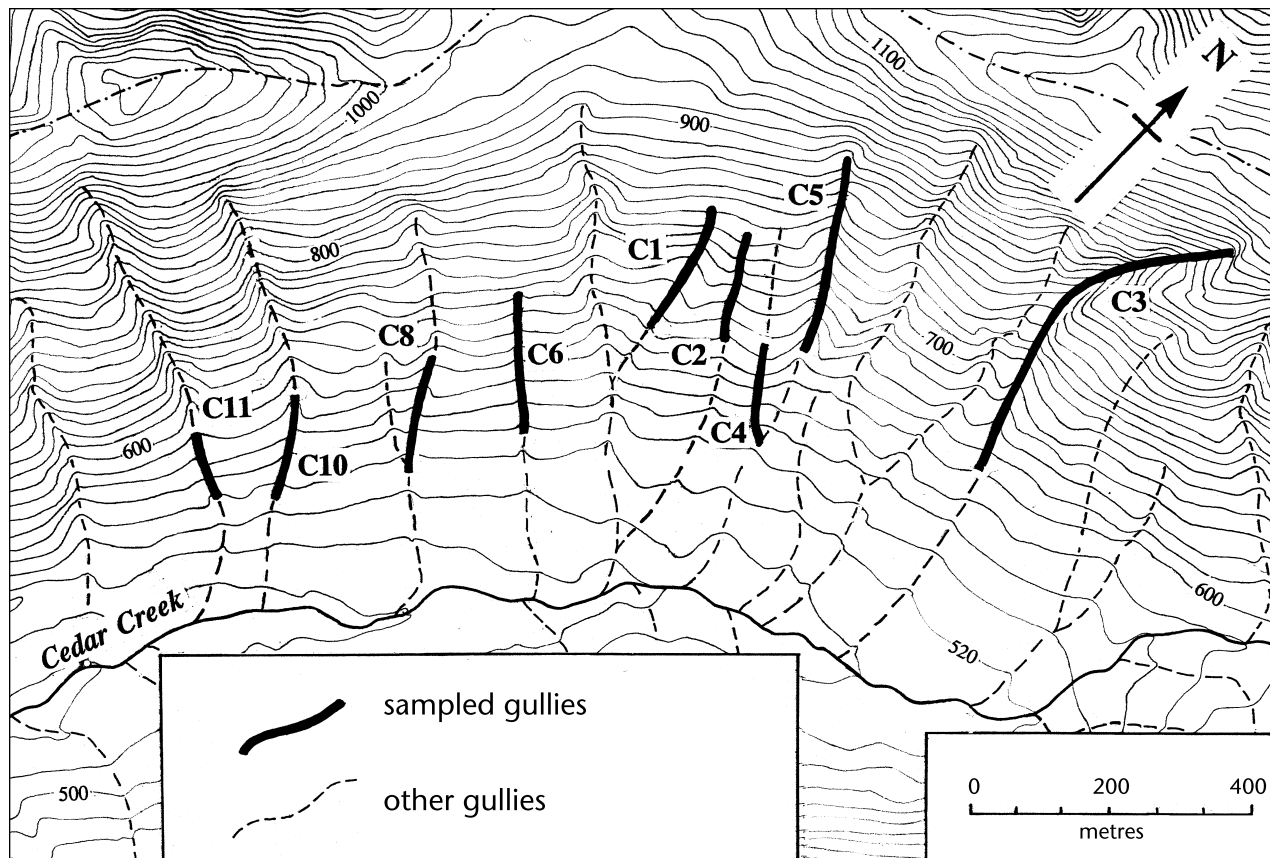


FIGURE 6 Coquitlam basin study area.

usually mantles bedrock and till to a depth of less than 2 m. Large colluvial fans have accumulated at the mouths of most of the gullies. Much of the area above 850 m is old-growth forest and was high-lead logged during the late 1980s and early 1990s. Several debris flows occurred in Cedar Creek basin during the large rainstorms in November 1990. Two of the flows, one of which initiated in an unlogged area, ran the full length of two instrumented gullies and destroyed the gully monitoring equipment.

Table 1 summarizes the attributes of all instrumented gullies in Macmillan, Deena, and Coquitlam basins. Despite the variety of terrain and geologic conditions in the three study areas, the total sample of gullies is relatively homogeneous with respect to morphology. Most gully gradients are close to 30°, and with the exception of gullies C5 and C8 in Coquitlam basin, most are 3–4 m in depth. Gully lengths, and therefore drainage areas, are more variable.

Synoptic Study Field Area Twenty-nine gullies were investigated for the synoptic study in four basins draining to Rennell Sound, namely Bonanza Creek, Gregory Creek, Riley Creek, and Shelly Creek (Fig. 7). Most of the area is underlain by weak volcanic and sedimentary rocks of the Jurassic Yakoun Formation. Also present are carbonates and argillites of the lower Mesozoic Kunga Group (Hesthammer et al. 1991). All of the formations weather rapidly and have a low resistance to surface erosion and mass movement (Alley and Thompson 1978; Wilford and Schwab 1983). Although the area has been glaciated, most of the steeper slopes now lack glacial deposits and the dominant surficial material found cropping out on gully walls is colluvium. Debris torrents from gullies have reworked these colluvial blankets to produce thick colluvial aprons and fans in most of the basins.

TABLE 1 *Process study: gully characteristics*

Basin	Gully	Treatment type ^a	Channel length (m)	Channel slope (deg)	Gully depth (m)	Gully width (m)	Drainage area (ha)
Macmillan	M1	LT	150	36	3.5	10	0.20
	M3	LT	240	20	3.0	10	0.24
	M9	LT	120	25	2.5	9	0.10
	M12	LT	170	30	3.5	11	0.19
	M2	SF	260	31	4.0	13	0.34
	M8	SF	180	19	3.0	12	0.21
	M10	SF	170	26	2.0	15	0.25
	M11	SF	120	27	3.0	12	0.15
	M4	U	100	33	3.0	10	0.10
	M5	U	100	31	2.5	12	0.12
	M6	U	80	31	2.0	5	0.04
	M7	U	80	30	2.5	11	0.09
Deena	D1	SF	140	29	3.5	6	0.22
	D2	SF	90	29	3.0	6	0.13
	D3	U	110	30	5.0	17	0.19
	D4	U	120	28	4.0	12	0.15
	D5	SC	60	18	3.5	10	0.09
	D6	SC	80	28	4.5	10	0.06
Coquitlam	C3	LT	230	20	4.5	18	0.49
	C5	LT	170	24	10.5	27	0.55
	C6	LT	230	32	3.5	13	0.35
	C4	SF	140	29	4.0	21	0.42
	C8	SF	190	34	1.0	12	0.29
	C1	U	120	28	2.0	14	0.17
	C2	U	105	27	4.5	17	0.20
	C7	U	140	26	4.5	14	0.19
	C10	SC	45	30	2.5	10	0.07
	C11	SC	80	30	4.0	13	0.12
Mean:			130	28	3.5	13	0.19
Stand. dev:			55	4	2.0	5	0.10

^a LT = logged-torrented; SF = logged, slash-full; U = unlogged; SC = logged slash-clear.

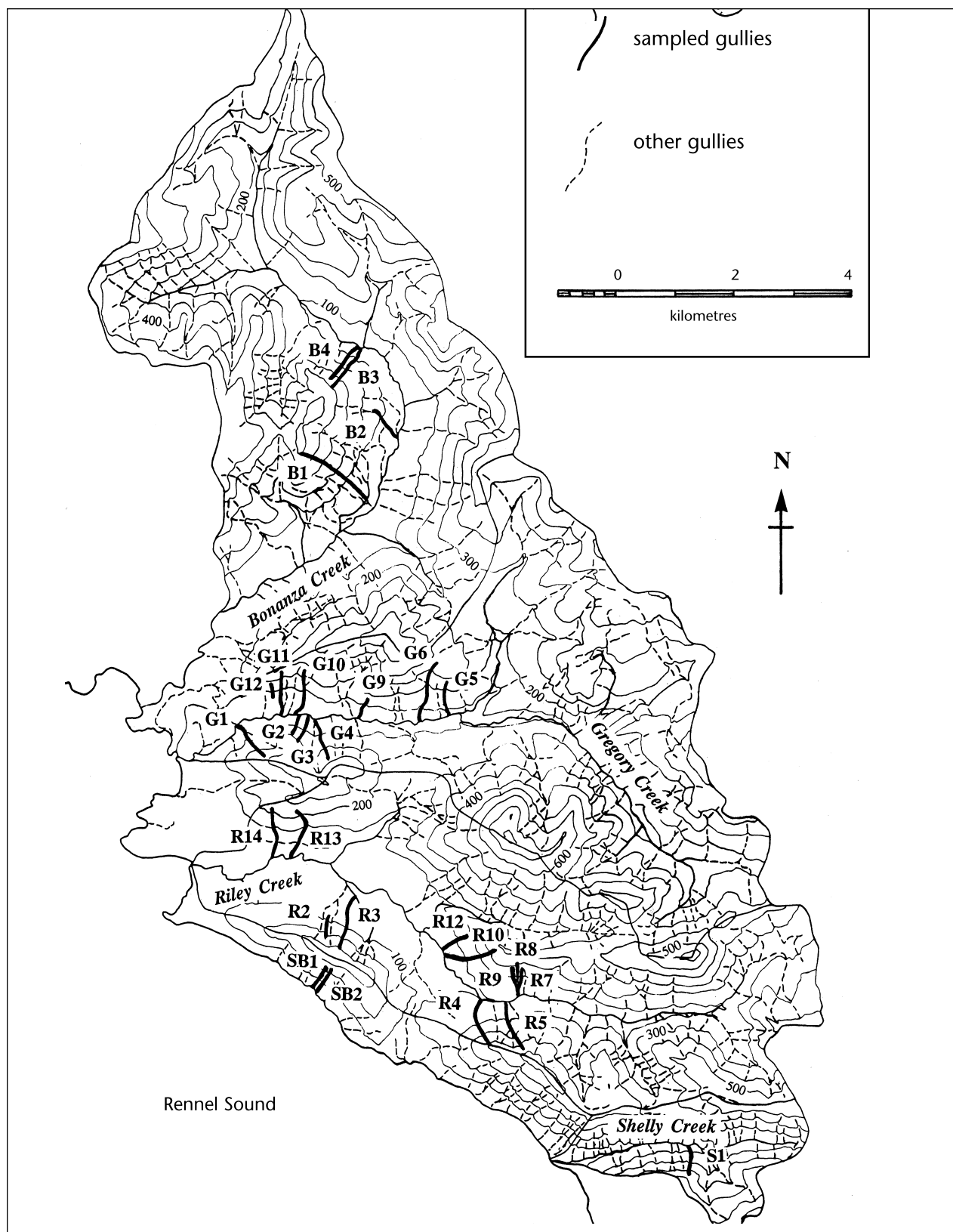


FIGURE 7 Rennell Sound study area, showing locations of gullies sampled in the synoptic study.

The physical characteristics of gullies in the synoptic study are summarized in Table 2. Apart from the fact that gullies investigated in the synoptic study are longer than those in the process study, the two groups of gullies are similar in terms of their attributes. These similarities allow comparisons to be made between the results of the two studies below, under “Discussion.”

The Process Study

Experimental Design The process study was conducted in the period 1990–1993 to measure the seasonal and year-to-year differences in sediment production, storage and output across four groups of gullies (Fig. 2):

- a) logged, slash-full (SF): no logging debris removed, no debris flows since harvest
- b) logged, slash-cleared (SC): no debris flows since harvest; logging debris removed by conventional yarding, followed by hand cleaning
- c) logged, “torrented” (LT): logged, formerly slash-full gullies with at least one debris flow since harvest
- d) unlogged (U): old-growth gullies with natural debris loads and no recent debris flows.

Gully groups (a) and (b) allowed the effects of logging debris removal to be assessed directly. Group (c) allowed post-torrent sediment yield to be compared with that of SC gullies. Group (d) provided a control comparison for Group (a).

The original experimental objective was to have a balanced, replicated design involving three replicate gullies in each of the four treatment groups (a)–(d), giving a total of 12 gullies in each study area. This design was subsequently modified since available funds permitted the clearing of LWD and logging slash from only two “treated” Group (b) gullies in each study area. Macmillan basin (Figs. 3–4) afforded an accessible area containing unlogged, slash-full, and many logged-torrented gullies. In this basin, four gullies in each of Groups (a), (c) and (d) were monitored. However, since Macmillan basin had been logged some 15 years prior to the start of this study, it was not a suitable basin for slash-clear gullies, given that the term “treated gully” in this study refers to debris removal concurrent with or shortly after the yarding of timber. Conversion of the slash-full gullies to slash-clear status in

Macmillan basin many years after logging would have entailed the release of considerable volumes of sediment stored behind the slash barriers.

Accordingly, treated gully sites were sought in areas where timber harvesting was in progress on North Moresby Island during 1990/91.

Two gullies were selected for logging debris removal in the southeastern part of Deena Creek basin (Fig. 5). Machine cleaning (with an American 100 grapple yarder), supplemented by hand removal of LWD pieces down to 5 cm diameter, was completed in September 1991. Because of geologic and terrain differences between Macmillan and Deena basins, two additional slash-full and unlogged gullies were selected in Deena basin, in close proximity to the slash-cleared gullies, to provide control for the two slash-cleared gullies. The total number of gullies in Deena basin was then six, yielding a Moresby Island total of 18 instrumented gullies.

In Coquitlam basin (Fig. 6), gullies in each of groups (a), (c), and (d) were instrumented during summer 1990. In summer 1991, two SC gullies were skyline-logged, then cleared of logging debris with the yarder and hand cleaning. This yielded a total of 11 instrumented gullies in Coquitlam basin. Destruction of two gully installations in Coquitlam basin by debris flows during the November 1990 rainstorms forced their abandonment in Coquitlam basin. Consequently, the sample size of gullies suitable for treatment-group comparisons in all field areas combined, over the period 1990–1993, was unavoidably reduced from 29 to 26. However, the debris flow events provided a basis for comparing chronic, fluvial rates of sediment delivery with the more catastrophic debris flow process (see “Discussion”).

Field Installations and Measurements: Process Study

Each gully in the process study was instrumented to provide information on all three components of the gully sediment budget: sediment input, changes in sediment storage, and sediment output. A quarterly program of site monitoring was maintained at most sites during the period March 1990 through November 1993. Sediment input was assessed from arrays of erosion pins (25-cm spikes) inserted at right angles to gully sidewall slopes at locations where surface erosion seemed to be most active. Each pin array consisted of 15–20 pins, with numbered tags, installed over areas of several square metres to provide a local average erosion rate for

TABLE 2 *Synoptic study: gully characteristics*

Basin	Gully	Treatment type ^a	Channel length (m)	Channel slope (deg)	Gully depth (m)	Gully width (m)	Drainage area (ha)
Bonanza	B1	LT	900	24	5.0	9	0.61
	B2	LT	230	19	6.0	9	0.17
	B3	LT	780	24	3.5	8	0.43
	B4	LT	280	20	4.5	9	0.17
Gregory	G1	U	220	29	6.0	14	0.20
	G2	U	340	23	6.0	12	0.29
	G3	U	230	17	6.0	12	0.19
	G4	U	240	17	6.0	12	0.20
	G5	U	250	23	6.0	16	0.24
	G6	U	510	17	9.0	15	0.61
	G9	U	410	21	5.0	11	0.31
	G10	U	180	25	7.0	15	0.18
	G11	U	280	28	7.5	17	0.32
	G12	U	50	35	6.0	14	0.05
Riley	R2	LT	160	30	3.0	6	0.06
	R3	LT	260	32	5.5	11	0.19
	R4	U	350	24	5.0	12	0.28
	R5	U	300	29	4.0	7	0.16
	R7	LT	340	27	2.0	5	0.11
	R8	LT	320	29	5.0	11	0.23
	R9	LT	330	27	3.0	7	0.15
	R10	LT	310	27	3.5	8	0.10
	R12	LT	390	21	3.0	8	0.20
	R13	LT	250	27	1.0	2	0.04
	R14	LT	150	29	2.0	6	0.06
Shelly ^b	S1 u	U	120	38	9.5	14	0.14
	S1 l	LT	180	32	3.5	8	0.10
Shields Bay	SB1	LT	130	27	2.0	5	0.05
	SB2	LT	190	25	2.0	6	0.07
Mean:			300	26	4.5	10	0.20
Stan. Dev:			180	5	2.0	4	0.15

^a LT = logged-torrented; SF = logged, slash-full; U = unlogged; SC = logged slash-clear.^b Lower case u indicates unlogged section of gully; lower case l indicates logged section of gully.

each eroding soil patch. Each gully contained several such arrays. In addition, periodic inventories of small slides and slumps were conducted to supplement the erosion pin results. To convert erosion rates derived from pin surveys were converted to volumes, pin array areas were multiplied and then supplemented by the estimated volumes of small slumps. Division by the total area of each pin array yielded an annual rate of equivalent surface lowering in mm/yr.

Sediment storage changes along gully channels were estimated from measured cross-sections at sites where net accumulation or net removal of material appeared to be taking place. Given the morphological complexity of most of the gully channels, it was considered impractical to apply the measured cross-sectional area changes to a representative length of gully channel to calculate volume changes for a particular gully reach. These were normalized by the width of the given cross-section to yield values in m^3/m per year.

Sediment output from each gully was determined from the volume of sediment and woody debris stored behind a porous geocloth screen secured across a gully channel (Fig. 8). (In Coquitlam basin, somewhat larger sediment traps were established in some gullies by using sediment catchment basins excavated on the upslope side of logging roads.) Reinforcing rods driven into the gully channel upslope of the geocloth screen were used to measure the changing level of accumulated material over a given time interval. To convert this depth of



FIGURE 8 View of lower M1 gully, a torrented channel in upper Macmillan Creek basin, showing typical geocloth screen installation. Channel is 6 m wide at the screen.

deposition to a volume, the depth values were applied to representative areas (of the order 0.5 m^2) around each deposition bar. The total volume of material trapped behind each screen was then normalized by the gully drainage area as m^3/ha .

In the more actively eroding gullies, periodic excavation of sediment was required to prevent overtopping of the screen in the ensuing measurement period. Gully M1, a logged-torrented example in Macmillan basin, proved to be anomalous in its extremely high rate of sediment delivery, which resulted in complete burial of the geocloth screen on several occasions. From 1992 until the end of the study, net sediment output from this gully was estimated by resurveying several channel cross-sections downstream of the original geocloth screen.

Inspection of geocloth screens during high flow periods indicated some loss of sand, silt, and clay around the margins of certain of the screens (for example, those in gullies M3 and M8 in Macmillan basin). As the geotextile aged, its permeability decreased as a result of fine sediment plugging the pores. In effect, the geotextile became a small dam, and sediment settled out in the pool upstream. At times of high flow, water was observed flowing over the screen. Results from Coquitlam basin suggest that about 30% of all suspended fine sediment (silt and clay) was lost from the trap because of fine sediment remaining in suspension as water passed over the trap.

A morphological description of each gully was completed using compass, hip-chain and tape measure, supplemented with photogrammetry and electronic distance measurement. Gullies longer than about 250 m were generally avoided, since the sediment screens installed across each gully would likely have been overwhelmed by either water or sediment discharges.

The Synoptic Study

Experimental Design The second phase of the project, termed the synoptic study, was conducted in the period 1992–1994 and focussed on patterns of sediment build-up in gullies over time spans of several decades. This approach was designed to complement the relatively short time-frame of the process study. Gullies were investigated in the Rennell Sound area of southern Graham Island (Fig. 7) with the objective of comparing rates of

debris recharge between logged and unlogged gullies. The calculation of debris recharge rates required knowledge of the elapsed time since the last debris flow in a given gully. Good dating control was a major factor favouring the Rennell Sound area, where there existed a high frequency of recent debris flows in both logged and unlogged areas, as well as previous investigations of debris flow ages (Wilford and Schwab 1983; J. Schwab, unpublished data). Twenty-nine gullies were used in the synoptic study (Fig. 7). Although the study areas used in the process and synoptic studies do not overlap, the similarity in geologic and terrain conditions between north Moresby Island and southwestern Graham Island allows the longer-term synoptic study to complement the process study.

Measurement Procedures: Synoptic Study Determination of debris recharge rates in logged and unlogged gullies was based on the volume of LWD and sediment stored along the gully channel and the time elapsed since the last debris flow event. An important assumption was that all of the pre-existing debris fill along a gully had been scoured out by the last debris flow. Examination of recently torrented gully channels confirmed the validity of this assumption (Fig. 9). Debris fill volumes were calculated from measured cross-sections at 25-m intervals along the gully channel. Although the surface area of various debris prisms along a gully could be accurately surveyed, there was less certainty as to depth. In most cases, the cross-sectional shape of a debris prism was well approximated by either a triangle or a trapezium. The longitudinal shape was idealized as a uniformly tapering triangle. The validity of these assumptions was tested by excavation through the fill material to bedrock in a number of gullies. Based on 20 such excavations in nine gullies, the observed average cross-sectional area was 0.87 m^2 (standard deviation 0.02 m^2), and the estimated mean area was 0.71 m^2 (standard deviation 0.07 m^2). These tests show that the methods used to estimate the cross-sectional areas of debris prisms yielded fairly reliable results.

The total debris volume stored in a gully was obtained by summing the individual debris prism volumes, then normalized by gully area to yield recharge as m^3/ha as well as by gully length (m^3/m). Annual average yields (m^3/ha per year) were obtained by dividing area-normalized volumes by elapsed



FIGURE 9 *Torrented gully scoured to bedrock after recent debris flow in Bonanza Creek basin, Rennell Sound.*

time since the last debris flow. In some cases, forest-industry and B.C. Ministry of Forests personnel were able to recall from memory or written records both the year and month of occurrence of debris flows. In addition, unpublished investigations by J. Schwab (B.C. Ministry of Forests, Smithers, BC) revealed the occurrence of major cycles of debris flows in the years 1891, 1917, 1935, and 1978 (J. Schwab, pers. comm., 1992; Schwab, this volume). Both dendrochronology and air photograph analyses were then used to corroborate this evidence, and to search for additional debris flow dates.

A chronological sequence of air photographs over the period 1935 to 1989 was used to constrain the time span within which known events could have occurred. This record of vertical air photographs was supplemented in summer 1992 with aerial oblique images of selected gullies in Bonanza, Gregory, and Riley creek basins. Tree-ring dating confirmed many of the dates previously noted by

Schwab and narrowed the time intervals obtained from the air-photograph record. Most debris flows were dated either by determining the age of alder stands in areas previously scoured by debris flow, or by dating impact scars on older trees growing close to the margins of a debris flow channel.

Results

Process Study Results

Sediment Output from Gullies The sediment outputs measured from gullies over a three-year period are shown as cumulative curves in Figures 10–12. All values are normalized as m³/ha by dividing by gully contributing area (Table 1). Variations in the slopes of the cumulative curves show that most gully types have a peak of sediment production and delivery in the autumn and winter quarters when maximum precipitation and runoff occur. Minimum values tend to occur during the summer period of least precipitation. Significant variations in total sediment output are evident across the gully types in each study area. Over the entire period of record, logged-tormented gullies showed the highest output

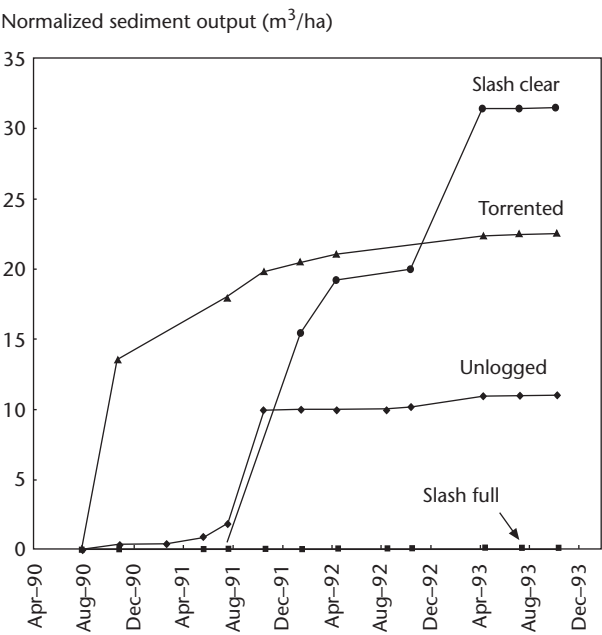


FIGURE 11 Cumulative mean sediment output for Coquitlam basin gully groups, 1990–1993, based on material trapped by geocloth screens.

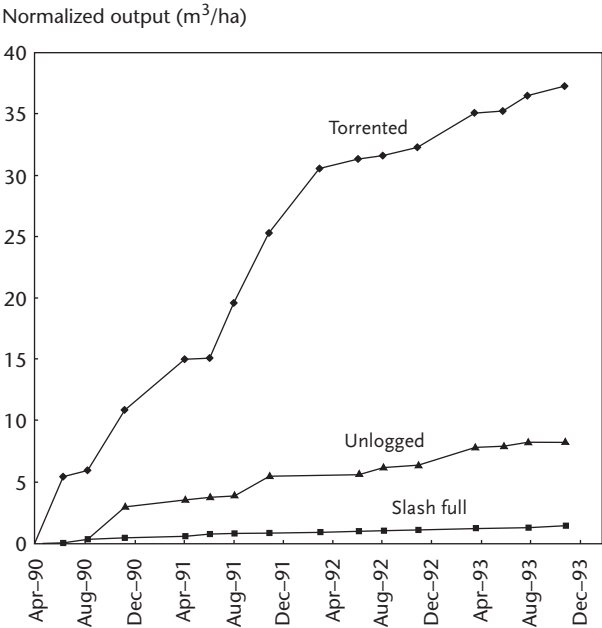


FIGURE 10 Cumulative mean sediment output for Macmillan basin gully groups, based on material trapped by geocloth screens.

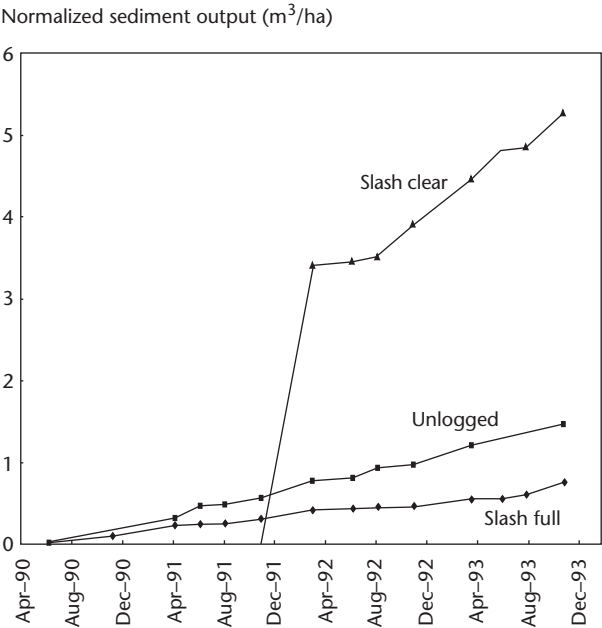


FIGURE 12 Cumulative mean sediment output for Deena basin gullies, 1990–1993, based on material trapped by geocloth screens.

values in all three study areas; however, both Figures 11 and 12 show that, in the period 1991–1993 when slash-clear gullies operated, they had the highest sediment output. Unlogged gullies are third in rank order of sediment production and delivery, with logged slash-full consistently showing the least output of sediment in all three study areas.

The similarity in rank ordering of gully sediment responses within different geographic areas suggests that geologic differences between the study basins have a lesser effect on gully sediment output than do differences in either land-treatment effect (i.e., logged versus unlogged) or mass movement history (i.e., torrented versus non-torrented). High sediment outputs from torrented gullies are explained in part by a lack of LWD—and hence sediment storage sites—and in part by the high rates of sediment production from recently scoured gully walls. In slash-cleared gullies, high sediment output was apparently related more to channel erosion than to sidewall erosion. Removal of logging debris disturbed the gully channel sufficiently to release sediment that otherwise would have been stored behind LWD. Low sediment outputs from slash-full gullies are explained by the high trap efficiency of thick LWD fills. Moderate sediment outputs from unlogged gullies are attributable to the relative stability of naturally vegetated gully walls, and to the development of fluvial sediment pathways through the decaying LWD fills.

Sediment Storage in Gullies Changes in debris storage in gullies were derived from repeated measurements of 15–20 points at each of several channel cross-sections in gullies. As noted earlier, it was not possible to report actual volume changes in gully reaches because of uncertainty in extrapolating changes upstream and downstream from the measured cross-section. Results reported in Tables 3 and 4 show normalized changes (m^3/m of cross-section width) in Queen Charlotte gullies over the period of record. Negative values indicate net erosion, positive values net deposition. Table 5 gives average values by both geographic area and gully treatment group. In most cases, negligible changes were recorded in slash-full and unlogged gullies; however, both logged-torrented and slash-clear gullies registered significant sediment losses. These results emphasize the importance of LWD in regulating sediment storage. In particular, the lack

of LWD in torrented gullies in Macmillan Creek reflects the fact that most LT gullies in this basin had been scoured by debris flows in the 5–8 years prior to the inception of the process study. Significant sediment recharge had not yet occurred, since most channels were totally devoid of LWD at the start of the study. In the slash-clear (SC) gullies in Deena Creek (Table 4), significant erosion of channel bed materials was evident following machine and hand-cleaning operations.

In Coquitlam basin, over a similar period of record (Table 6), negligible changes were also noted in both unlogged and slash-full gullies, consistent with the Queen Charlotte results. The response of Coquitlam slash-clear gullies was also similar to those in Deena Creek. Gullies C10 and C11 in Coquitlam showed very rapid scour of their channels down to bedrock or an armoured bouldery surface within a few months of the completion of machine and hand cleaning (as clearly seen in Figure 11). However, a significant difference in Table 6, relative to the Queen Charlotte results in Tables 3 and 4, is an appreciable net gain of material in two of the logged-torrented gullies in Coquitlam basin. This may reflect the much coarser calibre of colluvial materials in Coquitlam basin, as well as the existence of large granitic boulders which provided fine-sediment storage sites along many channels. By contrast, the less competent bedrock materials in the Queen Charlotte gullies disintegrated almost completely to gravel or finer sizes. Queen Charlotte colluvium and till materials generally lacked large boulders, and thus were more readily eroded by fluvial transport.

Sediment Input to Gullies The available data on sediment inputs (Table 7) are based on repeated measurement of erosion pin arrays established within obviously eroding patches of exposed mineral soil along gully sidewalls. Each of the data points in the table represents an average value from hundreds of individual pin measurements within each gully. The data are somewhat more difficult to interpret than the channel storage data just described because of concerns about a lack of areal coverage, since it was neither possible nor desirable for reasons of site disturbance to monitor every patch of eroding soil within a gully. Given estimated errors of at least ± 2 mm per year, all values in Table 7 have been rounded to the nearest 5 mm. The values are average rates of surface lowering in the

TABLE 3 *Cross-sectional area changes in Macmillan basin gullies, 1991–1993*

Gully	Cross-section	Width section (m)	Cross-section change (m ² /m)	Inclusive dates	Normalized change (m ² /m)	Mean (m ² /m)	Gully type ^a
M1	XS-1	6.02	-1.55	4/91–11/93	-0.26	-0.25	LT
	XS-2	5.54	-2.36		-0.43		
	XS-4	6	-0.49	11/91–11/93	-0.08		
	XS-5	.87	1.02		0.17		
	XS-6	8.10	-5.17		-0.64		
M3	XS-1	5.91	0.10	4/91–11/93	0.02	0.03	LT
	XS-2	4.60	0.27	8/91–11/93	0.06		
	XS-3	11.30	0.07		0.01		
M4	XS-1	2.97	0.68	8/91–11/93	0.23	-0.12	U
	XS-2	4.82			-0.56		
	XS-3	3.90	-0.28		-0.07		
	XS-1	3.80	0.16	8/91–11/93	0.04	-0.01	U
	XS-2	3.16	0.01		0.00		
	XS-3	5.80	-0.41		-0.07		
M6	XS-1	3.03	0.14	8/91–11/93	0.05	0.02	U
	XS-2	3.00	-0.01		-0.00		
M7	XS-1	3.84	-0.22	8/91–11/93	-0.06	-0.02	SF
	XS-2	2.94	0.07		0.02		
M8	XS-1	7.15	-0.30	8/91–11/93	-0.04	-0.02	LT
	XS-2	6.82	-0.09		-0.01		
	XS-3	5.70	-0.07		-0.01		
	XS-4	6.60	-0.04		-0.01		
M9	XS-1	2.60	-0.02	8/91–11/93	-0.01	-0.01	LT
	XS-2	3.80	0.11		0.03		
	XS-3	3.45	-0.18		-0.05		
M10	XS-1	4.24	-0.05	8/91–11/93	-0.01	0.02	SF
	XS-2	2.72	0.06		0.02		
	XS-3	3.57	0.23		0.06		
M11	XS-1	3.52	0.04	8/91–11/93	0.01	-0.03	SF
	XS-2	5.78	-0.40		-0.07		
M12	XS-1	3.20	0.01	8/91–11/93	0.00	0.05	LT
	XS-2	3.77	0.36		0.10		
	XS-3	7.83	0.32		0.04		

^a LT = logged-torrented; SF = logged, slash-full; U = unlogged; SC = logged slash-clear.

TABLE 4 *Cross-sectional area changes in Deena basin gullies, 1991–1993*

Gully	Cross-section	Width section (m)	Cross-section change (m ³ /m)	Inclusive dates	Normalized change (m ³ /m)	Mean (m ³ /m)	Gully type ^a
D1	XS-1	4.95	-0.02	8/91–11/93	-0.00	0.01	SF
	XS-2	8.30	0.10		0.01		
	XS-3	3.38	0.11		0.03		
D2	XS-2	3.47	0.07	8/91–11/93	0.02	0.02	SF
	XS-2	2.91	-0.03		-0.01		
	XS-3	8.00	0.41		0.05		
D3	XS-1	1.80	0.11	8/91–11/93	0.06	0.02	U
	XS-2	4.42	-0.08		-0.02		
D4	XS-1	2.35	-0.14	4/91–11/92	-0.06	-0.02	U
	XS-2	7.60	0.04	6/91–11/92	0.01		
	XS-3	6.26	-0.08	8/91–11/92	-0.01		
D5	XS-1	3.35	0.02	11/91–11/93	0.01	-0.02	SC
	XS-2	4.01	-0.10		-0.03		
	XS-3	3.39	-0.18		-0.05		
D6	XS-1	2.63	-0.15	11/91–11/93	-0.06	-0.06	SC
	XS-2	3.15	-0.19		-0.06		

^a LT = logged-torrented; SF = logged, slash-full; U = unlogged; SC = logged slash-clear.

TABLE 5 *Cross-sectional area changes in Queen Charlotte gullies, 1991–1993*

Basin	Gully treatment groups ^a				Basin mean (m ³ /m)
	LT (m ³ /m)	SF (m ³ /m)	U (m ³ /m)	SC (m ³ /m)	
Macmillan	-0.062	-0.007	0.003		-0.022
Deena		0.017	-0.001	-0.041	-0.008
Regional means	-0.062	0.005	0.001	-0.041	

^a LT = logged-torrented; SF = logged, slash-full; U = unlogged; SC = logged slash-clear.

TABLE 6 *Cross-sectional area changes in Coquitlam gullies, 1991–1993*

Gully site	Cross-section	Width of section (m)	Cross-section area change (m ²)	Inclusive dates	Normalized cross-section area change (m ³ /m)	Site mean values (m ³)	Gully treatment ^a
C2	XS-2	5.7	0.00	10/91–5/93	0.00	-0.00	U
	XS-3	4.7	-0.32		-0.07		
	XS-4	4.2	0.04		0.01		
	XS-5	5.8	0.23		0.04		
C3	XS-1	6.3	0.09	10/91–5/93	0.01	0.01	LT
	XS-2	7.6	0.11		0.01		
	XS-3	10.1	-0.01		-0.00		
	XS-4	7.0	0.30		0.04		
	XS-5	8.0	-0.02		-0.00		
C5	XS-2	10.0	0.21	10/91–5/93	0.02	0.02	LT
	XS-3	7.8	0.15	11/91–5/93	0.02		
	XS-4	7.0	0.14		0.02		
	XS-5	8.0	0.20		0.03		
	XS-6	5.7	0.03		0.01		
C6	XS-1	5.3	-0.18	10/91–5/93	-0.03	-0.02	LT
	XS-2	3.8	-0.14		-0.04		
	XS-3	4.7	0.06		0.01		
C10	XS-1	3.4	-0.32	10/91–5/93	-0.09	-0.08	SC
	XS-2	3.3	-0.43		-0.13		
	XS-3	3.7	0.11		0.03		
	XS-4	4.5	-0.51		-0.11		
C11	XS-1	3.7	-0.09	10/91–5/93	-0.02	-0.04	SC
	XS-2	4.0	-0.29		-0.07		
	XS-3	5.8	-0.20		-0.03		
	XS-4	5.3	-0.27		-0.05		

^a LT = logged-torrented; SF = logged, slash-full; U = unlogged; SC = logged slash-clear.

TABLE 7 Average erosion pin response by gully treatment group, 1990–1993

Study area	Treatment group ^a	Average erosion rate (mm/yr)
Coquitlam basin	LT	15
	SF	10
	U	5
Macmillan and Deena basins	LT	25
	SF	20
	U	10
	SC	10

^a SC value refers to period March 1992–November 1993 only.

soil patches monitored; they do not reflect average erosion rates over the entire gully sidewalls, but give some idea of typical rates of change within the most rapidly eroding sidewall areas.

The highest group means in Table 7 occur in the logged-tormented (LT) category, followed in rank order by slash-full (SF), slash-clear (SC), and unlogged (U) gullies. Since many SF gullies were logged at least 10 years prior to the inception of this study, the implication is that healing of bare soil areas caused by yarding disturbance takes a significant time to complete. Slash-clear gullies have relatively low erosion values, which may reflect the relatively careful logging practices used in these gullies. The highest erosion pin values in logged-tormented gullies in both study areas reflect the relatively recent scour of sidewalls below the root depth of most shrubs. Significant erosion by rainsplash, overland flow, dry ravelling, and frost action occurs before the gully walls eventually become revegetated.

Sediment Transport During the November 23, 1990, Debris Flows in Coquitlam Basin During the autumn and winter of 1990/91, several large storms occurred in the southern Coast Mountains, causing numerous debris flows. The storm of November 23, 1990, caused a total of 19 debris flows in Coquitlam basin alone, nine of which occurred in Cedar Creek basin. Most of these debris flows initiated in old-growth forest areas, then scoured the clearcut sections of the affected gullies. Two of the monitored gullies experienced debris flows (gullies C1 and C6; Fig. 6), causing complete destruction of the gully-monitoring installations. The C1 event initiated in old-growth

forest and therefore may be regarded as a natural event. The C6 event initiated within the clearcut portion of the gully. Both debris flows were surveyed in early December 1990, shortly after their occurrence, to assess the total volume of material involved (Table 8). These surveys indicated about 1.2 m³/m of LWD derived from logging in gully C6. This debris and its associated sediment are estimated to have increased the magnitude of this event by approximately 20%.

The occurrence of the events within monitored gullies allows a comparison of the quantities of material moved by chronic, non-catastrophic fluvial events and episodic mass-transport events. Normalized by gully length, the C1 debris flow yielded 3.5 m³/m of scoured channel length and the C6 flow yielded 5.9 m³/m, for an average of 4.7 m³/m from both flows (Table 8). Using somewhat larger gullies on the Queen Charlotte Islands, Fannin and Rollerson (1993) calculated typical debris yields of 5–10 m³/m. Thus, the events in C1 and C6 are probably typical of debris flows in the smaller-sized

TABLE 8 Volumes of November 1990 debris flows, Coquitlam basin

Gully	Initial failure volume (m ³)	Transport zone volume (m ³)	Deposited volume (m ³)	Total volume (m ³)
C1	400	1340	-170	1560
C6	220	900	-230	890
Mean volume:				1230

gullies considered in this study. The average volume from the two debris flows was 1230 m³ (Table 8). By comparison, the average fluvial sediment yield calculated from Coquitlam basin sediment traps in gullies was only 2.7 m³/yr. (This figure ignores slash-full gullies which registered virtually zero output over the period of study.) Assuming a recurrence interval of 50 years for such debris flows (as suggested by the work of Schwab, this volume), episodic sediment export by debris flows over a 50-year period would be 9 times greater than the cumulative fluvial transport of sediment (i.e., 1230 m³ versus 135 m³). However, many old-growth gullies contain apparently undamaged trees 300–400 years old, growing close to the margins of gully channels. In these cases, debris flow frequency may be of the order 500–1000 years and fluvial sediment output would equal or exceed the debris flow sediment output.

Synoptic Study Results As noted previously, the principal objective of the synoptic study was to estimate the rates of sediment and woody debris recharge following torrenting in a representative sample of 13 unlogged and 16 logged gullies in the Rennell Sound area of southwestern Graham Island (Fig. 7). Gully fill volumes were estimated from a combination of profile surveying and outright excavation of fills in 15 of the 29 gullies, then normalized by gully drainage area to yield m³/ha. Annual average debris recharge rates (m³/ha per year) were obtained by dividing each normalized storage volume by elapsed time since the last debris flow (Table 9). During the gully surveys, separate inventories were kept of both coarse woody debris (CWD) and clastic sediment. All data are rounded to the nearest five units.

Recharge Rates of LWD and Clastic Sediment From Table 9 it is evident that after a debris torrent has occurred, LWD is delivered to unlogged, old-growth gullies at a rate more than twice that of clearcut gullies. It is worth re-emphasizing that this assumes that the original surcharge load of LWD from logging has already been removed by a post-harvest debris flow, which was the case in all examples reviewed here. The LWD supply rate in old-growth gullies is related to the higher potential for wind-throw of branches and entire trees in mature to over-mature forests. The inference is that, until second-growth forest reaches maturity, lower rates

of LWD input should be expected relative to those of old-growth gullies. It is not known whether clearcut gullies are likely to recover to the background rates of LWD supply found in old-growth gullies over the 80- to 100-year rotation period typical of coastal harvesting. The supply rate of clastic sediment to clearcut gullies is roughly double that observed in old-growth gullies (Table 9). However, the clearcut standard deviations are much higher, indicating much more variability in this gully group. The reason for this is that surface erosion rates typically produce a right-skew distribution in which the mean and variance are correlated. The higher LWD supply in unlogged gullies offsets the lesser rate of sediment supply, to yield a total debris supply rate that is some 75% of the clearcut figure (Table 9, mean values).

These simple comparisons of LWD and sediment recharge rates ignore the differences in mean debris recharge times between the two sub-samples of gullies. For example, in logged gullies, the mean elapsed time since the last debris flow was 7 years, and the earliest documented event was 14 years old at the time of the 1992 surveys (i.e., 1978). In unlogged gullies, the mean elapsed time is 21 years and the earliest event is 75 years old (i.e., 1917). Since the earliest documented debris flow in the logged sample is only 14 years old, recharge rates were re-compared over this common time scale. For clastic sediment, the mean rate of recharge in clearcut gullies is almost double that recorded in old-growth gullies over the 14-year period of common record. However, the high variance in both samples precludes a statistically significant distinction. Given the lower rates of LWD input to clearcut gullies, the higher rate of sediment recharge in this gully group implies much higher rates of sediment delivery. This is explained by the greater instability of gully sidewalls and bank tops where vegetation has been removed, and by higher sediment production from hillslopes disturbed by logging operations (Schwab 1983; Rood 1984; Sidle et al. 1985).

The changing rates of sediment recharge over the entire 75-year period of record are shown in Figure 13. The data indicate a decline in the rate of recharge over time within both gully groups, with the suggestion of a steeper rate of decrease in recharge rate in clearcut gullies. This is consistent with the progressive stabilization of gully walls with time, causing a decrease in sediment supply.

TABLE 9 *Recharge rates of LWD and sediment in Rennell Sound gullies*

Gully	LWD recharge (m ³ ha ⁻¹ yr ⁻¹)	Sediment recharge (m ³ ha ⁻¹ yr ⁻¹)	Total recharge (m ³ ha ⁻¹ yr ⁻¹)	Total recharge (m ³ m ⁻¹ yr ⁻¹)	Time since last debris flow (yr)
Unlogged					
G1	10	135	145	0.14	14
G2	10	140	150	0.13	14
G3	30	120	150	0.13	14
G4	15	130	145	0.13	14
G5	<5	20	20	0.03	75
G6	<5	20	20	0.03	57
G9	20	40	60	0.06	14
G10	<5	40	40	0.13	14
G11	30	95	125	0.16	14
G12	<5	50	50	0.08	14
R4	<5	90	90	0.11	6
R5	<5	70	70	0.04	10
S1u	<5	30	30	0.05	8
Means:	10	75	85	0.09	21
Standard Dev:	10	45	50	0.05	20
Clearcut					
B1	25	530	555	0.42	1
B2	25	195	220	0.19	8
B3	0	75	75	0.05	10
B4	<5	75	75	0.06	6
R2	0	195	195	0.15	3
R3	<5	60	60	0.06	11
R7	<5	210	210	0.11	2
R8	<5	25	30	0.03	7
R9	<5	60	65	0.04	14
R10	<5	165	170	0.18	7
R12	10	300	310	0.28	1
R13	<5	90	90	0.05	8
R14	<5	40	40	0.03	14
S1l	<5	135	140	0.14	8
SB1	0	65	65	0.04	8
SB2	<5	15	15	0.01	8
Means:	5	140	145	0.12	7
Standard Dev:	10	130	135	0.11	4

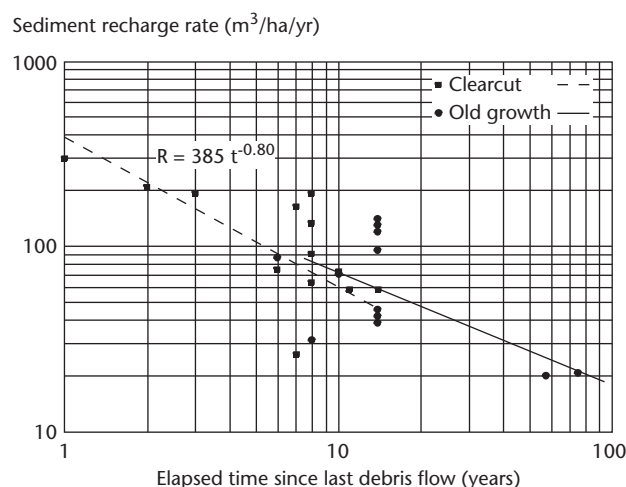


FIGURE 13 *Rate of sediment recharge in logged and unlogged Rennell Sound gullies over the period, 1917–1992. Rates are based on the volumes of clastic material stored in gullies, normalized by gully contributing area and time since last debris flow.*

Although there are only two data points controlling the long-term part of the recharge curve, one can speculate that most gullies might be fully recharged with material within the time frame of a coastal forest-harvest rotation.

Discussion

Comparison of Process Study and Synoptic Study Results Both studies reported here were designed to provide quantitative data on the effects of LWD on sediment production, storage, and delivery in coastal gullies. The process study provided a detailed assessment of the effects of varying concentrations of LWD, including deliberate removal of LWD following harvest, over a three-year period. The influence of LWD on the sediment regimen of gullies is seen in the sediment output data (Figs. 10–12). These data integrate the net effects of both sediment input and storage across entire gully groups. Of particular note are the consistently very low sediment outputs from slash-full gullies in comparison with all other gully groups, whereas erosion pin data (Table 7) suggest that slash-full and logged-torrented gullies have similar sediment input values, well above those of unlogged gullies. Together these data on sediment

input and output imply higher sediment storage in slash-full gullies, a tendency partly confirmed by the treatment group means in Tables 4, 5 and 6.

The synoptic study provides up to a 75-year history of debris recharge in previously torrented gullies and therefore gives a more reliable picture of long-term sediment storage. In many cases, the volumes of channel fill were corroborated by actual excavation of gully fill material. As the regression lines in Figure 13 show, the mean fill rate of LWD plus sediment in both logged and unlogged gullies is approximately 0.08 m³/m per year. Over a 2.5-year period comparable to the duration of the process study, the average recharge would be 0.20 m³/m of channel length, which reduces to 0.04 m³/m of channel width when an average channel width of 5 m is used. This value is of the same order of magnitude as many of the positive values reported in Tables 4 and 6, indicating a broad similarity of behaviour across gullies in both the process and synoptic studies.

It is instructive to compare the above values of post-torrent recharge with other estimates from similar environments. Fannin and Rollerson (1993) estimated average gully debris yields by dividing the total volume of recent debris flows by the length of scoured channel, obtaining a mean value of 6.6 m³/m. In our study, we have calculated 3.5 m³/m and 5.9 m³/m, respectively, for the C1 and C6 debris flows of November 1990 in Coquitlam basin. These values are, of course, significantly higher than our short-term recharge rate of 0.08 m³/m computed from the synoptic study, since much of the surcharge load of LWD and sediment derived from logging had already been scoured from the clearcut sample of gullies by recent debris flows. When our short-term recharge rate of 0.08 m³/m is extrapolated, the Fannin-Rollerson yield represents about 80 years of recharge, and the Coquitlam about 40–70 years of recharge. Since debris flows may be more frequent than this in many gullies, it is likely that the surcharge load of LWD from logging operations accounts for the high debris yields obtained from the debris flow volume calculations. Estimates of LWD surcharge from logging operations range from 0.4 m³/m by Froelich (1973) to as much as 1.2 m³/m by Millard (1993) in non-torrented slash-full gullies in Coquitlam basin. Many slash-full gullies probably have LWD loads even higher than this. Thus, logging

operations apparently increase debris flow magnitude by 6–18% if slash is left in gullies, and probably by as much as 30% if the sediment surcharge load is included. The volume of woody debris in a gully is therefore as much an issue as the volume of sediment stored within the woody debris, and in many cases is volumetrically greater.

Implications for Clearing Woody Debris from Gullies It is well known that logging results in a significant increase in the volume of woody debris in a channel, and that over time sediment is trapped by this debris. The sediment outputs in Figures 10–12 suggest that removal of LWD from slash-clear gullies causes an increase in the level of chronic fluvial sediment output compared with that in logged gullies which retain their logging debris. This is attributed both to channel disturbance during gully cleaning, and to removal of LWD which provides sediment storage sites. In the event of future debris flows, slash-clear gullies should produce lesser-magnitude events, since higher chronic outputs of sediment imply lesser volumes of long-term sediment storage. Woody debris is therefore a critical factor in gully behaviour, but affects fluvial and debris flow processes differently. Water transport of woody debris depends on sufficient discharge to float and move the debris. Generally, the larger the channel, the larger the size of woody debris moved. Water-transported debris tends to develop a clumped distribution along the length of the channel, frequently resulting in small wedges of debris and sediment and the development of a stepped channel profile. In severe cases, the channel is filled with debris and sediment, and erosion of the banks or sidewalls may result.

Of greater consequence is the occurrence of a debris flow, since the entire debris fill in the gully is usually scoured away and the surcharge loads of woody debris and sediment augment debris flow magnitudes. The decision concerning removal of woody debris from logged gullies therefore requires an assessment of the probability of debris flow occurrence. This is one of the main functions of the Gully Assessment Procedures within the Forest Practices Code. As detailed in those guidelines, several factors must be considered, including the steepness and drainage area of a gully channel, the

steepness and surface area of the sidewalls and headwall, the thickness of colluvium on sidewalls, the degree to which sidewalls were disturbed during harvest and the sensitivity of main-stem channels downstream of the gully. A major consideration is cost, since cleaning debris from gullies is expensive and can only be considered where the benefits justify the expenditure. Worker safety is also an important issue. If the likelihood of a debris flow is high, then woody debris should be cleaned. In some cases, cleaning debris from gullies may not be financially feasible and may preclude logging of a gully or require modified logging methods.

As noted in this study, removal of woody debris also has physical consequences. Gully channels cleared of debris in this study responded by eroding their channel beds, and it is unlikely that this erosion would have occurred had woody debris remained in the channel. Thus, an increase in fine sediment output is to be expected when LWD is removed. Provided that the long-term, chronic output of fine sediment is not deleterious to the receiving channel, there may be a land-management advantage to clearing logging debris from gullies if the objective is to reduce the magnitude of future debris flows. Conversely, if a gully is cleaned to minimize debris flow volume and a debris flow does not occur, an environmental cost is incurred from chronic sediment output from the gully, in addition to the financial costs incurred.

Recommendations for Clearing Woody Debris The following recommendations are provided as guidelines for cleaning woody debris. Although the results presented earlier in this study apply to some of the recommended treatments, it is important to emphasize that there are as yet no data available to quantify the effects of many of these recommendations on sediment storage and delivery in gullies. In any event, each gully would need to be assessed for the likelihood of debris flow occurrence, as well as for channel capability to transport woody debris and sediment by fluvial action. If woody debris is left in a gully after harvest, it is likely to become incorporated into the channel structure over time. Prescriptions for woody debris cleaning should therefore reflect the current condition of both the woody debris as well as the channel, as outlined below.

Recently Logged Gullies (Less than 1 Year After Harvest) with Moderate to High Water Flows and a Low Probability of Debris Flows The objectives in this case are to prevent excess transport of woody debris downstream, or to prevent woody debris from diverting flows towards erodible channel banks and sidewalls. Two cases should be considered:

- ***Woody Debris that may be Moved by Water Flows***
This situation requires that small woody debris be removed first and large debris left behind. The greater the water discharge of the gully, the larger the maximum size of woody debris to be removed. At present, there are few quantitative guidelines for woody debris flotation and transport in gullies.
- ***Large Woody Debris Directing Water Flow Towards Erodible Banks or Sidewalls*** If large woody debris remaining in the channel will block the channel and cause bank or sidewall erosion, then some of the large debris should be removed as well. Occasional large pieces of debris should be left in the channel, particularly if removal of the debris would significantly disturb the channel, or would disturb natural woody debris present prior to harvest.

Recently Logged Gullies with High Debris Flow Potential and Low to Moderate Water Transport Potential The objective in this case is to minimize the additional volume of debris and sediment which could be incorporated into a post-harvest debris flow. Since there is not sufficient water power to move most of the debris, much will stay in place until a debris flow occurs. Channels with high debris flow potential and more than 2 m³ of woody debris per metre of channel length should be cleaned to remove most of the woody debris. The 2 m³/m guideline is derived from the study by Fannin and Rollerson (1993). Small gullies that likely have low water flows typically generate 1–5 m³ of sediment and debris per metre length of channel in a debris flow. Channels with greater than 2 m³ of logging debris will yield an approximate doubling of debris flow volume per metre of channel length in the logged area should the gully fail. However, since the logged, low-flow portion of the gully generates only a fraction of the volume in a debris flow, the increase in the final volume of the debris flow is likely to be less than double.

Recently Logged Gullies with Moderate to High Water Transport Potential and Moderate to High Debris Flow Potential For gullies having significant water transport and debris flow potential, woody debris should be managed to consider both hazards. Small woody debris should be removed. The total volume of woody debris should be assessed and, if greater than 2 m³/m, then the total volume should be reduced to minimize debris flow volume.

Recently Logged, Steep Channels with High Water Transport Potential Casual observation of some gullies shows that woody debris loads may occasionally be mobilized causing debris jams or, in the event of flotation of large volumes of LWD, perhaps even debris flows. Debris flows mobilized in this manner are known to have occurred in upper Gordon River basin, southwestern Vancouver Island. To minimize this type of activity, removal of all logging-related woody debris (except for the occasional very large piece) should be considered in gullies with the following characteristics:

- steep channels, typically greater than 60% grade with sufficient water discharge to mobilize large amounts of woody debris by flotation; these are likely to be channels wider than 5 m, with peak flows deeper than 0.5 m; and
- channels developed in bedrock or hard glacial till, where woody debris has little chance of being buttressed against flotation by channel deposits.

Gullies Logged more than 5 Years Ago with Moderate to High Water Transport Potential Gullies that have not already produced a debris flow within several years of harvest are likely to have incorporated some of the woody debris into the channel deposits by partial burial, and some smaller woody debris will have been transported farther down the gully or into lower gradient streams. The objective here should be to minimize storage of sediment and woody debris in the gully reach, since this could lead to channel widening and increased erosion of sidewalls. The efficacy of LWD cleaning in this situation decreases as elapsed time since harvest increases, because ever-increasing proportion of the woody debris becomes buried by sediment and incorporated into the channel structure. All loose, transportable woody debris should be removed, but buried or partly buried material should be left undisturbed unless the

part of a log still exposed can be cut and removed. If erosion of gully sidewalls is occurring, consideration should be given to removing woody debris that is directing water flows against the sidewalls, or to placing woody debris in a way that protects the sidewalls.

Gullies Logged more than 5 Years Ago with High to Moderate Debris Flow Potential, but Low Water Transport Potential Woody debris in these types of gullies tends to remain in place over time, unless a debris flow occurs. There is no significant hazard of the woody debris initiating a debris flow or causing erosion. The objective in these gullies is to avoid a significant increase in the total volume of a debris flow should one occur. Estimates of the amount of stored woody debris should be made along the entire logged gully reaches, and compared to the total volume of material likely to be generated from source area to deposition zone (consult Fannin and Rollerson 1993). If the total volume of a debris flow would increase by more than 50%, then the woody debris should be cleaned. If the gully was logged more than 10 years ago, the volume increase should be greater than 100% to warrant cleaning. It is important to consider how much damage to sidewalls and vegetation will occur before deciding to clean.

Debris Jams in Gullies Log jams may result from either debris flows coming to rest or from water transport of woody debris. Jams may be breached in three main ways. First, the LWD of the jam itself may fail and develop into a debris flow as the impounded saturated sediment is released. In general, jams tend to occur in areas of net deposition, so, because of inadequate channel slope, such catastrophic failure is not likely to occur. A second, more likely failure mechanism involves a debris flow from higher up the gully system, which breaches the jam and incorporates the stored material into the flow. The first post-logging debris flow is generally the largest and is also likely to travel the farthest. Consequently, if a debris jam forms in the lower part of the gully channel as a result of from the first post-logging event, subsequent smaller events are less likely to re-mobilize the jam. Water flows may erode part or all of the jam in a short time, or over a number of flood events. If the jam is very recent, the probability of subsequent jam failure or release is greater than if the jam has survived a

number of high flows. This is particularly true of jams that are wedged into erosion-resistant locations, such as bedrock sidewalls, or jams that incorporate pieces of woody debris several metres in length. These are unlikely to fail or erode until the wood in the jam becomes rotten. Even in such cases, breakdown of the jam and gradual release of stored sediment is likely to occur over a period of many years.

Debris Jams Subject to Moderate to High Water Flows Jams should have all wood not buried in sediment removed, so the sediment wedge behind the jam does not increase in volume over time. If a jam is located adjacent to erodible sidewalls, part of the middle of the jam should be notched, to maintain water flows down the middle of the gully. This will alleviate erosion of the sidewalls.

Debris Jams in Gullies with High Debris Flow Potential If a jam is structurally weak (i.e., not wedged against bedrock or composed of small debris pieces), sits high in the gully system where channel gradients are close to 50%, and has a high potential for future debris flows, the jam should be removed if practicable so that catastrophic breaching is avoided.

Conclusions

Despite the acknowledged importance of woody debris in the sediment dynamics of gullies, there are very few quantitative data documenting the real-time interactions between sediment and coarse woody debris in gullies. The study results reported here provide data on the effects of woody debris in both logged and unlogged channels, including observations on the effects of woody debris removal following timber harvest. A three-year monitoring of gullies in the Queen Charlotte Islands and the southern Coast Mountains reveals similar rank-orderings of gully types with regard to sediment output when results are normalized by gully size. Logged tormented gullies show the highest outputs in the Queen Charlotte gullies, followed in rank order by logged slash-clear gullies and unlogged old-growth gullies. In Coquitlam basin, slash-clear gullies have the highest rank. In both study areas, logged slash-full gullies registered the lowest sediment outputs over the three-year study period.

A longer-term synoptic study of sediment recharge rates over periods of decades in torrented gullies produced normalized rates of the same order of magnitude as those noted in the three-year process study. In both the process and synoptic studies, variations in sediment output and storage rate are explained by the variable trap-efficiency of logging debris for sediment moving down gully channels in the various types of gullies. This is high in the case of logged slash-full gullies, very low in recently torrented or slash-cleared gullies, and moderate in most unlogged gullies.

The recommendations presented here for post-harvest removal of woody debris from logged gullies emphasize the importance of local assessments of debris flow and water transport hazards, in addition to the time elapsed since logging and the sensitivity of downstream areas to debris loadings. Although some of the treatments recommended stem directly from the results presented in this study, many have yet to be corroborated by measurements of sediment movement in gullies. An important objective for future work is to fill these gaps in knowledge to allow more precise evaluations of the benefits and costs of woody debris removal.

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Stream Channel Morphology and Recovery Processes

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Coastal Fish/Forestry Interaction Programs

There is a direct 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 young (Toews and Brownlee 1981). Salmonids spawn in riffles composed of clean, stable gravels with well-oxygenated streamflows. Certain species also require stable pools to rear in for periods of time ranging from months to years (young fish use pools to hide from predators, to feed in, and to grow in before migrating to the sea). Adult fish require an unobstructed migration path between the ocean and the stream spawning grounds. Similarly, young salmonids (fry and juveniles) require access along the stream channel and into tributaries and side channels.

A central goal of forest and watershed management in British Columbia has been to minimize changes in sediment and debris production and its delivery to streams, to avoid changes to runoff patterns, and to eliminate direct disturbance of channel banks and beds. To accomplish this, harvesting plans are now 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 (B.C. Ministry of Forests, Forest Practices Code [draft] 1994). Past practices, however, were not as carefully applied and serious environmental impacts on stream channels and aquatic ecosystems have been widespread (Tripp 1994).

Most previous studies of the response and recovery of small streams to past forest management have concentrated on identifying specific channel impacts and their logging-related cause, and have generally speculated on the temporal duration of the impact.

Studies throughout the Pacific Northwest show that in most cases the channel bed aggrades, bank stability is reduced as the channel widens, and pools are infilled by sediment inputs from landslides (Sullivan et al. 1987). The time required for the channel to recover to pre-disturbance conditions varies from 5 to over 60 years. The recovery time depends upon input sediment characteristics (location along the stream system, amount, and particle size distribution) and the form and structure of the riparian area.

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 individual LWD *pieces* on channel morphology has been investigated for more than two decades (cf. Thomson 1991). An integral component of stream ecology (Hartman and Scrivener 1990), LWD influences both physical and biological characteristics of stream channels with bankfull widths less than or equal to the length of in-stream LWD. In comparison, relatively little research has been undertaken on the importance of LWD *accumulations* (log jams) on channel morphology.

In this paper we review research conducted in small coastal streams on the Queen Charlotte Islands and Vancouver Island. Research on the Queen Charlotte Islands was designed specifically to identify and describe the long-term response of stream channels to increased sediment and debris loadings resulting from both natural processes and forest management practices. The focus of this research is on log-jam characteristics (e.g., origin, function, and longevity) because jams are the major factor controlling the long-term evolution of channel morphology and fish habitats. The streams have a range of natural disturbance histories, with hillslope failure events documented back to the 1820s and impacts from logging that began 40 years ago.

Research undertaken by the Carnation Creek Fish/Forestry Interactions Program was established to document annual changes in a series of study areas all located within a single watershed. The physical setting of Carnation Creek on Vancouver Island is similar to that of watersheds investigated on the Queen Charlotte Islands (Church, this volume) and enable much finer temporal resolution of channel changes than does the research on the Queen Charlotte Islands. The results from Carnation Creek are used to illustrate a detailed, annual sequence of channel changes that support the longer-term (decades-long) results from the Queen Charlotte Islands.

Environmental Setting

The Queen Charlotte Islands are located approximately 80 km west of Prince Rupert in north coastal British Columbia (Fig. 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 and Thomson 1978) and several soil types that are prone to mass movement (Wilford and Schwab 1982). The



FIGURE 1 Location map showing the Queen Charlotte Islands and Carnation Creek Fish/Forestry Interaction Program sites. Channel research on the Queen Charlotte Islands reviewed in this paper is indicated by location and by authors.

incidence of slope failure is also high because the islands have a predominantly wet climate and they experience frequent seismic activity. The average annual precipitation exceeds 3600 mm along the west coast, but Williams (1968) estimates this may reach 7000 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, this volume). All of the study watersheds are in the Coastal Western Hemlock (CWH) biogeoclimatic zone.

Carnation Creek (Fig. 1) drains into Barkley Sound on the west side of Vancouver Island. A complete description of the Carnation Creek study is included in Hartman and Scrivener (1990). The Carnation Creek watershed is also in the CWH biogeoclimatic zone, and is approximately 11 km² in drainage basin area with no lakes in the watershed. The local climate is per-humid and 95% of the annual precipitation falls as rain. Monthly streamflows are highly variable, ranging from 0.025 m³s⁻¹ in summer to 33 m³s⁻¹ during winter freshet. Peak flows up to 64 m³s⁻¹ have been measured. The basin is characterized by irregular topography, with a wide valley flat downstream, confined channels in the mid-valley, and steep valley walls with bluffs and rock outcrops in headwater areas. The bedrock is primarily volcanic with thin, coarse-textured soils that are well drained in most non-alluvial locations. Landslides are prevalent in the headwater and canyon areas.

This paper reviews the results of research completed on stream channels both in the Queen Charlotte Islands and Carnation Creek. The channels range in gradient from 0.003 to 0.08 and in width from 5 to 45 m. The drainage basin areas range from 1 to 68 km². Channel morphologies are typified by a riffle-pool sequence, although cascade-pool and step-pool channels are identified in the steeper reaches. Channel beds are composed of gravels and cobbles, and LWD is abundant with volumes as high as 0.24 m³/m² in selected reaches.

The Morphology of Forested and Logged Stream Channels

Recent concerns regarding changes in channel morphology on the Queen Charlotte Islands began in 1978 after a series of intense storms caused

extensive landslide events on logged and forested hillslopes (details of these landslide events are given by Schwab, 1983). In response to these concerns, Hogan (1986) provides one of the first detailed descriptions of channel morphology in forested and logged watersheds on the Queen Charlotte Islands as part of the Fish/Forestry Interaction Program. The morphological characteristics of Government Creek (Fig. 2) are typical of many stream channels flowing through old-growth forest in the CWH biogeoclimatic zone. The channel is diverse, with complex longitudinal and planimetric forms. The longitudinal profile has distinct, well-defined pools and riffles (pools—primarily lateral scour pools—account for almost 65% of the overall channel area). The width of the channel is variable, alternating between narrow sections with stable banks and wide sections where the channel becomes locally unstable. The channel banks are commonly undercut while channel bars consist of cobble, gravel, and sand-textured sediment.

By comparison, the morphological characteristics of Mosquito Creek (Fig. 3) are relatively simple, with minimal variability in longitudinal, planimetric and sedimentologic characteristics. The channel is in a logged CWH watershed (57% logged during the 1960s by high-lead methods without leave strips) and is similar in most morphometric attributes (e.g., drainage basin area and shape, drainage density, average channel and hillslope gradient, and geology) to the Government Creek watershed. The longitudinal profile shows long pools with relatively uniform depths. Although riffles and glides are more prevalent in the logged stream (45% riffle and glide in Mosquito Creek compared to 35% Government Creek), the shape of each morphological feature differs from those in the forested stream. For example, both pools and riffles in Mosquito Creek are relatively long, narrow and shallow. Channel width is not only wider than expected for the drainage size and hydrological nature, it is consistently

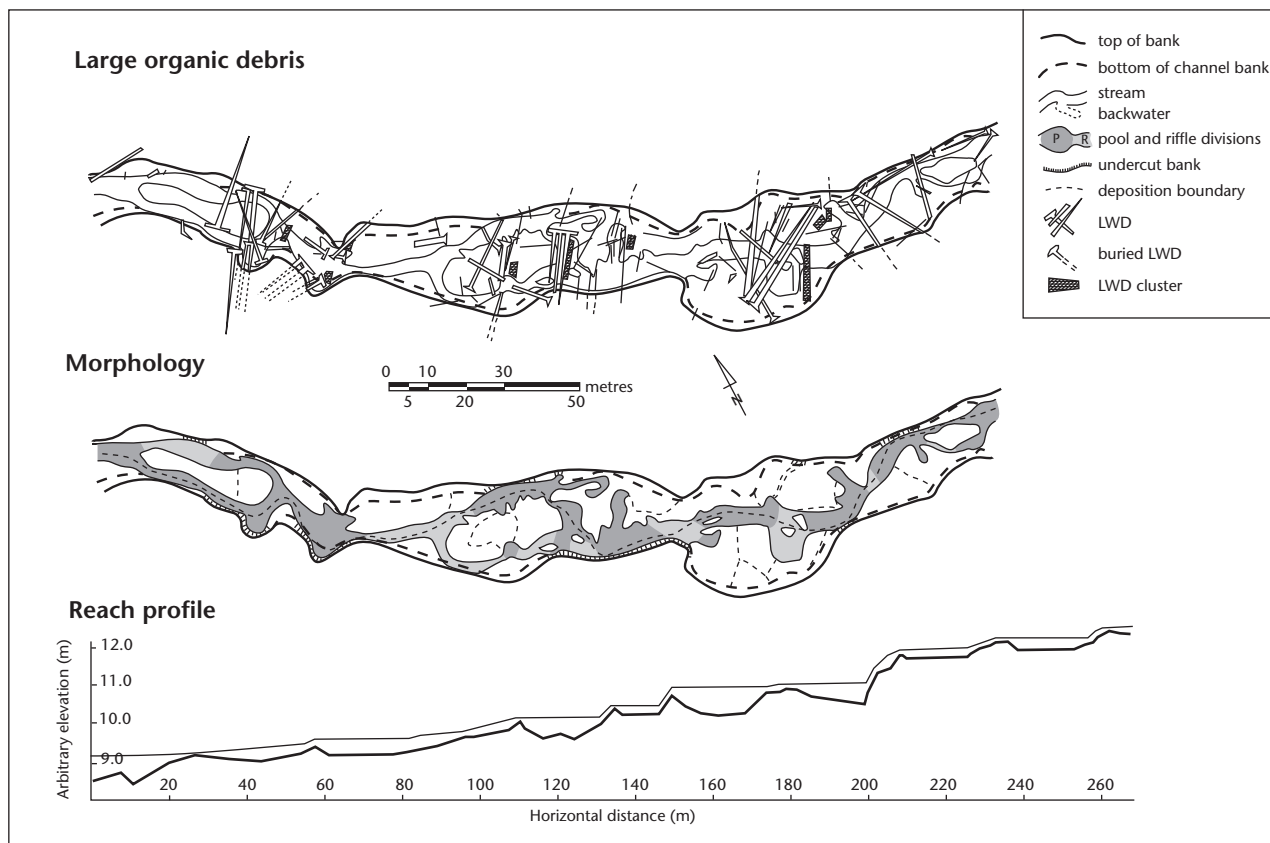


FIGURE 2 Large woody debris, morphology and longitudinal profile of an old growth watershed stream (Government Creek reach B, after Hogan 1986).

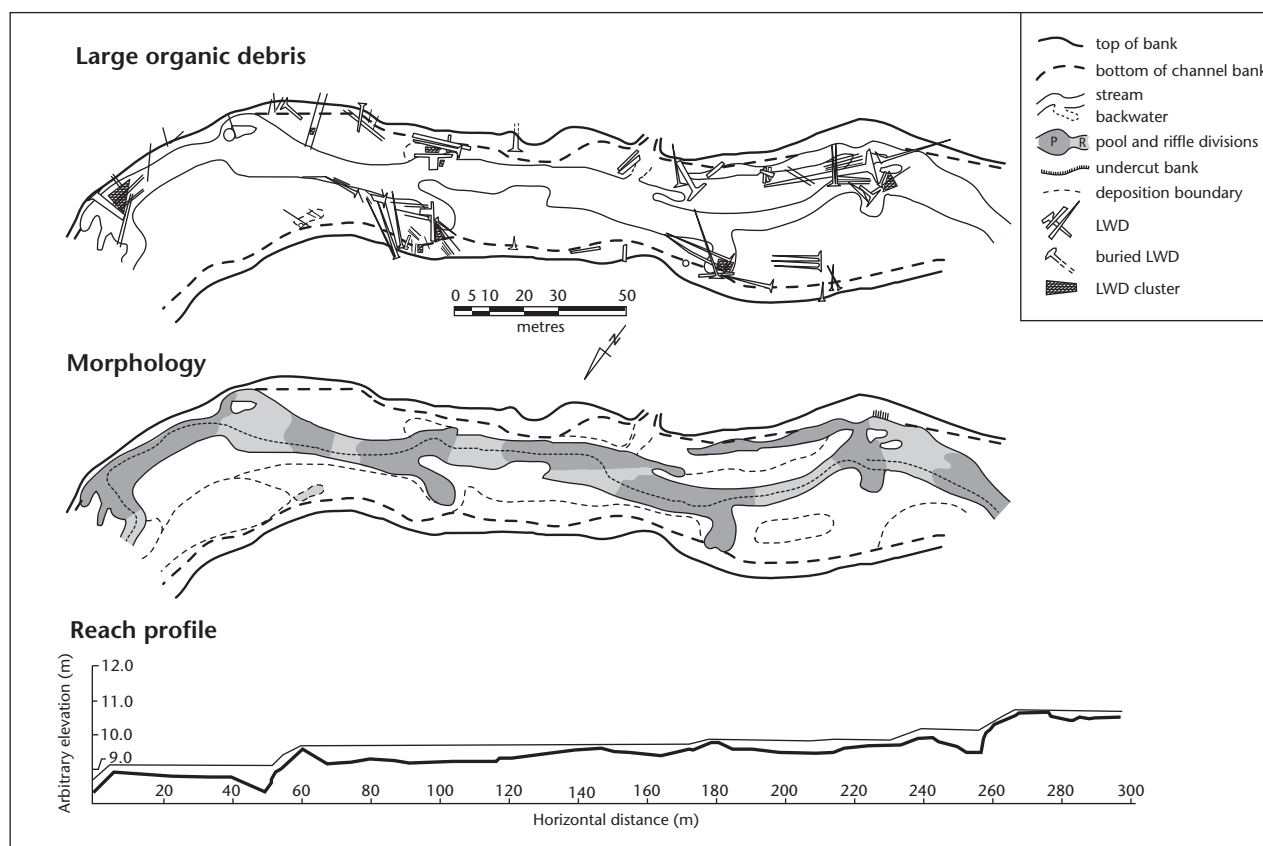


FIGURE 3 Large woody debris, morphology and longitudinal profile of a logged watershed stream (Mosquito Creek Main, after Hogan 1986).

wide with minimal variability. Channel banks are rarely undercut and most channel bars consist of uniformly textured gravels.

The underlying difference between the morphologies of Government and Mosquito creeks is explained by the LWD characteristics associated with each channel (Hogan 1986, 1987). The most important difference appears to be a shift in LWD orientation; there is significantly more LWD oriented parallel to the channel banks in Mosquito Creek compared to the predominantly diagonal arrangement in Government Creek. A similar pattern of LWD orientation was found between logged and forested channels in South Bay Dump Creek and in two other reaches of Government and Mosquito creeks. The shift in orientation reduces the interaction among LWD, stream flow and sediment transport, so that the same amount of debris has less influence on scouring and trapping of sediment in the logged stream. Although there is almost twice as much sediment stored along the logged channel bed

in Mosquito Creek compared to Government Creek, this material is located in fewer than one-quarter as many storage sites (Figs. 2 and 3).

In addition to changes in orientation, the total volume of LWD is reduced in logged channels, as is the size distribution of individual LWD pieces (Hogan 1986, 1987). In Government Creek (Fig. 2), LWD is prevalent and frequently spans the channel from bank to bank. Most of the LWD has root wads attached to the log trunk that acts as an anchor during high flows. In Mosquito Creek (Fig. 3), on the other hand, relatively small pieces of LWD float downstream and have accumulated in debris jams. As a consequence, the influence of individual LWD pieces on channel morphology between log jams is reduced while the size of individual log jams is increased following logging.

The importance of LWD pieces on channel morphology was established in the early years of the Fish/Forestry Interaction Program on the Queen Charlotte Islands. However, the functional role of

LWD jams has not been considered systematically. The remainder of this paper deals with LWD jams, including their formation, function, and longevity.

The Formation and Influence of Log Jams

Log jams form in coastal streams by several mechanisms. The most important factors are related to watershed attributes, particularly the linkage between hillslopes and stream channels. Church (1983) stratifies stream reaches on the Queen Charlotte Islands according to the relative coupling among the hillslope, valley flat, and stream channel. Coupled reaches occur when coarse sediment (>2 mm) and LWD, mobilized on the hillslope by mass wasting, directly enters the stream channel. Decoupled reaches occur when the coarse sediment and LWD are intercepted by the valley flat and do not directly enter the stream channel.

Channelized debris flows (or *torrents*) introduce large amounts of sediment and debris to the channel (Fig. 4). In coupled reaches, log jams form initially at the terminus of debris flows that enter the channel (Hogan and Bird, in prep.). Subsequent flows can reorganize this LWD and influence jam development in downstream reaches. In coupled

reaches, much of the volume of LWD in a jam is derived from upslope and upstream; relatively minor amounts are derived from the proximal riparian area. In decoupled reaches, log jams originate from floated debris that becomes anchored at some point along the channel. Approximately equal amounts of LWD in a jam are derived from upstream and the proximal riparian area. Riparian vegetation is introduced into the channel as a result of bank erosion initiated by the formation of the jam. Once the jam forms, it has a tendency to grow by the addition of wood from overbank areas.

The development of an individual log jam and the short-term channel adjustments following debris flows were documented through annual surveys of Carnation Creek. A sequence of channel maps (Fig. 5) shows the same study area over a time period of 1.5 decades (note that the survey lines are in the same spot in each map and can be used as comparison references). In the early years (1972–1979), the channel was relatively narrow, with stable banks and a series of pools and riffles. The jam, clearly evident in 1982, began to form in 1979 as a result of the interlocking of two large logs and several small pieces of wood. The jam was enlarged substantially in 1984 as a result of a series of large



4a.



4b.

FIGURE 4 Examples of landslides and debris delivery to stream channels. a) Photograph of an old, revegetated landslide track on the Queen Charlotte Islands. b) Photograph of sediment and debris delivered directly into the stream (coupled hillslope and stream). LWD jam formed at the terminus of the debris flow.

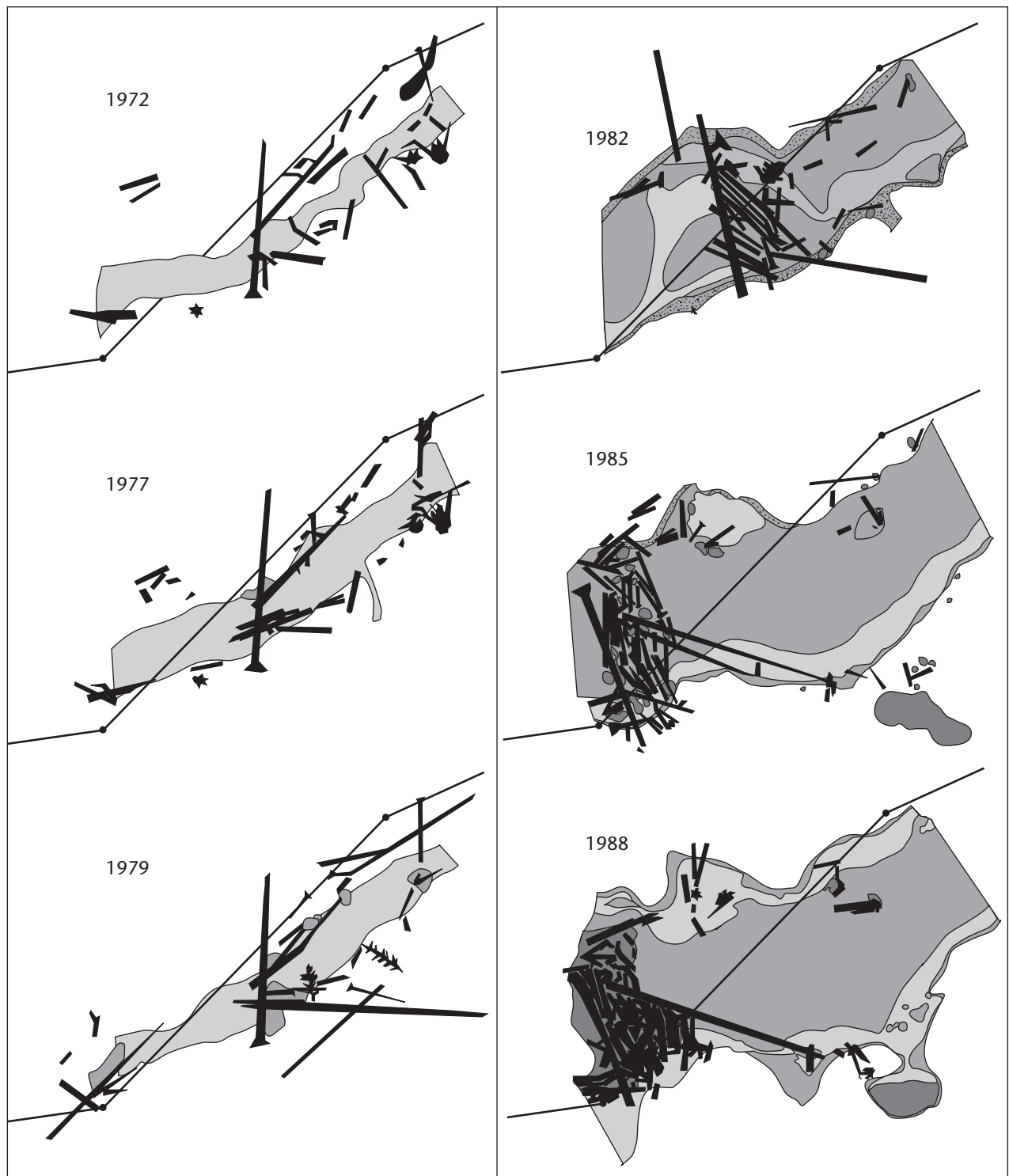


FIGURE 5 Example of log-jam formation in Carnation Creek (for a photograph, see Figure 10a).

storms, and in particular an unusually large flood in January 1984. The channel width upstream of the fully developed jam increased dramatically (Figs. 5 and 6) and there was over 2 m of net aggradation (Fig. 7). As the jam grew in size and influence on the

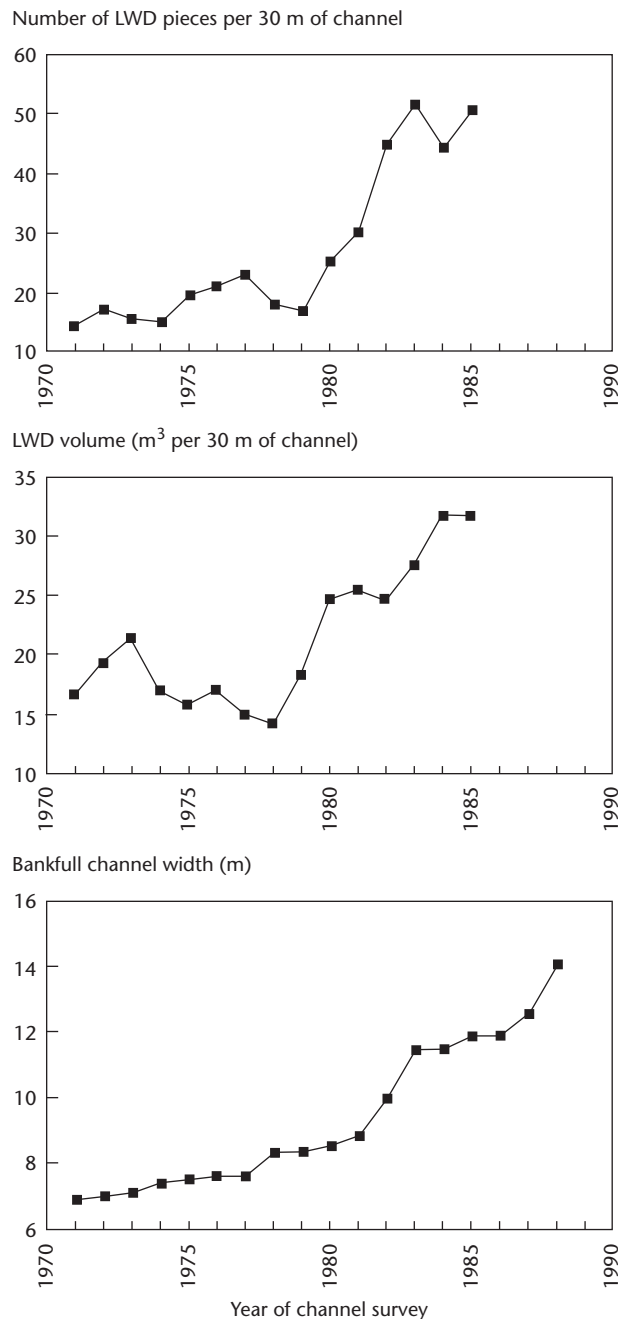


FIGURE 6 Change in the number of LWD pieces, LWD volume, and channel width in Carnation Creek with the development of a new log jam.

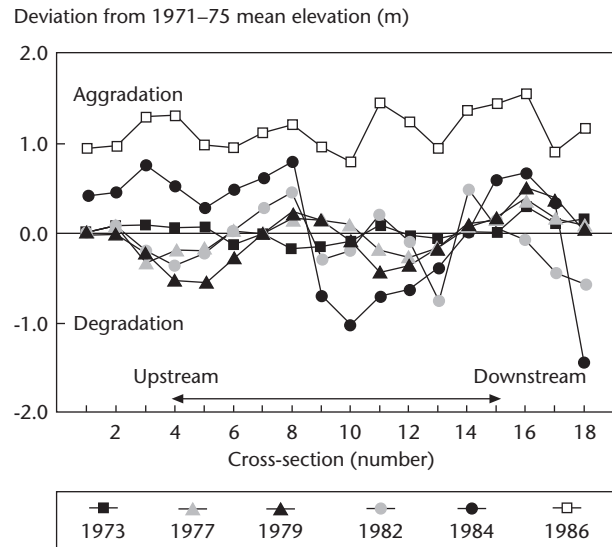


FIGURE 7 Change in the net aggradation and degradation in Carnation Creek with the development of a new log jam.

channel, it began to move downstream (from the centre of the 1982 map to the far left-hand side of the 1985 map, Fig. 5) as LWD in the jam was reorganized by subsequent high flows. All previously existing pools, riffles, and bars were completely destroyed as the jam developed and migrated downstream.

Log jams are an important influence on the longitudinal profile of small coastal streams. A longitudinal profile of Riley Creek surveyed by Hogan (1989) shows extensive aggradation upstream of several log jams (Fig. 8a). Individual log jams, or a series of closely spaced log jams, impede the downstream transport of sediment and form an extensive sediment wedge upstream of the jam(s) (Fig. 8b). Between log jams, the channel has a typical pool-riffle sequence (mean spacing distance of $4.3 W_b$), cobble-gravel textured bars, and individual LWD pieces. In relative terms, because log jams control sediment transport and create extensive upstream sedimentation and downstream degradation, they have the greatest influence on channel morphology. Individual LWD pieces, and especially log steps, are important to channel morphology and fish habitat features at a smaller scale (e.g., a distance of several bankfull widths), primarily between log jams.

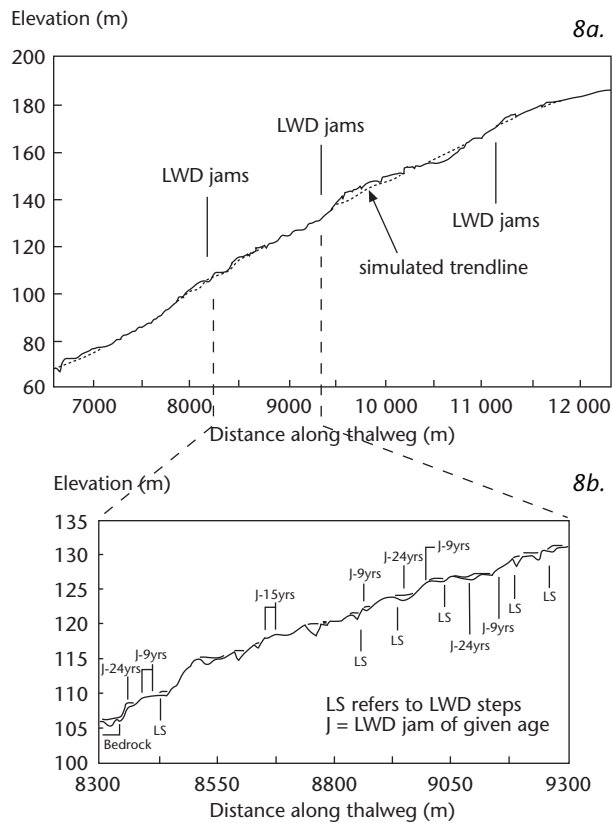


FIGURE 8 Longitudinal profile of Riley Creek (after Hogan 1989). a) Entire longitudinal survey (zones lying above the smooth line drawn through the data points—the smooth line is a second-order polynomial placed simply to make visual inspection easier). b) Detailed profile of selected section from A.

Hogan (1986) documents the morphology of a cobble-gravel bed channel in Hangover Creek, showing the two distinctly different sections upstream and downstream of a relatively old log jam (Fig. 9). The LWD located in the middle of the channel is of two ages and origins. That on top of the debris cluster is a result of recent blowdown (logs mapped as above the channel bed and with attached root wads located in the overbank zone). Because these logs are above the bed, they have had relatively little influence on bed and bank sediment scour or deposition. However, upon close inspection of Figure 9, one can identify an old log jam beneath the blowdown. Nurse trees growing on in-stream LWD have ages ranging from 32 to 45 years, indicating

that the jam has been in place for several decades; the stable vegetated and undercut banks and islands attest to these ages. Remnants of logs are also incorporated into the fluvial sediments making up the channel banks.

The morphology of Hangover Creek, as influenced by relatively old log jams (at least 45 years old), contrasts with that of Carnation Creek shortly after the formation of the log jam shown in Figure 5. The downstream zone in Hangover Creek, extending from 0 to 180 m in Figure 9, 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, and has multiple channels with mid-channel bars and vegetated islands. Pool and riffle shapes are very different in the upstream section compared to the downstream section, with increased lateral and vertical variability. The contrast in appearance between recent and old log jams (300+ years since jam formation) is shown in Figure 10.

Changes in channel morphology associated with LWD longevity in Riley Creek are shown in Figure 11 (Hogan 1989). Log jam locations and ages are shown in the longitudinal profiles to enable comparison of specific features associated with the various ages. In all cases there is substantial channel aggradation upstream of the recently formed, young log jams. For example, at the 3400 m distance (Fig. 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 (3350–3400 m). As log jams age, more sediment is excavated, the bed upstream of the jam downcuts, and eroded sediment is transferred downstream. For example, there is relatively little aggradation between 2800 and 3000 m and from 3150 to 3350 m, although there are two large older jams present in these zones.

The volume of LWD in a jam also decreases with time (Fig. 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 streambank (Fig. 11c). As described

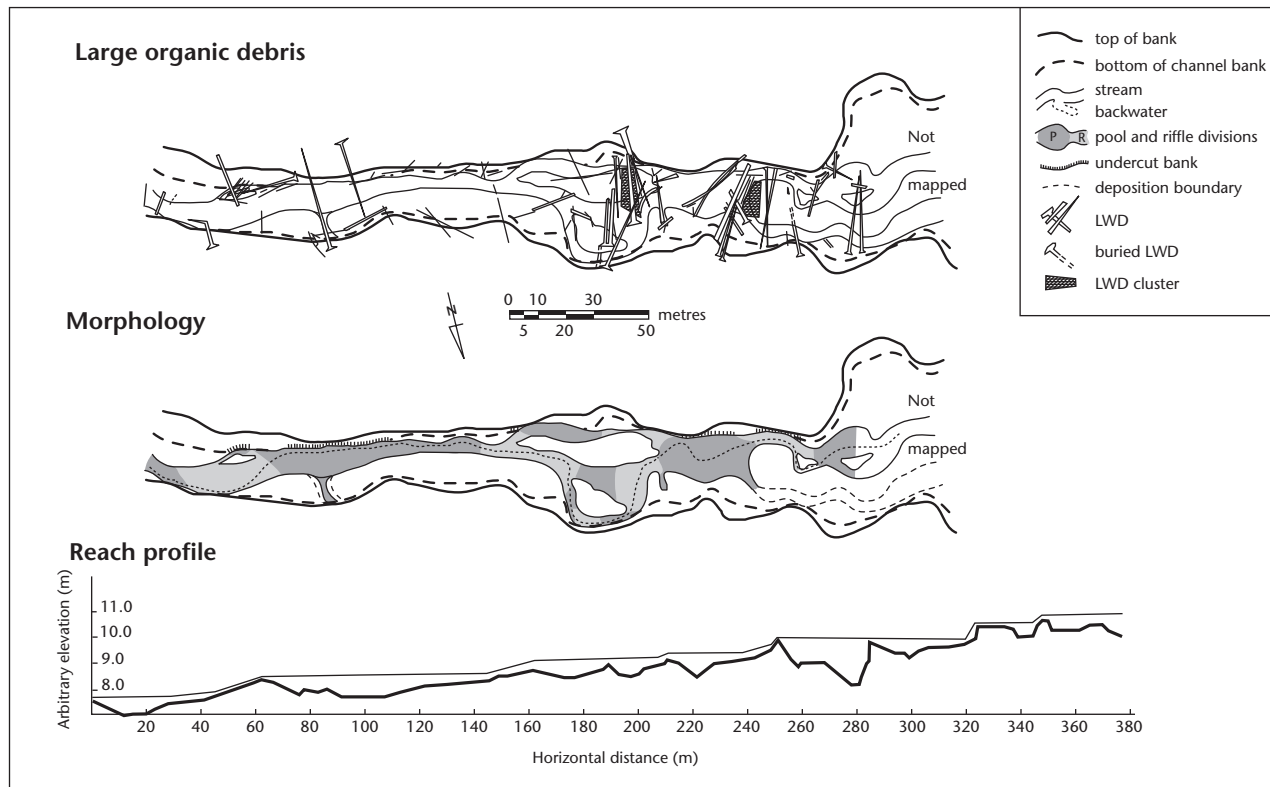


FIGURE 9 Large woody debris, morphology, and longitudinal profile of Hangover Creek (after Hogan 1986).

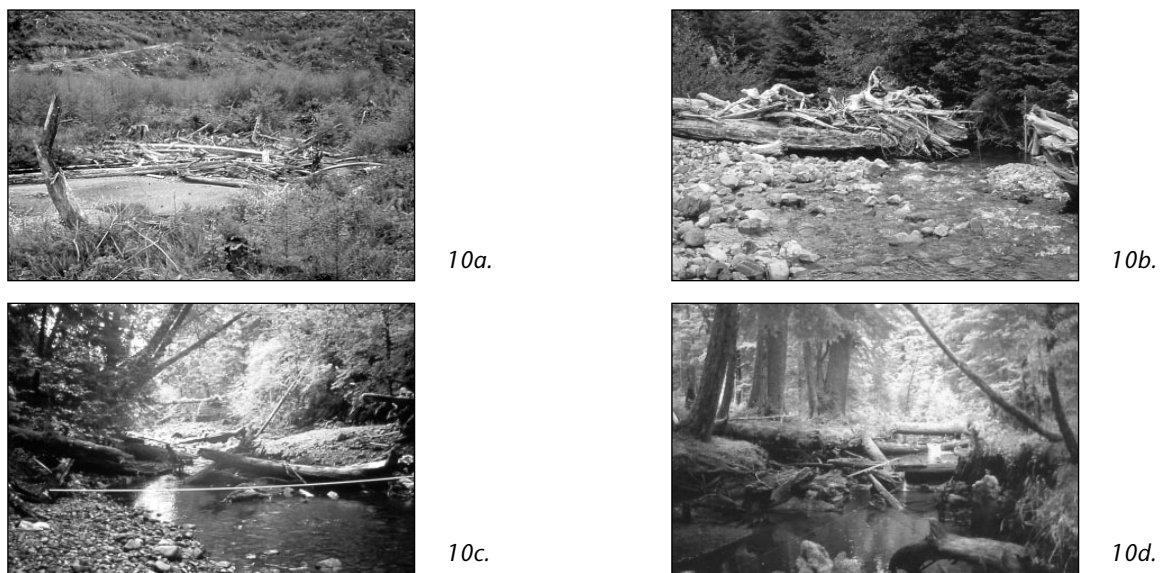


FIGURE 10 Log jams of different ages. a) Recently formed jam in Carnation Creek with extensive sediment wedge upstream of intact debris that effectively stops sediment transfer downstream. b) Moderately old jam (25 years since formation) showing evidence of downcutting of the sediment wedge as the jam deteriorates (no longer spans the channel). 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, undercut banks, stable bars, and back channels, etc.).

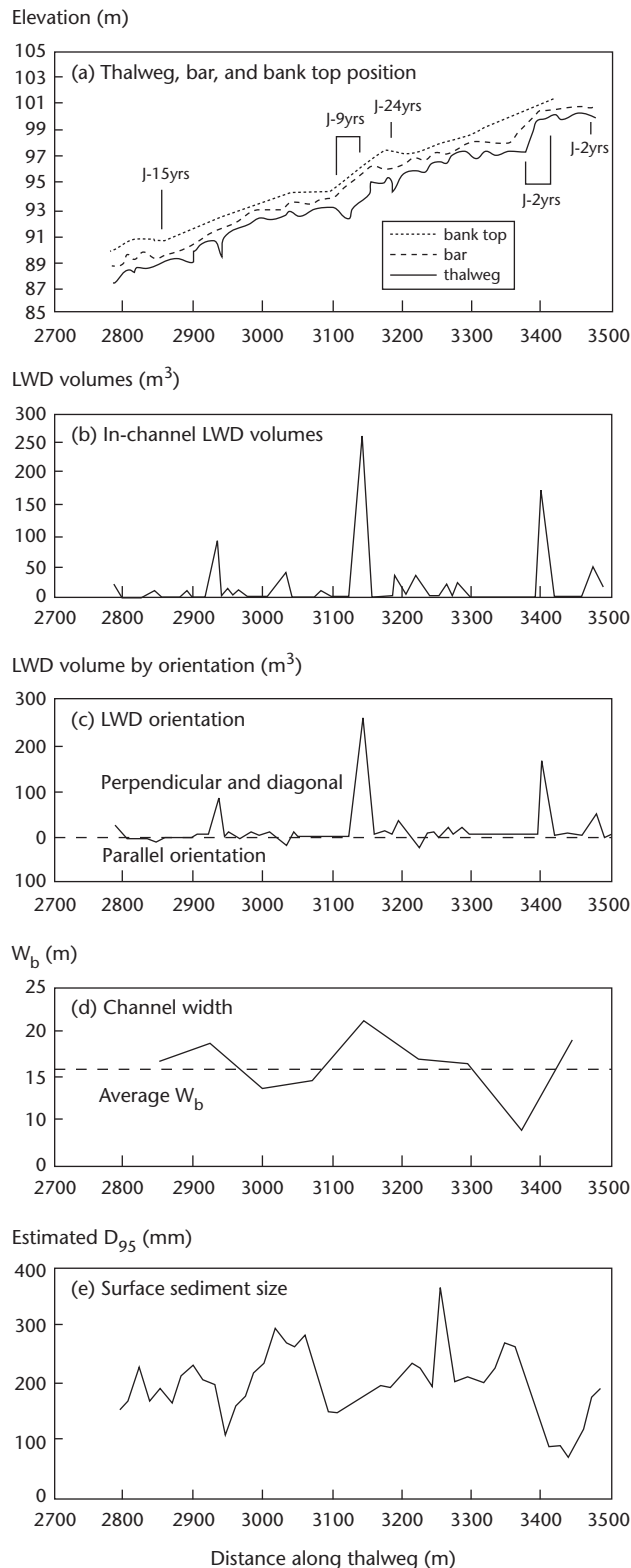


FIGURE 11 Channel changes associated with LWD jam longevity in Riley Creek (after Hogan 1989).

previously, this shift in orientation influences 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 the age of a log jam (Figs. 11d and e). In general, when the channel boundary is not confined by bedrock, there is an increase in channel width upstream of recently formed jams. As sediment transport is restricted by a jam, the channel aggrades and becomes wider and finer-textured. Downstream, the channel can become narrow and coarse-textured as the sediment supply is impeded. Rice (1990) characterizes the sediment upstream and downstream of log jams with a range of ages in Riley Creek (Fig. 12). Jam U (less than 5 years old) spans the entire channel and is highly impermeable to sediment. A sediment wedge, extending some 50 m, has been initiated upstream of the jam. In contrast, jam N (between 30 and 50 years old) spans three-quarters of the total bankfull width and is undercut by three separate channels. However, remnants of a sediment wedge are apparent upstream of jam N. Most of the stored sediment has been re-mobilized and transported downstream. These differences in permeability between relatively old and young log jams are reflected in the texture of the bed, as the contrast between fine-textured sediments upstream and coarse-textured sediments downstream decreases with time (Fig. 12).

To better understand the sediment transport regime associated with log jams, Rice (1990) placed tracer particles upstream and downstream of jam U and jam N (Fig. 13). A year after placement of particles upstream of the recently formed jam (jam U), all tracer particles recovered were found near their original position (≤ 1 bankfull widths) and buried by 2 and 60 cm of sand and gravel. In contrast, of those tracer stones recovered upstream of the relatively old jam (jam N), only two were found near their original position. The remainder were found as much as 7 bankfull widths downstream of the jam. Tracer particles placed downstream of both jams U and N moved as much as 6 and 4 bankfull widths downstream, respectively. However, a greater proportion of stones downstream of jam U remained in their original position. Downstream of jam N, the channel bed experienced deep scour (> 0.4 m) as tracer particles were transported downstream.

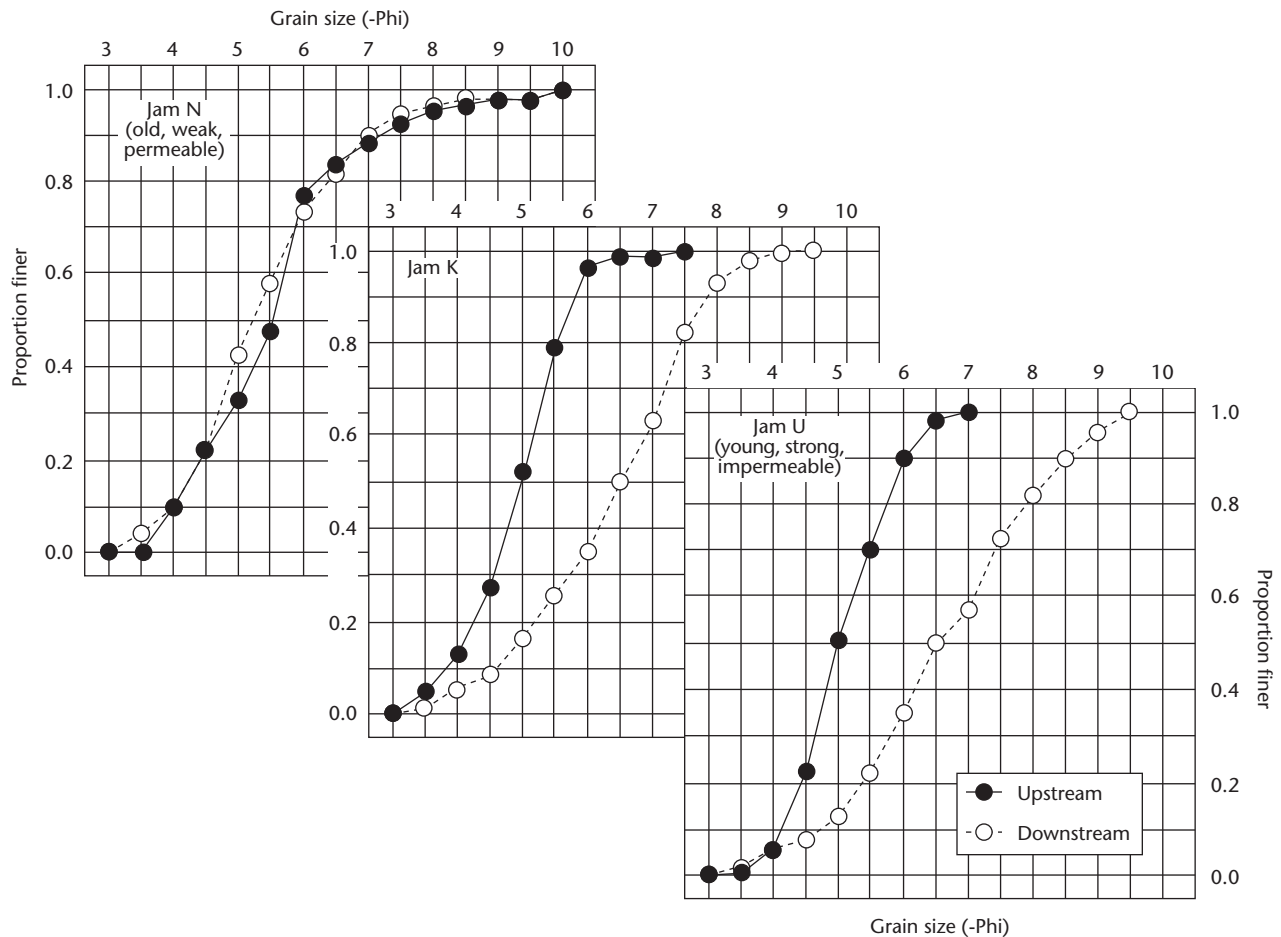


FIGURE 12 Surface grain-size distributions associated with log-jam age (after Rice 1990).

The longitudinal profiles, detailed mapping, sediment sampling, and tracer particle studies show a consistent pattern of channel adjustments to landslide events. Debris flows, often triggered by forest harvesting and related activities, can introduce sediment and debris into stream channels, a process that leads to the formation of log jams. Stream channels respond to log jams by widening and aggrading as a sediment wedge develops on the long profile. Through time, a log jam deteriorates and its influence on sediment transport is reduced. The temporal and spatial distribution of debris flows and the subsequent development of log jams together act as a primary control of channel morphology.

Forest Harvesting and the Formation of Log Jams

Forestry activities can influence the amount, timing and nature of sediment and water moving through a stream system. The impacts of forestry activities on channel morphology and fish habitat have been studied intensively over the last several decades (e.g., Salo and Cundy 1987; Hartman and Scrivener 1990). In general, logging and related activities have led to increased levels of sediment entering stream channels. Excess loads of coarse-textured materials tend to promote bed aggradation, in turn leading to expanded bars and riffles, infilled pools, and bank erosion. The gravel composition of riffles can

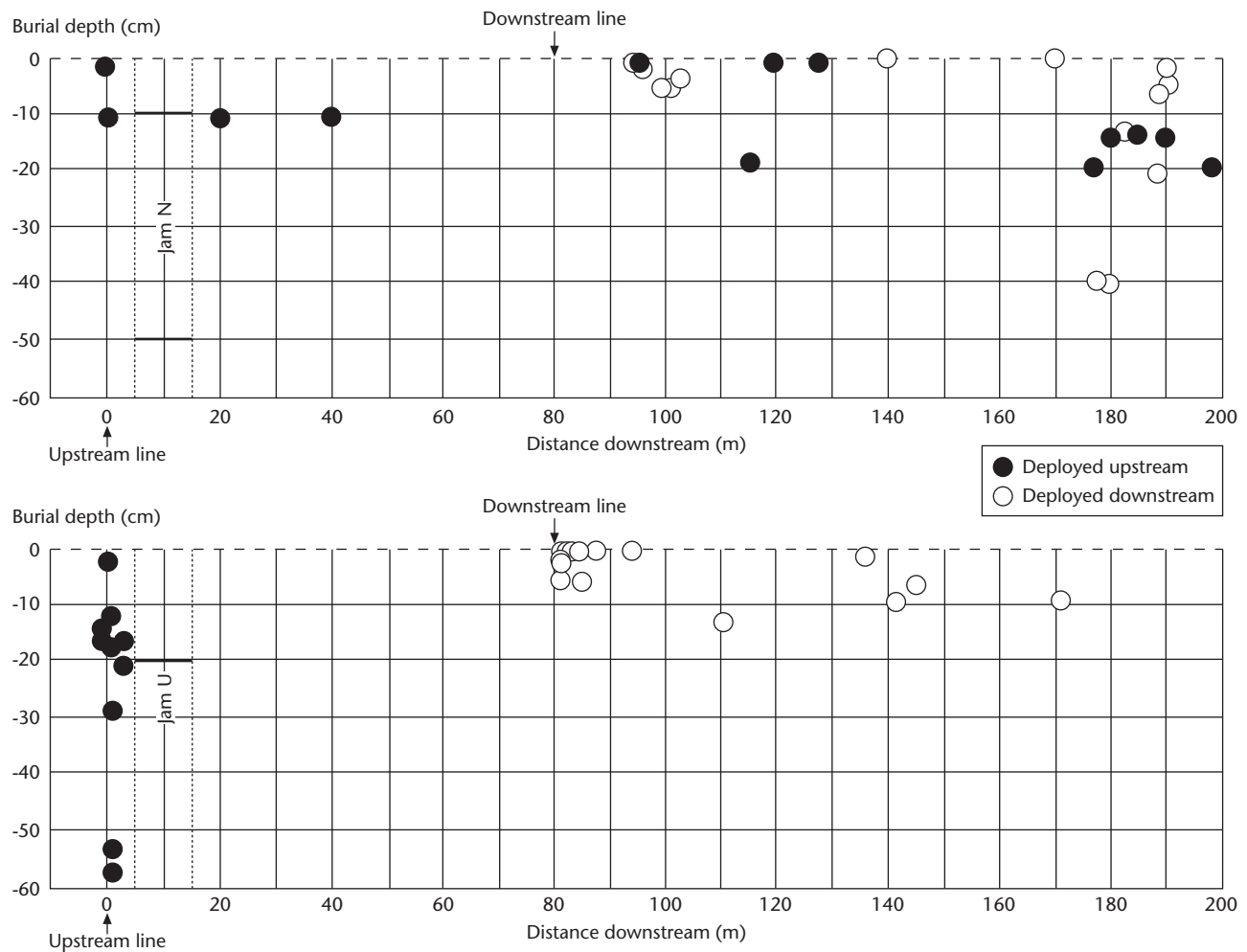


FIGURE 13 *Tracer stone displacement associated with log-jam age (after Rice 1990).*

become less suitable for egg incubation, as the proportion of fine sediment (<1 mm) increases. Egg-to-fry survival rates can also be reduced because the 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.

The Queen Charlotte Islands have vast tracts of valuable commercial timber that, for over half a century, has made logging an important economic resource. The CWH biogeoclimatic forests consist of western hemlock, Sitka spruce, amabilis fir, and western redcedar, each of which is harvested extensively. The inherent instability of the steep Queen Charlotte Islands hillslopes has been increased locally by logging (Schwab 1983; Rood 1984;

Gimbarzevsky 1986) and thus so, too, has the formation of log jams (Hogan et al., in prep.). Rood 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 that 43 times more sediment derived from hillslopes enters stream channels in logged areas than in forested areas.

Mass wasting events on the Queen Charlotte Islands occur episodically through time. There is ample evidence of historical landslides in the island landscape (Fig. 14). Gimbarzevsky (1986) inventoried almost 9000 landslides from a series of aerial photographs (the first set of which were available in 1939) on the Queen Charlotte Islands. Schwab (this

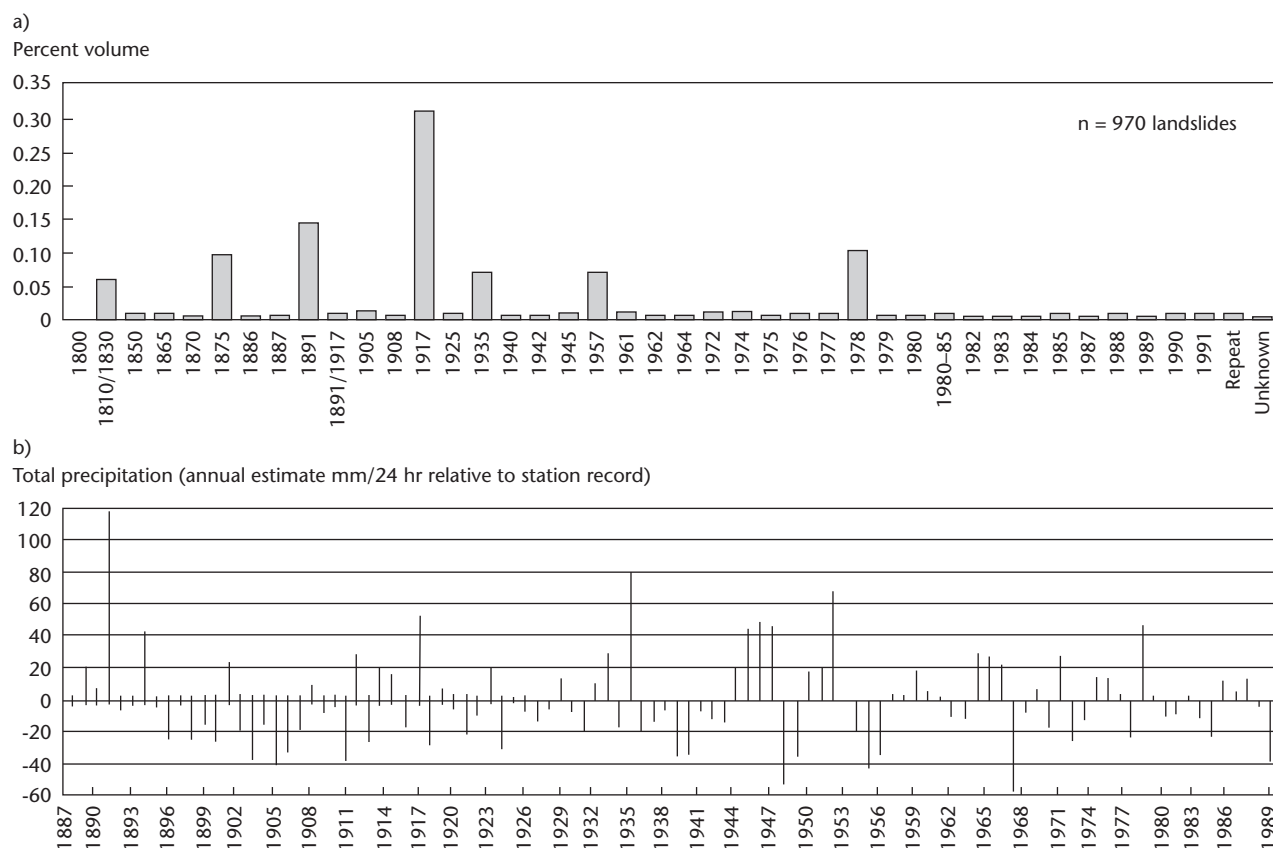


FIGURE 14 *Historical landslide and precipitation records. A) Landslide events occurring in the Queen Charlotte Islands, 1810–1991 (from Schwab, this volume). B) Annual maximum 24-hour precipitation records for selected stations (aggregate record: Port Simpson, 1887–1909; Masset, 1910–1914; Queen Charlotte City, 1915–1948; Sandspit, 1949–1962; Tasu, 1963–1972; Sewell Inlet, 1973–1989).*

volume) sampled 970 of these landslides and determined their date of occurrence by dendrochronological field surveys. His results (Fig. 14a) 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 throughout the last two centuries (1810–1991). 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 local logging.

The landslides documented by Schwab (this volume) occurred during years that experienced severe rainstorms. The combined federal Atmospheric Environment Service records (Fig. 14b), 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 for 3 days. It delivered 305 mm of rainfall in the first 24 hours and set off debris slides that 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 1000 landslides on the Queen Charlotte Islands alone (Schwab 1983), mainly as a result of the very short duration rainfalls (120 mm/12 hr) on steep terrain where logging practices—particularly road building and harvesting—had occurred.

Hogan et al. (in prep.) analyzed channel surveys of 44 km of stream channel in 12 watersheds (including 1193 and 1547 channel widths in forested and logged watersheds, respectively) and identified

620 log jams, including 238 and 382 log jams in forested and logged watersheds, respectively. The frequency of log jams through time (Fig. 15) indicates that the rate of log-jam creation has been episodic over the past century. The distribution is bimodal, with the first peak centred near the turn of the 20th century and the second in the 1970s. In comparison with landslide histories provided by Schwab (this volume) and the corresponding meteorological histories provided by Septer and Schwab (1995), episodes of jam initiation correspond to landslide events triggered by severe rainstorms. The first peak on the histogram identifies an episode of log-jam formation corresponding to storms that occurred in 1891 and 1917, while the second peak identifies another episode of log-jam formation corresponding to storms that occurred in 1964, 1974, and 1978.

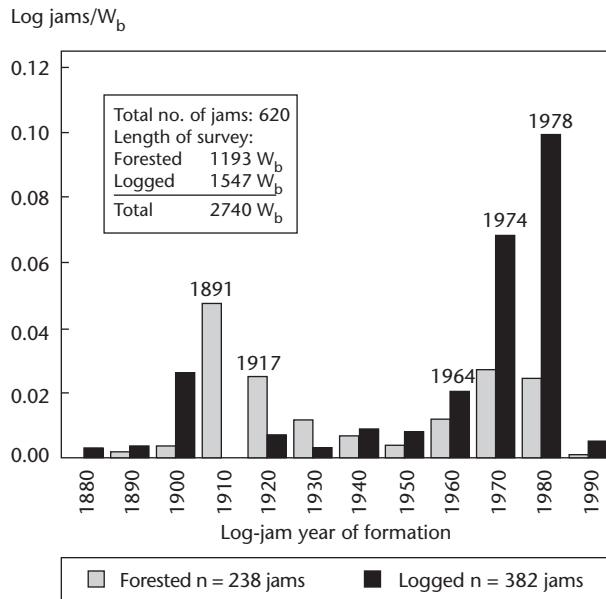


FIGURE 15 LWD jam age distributions for forested and logged watershed streams in the Queen Charlotte Islands (after Hogan et al., in prep.).

Both episodes of log-jam formation are evident in all watersheds regardless of land use. However, the frequency of log-jam formation through time is dependent on both watershed type (see Hogan et al., in prep., for details) and land use. Generally, the relative frequency of young jams increases as a

watershed becomes smaller and steeper. In relatively large watersheds with predominantly decoupled stream channels, mass wasting events rarely impact the channel. Consequently, relatively few new log jams are created during episodes of watershed disturbance. As the connection between the hillslope and the stream channel becomes stronger, mass wasting events create log jams at an increasing rate, often destroying old log jams in the process. As channel gradient becomes increasingly steep, the rate of jam production with an increasing connection to the hillslope appears to reach a critical point. For example, during a debris flow in a steep, coupled stream, an entire channel can be scoured by debris passing completely through to the stream mouth from upslope source areas. Log jams that exist before such an event can be completely destroyed.

The influence of land use on log-jam formation is shown clearly by the impact of the 1978 storm. The large number of jams initiated in 1978 was due to the accelerated rate of landslide occurrence in logged watersheds (Hogan et al., in prep.). The lack of old jams (initiated in 1917) in logged watersheds is likely a result of their replacement by young jams initiated by the 1978 episode.

The Evolution of Channel Morphology

Hogan (1989) defines log jams as major accumulations of LWD, either currently or over the last decades (remnants of which are still evident) that alters channel morphology and downstream sediment transport. Log jams are different from other in-channel blockages such as those caused by rock slides that create essentially permanent dams. Log jams begin to break down over time. The debris pieces rot, are broken into smaller sizes, and are moved by floods. The longevity of each jam influences its temporal role in controlling channel morphology, as the interruption of sediment transport decreases through time.

Because LWD age and channel morphology are intricately linked, the shift in log-jam age distribution shown in Figure 15 corresponds with a shift in expected channel morphology. Hogan (1989) proposes a model of temporal and spatial adjustments of channel morphology in response to the development of log jams (Fig. 16). Initially, before the formation of a log jam, a channel is morphologically complex, with many of the features shown

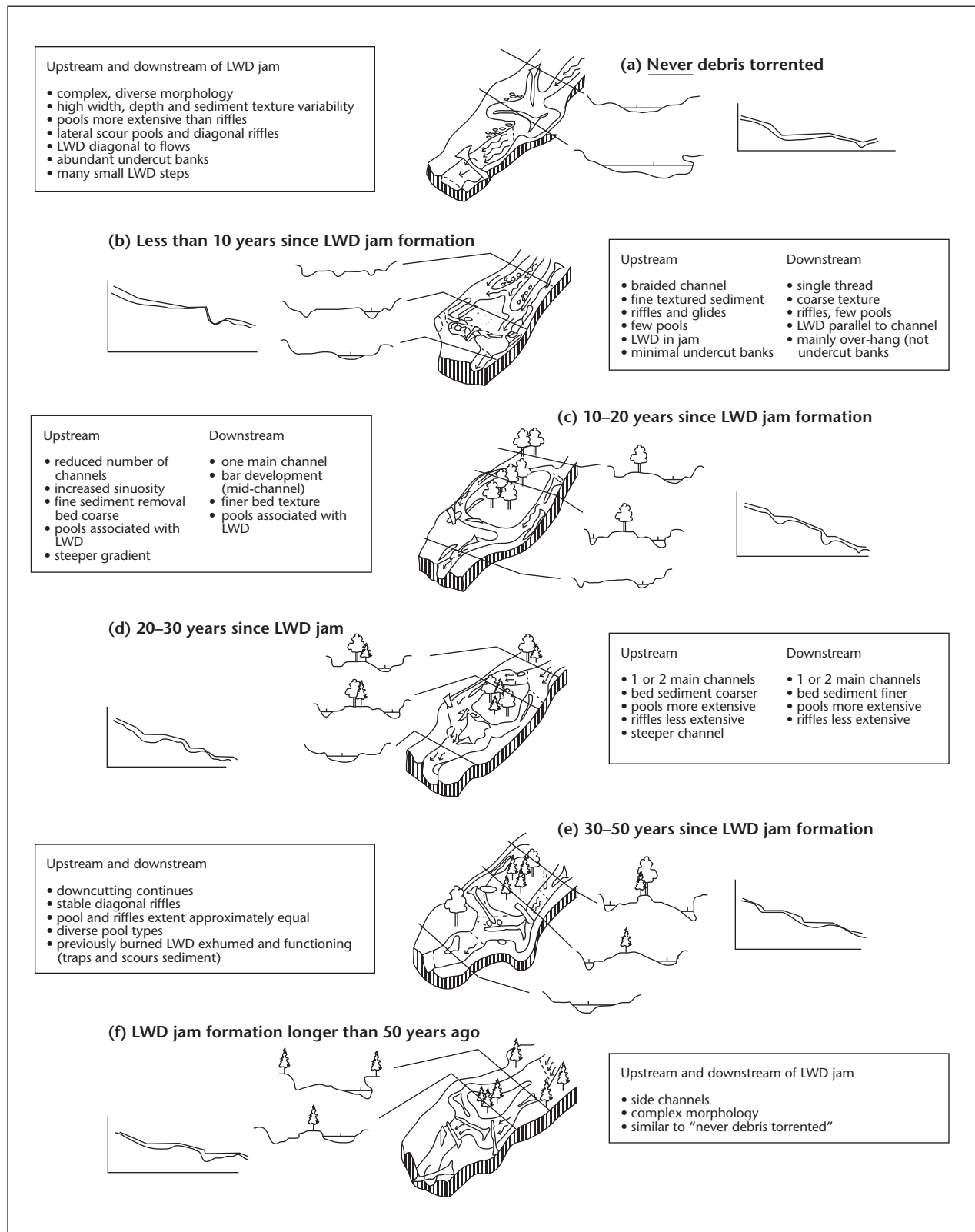


FIGURE 16 Adjustment of channel morphology in response to LWD jam formation and deterioration (after Hogan 1989).

in Figure 16a. After the jam has been established, the channel undergoes fundamental changes, the most severe occurring during the first decade (Fig. 16b). Recently formed jams are effective sediment traps that cause bank erosion and increased channel widths, reduced gradients, and finer sediment textures upstream of the jam. During the second and third decades, the jam begins to deteriorate. As it becomes a less effective sediment trap, the sediment supply to downstream zones increases. In turn, the upstream wedge is downcut, preferred channels are established, and riparian vegetation begins to colonize the bar and bank surfaces (Fig. 16c and d). Typically, after approximately 30 years, the channel begins to resemble pre-jam formation conditions (Fig. 16e and f). Although remnants remain along the channel margin and individual LWD pieces remain along the bed and function as indicated previously, after 50 years there is very little evidence of the original jam (e.g., Hangover Creek shown in Figure 9). Many of the debris steps shown in Figure 8 are actually the final remains of ancient jams.

The evolution of stream channels in the Queen Charlotte Islands is often linked to the evolution of adjacent riparian areas (Bird 1993). In the lower reaches of Gregory Creek, landslides on forested terrain occurring in 1891, 1917, and 1978 produced debris floods that forced the channel around log jams and into the riparian area (Fig. 17). Almost half of the riparian area was activated by these three events, removing the riparian canopy and transferring LWD from the riparian area to the stream channel. Following the debris floods, riparian vegetation colonized several active sediment wedges associated with log jams, leaving at least two log jams abandoned in the present-day riparian area. The result of log jam adjustment and development in the riparian area of Gregory Creek is a diverse and complex successional pattern of riparian forest patches, ranging in age from 12 to over 300 years old. Intensive logging upstream and within these depositional riparian areas can produce extensive and active sediment wedges that coincide with the development of relatively young log jams. Roberts and Church (1986) identify these features in four logged watersheds (Mosquito Tributary, Armentieres, Mountain, and Lagins) where streambank retreat into the riparian area was followed by excessive deposition of sediment in the newly widened stream channels. Recent observations of Mosquito Tributary

indicate a relatively uniform, even-aged riparian canopy dominated by red alder established on the edges of a still-active sediment wedge.

Log jams are fundamental structural elements in the small coastal streams investigated by the research reviewed in this paper. Recently formed jams alter channel morphology to the point that in-stream fish habitats are essentially destroyed. Over the course of 50 years the same log jam creates complex, diverse morphologies and riparian areas that are highly productive fish habitats. Thus, the shift from an even distribution of young, moderate and old log jams to a distribution of predominantly young log jams constitutes a critical impact.

Hogan et al. (in prep.) identify two episodes of log-jam formation in the Queen Charlotte Islands in the last century (Fig. 15). The jam-forming magnitude of Episode I (storms in 1891 and 1917) is fairly similar in both forested and logged watersheds (peak rate of log-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 Episode II (1964, 1974, and 1978 storms) is substantially greater in the logged watersheds, where the rate of log-jam formation increased by a factor of 3.8, than in the forested watersheds, where the rate decreased by 0.6 (peak rate of log-jam formation is 0.0027 and 0.0099 jams/ W_b /yr in forested and logged watersheds, respectively). Generally, both forested and logged watersheds have similar distributions of old jams, but logged watersheds have more new jams. Therefore, given the distribution of log-jam frequency through time (Fig. 15), we would expect in a contemporary inspection of a forested stream in the Queen Charlotte Islands to find young channel characteristics half as often as old channel characteristics through space (Fig. 16a and b). In logged watersheds, we would expect to find young channel characteristics nearly 4 times as often as the old morphologies.

Management Implications

Much of the channel and riparian diversity that characterizes coastal streams is a result of log-jam formation and longevity. Over the long term (on the order of half a century), the complex channels and riparian areas that develop as a log jam deteriorates are highly productive fish habitats. However, the

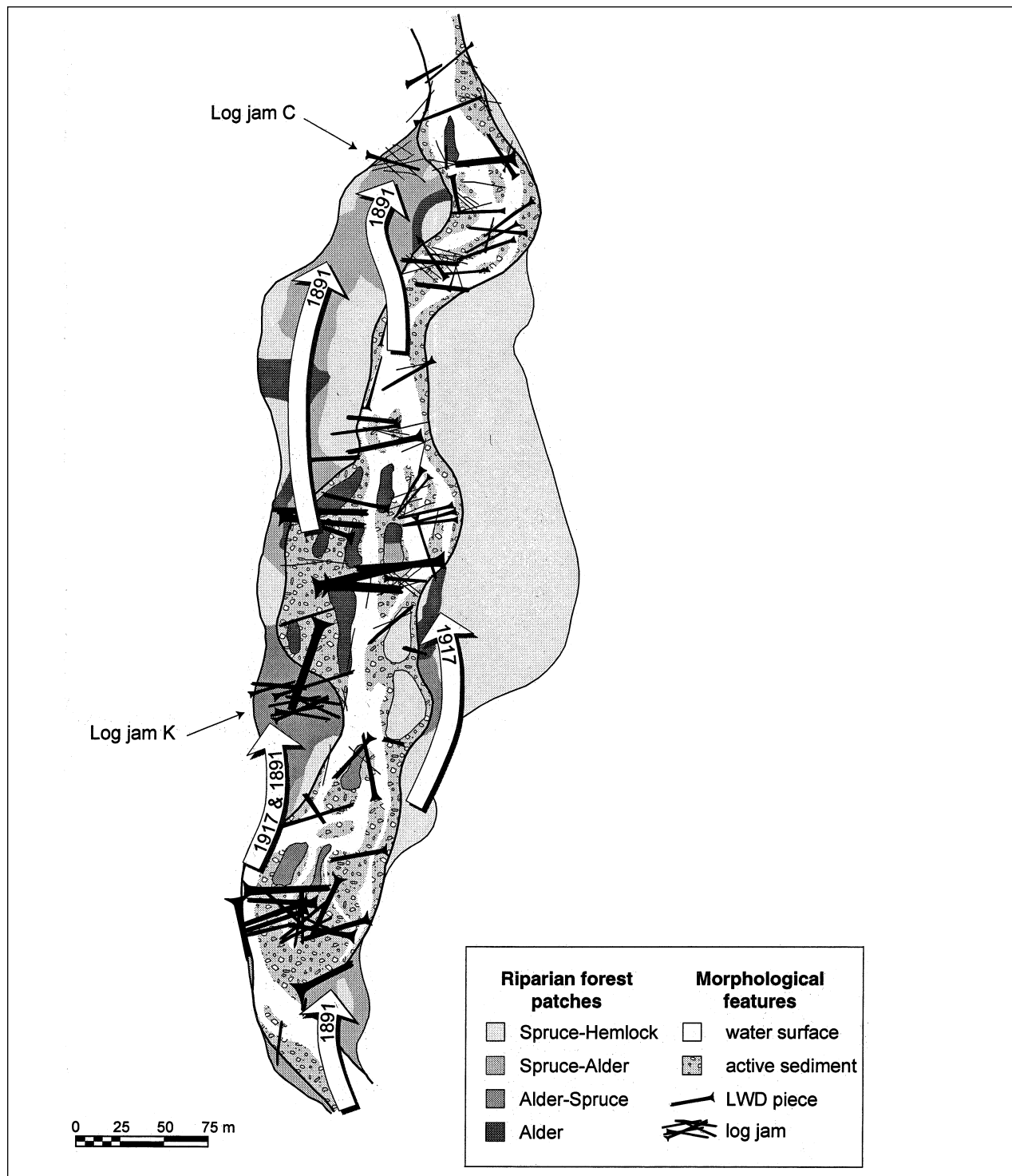


FIGURE 17 Pathways of fluvial disturbance in the riparian area (after Bird 1993). The arrows identify two events occurring in 1891 and 1917, indicated by Spruce-Alder and the Alder-Spruce patches, respectively, when the channel was forced into the riparian area. Log jams C and K formed during these events and are now abandoned by the channel. A third event in 1978, indicated by Alder patches, was responsible for the creation of several islands. The riparian area occupied by Spruce-Hemlock patches has been undisturbed for at least three centuries.

habitat conditions are very inhospitable for fish during the early phases of channel adjustment to jam formation. Spawning areas (riffles) are buried (upstream of the jam) or eroded (downstream of the jam), rearing pools are infilled, and egg incubation environments are smothered with fine-textured sediments. Therefore, shifting the relative frequency of recently formed jams, thereby interfering with the natural evolution of stream channels, constitutes a fundamental environmental impact.

Log jams are spatially prevalent. For all channels surveyed on the Queen Charlotte Islands by Hogan et al. (in prep.), the median spacing is 2.85 and 2.30 W_b in forested and logged streams, respectively (Fig. 18a). The spacing is slightly longer in Carnation

Creek, averaging 3.7 W_b in the logged sections. This means that, on average, there is one debris jam every two to four channel widths (if $W_b=15$ m, then one jam is found along every 30–60 m of channel). In the field, however, only the recently formed jams are obvious, so the spacing appears much longer than reported here. Generally, in forested watershed streams, the main anchors of log jams are large root wads, previously existing jams, mid-channel islands, and bedrock knobs that constrict flow. However, in logged watershed streams, most jams develop on top or immediately upstream of older jams and do not, therefore, significantly alter average jam frequency. The spacing distance of young jams is much greater than for the total of all ages. For instance, in one

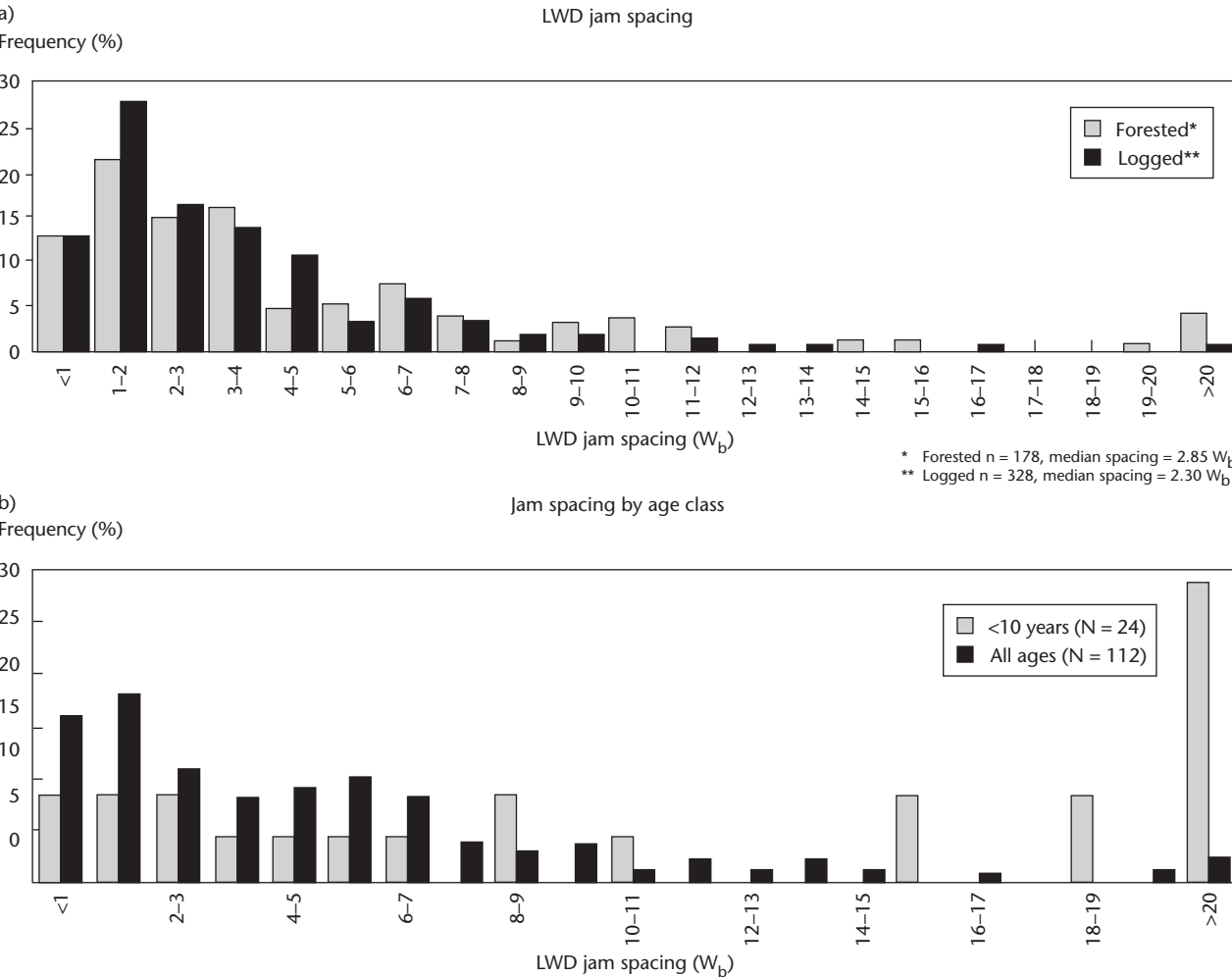


FIGURE 18 Spacing of log jams. a) Log jams in forested and logged streams, and b) recently formed log jams (after Hogan et al., in prep.).

Queen Charlotte Islands stream, approximately 50% of the young jams are spaced farther than 14 W_b apart (Fig. 18b).

In an old-growth forest watershed, the natural rate of log-jam formation is relatively low, resulting in a wide range of jam ages so that individual age classes do not affect the morphology. Although some age classes will be more prevalent because of the episodic nature of landslides, the range of ages produces a diverse mosaic of channel and riparian patterns that have rich habitat attributes. In a logged watershed, the rate of log-jam formation is accelerated. The nature of entire channel systems can be altered because the steep headwater streams receive proportionally more jam-forming events but the influence of these are transferred downstream into larger, lower gradient streams.

A troublesome legacy of past forest management practices in steep terrain is the severity of the environmental damage produced by relatively low magnitude-high frequency storm events. The 1978 storm on the Queen Charlotte Islands was not as intense as events occurring earlier in the century. Nevertheless, far more landslides occurred during 1978 than in earlier storms of the same or greater magnitude. Previous studies have confirmed that logging on unstable slopes accelerates the already high rate of landslide activity along much of coastal British Columbia. This leads to a corresponding increase in recently formed log jams, with all of the associated channel morphology and fish habitat changes. New management initiatives, particularly the British Columbia Forest Practices Code, will attempt to minimize future environmental impacts in streams. However, the current recovery of stream channels to their pre-logging conditions is dependent on the time required—approximately 50 years—for a diverse array of log-jam ages to establish.

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Evolution of Fish Habitat Structure and Diversity at Log Jams in Logged and Unlogged Streams Subject to Mass Wasting

DEREK TRIPP

Introduction

Large woody or organic debris is an essential component of most streams on the Queen Charlotte Islands (Hogan 1986; Tripp and Poulin 1986). It is frequently also closely linked with upslope processes, inasmuch as debris torrents and other mass wasting events appear to be a significant source of debris for streams on the Queen Charlotte Islands (Schwab, this volume). Where the gradient is steep enough, slides or torrents may be carried down in small streams for a considerable distance before halting in a lower gradient reach. When the floodplain is confined between steep hillsides, debris torrents also enter the low gradient sections of larger streams directly from gully failures alongside the stream.

Most of the large organic debris in medium-size streams (15–25 m wide) on the Queen Charlotte Islands is organized into log jams (Hogan 1989). These log jams physically occupy a significant portion of the total stream length available to fish. Because log jams also control many of the habitat characteristics upstream of a jam as well as below a jam, understanding how the fish habitat at log jams develops or evolves in many streams can require study of most of the fish habitat present.

Logging to the stream edge changes the type and rate of debris entering a stream. In steep land areas on the Queen Charlotte Islands, logging in upslope areas also accelerates the amount of sediment and debris introduced into streams (Rood 1984). Both factors should affect the structure of the log jams, but to what degree or how quickly is unknown. The present study attempts to determine how log jams and the fish habitat associated with them evolve over time. It also attempts to determine if log jams in logged streams show the same patterns and rates of change as log jams in unlogged streams.

Methods

Site Selection and Aging In this study, a log jam is defined as any deadlocked jumble of large woody or organic debris (LOD) large enough to completely span a stream and obstruct the movements of gravel and debris downstream. A log jam did not actually still have to be present, as long as there was clear evidence that such a jam once existed. A combination of large debris piles on one or both sides of the channel, large alluvial flats or terraces representing major sediment deposits, and relic channels were all considered to be strong evidence of a major log jam at one time.

Log jams were selected to provide a range of ages on both logged and unlogged streams. During the initial selection process, the age of each log jam encountered during reconnaissance surveys of logged and unlogged streams was roughly estimated as young (0–30 years), mature (30–60 years), or old (greater than 60 years). Age was initially based on the following visual characteristics: the amount of moss present on the debris, the integrity of the jam and thus the amount of gravel backed up in front of the jam face, and the number and size of trees growing on the debris or alluvial terraces that marked the initial depth of the sediments piled up by the log jam.

Log jams with bare, moss-free logs, large accumulations of gravel above the jam compared to downstream, and a thick growth of small-stemmed alders were considered to be young. Log jams with a heavy cover of moss or trees growing on the logs, even or randomly distributed gravel deposits, and open groves of large alders were considered to be old. For the log jams selected for further study, final age was based on tree cores. The latter were taken with an increment borer from a range of what appeared to be

the oldest trees above and below the face of the jam. Trees that were growing on logs in the log jam were preferred because they provided a minimum jam age that was less equivocal than other trees.

Habitat Measurements Each log jam site encompassed a length of channel equal to five bankfull widths above and below the face of the log jam. Bankfull width was average width from rooted edge to rooted edge in the main channel between log jams. The centre of each log jam site was considered to be the upstream face of the jam, which was easily and consistently located. The upper log jam section referred to the stream area above the face of the jam; the lower jam section referred to the stream area below the face of the jam.

A sketch map was drawn of each site to determine where the main debris accumulations were located, where the main channels and side channels were located, and where each pool and riffle was located. All mapping was at a stable, low flow period when each pool and riffle present was readily identifiable.

Each pool at each log jam site was numbered and described as either a lateral scour pool, backwater pool, dammed pool, trench pool, underscour pool, or plunge pool according to Bisson et al. (1982), while riffles were distinguished as either riffles, runs, or cascades. Other pool types identified included underscour pools, drawdown (i.e., isolated) pools, and glide pools. All features were recorded as main-stem or side channel habitats and, in the case of side channels, as temporary or permanent depending on whether the intervening ground was vegetated or not. Each channel was also recorded as “capped” or “uncapped” depending on whether or not flows in the channel originated from seepage water at the base of a log jam. The position of each habitat unit relative to the “face” of the main log jam in the reach was recorded as being upstream or downstream.

The structure or material most responsible for the formation of each habitat unit (e.g., tree roots, LOD, boulder, cobble or gravel deposits, stream banks) was recorded to determine the principal hydraulic controls present above and below debris jams in each reach. Maximum depth was recorded to estimate maximum pool depth at zero discharge, and therefore the extent of the deep water cover in each pool. Other variables measured in each habitat unit included length and width to determine the amount of each habitat type present, substrate

composition (visual estimates of % fines, gravel, lags, and bedrock), and substrate size (D90).

Fish Cover Measurements The amount of fish cover present in the form of LOD, deep water, boulders, and stable rooted undercut banks in or beside each habitat unit was measured in plan view to the nearest 0.1 m². Stream cover was measured separately from channel cover. The former included only the cover (LOD, rocks, deep water, and undercut banks) that was actually in water and influencing the distribution and abundance of fish at the time of the survey. Where portions of the cover were partly in and partly out of the water, only the portion in water was counted as stream cover. Channel cover (LOD, undercut banks, and rocks) was all the cover in the channel up to the top of the banks, both in and out of the water. Pieces of LOD that overlapped more than one habitat unit along the length of the channel were assigned to the habitat unit that the piece was considered to have the greatest effect on. Where more than one habitat unit was present across the channel, the LOD was assigned to the feature least likely to be drowned out at higher flows.

Length and width of individual LOD pieces, deep water areas, and undercut banks were measured directly with metre sticks and metre tapes. Cover rocks were counted along a 1-m wide strip across the middle of the habitat unit, from water's edge to water's edge in the case of stream cover, and from bank to bank in the case of channel cover. Total amount of rock cover was then calculated as the product of the number of large, stable rocks on the transect, times the length of the habitat unit. Unusually large rocks or bedrock outcrops that could provide cover from high flows were measured separately and added to the transect estimates.

The number of pieces of LOD present in each feature, and the average length, diameter, orientation (parallel, diagonal, perpendicular), and position (under, over, alongside) of the LOD relative to stream flows was recorded. In large debris piles, where the precise number of LOD pieces present could not be determined, the total number present was estimated by comparing the number of pieces present in the area or volume of the visible logs present to the total area or volume of the debris present. Total length and diameter at mid-length was measured to the nearest 0.1 m on a maximum of three pieces of LOD in each habitat unit. Where

more than three pieces of LOD were present, the largest and smallest pieces were measured, along with a third piece judged to be representative of all the debris by each pool or riffle.

Data Analysis Habitat characteristics such as age, number of channels, sinuosity, and percent pool or riffle area that were independent of stream size were compared directly between reaches. To remove the scale effects caused by differences in stream size, all other depth, area, or volume measurements were expressed as per unit of channel area or unit of channel length. A unit of channel length was equivalent to average bankfull width as defined above.

A habitat diversity index H' was calculated to integrate various measures of channel complexity such as the different types of channels present, the different types of pools and riffles present, and the different hydraulic controls responsible for each pool or riffle. The index is similar to the common Shannon-Weaver diversity index often calculated for samples of benthic invertebrates, except the different habitat types here are compared by area rather than by number. Each pool and riffle was classified as to type (e.g., lateral, plunge, glide), hydraulic control (e.g., LOD, bedrock), and channel type (capped or uncapped, permanent or temporary). Habitat diversity H' was then calculated separately for each upper and lower jam section as follows (from Lloyd et al. 1968):

$$H' = C/A \times ((A \log A) - \sum (a_i \log a_i))$$

where $C = 3.32193$;
 A = total wetted area of each jam section;
 a_i = wetted area of the i th habitat type with the same hydraulic control and channel type.

Differences between jam sections were tested with paired t-tests, while differences between logged and unlogged streams were tested with independent t-tests. Relationships among the various habitat parameters were explored with a Pearson correlation matrix, using Bonferroni-adjusted probabilities to reduce the likelihood of spurious correlations.

Results

A total of 32 sites were investigated (Fig. 1), 26 of which had obvious log jams that were still affecting streamflow patterns. Six sites were debris torrent

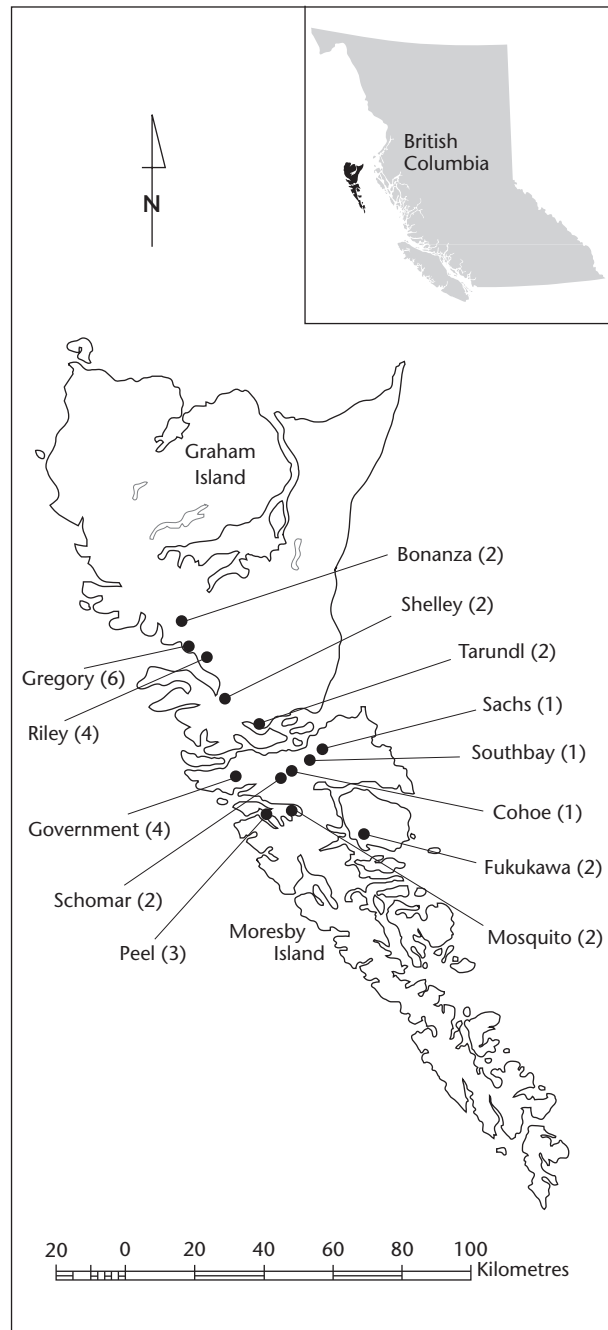


FIGURE 1 Location of study streams on the Queen Charlotte Islands. Numbers in brackets are the number of log jam study sites on each stream.

tracks that had largely obliterated any evidence of a log jam in the stream, other than some remnants still embedded in the banks or lying on the floodplain.

Of the 26 intact log jams formed by mass wasting or large fluvial events, 13 were formed in unlogged stream reaches and 13 were formed in logged stream reaches. All of the unlogged sites were located on the west coast of the Queen Charlotte Islands. Of the 13 logged sites, eight were on the east coast and five were on the west coast. Of the six torrented sites, two were unlogged sites on the west coast, and four were logged sites, three on the east coast and one on the west coast. One debris torrent site (Southbay Dump Creek) had six to eight pieces of LOD added to it 8 years previously in a study on the use of LOD to restore stream habitats.

Stream Size and Log Jam Age Log jam sites were all located on medium-size streams 15–24 m wide, while the sites where torrents had passed by were all in smaller streams 8–11 m wide (Table 1). The estimated age of the log jams in logged streams ranged from 8 to 42 years, while log jams in unlogged streams varied from 11 to 110 years. All logged torrent sites were 11 years old; unlogged sites were an estimated to be between 69 and 75 years old.

Log jams in logged streams were the same age above and below the face of the jams. The log jams in unlogged streams, however—particularly the older jams—tended to have more recent debris deposits on top of the original debris. The upper sections of each log jam site were therefore 18 years younger, on average, than the sections below the face of the jam.

Habitat Differences Above and Below Log Jams

Differences between the fish habitat above and below the face of a log jam were much greater than the differences between log jams in logged and unlogged streams. Of the 25 channel, substrate, LOD, and fish cover characteristics recorded for upper and lower log jam sections, 15 differed significantly from each other ($P<0.05$), in most cases by a large margin (Table 2). By comparison, only 8 of 27 parameters measured on logged and unlogged streams differed significantly (Table 3).

Most of the differences in habitat above and below the face of log jams were related to the extra side channels present below the face of the jam. Because of the extra side channels and the habitat replication they represent, the number of pools and riffles per unit of channel length was also significantly higher downstream, as was wetted length and overall habitat diversity. The amount of LOD present in any given watercourse was not appreciably higher below the face of the jam compared to upstream. However, because of the greater number of parallel watercourses below the jam, the total amount of LOD below the jam face was substantially higher than above the jam.

Percent of wetted area that was pool area did not differ significantly above and below log jams. While pools in the single channel above a log jam tended to be half again larger than pools below a jam, there was a greater number of pools in the main channel and side channels below the jam. The net result was actually a significantly greater wetted area and a significantly greater volume of water below the face of the jam compared to upstream. Similarly, while

TABLE 1 Average channel width and age of the study sites

Logged condition	N	Average bankfull width (m, range)	Average age (years, range)	
			Above jam	Below jam
Log jam sites				
Logged	13	14.2 (8–23.5)	26.8 (8–42)	26.8 (8–42)
Unlogged	13	19.5 (8–24)	54.2 (12–105)	72.2 (33–110)
Torrent path sites				
Logged	4	10.0 (8–11)	11.0 (11–11)	11 (11–11)
Unlogged	2	8.5 (8–9)	72.0 (69–75)	72.0 (69–75)

TABLE 2 Differences between the main fish habitat characteristics of the upstream and downstream sections of log jams in logged and unlogged streams. *P* values are probabilities of no significant differences between upper and lower jam sections, using a paired *t*-test to test for differences. Bold faced *P* values are values < 0.05.

Habitat variable	Log-jam section		<i>P</i>
	Upper	Lower	
No. reaches	26	26	
Age (years)	40.5±26.6	49.5±28.9	0.0571
Stream characteristics			
No. stream channels	1.31±0.62	< 2.85±1.69	<0.0001
No. habitat units/channel width	2.15±1.12	< 4.78±3.40	<0.0001
Habitat diversity (<i>H'</i>)	2.12±0.54	< 2.82±0.81	0.0012
Wetted length/channel length	1.38±0.37	< 2.29±1.03	0.0001
Wetted area (m ² /m ² of channel)	0.45±0.09	< 0.65±0.25	0.0001
Wetted volume (m ³ /m ² of channel)	0.23±0.12	< 0.30±0.15	0.0246
Proportion of wetted area pool	0.58±0.22	0.63±0.21	0.2951
No. pools/channel width	1.34±0.94	< 3.12±2.27	<0.0001
Mean pool area (m ²)	78.4±68.2	> 52.1±58.2	0.0302
Mean net pool depth (m)	0.59±0.32	0.57±0.27	0.7747
Substrate			
Fines (m ² /m ² of channel)	0.08±0.07	0.11±0.07	0.0699
Gravel (m ² /m ² of channel)	0.18±0.10	< 0.28±0.14	0.0016
Larges (m ² /m ² of channel)	0.17±0.11	< 0.24±0.14	0.0050
Bedrock (m ² /m ² of channel)	0.02±0.03	0.02±0.03	0.9357
D90 (m)	0.22±0.16	0.20±0.15	0.6350
LOD			
No. pieces/m ² of channel	0.04±0.02	< 0.10±0.05	<0.0001
Piece volume (m ³)	2.86±2.43	3.18±2.32	0.5991
Stream volume (m ³ /m ² of channel)	0.02±0.02	< 0.07±0.07	0.0033
Channel volume (m ³ /m ² of channel)	0.08±0.05	< 0.33±0.35	<0.0001
Other cover			
Stream undercut (m ² /m ² of channel)	0.01±0.01	< 0.02±0.03	0.0045
Total undercut (m ² /m ² of channel)	0.02±0.01	< 0.05±0.06	0.0018
Stream boulders (m ² /m ² of channel)	0.07±0.13	0.10±0.13	0.2335
Total boulders (m ² /m ² of channel)	0.12±0.17	0.17±0.21	0.2966
Deep water (m ² /m ² of channel)	0.09±0.07	0.11±0.08	0.1541

the amount of gravel present in terms of volume may be greatest above the jam face, gravel area—and thus the amount of spawning habitat available to fish—was greatest below the jam face.

Parameters that did not differ above and below the face of a log jam suggest that it is primarily bedload that is affected by the log jam, and that bedload movements may be responsible for many of the

habitat differences observed. The amount of fines, for example, that would be transported mainly as suspended materials and thus be less affected by a log jam, was the same above and below the face of the jam. Bedrock, which is a permanent fixture unaffected by stream flows, also had the same surface area above and below the jam face.

TABLE 3 Differences between the main fish habitat characteristics of log jams in logged and unlogged streams. P values are probabilities of no significant differences between log jam characteristics in logged and unlogged streams, using a t-test to test for differences. Bold faced P values are values < 0.05.

Habitat variable	Log-jam section		P
	Upper	Lower	
No. reaches	26	26	
Age (years)	26.8±10.6	< 63.2±28.0	<0.0001
Channel width (m)	14.2±3.5	< 19.5±4.2	<0.0001
Stream characteristics			
No. stream channels	1.62±0.75	< 2.54±1.86	0.0230
No. habitat units/channel width	2.50±1.14	< 4.43±3.63	0.0123
Habitat diversity (H')	2.23±0.63	< 2.71±0.82	0.0228
Wetted length/channel length	1.58±0.49	< 2.10±1.12	0.0337
Wetted area (m ² /m ² of channel)	0.56±0.20	0.53±0.19	0.5611
Wetted volume (m ³ /m ² of channel)	0.26±0.16	0.27±0.11	0.7400
Proportion of wetted area pool	52.8±22.8	< 68.1±18.0	0.0097
No. pools/channel width	1.56±0.83	< 2.90±2.46	0.0117
Mean pool area/channel width	2.93±1.51	4.19±3.48	0.0960
Mean net pool depth (m)	52.1±28.5	63.1±29.0	0.1717
Mean net pool depth/channel width	3.74±2.01	3.19±1.20	0.2334
Substrate			
Fines (m ² /m ² of channel)	0.08±0.08	0.10±0.07	0.2309
Gravel (m ² /m ² of channel)	0.25±0.14	0.21±0.11	0.1793
Larges (m ² /m ² of channel)	0.22±0.14	0.19±0.11	0.4268
Bedrock (m ² /m ² of channel)	0.01±0.03	0.02±0.03	0.7547
D90 (m)	23.7±18.3	18.5±12.7	0.2381
LOD			
No. pieces/m ² of channel	0.08±0.05	0.06±0.04	0.0823
Piece volume (m ³)	2.63±2.28	3.38±2.42	0.2572
Stream volume (m ³ /m ² of channel)	0.05±0.06	0.05±0.06	0.8334
Channel volume (m ³ /m ² of channel)	0.25±0.37	0.17±0.14	0.3091
Other cover			
Stream undercut (m ² /m ² of channel)	0.01±0.01	0.02±0.03	0.3310
Total undercut (m ² /m ² of channel)	0.03±0.03	0.04±0.06	0.6710
Stream boulders (m ² /m ² of channel)	0.10±0.17	0.07±0.08	0.4824
Total boulders (m ² /m ² of channel)	0.14±0.22	0.14±0.16	0.9290
Deep water (m ² /m ² of channel)	0.10±0.10	0.10±0.05	0.8136

Differences Between Logged and Unlogged Streams

In logged/unlogged stream comparisons, habitat differences related almost exclusively to the greater number of channels present below the face of the log jam in unlogged streams. More side channels in turn meant a greater total wetted length relative to

overall channel length, a greater number of pools and riffles, and a higher diversity (H').

A greater number of side channels below the face of a jam in unlogged streams is probably related to the significantly greater age of the unlogged stream log jams, inasmuch as unlogged stream log jams had

more time to develop side channels. Unlogged sites also had significantly wider channels than the unlogged sites, but it is not known how important channel width is in determining the number of side channels, or what the potential complexity of a log jam can be.

For other habitat characteristics, only percent pool area was greater at log jams in unlogged streams, a difference that may be more attributable to differences in bedload than to age. There were no other differences between logged and unlogged streams with regard to substrate characteristics, or other fish cover characteristics measured (e.g., undercut bank area, deep water area, boulders). When only the upper sections of log jams were compared, logged streams had significantly smaller debris pieces than unlogged streams, but they also had significantly more pieces. The net result was the same LOD volumes. For the lower log jam sections or both the upper and lower sections combined, there were no significant differences in the number of LOD pieces, piece volume, or total volume.

Habitat Relationships For stream habitats above the face of the log jam, pool area showed a significant negative correlation with cobble and boulder area ($P < 0.05$). When there was little pool area, there was a large riffle area, which is also where most of the boulders and cobbles are located. Fines showed the opposite pattern, a significant positive correlation with pool area, water volume, and deep water cover. This pattern may be related to the fact that very large pools tended to form upstream of log jams. Because of the slow flows in these pools at most stage heights, these pools would be the sites where fine size particles would most likely accumulate, or at least be most visible. Gravel area, undercut bank area, and deep water area were also positively correlated with LOD abundance (either stream LOD area or the number of channel LOD pieces).

Significant ($P < 0.05$) correlations among habitat parameters differed slightly below the face of the log jams. Ignoring obviously related parameters (e.g., LOD area and LOD volume), the number of LOD pieces in the water was strongly negatively correlated with D90, but positively correlated with deep water area and gravel area. Deep water area was

in turn positively correlated with gravel area and fine area, while percent pool area was negatively correlated with boulder area.

Combining the data for upper and lower jam sections increased the sample size and the significance of the relationships among the various habitat characteristics, but the relationships remained otherwise similar. As expected, closely related characteristics remained highly correlated. For example, D90, stream boulder cover, and total substrate coverage by cobbles and boulders were all strongly correlated with each other. Similarly, habitat diversity, the number of channels, wetted length over channel length, and the number of pools and riffles per unit of channel length were also closely correlated, as were the number of LOD pieces, LOD areas, and LOD volumes.

There were also five parameters not obviously related to each other that showed significant correlations. These were total gravel area, total fines area, deep water area or total water volume, habitat diversity (H'), number of streams, or number of pools and riffles), and LOD abundance (number of pieces, area, or volume). As indicated in Figure 2, LOD abundance was significantly correlated with the four other parameters. Total water volume was significantly correlated with fine area, while gravel area was correlated with habitat diversity. Gravel area and deep water cover were also correlated.

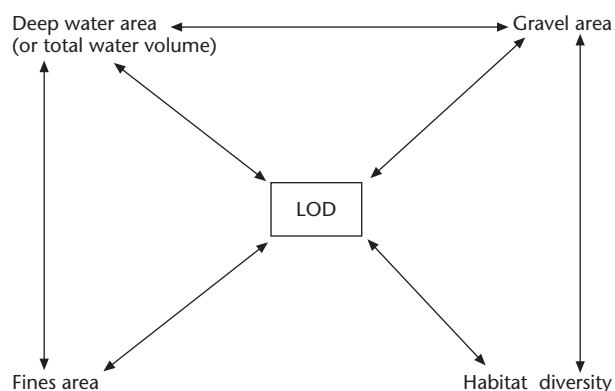


FIGURE 2 *Habitat parameters that showed significant, positive correlations with each other at log jams in logged and unlogged streams on the Queen Charlotte Islands.*

All of the above correlations were positive. The only significant negative correlation apparent was between D90 and the number of LOD pieces present in the wetted portion of the channel. The relationship indicated the larger the number of LOD pieces present in the stream, the smaller the D90, which complemented the significant, positive correlations observed between LOD and fine and gravel sized sediments.

Rate of Change Habitat diversity H' was the only variable that correlated well with jam age, and only then when the results for the lower log jam sections of logged and unlogged streams were combined (Fig. 3). There was no correlation between age and diversity when the lower jam sections of logged or unlogged streams were treated separately. There was also no correlation between age and diversity for the upper jam sections.

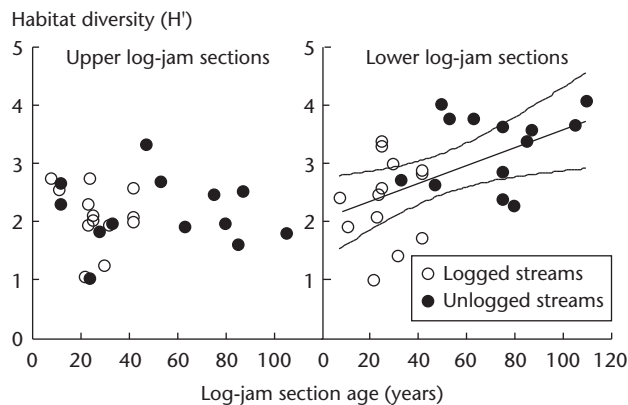


FIGURE 3 The relationships between log jam age and habitat diversity H' in logged and unlogged streams.

With one exception, diversity H' in the upper jam sections (i.e., the channel section above the face of a log jam) of logged streams showed the same range (1.0–2.8, $N = 13$) as unlogged upper jam sections (1.0–2.7, $N = 12$), regardless of age. The exception was a 47-year-old upper log jam site that was essentially the lower end of another log jam upstream. Diversity in this section (3.3) was much higher than in other upper jam sections that did not impinge on a log jam upstream, but it was typical of lower jam sections.

For lower jam sections, diversity increased, on average, from approximately 2.2 for a jam 8 years old to 3.7 for a jams 105 years old (Fig. 3). Based on the relationship between diversity H' and the number of habitat units per unit of channel length equal to one bankfull width (Fig. 4), this is equivalent to a 4-fold increase in the number of individual pools and riffles present, from approximately two to eight per unit of channel length. In terms of channel development and overall habitat diversity, log jams in logged streams appeared to be developing in the same manner and at the same rate as log jams in unlogged streams.

The highest diversities recorded were 4.0–4.1. Equivalent to approximately 12 habitat units per unit length of channel, this level of complexity was achieved at two sites where six to seven separate channels had formed through 50- to 110-year-old log jams that extended over 50–100 m of stream. In both cases, the most recent channels had formed as a result of temporary stream blockages at the face

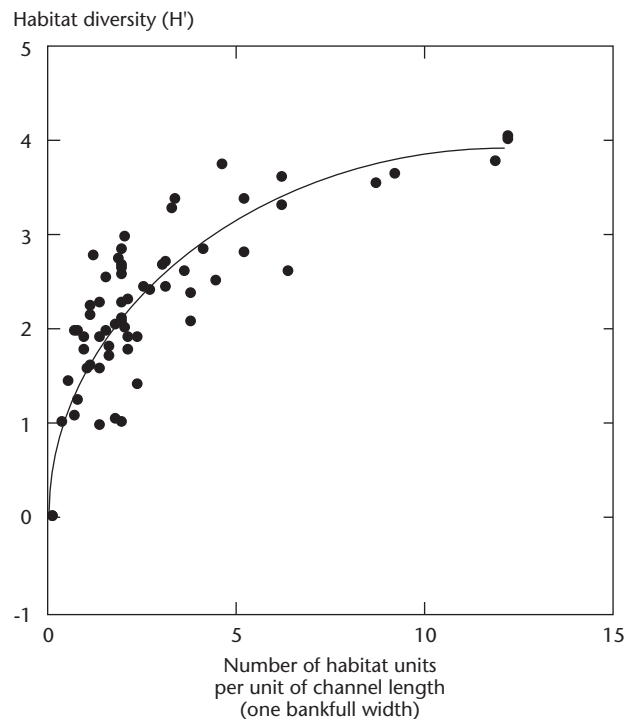


FIGURE 4 The relationship between habitat diversity H' and the number of habitat units (pools and riffles) at log jams in streams on the Queen Charlotte Islands.

of the jam. The blockages occurred when gullies upstream of the jams torrented and deposited a new layer of debris on the face of the jams. Estimated age of the torrents based on the age of the alders growing above the jams was 24–28 years.

Most of the jams inspected with their large complex of side channels were clearly permanent or persistent features, with ongoing side channel development as a result of periodic debris and sediment blockages or breaches on a relatively wide section of the floodplain. As new channels were formed, accumulations of old debris from even older log jams were occasionally exhumed out of the floodplain.

Three jams were simpler, more temporary looking structures with possibly only one relic side channel. The log jams were concentrated over a short section of the channel, with little or no LOD evident other than what was originally deposited at the site, plus some windthrown trees. The latter may have formed the original obstruction, or were added later when the log jam formed and increased local bank erosion. In all three cases, the stream was confined to a narrow channel with little or no floodplain. With little opportunity to flow around the jam, the stream had little recourse but to flow over the jam, eventually breaching it. With no subsequent debris deposits to block the channel again, there was never a reason for the stream to seek a new course.

Torrented Streams Diversity H' in small torrented streams was highest (2.3–2.8) in a stream that had LOD added to the channel 8 years previously (Fig. 5). Elsewhere, diversity was 0.0–2.0 in recently torrented logged streams, and 1.0–2.1 in old torrented, unlogged streams.

The habitat in small, torrented streams without log jams was much more uniform than in streams with log jams. There was also little indication that the complexity of these channels changes very much over time. The main habitat characteristics of recently torrented, logged stream reaches (small pools and long riffles, little LOD, a streambed armoured with boulders) were still very evident in old (69–75 years) unlogged torrented streams.

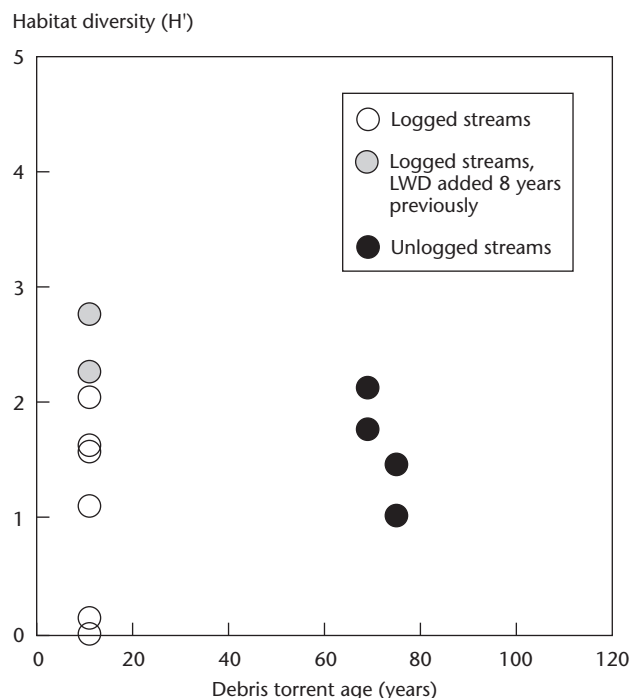


FIGURE 5 *Habitat diversity H' in torrented logged and unlogged streams.*

Discussion

Logged versus Unlogged Log Jams There were no differences between the habitat at log jams in logged and unlogged streams that could not be attributed to differences in stream size or log jam age. In particular, the habitat upstream of the face of the log jams was very similar in logged and unlogged streams. One of the few measurable differences was a decrease in the average size of the LOD pieces present. This was compensated for by an increase in the number of LOD pieces. As a result, total LOD volumes remained similar, as did other key habitat characteristics such as wetted area, pool depth, substrate composition, bank cover, and deep water cover. Percent pool area was greater above log jams in unlogged streams than in logged streams, but this may be attributable to the fact that unlogged stream jams had twice the time (27 vs. 54 years) to scour out the gravel accumulated in front of the log jam.

Downstream, below the face of the log jams, unlogged stream log jams had more habitat than logged stream log jams because they also had a greater number of side channels and thus more wetted area and more pools. The greater number of side channels is attributable to the greater age of the jams, which allowed time for more slope failures, debris torrents, and major floods to apply another layer of debris to the jam and force the stream to seek new channels or reactivate old channels.

The absence of any major differences in habitat not attributable to age differences at log jams in logged and unlogged streams agrees with earlier findings on the habitat characteristics of logged and unlogged streams on the Queen Charlotte Islands. In a synoptic survey of 33 logged, unlogged, and debris-torrented (logged) stream reaches (Tripp and Poulin 1992), debris-torrented streams stood out in stark contrast to non-torrented stream reaches (logged or unlogged). By comparison, logged and unlogged streams differed only in the amount of undercut bank cover present (logged streams had less). Logged stream reaches had less LOD, but not significantly so.

Log Jam Formation Debris for log jams in streams can come from the riparian zone as windfalls or undercut trees, or from the adjacent slopes as debris torrents or slides. Field observations suggest that log jams derived exclusively from debris in the riparian zone tended to be dominated by large intact trees with the root wads still attached. With relatively fewer small pieces of debris, the jams were more open and therefore relatively permeable to water and bedload movements downstream. They also extended over relatively short lengths of stream.

Log jams that were the result of a slide or debris torrent into the stream were mainly made up of broken or shattered stems and branches that knitted together more readily than large intact trees during a flood event. Log jams made of debris from torrents or slides, in combination with a large volume of new sediments, were therefore more likely to form an impenetrable mass that would block stream flows and deflect them elsewhere to form another channel. Subsequent additions of debris and sediment to the face of the jam have resulted in the formation of additional channels, or greater flows in some of the older channels, none of which are likely to disappear as long as the log jam is present.

Most log jams are a combination of debris from the riparian zone and the hillslopes. Log jams therefore represent points where the stream, riparian zone, and hillslopes are linked together. In this survey, large trees from the riparian zone were frequently observed at the core of a log jam, and were probably partly responsible for halting the debris flows from the adjacent hillside or gully once the debris flow entered the stream. If the stream channel is more or less completely blocked off by the original log jam, or by later debris deposits from subsequent gully failures, more trees will inevitably be recruited from the riparian zone as the stream seeks a new course through or around the jam.

Jam Morphology An old log jam in an unconfined, unlogged stream typically has one channel upstream of the face of the jam and several channels downstream. Above the jam, the habitat is often dominated by one or two pool/riffles sequences over a distance equivalent to five channel widths. Each pool and riffle combination therefore tends to be large in terms of surface area covered. The pools, which often have a sharp drop out at the head of the pool but a long, shallow tail, are also often the deepest pools associated with the jam. Partly this is because the build-up of gravel in front of the log jam allows for a greater depth of scouring than would be the case if the substrate were composed of more resistant materials (i.e., boulders); and partly it is because the stream's energy is still concentrated in one channel.

Deep water and low, rooted undercut banks constitute most of the cover upstream of the log jam. If it is present, LOD tends to be composed of relatively few, but very large, pieces in the main pools above the jam, with smaller pieces confined to the margins of the pools. A large, smooth gravel bar is frequently present between these pools and the face of the jam. The face of the main jam itself frequently has a line of bare, recently deposited woody debris plastered up against the main members of the jam. The face of the jam is otherwise obscured by a heavy growth of alders. The stream channel is typically deflected to one side.

Below the face of the jam, the habitat can be a maze of logs and channels, separated by islands of debris or flat alluvial deposits, all overgrown with a complex assortment of mosses, grass, shrubs, various age alders, and young conifers. In this study, the

length of channel occupied by the jam often extended to five channel widths downstream, at which point the side channels in the jam had usually coalesced to form a single channel again. Sometimes the distance between jams was less than five channel widths.

Log Jam Function The results of this study show that wetted area and wetted volume were significantly greater downstream below the face of a jam, logged or unlogged. Since a difference in water volume implies a greater transit time, log jams dissipate the kinetic energy of streams and slow the movement of water and bedload materials downstream. This supports similar findings by others on the role of LOD in a stream (e.g., Keller et al. 1981; Swanson and Lienkaemper 1978), but on a larger scale.

In streams like Carnation Creek on Vancouver Island, the off-channel habitats and tributary streams that are often located on wide, low-gradient floodplains are an important refuge for fish, away from other fish and floods in the mainstem (Bustard and Narver 1975; Hartman and Brown 1987). Many streams, however, do not have floodplains of any significance, and thus much less off-channel habitat for fish. In streams confined between steep hillsides, the log jams that are created as a result of repeated debris torrents or slides into the mainstem stream may more than offset the shortage of off-channel habitats.

By dividing up stream flows into several channels, log jams increase the gravel area covered by water. The amount of spawning habitat available to fish is therefore increased, even though the total volume of gravel present may be greater above log jams. Divided stream flows also increase total wetted area and thus the area for rearing fish. Numbers of fish per unit wetted area may remain the same (Hartman et al., this volume), but numbers of fish per unit of channel length can be greatly increased. Finally, dividing up the stream into several channels—some with a cap of LOD at the face of the jam and others free-flowing—should also reduce overall egg or juvenile losses resulting from excessive gravel scour or flooding, because flows in some channels are probably less severe than in others.

Management Implications If a log jam in a fish-bearing stream is dependent on gully failures beside the stream for creating, maintaining, or enhancing the complexity of the jam, then timber management

practices need to reflect this fact. They also need to recognize that periodic gully failures are normal, and possibly a critical means of maintaining or increasing the number of side channels in many log jams. In turn, more side channels at log jam sites translate into a greater ability to buffer gravel and water movements downstream, more spawning habitat, more rearing habitat, and ultimately greater productivity.

Current logging practices recognize the importance of careful logging around gullies so that the rate of gully failures in a watershed is not accelerated. Gullies were frequently logged in the past without regard to their role in watershed sediment budgets. As a result, many failed, greatly increasing the amount of sediment and debris in streams (Rood 1984).

Present-day prescriptions for logging around gullies usually require that timber be felled and yarded away from the gully, and that any debris introduced be removed concurrent with logging (Tripp 1995). This may reduce the frequency of gully failures, though if debris clean-up is too zealous, sediment movements downstream may still be accelerated, but without a debris component. Harvesting the timber in gullies should reduce the rate at which gullies are recharged with debris. However, by eliminating an important source of debris to the stream, it should also alter how log jams evolve to become more complex and productive.

Torrented Streams The habitat of small streams directly affected by the passage of a debris torrent is less dynamic than the habitat of large streams affected by a debris torrent deposit. Presumably the difference is attributable to differences in stream energy and thus the stream's ability to move debris and bedload. Recovery as a result may be very slow in directly affected reaches of small streams. Though the sample size for unlogged streams in this study was very small (two streams), the habitat conditions present in small, unlogged stream reaches affected by debris torrents 69–75 year ago suggest that there will be little further change in the habitat of small, logged streams affected 11 years ago.

Summary

The principal objectives of this research were to determine the fish habitat characteristics of log jams formed by mass wasting in unlogged streams, how these characteristics changed over time, and if log

jams in logged streams show similar types and rates of change. Debris transport zones in fish-bearing streams were also examined, though few such sites in unlogged streams were located.

At log jam sites, fish habitat varied more above and below the jams than between jams in logged and unlogged reaches. Rates and patterns of change also appeared to be similar between logged and unlogged streams, though no sites with logging older than 42 years were sampled. Longer term changes in habitat structure of log jams in logged streams could therefore not be assessed. Increases in log jam complexity appear to be dependent on periodic additions of new debris, which may or may not be as available in logged streams as it is in unlogged streams. In debris torrent transport zones lacking log jams, the habitat at all sites was much more uniform. There was also little difference between logged sites 11 years old and unlogged sites 69–75 years old.

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Channel Scour and Fill in Coastal Streams

JUDITH K. HASCHENBURGER

Introduction

The process of scour and fill in rivers is the key link between sediment transport and net morphological change in channels. Scour and fill are the results of sediment transport events, where the level of stream-flow controls the magnitude of transport. In specific locations in a channel, differences in the amount of scour and fill over time lead to net change in channel morphology.

Effective management of fishery resources within rivers requires an understanding of the relation between stream discharge and scour and fill. The direct link that exists between magnitude of scour depth and the loss of anadromous fish eggs underscores the need to understand and predict scour depths. The degree of impact is determined by a combination of the vertical distribution of fish eggs, which varies by species, and the depth of scour, which may be achieved by a single large-magnitude flood event or by the cumulative effect of numerous events over an entire flood season.

The purpose of this paper is to examine depths of scour and fill in coastal streams. The specific aims are: 1) to evaluate whether scour and fill depths can be modelled by a specific mathematical function; 2) to establish relations of stream discharge to depths of scour and fill; and 3) to examine relations of scour depths on a regional basis. Establishment of these relations could aid in decision-making related to fishery and forestry resources, by providing a means to predict depths of scour and fill in specific streams or within defined regions.

Study Areas

Twelve gravel-bed streams (Table 1) were selected for investigation of scour depths from the detailed phase of the Fish/Forestry Interaction Program completed in the Queen Charlotte Islands (Tripp

and Poulin 1986). Six of the streams are located on the west and southwest coasts of Graham Island; the remaining six are found on the northeast coast of Moresby Island (see Figure 1 in Tripp and Poulin [1986] for location map). The physical characteristics of the streams on the Queen Charlotte Islands span a range of basin areas, study reach gradients, and surficial sediment sizes (Table 1). Carnation Creek, on the west coast of Vancouver island, drains a relatively small basin over a relatively gentle gradient (Table 1). The most detailed studies of scour and fill were conducted in this stream. Surface sediments in the channel exhibit a median particle size of 47 mm, which is in the lower range of sediment sizes of the streams studied (Table 1).

Study reaches selected within each basin typically begin at the mouth and extend upstream for distances up to 900 m (Table 1). In Carnation, Tarundl, Bonanza, and Riley creeks, the downstream boundary is displaced upstream from the basin mouth, but these distances do not exceed 6 km. These lower segments of coastal river basins are typically used by anadromous fish for spawning and rearing habitat. The study reach in Carnation Creek encompasses study areas 6, 7, and 8 established for the Carnation Creek experimental program (see Figure 1 in Scrivener [1987] for study area locations).

Methods

Scour monitors and chains were used to measure scour and fill depths. Scour monitors are constructed from 100 kg test fishing line strung with 4 cm diameter perforated plastic balls tied off by a weighted base at one end and a plastic disk at the other. Metal chains with 4 cm long links, weighted at the one end, compose the scour chains. The monitors and chains are collectively referred to as scour indicators because comparable data are

TABLE 1 *Characteristics of study streams*

Stream	Basin area (km ²)	% logged ^a	Reach length (m)	Reach gradient (%)	Sediment median diameter (mm)	Number of scour indicators
Carnation Creek	11	61	900	0.9	47	108
Queen Charlotte Islands						288
Bonanza Creek	47	13	311	0.9	50	18
Haans Creek	29	43	312	1.0	48	18
Hangover Creek	21	—	400	0.7	71	18
Macmillan Creek	6	77	680	3.1	68	30
Miller Creek	22	3	660	3.1	67	18
Piper Creek	4	10	806	2.2	55	30
Riley Creek	29	12	247	1.5	72	18
Sachs Creek	18	62	500	0.8	46	18
Saltspring Creek	6	13	292	3.5	72	30
Schomar Creek	7	36	507	2.1	47	30
Southbay Dump Creek	4	82	260	3.7	60	30
Tarundl Creek	11	37	473	4.0	43	30

Data for streams on the Queen Charlotte Islands extracted from Table 2 in Tripp and Poulin (1986).

^a Percent at time of study.

derived from both types. The scour depth measured by an indicator is a maximum depth at the location of the indicator. The fill measured is a net depth because sediment deposition in the channel could be transient over the extent of a flood event.

Indicator length and the depth of a vertical insertion into the channel bed determine the maximum depth of scour that can be measured by an indicator. In Carnation Creek, the leading edge of the indicators reached a depth of 1 m in most cases, but in the streams of the Queen Charlotte Islands a maximum of 38 cm was achieved, in part due to the difficulty of driving indicators into the coarse sediment. The 38 cm upper limit of measurement was reached, and most likely exceeded, at 121 of the indicators by the end of the study period. Therefore, calculated mean scour depths are underestimates for some of the streams.

In both studies, scour indicators were positioned along channel cross-sections. In the streams on the Queen Charlotte Islands, three scour indicators were positioned in the low-flow channel of transects that

crossed the transition from pool to riffle in the channel bed morphology. Individual streams were instrumented with 18–30 indicators (Table 1). Collectively, the streams on the Queen Charlotte Islands contain 288 indicators. Scour monitors and chains the Carnation Creek were spaced along channel cross-sections at a 2-m interval across the full bank-to-bank width, and the cross-sections were positioned in pool and riffle areas. Over 100 indicators were installed in the study reach of Carnation Creek.

In Carnation Creek, scour indicators were recovered 15 times during the winter flood seasons of 1991–92 and 1992–93. These data characterize depths of scour and fill associated with individual flooding periods, and have peak magnitudes ranging from 4 to 49 m³s⁻¹. The maximum flood peak is used as an index when more than one flood event occurred during a flooding period. Recovery of scour indicators in the 12 streams of the Queen Charlotte Islands occurred twice, so scour depths characterize the maximum depths achieved over two

time periods: late October to early December 1983 and late October to late February 1984. Scour depths for the December to February period were derived by subtracting the depths observed during the first recovery from those observed over the complete study period. The absence of detailed hydrological records for the study streams prevents a direct assessment of scour depths as they relate to magnitude of flood events. The stream gauging station on nearby Premier Creek, however, indicates that several floods occurred within each measurement period.

Evaluation of scour and fill involved constructing frequency distributions of scour and fill depths and then fitting negative exponential functions to these empirical distributions. Model parameters were derived using a Newton-Raphson iterative procedure, with data grouped by a 4-cm interval. The exponential model was selected for use because it is successful in describing empirical observations from another technique used to estimate scour and fill depths: magnetically tagged stones (Hassan and Church 1994). The Cramér-von Mises goodness-of-fit statistic, specifically adapted for an exponential function when parameter estimation derives from empirical grouped data (J. Spinelli, pers. comm., 1994), was used to assess how well exponential models depict the empirical frequency distributions. This statistic compares theoretical cumulative frequency distributions for the models to observed

cumulative frequency distributions. The relations of mean depths of scour and fill to flood peak discharge were established using functional analysis rather than regression analysis (Mark and Church 1977), because the assumption of an error-free independent variable cannot be supported (Neter et al. 1982).

Results

Exponential Models of Scour and Fill Depths

Frequency distributions of scour and fill depths for five representative flooding periods that occurred during the field seasons in Carnation Creek are described in general by exponential functions (Table 2). Statistical results indicate that only the fill distributions for the 12.7 and 21.8 m³s⁻¹ events are different at the 0.05 significance level. For each flood peak magnitude, model parameters for scour and fill depths are comparable, with the largest difference of 0.09 obtained in the 21.8 m³s⁻¹ flood event (Fig. 1). As flood peak discharge increases over the range of discharge magnitudes, the slope of the relations decreases (Table 2). Thus, the range of depths noted increased, as illustrated by the maximum depth of scour and fill measured for these representative flood events (Table 2). This is true for both scour and fill relations.

TABLE 2 Exponential models for scour and fill depths for representative flood events in Carnation Creek

Flood peak magnitude (m ³ s ⁻¹)	Relation	Number of indicators	Maximum depth (cm) ^a	Model parameter	W ² probability ^b
5.7	Scour	108	10	0.62	0.66
	Fill	108	10	0.70	0.98
12.7	Scour	105	10	0.54	0.89
	Fill	105	14	0.46	0.01 ^c
21.8	Scour	108	18	0.28	0.75
	Fill	108	22	0.19	0.02 ^c
33.9	Sour	108	38	0.16	0.27
	Fill	107	50	0.11	0.68
48.8	Sour	108	98	0.064	0.17
	Fill	107	62	0.067	0.66

^a Mid-point value of the largest category of depths where an observation was recorded.

^b The Cramér-von Mises (W²) statistic was used to evaluate differences between observed and theoretical distributions.

^c Statistically different at the 0.05 significance level.

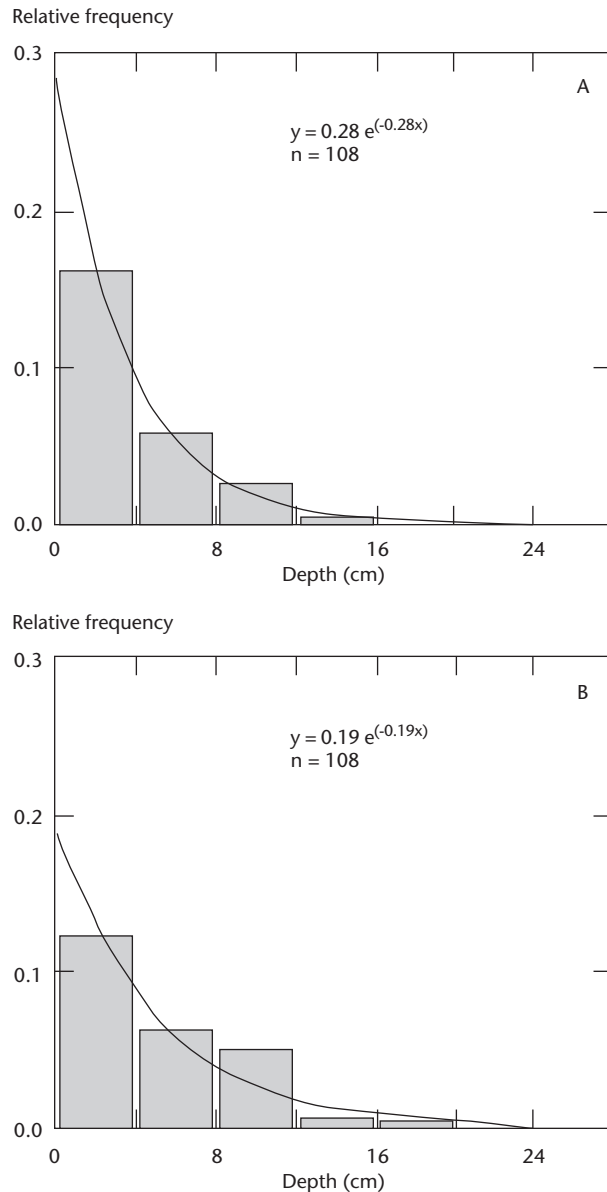


FIGURE 1 Frequency distributions and exponential models for scour (A) and fill (B) for a flooding period with a $21.8 \text{ m}^3\text{s}^{-1}$ peak magnitude. Relative frequencies are calculated by dividing the number of observations in each class by the total number of observations and the class interval width of 4. The width adjustment is necessary because data were grouped into 4-cm class intervals for analysis.

Exponential models constructed for the two indicator recoveries in four selected streams on the Queen Charlotte Islands (Haans, Riley, Sachs, and Tarundl creeks) describe, in general, the empirical scour distributions (Table 3). Only the distribution for the February recovery in Sachs Creek is statistically different from the associated exponential model at a 0.05 significance level. Riley Creek shows the largest change between recovery periods, with the model parameter decreasing from 0.35 to 0.024. Selection of these streams was based on two criteria; maximizing the geographic coverage within the Islands and maximizing the number of intact scour monitors over the study period. Model parameters vary between recovery periods (Table 3).

When frequency distributions of cumulative scour depths achieved over the study period are examined in the four selected streams (Fig. 2), the

TABLE 3 Exponential models for selected streams on the Queen Charlotte Islands

Stream	Number of indicators	Recovery ^a	Model parameter	W ² probability ^b
Haans	17	December	0.47	0.58
		February	0.34	0.84
		Study period	0.26	0.99
Riley	18	December	0.35	0.71
		February	0.024	0.76
		Study period	0.023	0.90
Sachs ^c	18	December	0.17	0.90
		February	0.21	<0.01 ^d
		Study period	0.11	0.72
Tarundl	27	December	0.14	0.66
		February	0.086	0.86
		Study period	0.057	0.44

^a Scour depth observations for the February recovery were determined by subtracting observations recorded during the December recovery from those recorded over the study period.

^b The Cramér-von Mises (W²) statistic was used to evaluate differences between observed and theoretical distributions.

^c Increase in model parameter between December and February recovery period is, most likely, the result of the calculation used to determine observations. See text.

^d Statistically different at the 0.05 significance level.

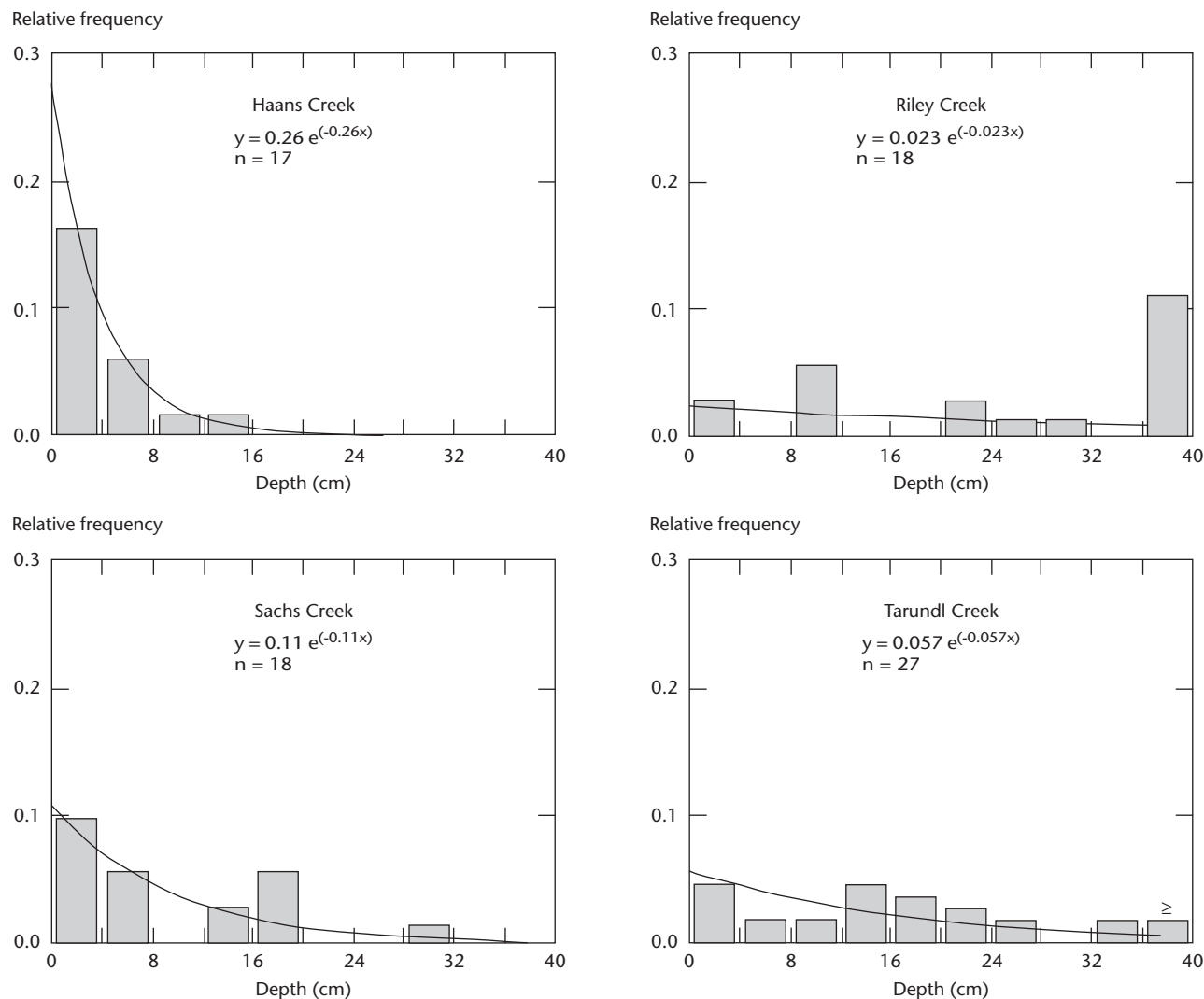


FIGURE 2 Frequency distributions and exponential models for four selected study streams in the Queen Charlotte Islands. Scour depths are cumulative depths for the complete study period (about 4 months). Relative frequencies are calculated by dividing the number of observations in each class by the total number of observations and the class interval width of 4. The width adjustment is necessary because data were grouped into 4-cm class intervals for analysis. Data derived from scour monitors that were eroded from the streambed during the study period are indicated by the greater-than-and-equal-to symbol.

exponential model adequately fits these distributions at the 0.05 significance level (Table 3). The range in model parameters is illustrated by comparing Riley Creek, with a parameter of 0.023, to Haans Creek, with a parameter of 0.26. Thus, these four creeks scoured to different degrees within each recovery period and over the seasonal study period.

Stream Discharge and Depths of Scour and Fill

Power functions relating mean scour and fill depth to flood peak magnitude were established, based on all available indicator recoveries in Carnation Creek (Fig. 3). Both mean scour and mean fill increase with flood magnitude as expected. Coefficients of determination for the linearized relations are 0.86

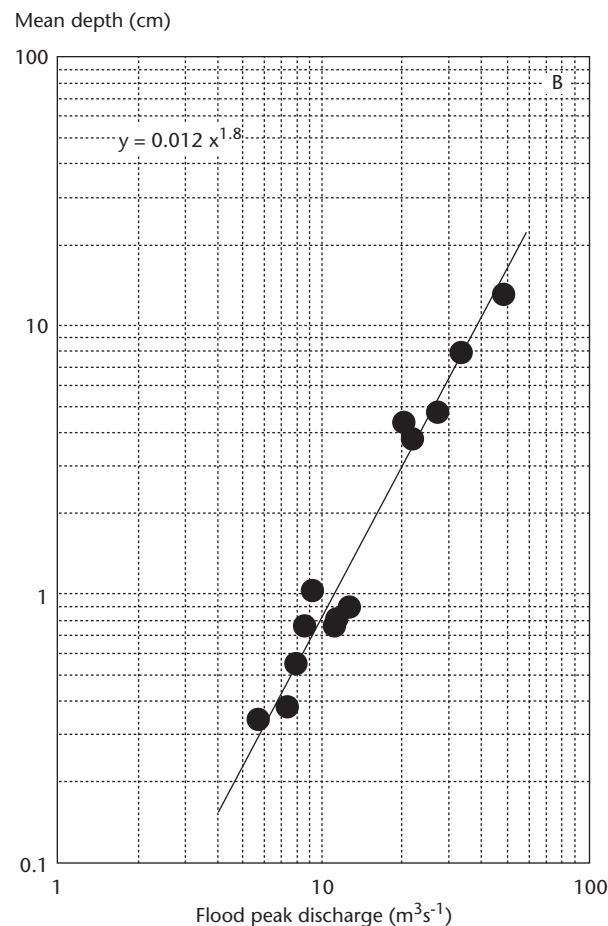
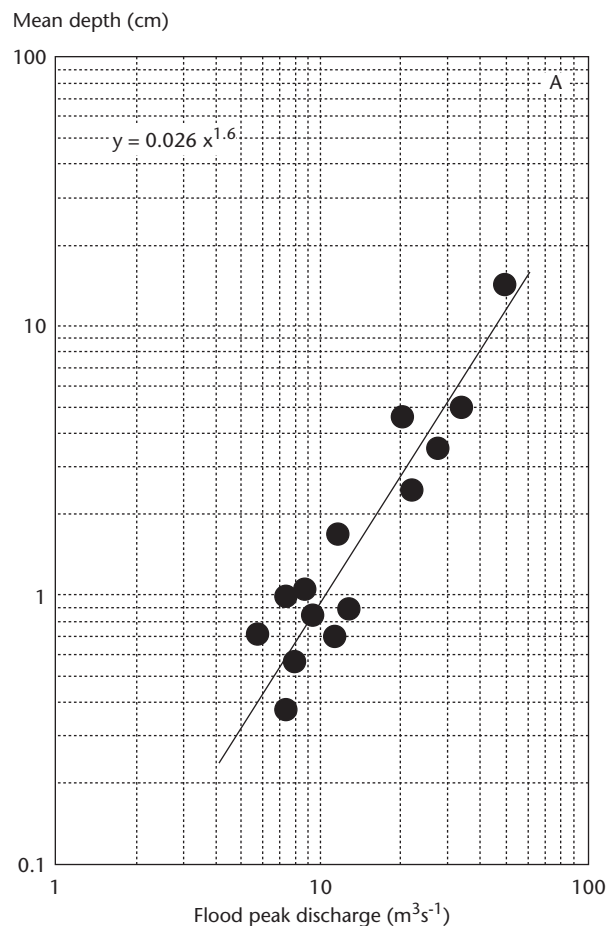


FIGURE 3 Power function relations of mean scour (A) and mean fill (B) to flood peak magnitude in Carnation Creek. Data analysis included scour indicator recoveries completed over two winter flood seasons.

and 0.96 for scour and fill, respectively. Confidence limits constructed for the slopes of the two relations indicate that they are not statistically different at the 0.05 significance level. Hence, the relations of mean scour depth to flood peak magnitude and mean fill depth to flood peak magnitude are similar.

Regional Relations

Mean Scour Depths Regional relations require identification of river basin and channel characteristics that control scour depth in channels. Tripp and Poulin (1986) reported both mass wasting history and study reach gradient as being factors that explain larger values of scour depths in the streams on the Queen Charlotte Islands. These data are being further examined and another factor—basin

area—evaluated in an attempt to establish predictive regional relations.

In the relation between seasonal scour depth and study reach gradient (Fig. 4a), mean depths range from 0.7 to 34 cm in an unsystematic manner with gradient. The mass wasting classification for streams, based on proximity and degree of mass wasting to the study reach within basins (Tripp and Poulin 1986), fails to resolve the scatter in the relation, in part because of the small sample size for each category. A stream with little or no mass wasting evidence may have relatively large mean scour, even in a moderate gradient reach. Furthermore, a stream classified into the second category of mass wasting with similar reach gradient may experience a mean scour depth of about 7 cm or sometimes nearly 30 cm (Fig. 4a).

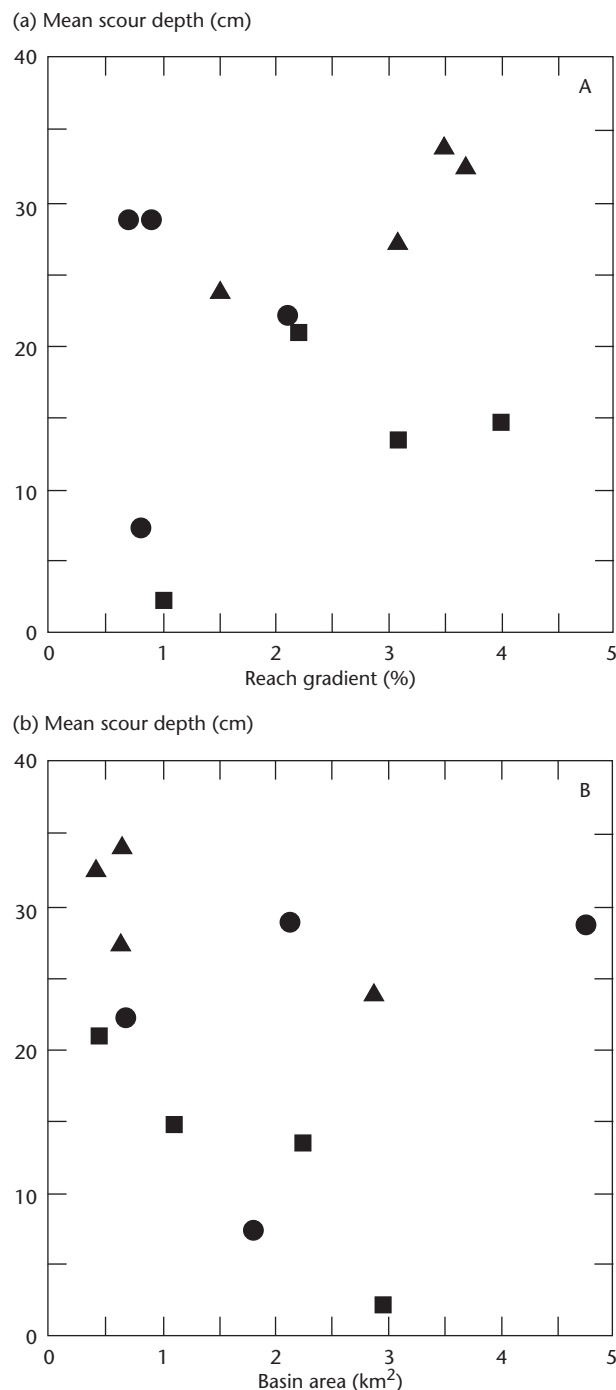


FIGURE 4 Relations of seasonal mean scour depth to study reach gradient (A) and basin area (B). Streams are classified by consideration of the proximity and degree of mass wasting to the study reach. Mass wasting category symbols are: ■ little or no mass wasting evidence in the stream; ● mass wasting evidence upstream of the study area; and ▲ mass wasting evidence within the study reach.

Most streams align within the lower left corner of the relation between seasonal mean scour depth and basin area (Fig. 4b). Three of the four streams with mass wasting evidence in the study reach have small basin areas and relatively large mean scour depths. The three points that deviate substantially from this trend represent the streams located in Rennell Sound, where relatively large mean scour depths in the channels are produced in relatively large basins.

Regional Frequency Distribution A regional frequency distribution of seasonal scour depths was constructed by combining results from the 12 study streams on the Queen Charlotte Islands. The streams were made comparable by using the median diameter of the channel surface sediment of each stream as a scaling factor for scour depth observations (Fig. 5). This distribution of seasonal scour appears exponential in form. The right portion of the distribution beginning at a ratio of 5 reflects the maximum depth of 38 cm that could be recorded by some of the scour indicators. The goodness-of-fit statistic, which incorporates this largest depth class as the right tail of the distribution, indicates that the exponential model adequately fits the empirical distribution at a significance level of 0.01.

Discussion

Frequency distributions of scour and fill depths for Carnation Creek and streams on the Queen Charlotte Islands illustrate that, for a particular flooding period or over a flood season, the channel is scoured and filled over a range of magnitudes. These frequency distributions can be modelled by negative exponential functions. Scour and fill models for a particular flood exhibit similar model parameters, which indicate that a balance exists between the amount of sediment scoured and filled over the study reach. The systematic inverse relation between model parameters and discharge level shows that the channel is scoured and filled more deeply with increasing flow levels, as expected. Empirical observations confirm that the maximum depth measured, and thus the absolute range of depths, increases as discharge level increases. Thus, greater amounts of mobilized sediment occur with larger flow levels, which results in the increased likelihood for changes in channel morphology and associated sediment size distributions in river channels. Difference in parameters of the exponential

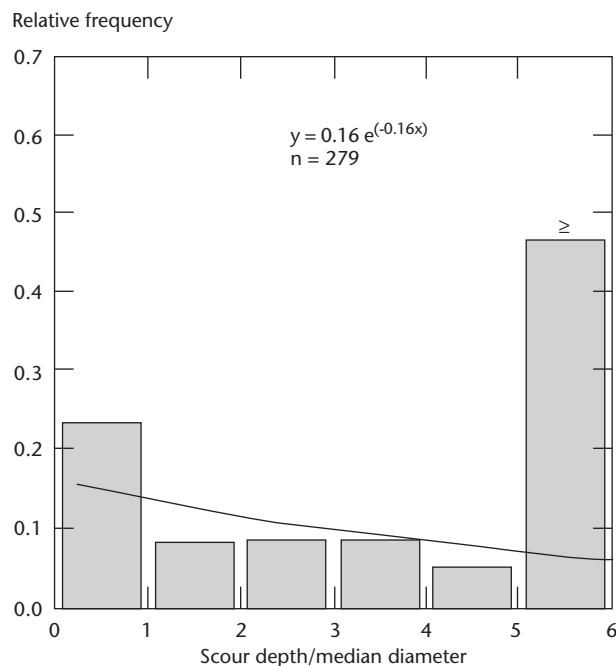


FIGURE 5 Regional frequency distribution and associated exponential model of seasonal scour depths that occurred over the study period. Median diameter characterizes channel surface sediment. Ratio values beginning at 5 are affected by the limitation of scour indicator length.

models portray the varied behaviour of streams on the Queen Charlotte Islands, a relatively small geographic area. In these exponential models the differences reflect, in part, the sharp precipitation gradient that exists in the Queen Charlotte Islands due to topographic influences.

Mean depth versus flood peak magnitude relations indicate that predictive relations for scour and fill based on streamflow are possible. In Carnation Creek, the functional form of these relations is a power function, which gives rise to an increase in mean depth of approximately 2 times, with a unit increase in flood peak discharge. Furthermore, the similarity in the exponents of the relations suggests that the channel within the study reach of Carnation Creek is scouring and filling at the same magnitude, and hence no systematic aggradation or degradation occurred over the study period. Development of explicit relations between mean depth and flood peak magnitude in other streams requires empirical observations.

The relation between mean scour and reach gradient is not yet firmly established, given the scatter exhibited in these limited data. The relation between mean scour depth and basin area suggests that the size of river basin may index the potential for large magnitudes of scour when mass wasting is active because small basins are most directly influenced by mass wasting processes. Moreover, large basins can experience large mean values of scour, given a relatively large input of precipitation as a result of geographic location, as evidenced by the three study streams located in Rennell Sound. A similar adjustment would be expected in other areas with definable precipitation subregions.

The collapse of frequency distributions of scour depth from individual streams into a regional frequency distribution demonstrates that channel sediment size and the structural tightness of surface particles play an important role in controlling scour depth. Given an adequate collection of rivers in a region and a statistically sound sample of scour indicators, a regional distribution of scour depths would most likely be exponential in form, as indicated by the analysis of scour that occurred that occurred in Queen Charlotte Islands streams. The bimodal nature of the observed distribution results from the measurement limitation of scour indicators used in the streams on the Charlottes.

Application to Management For the effective management of fishery and forestry resources, it is encouraging for prediction purposes that frequency distributions of scour and fill depths can be described by a single mathematical function. If mean scour or fill depths are known or can be estimated (for example, from discharge estimates), an exponential function depicting the frequency distribution could be generated to determine the proportion of a channel scouring to a defined threshold depth where critical loss of anadromous fish eggs would occur. Furthermore, prediction of cumulative scour depth for a flood season composed of a particular sequence and magnitude of flood events could be achieved by deriving exponential model parameters for specific flood peaks from a relation between mean scour and flood peak magnitude. These mean values serve as parameters in exponential models for predicting scour and fill depths associated with individual flood events. Determining the seasonal effect could be achieved

by summing individual exponential distributions. Thus, various flood season scenarios could be generated for planning purposes.

It would also be useful for management if predictions of scour and fill could be made on a regional basis. Overall, the attempts at regional relations emphasize that such relations depend on the definition of precipitation subregions (and thus hydrology) and of the physical parameters of river basins, such as basin area, channel gradient, sediment character, and historical evidence of mass wasting. These parameters are, in general, obtainable from maps, aerial photographs, and reconnaissance field work. If an integrated regional predictive relation could be established, streams could be evaluated from this relation based on individual characteristics and preliminary assessments—all with relatively minimal effort and expense. The major limitation of this work for management is the need for empirical observations with which to develop the relations.

Summary

Distributions of scour and fill depths can be described by negative exponential functions in Carnation Creek and the streams on the Queen Charlotte Islands. Thus, the exponential model appears to be generally applicable for coastal streams, whether scour results from single or numerous flood events. The models behave in a predictable manner based on flood peak magnitude, which suggests they may be integrated into management decision-making procedures. The observed differences in scour in the Queen Charlotte Islands streams indicate that both regional hydrology and state of the channel bed affect scour depth, and that further study is required before a general predictive scour model can be described. In the meantime, scour and fill models can be elaborated for particular streams based on observations in the streams. Applied on a seasonal basis, this has the potential to aid enhancement efforts in coastal streams that serve as anadromous fish habitat.

Acknowledgements

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Fine Sediments in Small Streams in Coastal British Columbia: A Review of Research Progress

MICHAEL CHURCH

Introduction

“Fine sediment” is conventionally considered to be material of sand size and finer—material that is frequently and easily moved in streams, usually in suspension. Such material can pose serious problems in the gravel-bed streams of the Pacific Northwest because, in sufficient concentration, it may interfere with the behaviour of fish and other aquatic organisms adapted to the environment of these streams, and even threaten their survival. When it settles onto the bed, it threatens benthic organisms and fish spawning success. More generally, fine sediment reduces water quality and, in community water supplies, poses problems for water delivery works.

The Carnation Creek experimental study and the Fish/Forestry Interaction Program (FFIP) were both initiated in substantial measure to understand the effects of logging on the aquatic environment, and particularly on the environment and life cycle of Pacific salmon, through the processes of sedimentation and associated stream channel changes. The purpose of this paper is to give a critical discussion of progress in these two programs toward furthering our understanding of the occurrence of fine sediments in small, salmon-supporting streams in coastal British Columbia, both natural and disturbed.

Characterization of Fine Sediments

It is first necessary to acknowledge that “fine sediment” has different operational definitions within different scientific disciplines, and even in different analyses within one discipline. Some common understanding about the meaning of the term would substantially aid study.

Sedimentologically, fine sediment is understood to consist of sand and finer material. However, there is no universal standard for the definition of size limits for various classes of material. In stream and aquatic studies in British Columbia, two standards

are common. Most scientific work is based on the Wentworth classification of clastic materials (Wentworth 1922). However, much engineering work uses a classification traceable to British standards. Table 1 compares the two scales. Differences between them are small but could significantly influence the characterization of sediments in some cases, since large amounts of material may occupy a narrow range of grain size.

TABLE 1 Sediment texture scales

Texture description	Class limits (mm)	
	Wentworth	British
Medium and coarse gravel	64.0	
Fine gravel	8.0	9.55
Granules (“pea gravel”)	4.0	
Very coarse sand	2.0	2.38
Coarse sand	1.0	coarse sand
Medium sand	0.5	1.19
Fine sand	0.25	0.30
Silt	0.064	0.074
Clay	0.004	

The Wentworth system is based on divisions in successive powers of 2 (e.g., the lower limit of gravel is $2^3 = 8.0$ mm; the lower limit of medium sand is $2^{-2} = 0.25$ mm). The British units follow a similar sequence, but the powers are displaced by 0.25 unit; for example, the lower limit of gravel is $2^{3.25} = 9.51$ mm. The minor discrepancy in the second decimal affects some of the division points.

Fisheries scientists interested in describing streambed sediments have selected a number of size-related measures to be indices of sediment quality in relation to fish behaviour. Fine sediment in the bed reduces spawning success, so the proportion of bed sediment finer than some selected size has often been used as such an index. In a review, Chapman

(1988) identified 9.5 mm, 3.3 mm, 0.85 mm, and 0.105 mm as sizes that have been selected, the latter being proposed as the “upper limit of silt.” (In comparison with standard texture breaks [Table 1], 3.3 mm = $2^{1.75}$ is within the granule range; 0.85 mm = $2^{-0.25}$ is within coarse sands; and 0.105 mm = $2^{-3.25}$ is within fine sands.) The two smallest sizes appear to have become prominent reference sizes as the result of field work by McNeil and Ahnell (1964) on the ability of pink salmon (*Oncorhynchus gorbuscha*) to remove material finer than these sizes from redd diggings. Subsequently, 0.85 mm appears to have become the most widely useful single reference size (see discussion in Chapman 1988). A 3.3-mm criterion emerged as a useful correlate from field studies by Koski (1966) on emergence of coho (*O. kisutch*) fry, while 9.5 mm was introduced as one index of gravel size distribution in laboratory studies by Tappel and Bjornn (1983). Chapman emphasizes that none of these index sizes represents a sufficient or physically satisfactory explanation of spawning success. The variable nature of streambed sediment size distributions, and the fact that it is intragravel pore spaces that actually facilitate the biological processes, are both reasons for that conclusion. It is interesting, nonetheless, to note that characteristic size distributions of good quality spawning gravel for several *Oncorhynchus* species have very little material finer than 0.85 mm (typically less than 3%).

Another way to characterize fine sediment in streams is to define it as material that commonly moves in suspension. In the most powerful currents this might include small granules, but in almost any small stream on the British Columbia coast it would be unusual for mineral material coarser than about 1 mm to be moved in suspension in normal water floods. Most of the time, nearly all of the suspended mineral material would be finer than 0.25 mm. For the purpose of appraising the normal stream environment, the value of 0.85 mm found useful in fishery studies could be taken as a practical upper limit for suspended mineral matter. (The writer is aware of only one size distribution measurement of suspended mineral material in a small coastal stream, taken at Carnation Creek. All of the material was fine sand or finer. Samples taken to determine total concentration are usually far too small to permit size analysis.) This may be no coincidence: the ability of fish to clean material from gravels

depends on the propensity of the material to remain suspended, once disturbed, for at least a short distance in water velocities commonly encountered near the streambed.

The size distribution of streambed gravels is often bimodal (Fig. 1). In clean gravels, the finer mode is very subordinate. The gap between the two modes commonly falls in the range 1–4 mm and is centred near 2 mm; in powerful rivers it may fall a bit higher. The reason for the bimodal distribution is not completely understood (see Wolcott 1988) but, in general, is considered to be related to relative hydraulic mobility of coarse versus fine material, coupled with the ability (or inability) of finer material to “hide” by penetrating the interstices of the coarser material. This division lends some rational support to the proposal for using 0.85–1.0 mm as a criterion for the limit of “fine material” in streams.

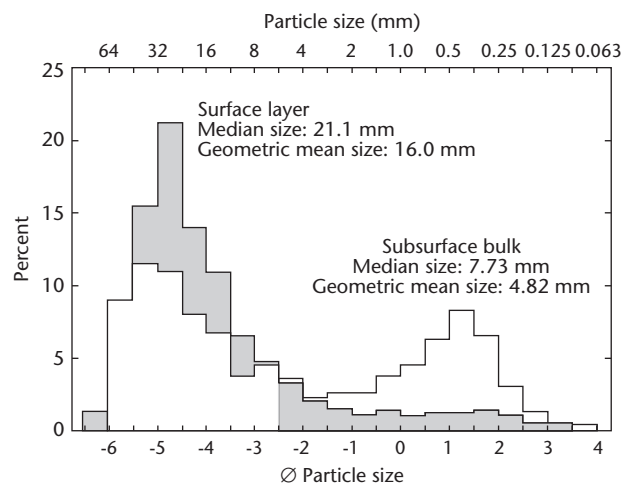


FIGURE 1 Grain size distribution from a gravel-bed stream, showing bimodal distribution of the subsurface material. The fine mode is missing from the surface material (Mamquam River, near Squamish, B.C.).

Another relevant classification of hydraulic behaviour of stream sediment is the division between bed material and wash material. The former is material normally found in the bed and lower banks of the channel, which forms the channel boundary. It must be able to withstand ambient fluid stresses most of the time. The latter is material which, once entrained, normally travels a long way,

so that it is not present in significant quantities in the bed and lower banks. Bed material may move in suspension or in traction (over the bed), but wash material always moves in suspension. In many rivers, the upper limit of wash material falls in the range 0.125–0.250 mm. In steep, gravel-bed channels, the division may be somewhat higher. There is a good hydraulic reason for the division: finer material is maintained in suspension at velocities lower than its entrainment velocity, so it always moves in suspension and can easily move a long way.

Wash material (in effect, fine sand and finer) normally contributes a few percent of the streambed composition. This material is trapped by the filtering action of larger material as water circulates through the streambed. If large volumes of such material are introduced into the stream, however, it is capable of penetrating deeply into formerly clean gravels and clogging them completely (Beschta and Jackson 1979). In comparison, substantial volumes of larger sands may seal the surface, but normally do not penetrate deeply.

To summarize, then, it may be useful to define “fine mineral material” in stream systems as particles finer than 1.0 mm (choice of the round number is deliberate), and to note that two distinct sub-populations divided at about 0.2 mm ($0.18 \text{ mm} = 2^{-2.5}$ is the nearest usual Wentworth break) exhibit significantly different behaviour. Stream power may play some role in the exact definition of these boundaries; in many streams, both boundaries appear to fall slightly below the proposed values.

None of the foregoing discussion considers fine organic material. That is because there have not been systematic measurements of fine organic material in many streams. Most such measurements have been research measurements in studies of carbon flux. In water quality studies, total suspended solids are commonly reported (as “non-filterable residue”), and this includes organics. However, the samples usually are dip samples which do not capture particles that are stratified in the water column. While one may assert from casual, but widespread, observations that fine organic matter commonly is a minor constituent of gravel deposits in coastal streams, there is in fact very little systematic knowledge about it.

Carnation Creek provides a single datum. In 1974–75, 32.5 tonnes of detritus entered the creek (Neaves 1978, in Hartman and Scrivener 1990);

suspended sediment transport was 146 tonnes. Most of the detritus was leaf litter which, at least initially, would have been large bits.

Carnation Creek Suspended Sediment Studies

At Carnation Creek, 43% of the 10.1 km² above the main Water Survey of Canada gauge (B-weir) was logged in a 5-year period between 1976 and 1981. Road construction began in 1975 after a 4-year period to determine pre-harvest conditions. With respect to fine sediment, the problem was to attempt to detect the effect of the logging activity on the regime of fine sediment transport in the stream.

In Carnation Creek, as in most steep coastal streams, it is reasonable to suppose that fine sediment is sediment transported in suspension. This coincidence makes it possible to establish straightforward procedures for sampling. At B-weir, near the mouth of the basin, an automatic pump sampler was used to obtain frequent samples. The observing program was undertaken by the Water Survey of Canada between 1973 and 1986, and the data have been reported by Tassone (1988) and Hartman and Scrivener (1990). The problem defined above was addressed by a before-and-after logging comparison of the suspended sediment transport regime at this one site. In this paper, the results are critically examined, with a view to drawing some lessons from the work.

All annual data presented here are for the “water year,” extending from 1 October until 30 September following. This treats each winter high flow season within a single annual time unit.

Figure 2 displays a summary of the annual load of Carnation Creek. There is no apparent evidence in these results for a land disturbance effect. The figure also shows mean annual suspended sediment concentration, the long-term discharge-weighted mean being 8 mg l⁻¹. In general, mean concentration follows the load pattern except in 1978–80, when it appears that concentrations were anomalously high. The numbers in the figure—the maximum daily suspended sediment concentration observed in each year—again show no trend. These sorts of results have been used to suggest that the effect of logging on the fine sediment regime of the creek was negligible or slight.

A direct plot of annual sediment load against annual flow volume (Fig. 3) confirms the anomalous character of the 1978–80 period. During this period,

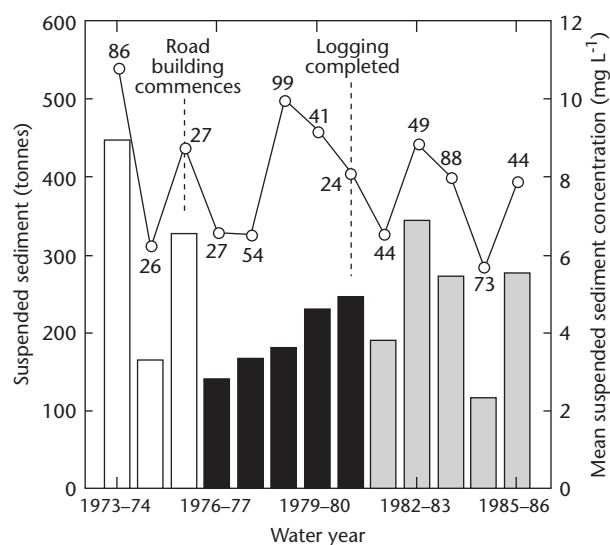


FIGURE 2 Annual suspended sediment yield from Carnation Creek (bars) and mean annual concentration of suspended sediment (line). The numbers beside each mean annual point represent the maximum suspended sediment concentration measured in that year (mg L^{-1}). Shading of the bars indicates years before, during, and after logging. (Display based on Fig. 47 of Hartman and Scrivener 1990.)

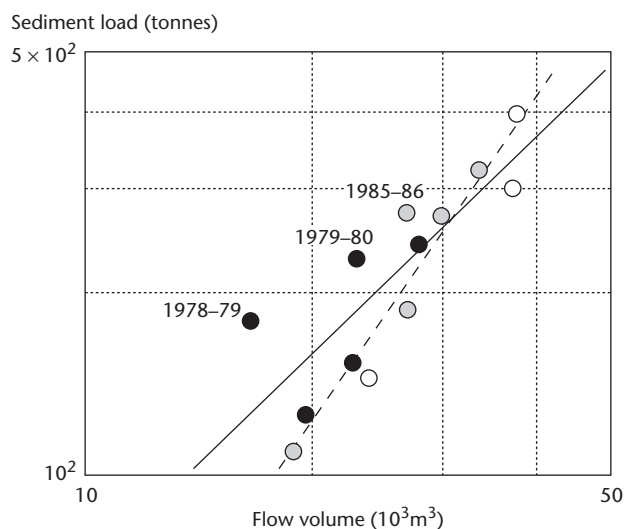


FIGURE 3 Annual suspended sediment load versus annual flow volume. The solid line indicates the regression relation. The dashed line was drawn by eye and is interpreted to represent the normal load-volume relation on the stream. Points coded as bars of Fig. 2.

creekside logging occurred with relatively careful treatment or with leave strips, but many creekside alders were blown down during a storm. Intensive creekside treatment had previously occurred on a block cut in 1976–77, with no obvious immediate effect on mean or total suspended sediment. That year experienced no significant high flow (instantaneous peak flow was $16.0 \text{ m}^3 \text{ s}^{-1}$). It is not known, and would be difficult to determine now, whether the apparently high incidence of suspended sediment in 1978–80 was the direct consequence of logging in those years, or represented a delayed effect of the earlier intensive treatment, or was due to some other cause altogether.

In the winter of 1978–79, a peak flow of $43.9 \text{ m}^3 \text{ s}^{-1}$ occurred, the largest observed up to that time in the study. The storm occurred on 7 November, 1978, when 58 mm of rain fell, following 41.7 mm during the previous day. Neither total is exceptional, and the 2-day event was much smaller than the 2-year 48-hour storm. There was also no snow on the ground. Nonetheless, this storm produced a daily mean suspended sediment concentration of 99 mg l^{-1} (the largest on record) and a daily load of 97.5 tonnes. These observations focus attention on individual storm events.

Runoff events that transport a significant amount of fine sediment are ones in which relatively high flows are sustained for a considerable length of time. A search was made of the records to identify days on which daily mean flow exceeded $10 \text{ m}^3 \text{ s}^{-1}$ (Table 2). (Many events fall just below that threshold and appear not to transport large amounts of sediment.) Maximum instantaneous flows are available for some events, and show that there is no obvious correlation between the instantaneous peak flow and the daily mean. Since both size and duration of flow influence total sediment transport, it is apparent that no simple correlation between flow and sediment transport is available. There have been 20 events in all (to the end of the 1986 water year), with a slightly greater rate of events in the pre-logging period. The biggest events, however, occurred from 1980 on.

There is a rough relation between storm mean flow (which is, in information terms, the same as runoff volume) and total fine sediment load (Fig. 4). (The floods of 7 November 1978 and 4 January 1984 stand out as notable exceptions.) Almost all of the highest sediment-yielding floods also had notably

TABLE 2 Major sediment transporting events at Carnation Creek, 1973–1986

Date	$\langle Q \rangle$ m^3s^{-1}	Q_p m^3s^{-1}	$\langle C \rangle$ mg l^{-1}	L tonnes	L/L_{ann} %
Pre-logging					
30 Feb. 74	12.4		20	23.6	5.81
24 Nov. 74	13.4		26	33.2	22.7
3 Nov. 75	13.9		27	35.7	11.6
13 Nov. 75	11.6		26	28.9	9.35
2 Dec. 75	13.8		26	32.9	10.6
During logging					
12 Feb. 77	13.1	34.8	27	33.7	26.5
7 Nov. 78	11.4	43.9	99	97.5	54.1
17 Dec. 79	13.5	23.4	41	47.8	20.5
1 Nov. 80	11.2	15	14.5	5.94	
10 Dec. 80	14.0	24	29.0	11.9	
26 Dec. 80	21.6	43.1	38E	78.9	29.1
Post-logging					
31 Oct. 81	11.0		15	14.3	7.52
23 Jan. 82	13.7	50.0	44	52.1	27.4
22 Oct. 82	10.3		45	40.0	12.4
11 Feb. 83	20.0	36.2	49	84.7	26.2
15 Nov. 83	13.7		11	13.0	4.79
4 Jan. 84	20.0	65.1	88	152.0	56.1
7 Oct. 84	13.2		14	16.0	5.71
9 Oct. 84 ^a	10.0		10	8.64	3.09
24 Feb. 86	23.2	49.3	44	88.0	31.4

^a This event probably is not independent of the preceding one.

Data are extracted from Water Survey of Canada records. $\langle Q \rangle$ is mean daily flow and Q_p is instantaneous maximum flow for the day; instantaneous maximum flow is shown only when the event yielded the highest instantaneous flow of the year. $\langle C \rangle$ is mean suspended sediment concentration for the day. L is daily load and L_{ann} is total annual load. E indicates an estimated quantity. Most suspended sediment samples at Carnation Creek were obtained by an automatic sampler with a fixed intake. Distance of the intake from the streambed varied according to the history of scour and fill of bed sediment near the intake. Hence, quoted sample concentrations are not closely comparable amongst all events. This circumstance introduces an unknown measure of error into the cumulated load estimates as well.

high peak flows. A peak flow threshold of $40 \text{ m}^3\text{s}^{-1}$ is identified in Figure 4, and the single, apparently disparate, event registered a peak flow of $36.2 \text{ m}^3\text{s}^{-1}$. Another evident feature of the plot is that the post-logging events show greater scatter than preceding ones.

In considering both the data of Table 2 and the pattern revealed in Figure 4, it should be noted that the data are based on calendar days (because that is the way the published records report them), so that they probably do not reflect complete flood events. This circumstance may contribute significant non-systematic variability to the displayed results.

Some details are known about the largest event, which occurred on 4 January 1984. The 190 mm of rain exceeded the 25-year 24-hour expected total. Although there was no snow on the ground, the preceding period had been wet, with 72 mm on January 1. Precipitation on the 3 days surrounding this day constituted a 15-year event. During this major storm, there were numerous landslides in the upper part of the drainage basin and a debris flow through the canyon in the middle reach of Carnation Creek. The debris debouched into the lower course and the downstream flood caused extensive reorganization of log jams and major movement of sediment stored

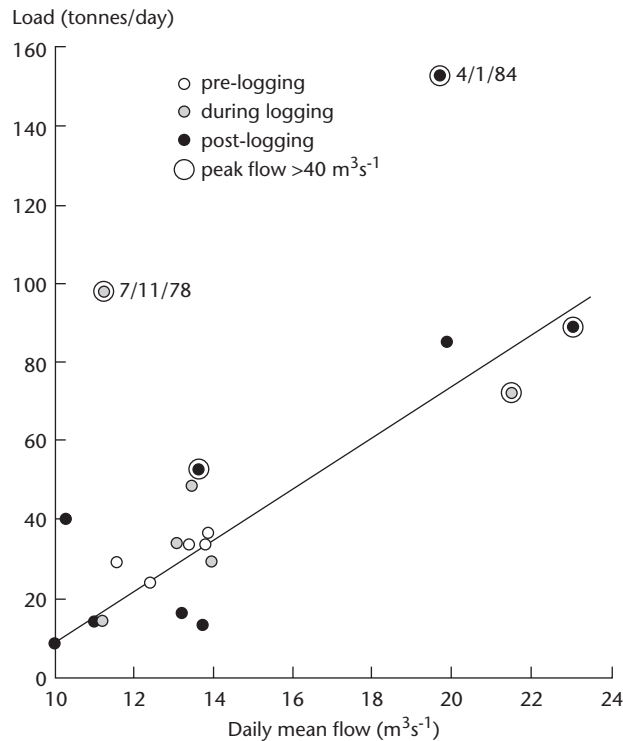


FIGURE 4 Daily suspended sediment load versus daily mean flow for days with greater than $10 \text{ m}^3 \text{ s}^{-1}$ mean flow. The indicated relation was drawn by eye.

in gravel wedges associated with the jams. Considering the debris flow on the main channel and the downstream disturbance, it is not surprising that the highest sediment concentrations (peak recorded, 842 mg l^{-1}) and load were observed in this event. This history, in turn, focuses attention on the actual sources of sediment associated with each flood and with within-storm details of sediment movement.

Details of individual floods have not been studied. Figure 5 illustrates the flow and sediment concentration in three storms. The first (12 February 1977) reveals a fairly direct sediment response to flows, but with concentration slightly leading the flow peak, and with an anomalously large response to the late secondary peak. Sediment concentration customarily “leads” flow when fine sediment is mobilized from the channel bed or banks on rising stage and then is exhausted before the peak flows are reached. The prominent late peak in sediment concentration probably is related to the release of a discrete store of sediment by the late flow rise. Such a sediment

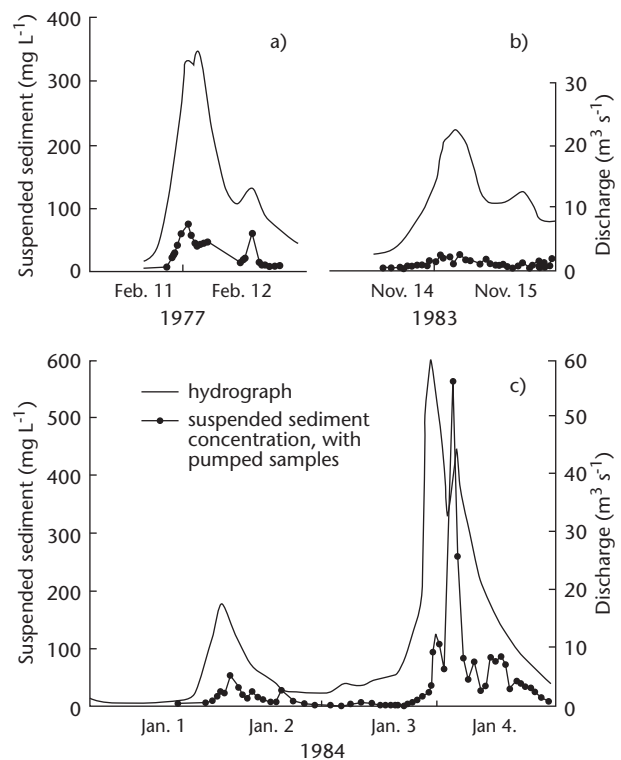


FIGURE 5 Flood hydrographs for some individual storms in Carnation Creek (from Tassone 1988: Fig. 8).

source could be a bank collapse or a significant change in a log jam. The peak was detected by a single sediment sample, so a small, transient event very close to the automatic sampler intake cannot be ruled out.

The 15 November 1983 event is remarkable for the lack of sedimentary response to a substantial flow. Evidently no major changes occurred along the channel during this event. In comparison, the 4 January 1984 event reveals a more sensitive but still initially moderate response. A major spike of sediment-charged water follows, with the secondary flow peak. This is the signature at B-weir of the upstream debris flow and log-jam-breaking event. Subsequent variability in suspended sediment concentration was caused by continuing changes along the channel in response to that primary event.

Fine sediment is mobilized in small drainage basins from a number of sources:

1. from the bed and lower banks, as bed material is entrained with rising flows. In Carnation Creek,

this source is very modest, as there is only a few percent of fine sand and silt in the bed (Hartman and Scrivener 1990). Sediment concentrations commonly are in phase with, or slightly lead the flow.

2. from streamside, where fine material falls into the creek during low flows as the result of wetting/drying or freeze/thaw erosion of the banks, or as the result of tree-throw. This source is probably also modest in Carnation Creek. Marine sediments exposed in the banks of the lower course constitute a potentially major source of fine material, but they are highly compact and erode only very slowly. Sediment concentration leads flow, since loosened material is mobilized on rising stage and soon exhausted.
3. directly from the land surface accompanying overland flow. This source is minor in most forested drainage basins. A significant source is direct drainage from roads, but this appears to have been a minor factor in Carnation Creek. Sediment concentration often lags behind flow because of travel-time from the terrestrial sources.
4. from episodic release of fine sediment associated with sediment mass movements into the channel. In Carnation Creek, this source includes major bank collapse and debris flows from gullies flowing into the canyon reach. Occurrence is random.
5. from episodic release of substantial volumes of fine sediment in the channel when a log jam fails.

The last two sources probably are the cause of major spikes of fine sediment in Carnation Creek, with (4) being by far the most efficient delivery mechanism for fine sediment. Individual events may or may not be related to forest management activities. To prove such effects, analysis must be conducted on a storm-by-storm basis, and there must be knowledge of events in the landscape that can be connected with the gauge records. Discrete sediment delivery events represent the major source of fine sediment in most small, forested streams in coastal British Columbia. Gauging records are not sufficient to explain the pattern of sediment mobilization, and time-aggregated analyses actually obscure the causes of sediment incidence. To properly examine the question whether logging activity influenced the occurrence of fine sediment in Carnation Creek, it will be necessary to explain within-storm sediment transport by knowledge of the causes of sediment

mobilization in the landscape. Such analyses have not, so far, been conducted.

FFIP Fine Sediment Studies In FFIP, two questions about fine sediment in stream channels were addressed:

1. Can land use effects be detected in fine sediment yield to streams?
2. If so, where does the fine sediment go?

The second question was prompted by the observation that spawning gravels in Queen Charlotte streams have low fine sediment content despite a high rate of land surface disturbance.

Land Use Effects The approach to answer the first question was to conduct a synoptic survey of sediment concentration in a substantial number of streams selected to cover a range of land surface conditions. Figure 6 locates the sampled streams and Table 3 gives some data of their drainage basins, along with a brief description of the classification system by which the results are organized. Samples were opportunistically taken between August 1983 and March 1984 to determine the fine sediment concentration in the water column.

Figure 7 displays the distribution of suspended sediment concentrations found in the survey. There were 249 samples in total, or an average of 12 samples per stream. It is not known how well the data truly reflect the regime of the streams: opportunistic sampling of a highly episodic phenomenon is very difficult. But, insofar as the streams were sampled as a group, the data do form an internally comparable set. It is first clear that suspended sediment concentration is a highly skewed variate. Approximately two-thirds of all samples returned results of $<25 \text{ mg l}^{-1}$ suspended sediment concentration—that is, little or no suspended sediment within the resolution of the measurements. About 20% of the samples exceeded 100 mg l^{-1} , with a few individual samples exceeding 1000 mg l^{-1} . The highest value observed was 4400 mg l^{-1} .

A slight preponderance of the higher suspended sediment concentrations are contributed by “old logged, mass wasted” basins. In comparison, “new logged, mass wasted” basins do not exhibit elevated sediment concentrations (in comparison with all not-mass-wasted classes). A reason for this may be the reduced degree of streambank damage associated

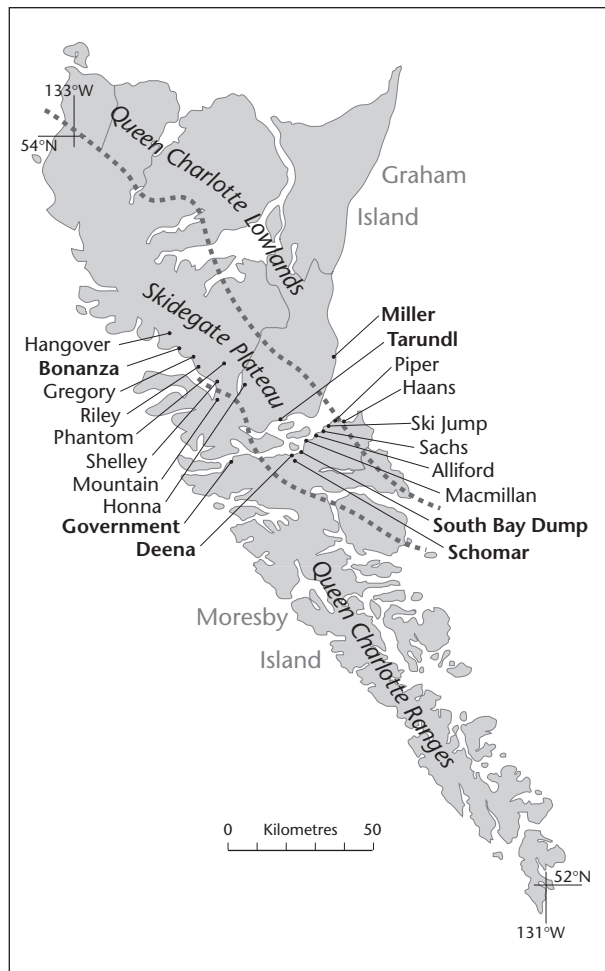


FIGURE 6 Location of streams sampled in the FFIP synoptic suspended sediment sampling program, and of streams (named in bold type) studied for environments of fine deposits.

with “new logged” methods. However, there are at least three possible confounding factors. Stream stage is well known to influence suspended sediment concentration. In this program, this factor was not controlled. However, the result is sustained when comparisons are constrained to samples taken on the same day (with, presumably, comparable runoff conditions from basin to basin). Another significant uncontrolled effect is drainage basin size. The old logged, mass wasted group includes the smallest

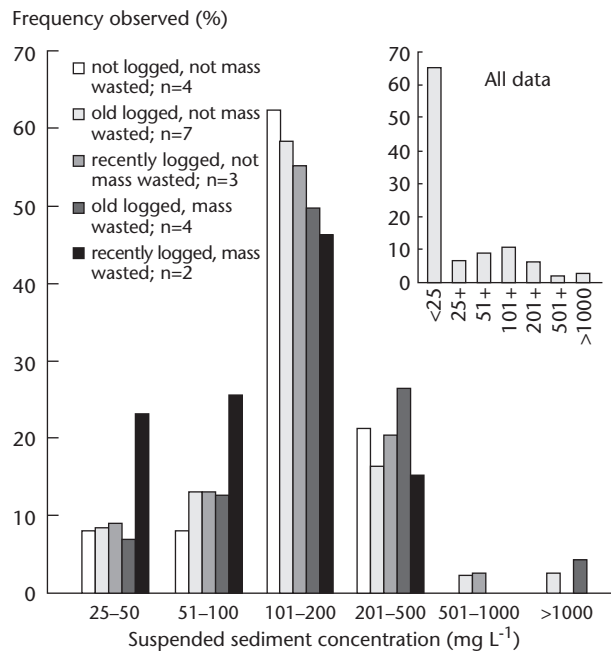


FIGURE 7 Distribution of observations of significant suspended sediment concentration in a synoptic survey of streams in the Queen Charlotte Islands (frequency distribution of all observations, not classified). A “significant concentration” is defined as being $> 25 \text{ mg L}^{-1}$. Streams are classified by land use history (see Table 3 for definitions). Note that the concentration classes are not uniform; n indicates the number of streams in each group (analysis by D. Hogan).

drainage basins in the study, and thus the ones in which measurements were generally taken closest to upstream sources of fine sediment. Finally, geology is confounded in the results: the old logged, mass wasted group of basins is situated entirely on the Honna and Haida formations, clastic sedimentary rocks known to be erodible. Most of the other basins are situated mainly on volcanic rocks (some of which are also considered to be susceptible to erosion).

TABLE 3 *Data of FFIP study streams^a*

Name	Drainage area		Logging history		Mass wasting ^b	
	Total	Steep land (km ²)	% cleared	Age (yr)	Occurrence no. km ⁻² yr ⁻¹	Yield to streams m ³ km ⁻² yr ⁻¹
Not logged, not mass wasted ^c						
Government	16.1	7.7	0	—	0.12	0.50
Gregory	36.7	14.8	0.8	4.4	0.30	1.2
Hangover	21.2	11.6	0	—	0.15	0.60
Phantom	18.6		3.2			
Old logged, not mass wasted						
Piper	4.2	?	9.5		0	0
Schomar	6.6	25.0	6.4	15		
Miller	22.4		13.4			
Mountain	12.8	10.2	9.4	17	0.13	0.20
Tarundl	11.3	3.2	35.4	8.6	?	0.34
Haans	34.8					
New logged, not mass wasted						
Deena	63.0					
Honna						
Bonanza	47.4	22.9	12.9	6.6	0.67	5.1
Old logged, mass wasted						
Sachs	17.8	6.8	64.7	9.5	1.7	9.8
So Bay Dump	4.0	2.0	80.0	7.6	2.6	25
Ski Jump						
Macmillan	6.2	3.1	64.5	5.5	2.6	24
Alliford						
New logged, mass wasted						
Riley	28.7	12.0	12.2	6.6	1.2	5.7
Shelley	5.2	2.9	17	13		

^a Names in bold indicate streams studied for downstream occurrence of fine sediments in sediment deposits.

^b Data from Rood (1984). Calculations are based on the steepland area in each basin.

^c Basin is considered “not logged” if only a small proportion of the total area is cleared. Logging style refers to methods rather than to age; “old logging” includes cat and skidder hauling, clearing to streambank and, possibly, hauling through the stream channel; “new logging” does not include these practices and is restricted mainly to high lead. “Old logging” mainly occurred or began before 1966. The area is considered to be “not mass wasted” if the sediment yield to streams is less than 1 m³km⁻²yr⁻¹.

Figure 8 provides a summary comparison of the results by stream class. Mean sediment concentration in the old logged, mass wasted group is considerably higher than in any other group. However, the huge variability of the results precludes the assertion that the difference is generically significant.

The investigation demonstrates the episodic occurrence of elevated concentrations of suspended sediment in Queen Charlotte streams and associates

them dominantly (but not exclusively) with basins on certain rock formations logged by obsolete methods. The results are consistent with knowledge that the incidence of elevated concentrations is episodic and relatively infrequent, yet very high (>1000 mg l⁻¹) concentrations can occur occasionally. However, the experimental design and the size of the program both preclude the extraction of more refined conclusions. Because of the episodic nature

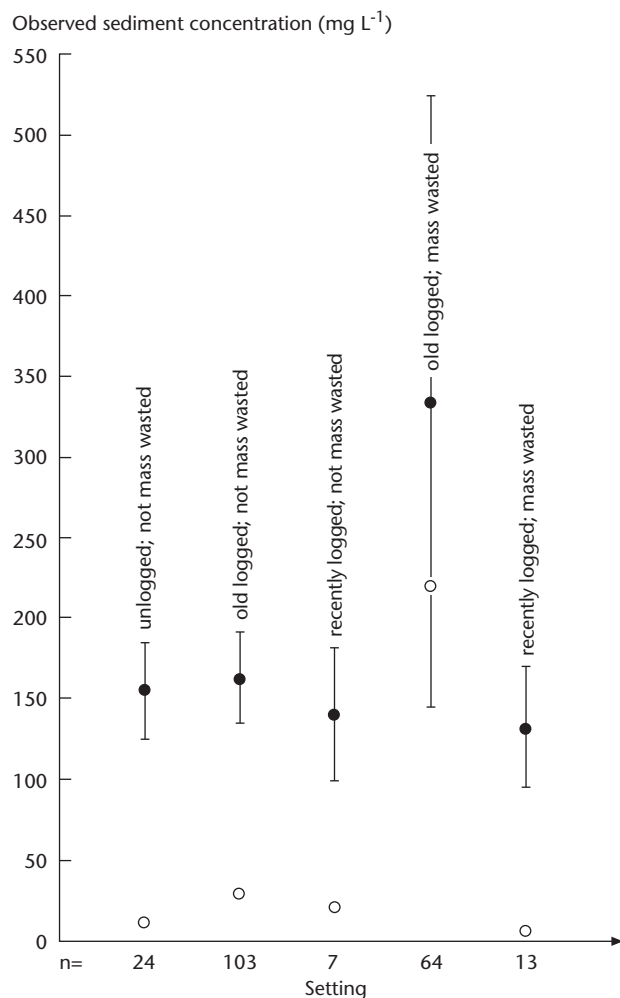


FIGURE 8 Mean of significant sediment concentrations observed in sampled streams, classified by land use history. Graph shows the mean \pm 2 standard errors. The open circles indicate mean concentration when the $< 25 \text{ mg L}^{-1}$ observations are included (see Fig. 7 inset for frequency); n indicates the number of observations in each group (analysis by D. Hogan).

of the phenomenon, temporal variability is large, so that an intensive sampling program or continuous monitoring devices would be required to obtain good discrimination between sites. In addition, the large variability of land surface condition and the need to account for geology, topography, exposure, and land use history all dictate that a very large sample of basins be included in post-treatment spatial comparisons. The requirements for a sensitive analysis are formidable.

At present, a good deal more is known, in general, about the temporal pattern of suspended sediment transport than is known about spatial variability. Very little is firmly known about the relative importance of the specific, spatially variable factors listed above in controlling the regime of fine sediment incidence in the long run. To overcome some of these lacunae, it appears well worthwhile to persist with studies of the type attempted in FFIP. The FFIP study clearly indicates the magnitude of the task and provides some clear lessons for study design.

Where Does the Fine Sediment Go? This question was studied by dividing the stream channel into a number of characteristic depositional environments across the channel and along the course of the stream (Fig. 9). These were systematically searched in a subsample of the synoptic study streams (identified by bold print in Figure 6 and Table 3) for the presence of fine sediment. It is important to note that the study design specifically targeted certain environments to search for the presence of fines (i.e., sub 1 mm material). In-channel depositional environments included medial bar tops and pocket deposits in the lee of major obstructions such as boulders or LOD pieces. Channel-side deposits included lateral bar tops and shadow deposits in the lee of bank projections and LOD. The overbank zone was taken to be any site adjacent to the channel where perennial terrestrial vegetation was growing. In overbank sites, recent flood deposits (rather than organic soil) were sampled. The results do not represent a characterization of the overall sedimentology of the study streams. However, the internal comparisons do indicate where the fine sediment occurs, and frequency gradients of fine material generally indicate the locus of travel of fine material. To emphasize the relative occurrence of fine materials in the selected environments, the results have been uniformly truncated at the upper end of the distribution at 8.0 mm. The truncation was not severe.

Figure 10 illustrates the overall, grouped results (based on proportional size distributions) for the study streams in a pattern that parallels the study design. Individual streams replicate the overall results. Fines were found in all the environments studied and sands dominate in all cases. Gravel declines abruptly from “in-channel” depositional environments to the others, while the incidence of very fine material (silts and clays) increases steadily

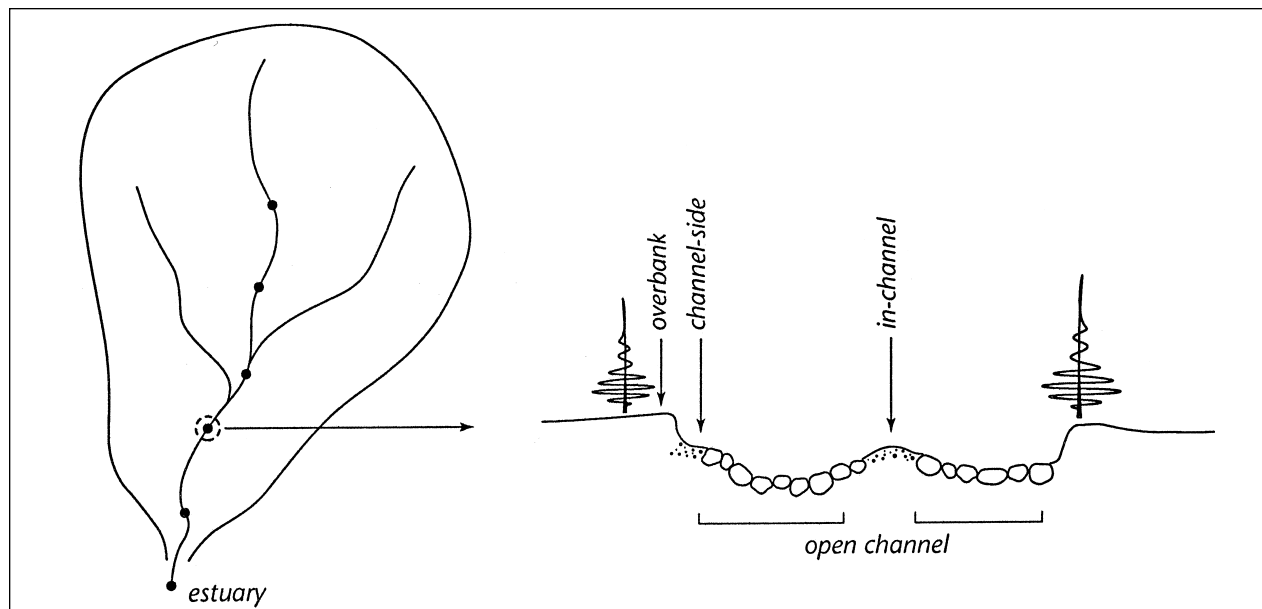


FIGURE 9 Sampling design for the detection of fine sediment in stream deposits, Queen Charlotte Islands streams (see Table 3 for streams studied).

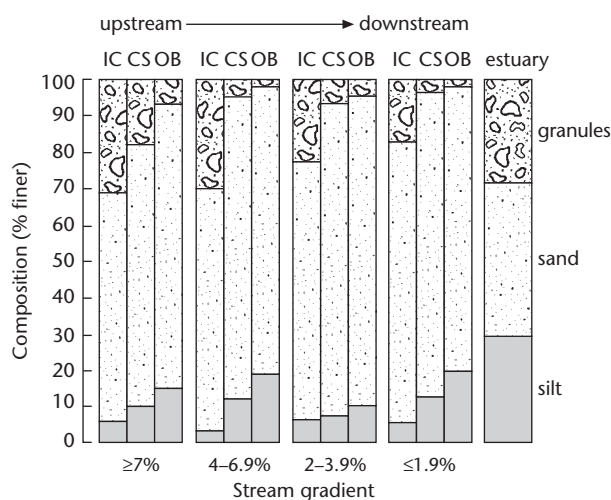


FIGURE 10 Proportional distribution of sizes finer than 8 mm in specified sedimentary environments along stream channels in the Queen Charlotte Islands classified by gradient (compare sampling design in Fig. 9); IC = in-channel; CS = channel-side; OB = overbank (analysis by D. Hogan).

from in-channel, to channel-side, to overbank, as should be expected.

Progressively downstream, there is a systematic trend toward reduced gravel and increased sand proportions in the in-channel and channel-side depositional environments, but this is not sustained overbank. Very fine materials exhibit no systematic downstream trend in any environment. This reflects entrainment controls on the incidence of the proper bed material of the channel, controls that do not influence the occurrence of very fine material. Very fine material is caught by being trapped in the interstices of coarser material in the channel, or by advecting into still water overbank. These processes appear to be equally effective everywhere along the channel.

In comparison with all these sites, spawning riffles are vigorously washed and frequently scoured, which removes the fines that accumulate there during periods of moderate flow. The steep gradients and frequent freshets in Queen Charlotte streams emphasize this cleaning effect. The net result (Fig. 11) is that the "open channel," cobble-gravel bottom of the pool-riffle sequence exhibits

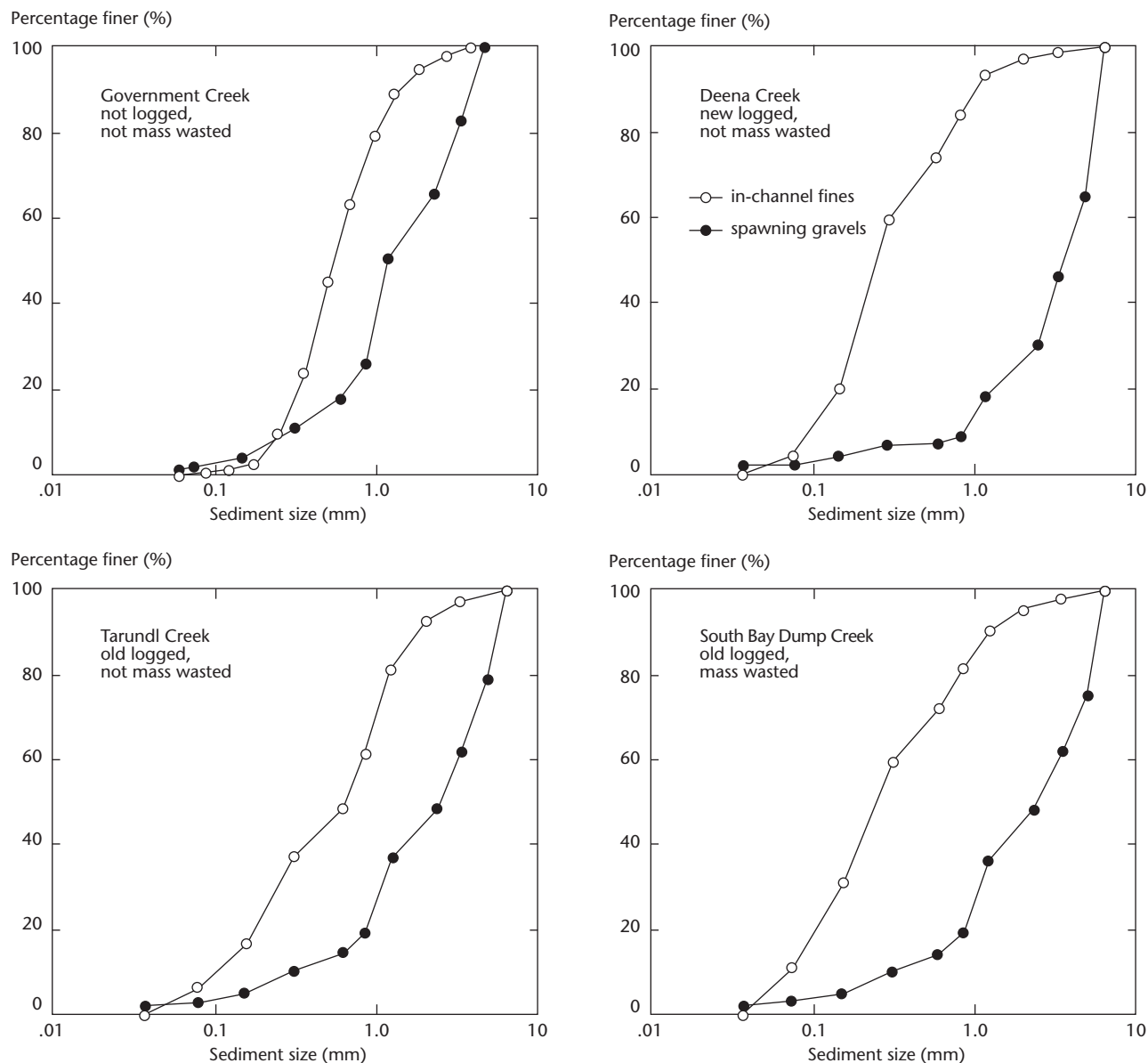


FIGURE 11 Comparison of the texture of fine sediment deposits in Queen Charlotte streams with that of spawning gravels from the same channels.

strongly coarse-skewed sediments, even within the truncated -8.0 mm range, whereas the protected, depositional environments exhibit normal or fine-skewed sediments.

In the delta/estuary reach of the study channels, the incidence of very fine material approaches 25%. More of it undoubtedly moves into deep water offshore. It appears, then, that much of the material moves relatively quickly right to the end of the

channel system. Very fine material remains truly wash material right through the channel system.

The gradients that occur in the sands and fine gravels in the depositional environments are not, in general, replicated in the sedimentology of the open channel deposits. In the steep, small drainage basins characteristic of the Queen Charlotte Islands, channels are coupled to overbank sources of sediment along nearly their entire course, so the overall

sedimentology of the channel is dominated by the texture of source sediments. No systematic downstream gradients of sediment texture occur in such reaches (Rice and Church 1996).

The summary lessons from this study are that very fine sediments are indeed found in transit through the stream system, but they are segregated into specific depositional environments along the channel. Apart from some trapping in interstices, these do not include the open channel environment of spawning gravels. The segregation of sediments into different local environments as the result of hydraulic action is evident along the channel by visual inspection. That highly mobile, fine sediments are relatively efficiently segregated should not be surprising.

Nonetheless, when very large inputs of fine sediments are experienced (e.g., in the reach immediately downstream from a debris flow lobe), the total volume of fines may be sufficient to produce significant transient deposition everywhere in the channel. Figure 12 shows the effect of a debris torrent entering a stream channel and the initial recovery of gravel quality within the winter season. It appears to require two or three seasons to completely clean the open-channel gravels. Even without large influxes of fine material, there are also minor variations in very fine sediment content of open-channel gravels between summer and winter, since low flows in summer will permit some deposition of fines in the gravels.

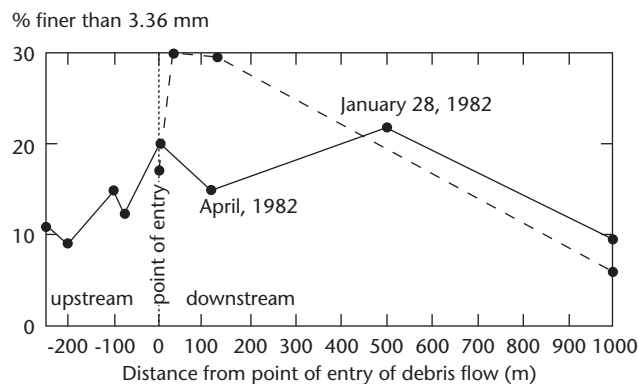


FIGURE 12 Percent finer than 3.36 mm in bed material samples recovered from riffles in Bonanza Creek at two dates following entry of a debris torrent into the channel on 14 January 1982 (data collected by E. Harding, B. Eccles, and M. Morris).

Conclusions

The studies of suspended sediment incidence in Carnation Creek and FFIP streams have contributed some useful results to knowledge of the regime of fine sediment transfers in forested and logged coastal streams. Probably more important, however, is what they have taught about the requirements for thorough characterization of the regime, and for definitive assessment of land use effects on fine sediment mobility. These lessons are summarized here.

In both Carnation Creek and the FFIP survey, it is apparent that the incidence of elevated suspended sediment concentrations is highly episodic. Fine material is prepared for fluvial transport either by freeze/thaw or wetting/drying along streambanks or is delivered by minor raveling and bank collapse. It is mobilized in the next freshet and the available stock may quickly be exhausted. But major bank collapse, or earthflow or debris flow impact on the channel, may episodically introduce substantial volumes of fine sediment. Such events occur naturally as well as in consequence of land use. Sometimes, the impacting event occurs long after the initial land surface disturbance began the preparation of material for eventual mobilization. In contrast to the foregoing mechanisms, drainage off active, unpaved roads, may provide a relatively persistent source of fine sediment, but even this source is active only during wet periods.

Given the circumstances described above, two important conditions must be met before fine sediment regime and sources can be properly characterized:

1. Temporal records must be continuous, or must at least incorporate frequent, systematic sampling so that the true magnitude and duration of fine sediment incidence in the stream can be characterized;
2. To connect the incidence of fine sediment unequivocally with sources, analyses must be conducted on an event-by-event basis, and information must be available about events releasing sediment into the stream, as well as about downstream concentrations.

These requirements have not been realized in any study in British Columbia to date, and in few studies elsewhere. Some events at Carnation Creek can be broadly analyzed if a good deal of inference is accepted (which is not unusual in studies of this

sort). Recent developments in water column monitoring promise to make the provision of continuous records of sediment concentration a good deal more convenient in the near future, but there remain serious problems in obtaining adequately detailed surveillance of land surface conditions, and in making the connection between sediment sources and downstream effects.

A third important condition is indicated by the FFIP synoptic survey. Variations in land surface condition (encompassing geology, topography, exposure, geomorphological and land use histories) and vegetation condition all create significant variability in the conditions for fine sediment mobilization. This appears to make the requirements for adequate regional knowledge very onerous indeed. An additional lesson that emerges from experience to date is that, in natural landscapes (including ones under forestry management, but explicitly excluding agricultural and urban landscapes) most of the fine sediment is derived from a very small portion of the land surface. In general, these places are mass failures on hillslopes, roadways, and stream channel banks. They characteristically comprise, in total, only about 1% of the landscape. It may be a good deal more efficient to concentrate on learning more about the occurrence of these source sites and the processes on them in various geological/topographic situations, than to attempt extensive regional monitoring. At the least, source studies should be incorporated into hierarchically arranged studies of suspended sediment movement in the landscape (e.g., Nistor 1996). But the ultimate implications of this strategy, like so many aspects of this topic, remain not at all clear.

Acknowledgements

Data of suspended sediment transport in Carnation Creek were collected by the Water Survey of Canada under the direction of Mr. Bruno Tassone, then Regional Sediment Engineer, Pacific and Yukon Region, Inland Waters Directorate, who also undertook the primary analysis. Queen Charlotte Islands data were collected by Dr. Lee Beaven, of the Fish/Forestry Interaction Program. Primary analysis was undertaken by Mr. Dan Hogan, B.C. Ministry of Forests, who undertook additional analyses for this paper. The writer thanks each of these individuals very much for allowing him to dissect their hard-won results.

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Changes of Spawning Gravel Characteristics after Forest Harvesting in Queen Charlotte Islands and Carnation Creek Watersheds and the Apparent Impacts on Incubating Salmonid Eggs

J. CHARLES SCRIVENER AND DEREK B. TRIPP

Introduction

In earlier presentations, results were outlined and discussed concerning landslide prediction, channel morphology changes, channel scour and fill processes, and fine sediment movements in coastal streams of British Columbia. Forest harvesting impacts on these processes were also demonstrated. These processes are known to affect the composition of streambed gravels and their incubating salmon eggs in Oregon (Hall et al. 1987), Washington (Cederholm and Reid 1987), and Alaska (McNeil and Ahnell 1964).

Sediment composition of the streambed influences two critical properties of salmon incubation gravels: permeability and porosity. Permeability affects delivery and removal rates of oxygen, carbon dioxide, and other metabolites (Wickett 1958; McNeil and Ahnell 1964), which influence fish embryo survival (Alderdice et al. 1958; Rombough 1983). Small pore size can restrict intergravel movement of alevins and create a barrier to fry emergence (Dill and Northcote 1970; Scrivener and Brownlee 1989). Other studies also show that unseasonal surges of fine sediments can reduce the number of benthic organisms inhabiting a stream (Hall et al. 1987) and ultimately affect fish food availability and fish growth after emergence (Phillips 1971).

Mass movements of gravel and sand into channels not only affected the composition of spawning gravels, but also their stability. Stability declined for channel structures, channel topography, and the riparian zone when mass wasting processes increased sediment loading of streams on the Queen Charlotte Islands (Hogan 1986; Hogan and Schwab 1991). Streambed scouring also increased (Tripp and Poulin 1986), with obvious consequences for the survival of incubating salmonid embryos.

Streambed Characteristics

Sand-sized particles increased in the streambed of Carnation Creek after forest harvesting, but the increase was not consistent until 8 years after logging had begun. Sands that represented $\geq 97\%$ of substrate particles < 2.4 mm in diameter showed little change during pre-logging years, 1971–1976, in the lower 1.3 km of the stream (Fig. 1). They increased significantly 3 years later (1979–1980), only after a large post-logging freshet on November 7, 1978 (Fig. 2). They probably came from the intensive streamside treatment immediately upstream where the banks were eroded during the freshet (Toews and Moore 1982). Sands were cleaned from the spawning gravel during the freshet of December 28, 1980 (Fig. 2), and they remained at pre-logging levels during 1981 and 1982 (Fig. 1). The proportion of sands increased significantly again by 1984 and it continued to increase through 1989. Particles < 0.074 mm in diameter (silt and clay) did not change significantly throughout these years (Scrivener and Brownlee 1989). Silts and clays were probably transported out of the ecosystem when they were mobilized by the stream (Hartman and Scrivener 1990). Sands continued accumulating 13 years after forest harvesting was begun. Variability among freeze-core samples taken from the streambed also increased as their sand content increased (Fig. 1).

These fine sediments in Carnation Creek originated from four main sources. First, when channel erosion occurred upstream during a freshet on February 11, 1983; second, when torrents in steep gully tributaries and the main stream dumped > 1500 m³ of sediment into the lower channel during the 25-year storm of January 3, 1984 (Fig. 2); third, when a new 150-m long channel was eroded during

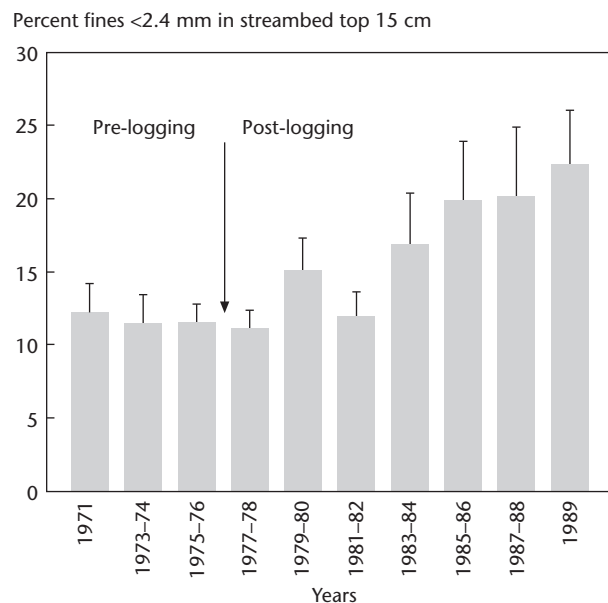


FIGURE 1 Percentage of sand size and smaller particles in the top layer of frozen gravel cores from the leave-strip treatment (0–1400 m) of Carnation Creek. Means and confidence limits (95%) were obtained from 24 to 46 freeze-cores of each period.

1986 (Hartman and Scrivener 1990); and finally, when gravel wedges were released from deteriorating debris jams during later storms (Hogan and Church 1989; Hartman and Scrivener 1990). Forest harvesting produced the potential sources of fine sediments, but fines were incorporated and transported in the channel only when major hydrological events occurred.

Changes to the sand content of streams on the Queen Charlotte Islands were complicated by incidents of mass wasting in both logged and unlogged watersheds. Sand content in streams from logged watersheds was greater than in those from unlogged ones, but similar those at unlogged sampling sites with a history of mass wasting in upstream reaches (Fig. 3). The greatest sand contents were observed at sites where both the streamside was logged and where mass wasting had occurred upstream. Sites that were directly affected by landslides and debris torrents appeared to have the fewest fines (clear bar, Fig. 3), but the greatest variability among sites (Tripp and Poulin 1986). Some sites had recently experienced mass wasting, while others had been scoured for years.

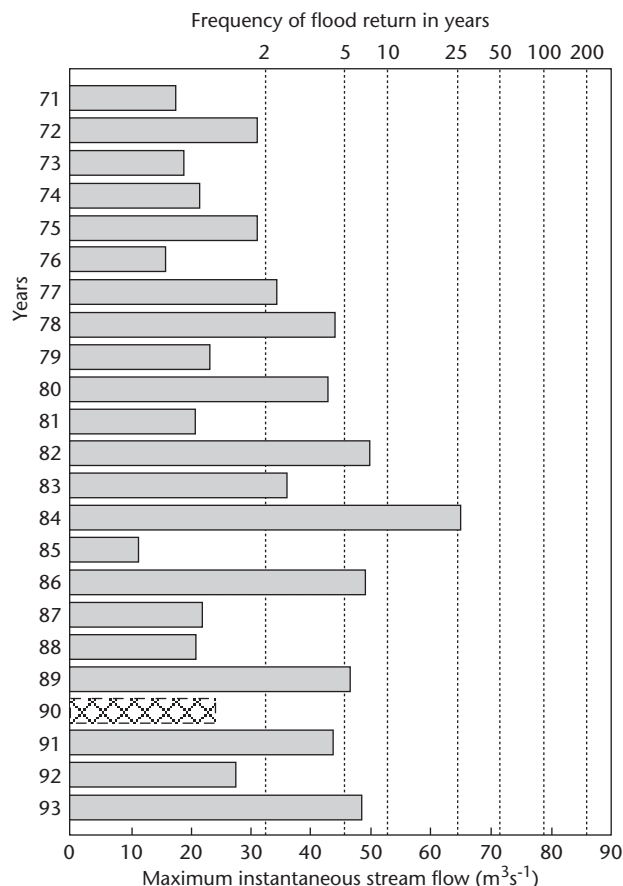


FIGURE 2 Maximum annual stream flows at B-weir from 1971 to 1993. A Gumbel frequency distribution is superimposed on the graph to show probable return periods for the floods. The 1990 maximum was predicted from a correlation of annual peak flows from B-weir and E-weir ($R^2 = 0.77$).

Two-way analyses of variance indicated differences among sites affected by mass wasting upstream and logging. Analyses were completed using Fredle Indices (geometric mean particle size/standard deviation), proportions of sample with particles <3.36 mm diameter (sand), and proportions with particles <0.85 mm diameter (fine sands) for a single sample set from each site (Tripp and Poulin 1986). The proportions of fine sediment in the samples were significantly greater in streams with mass wasting ($P = 0.03, 0.049, \text{ and } 0.005$) and with logging ($P = 0.067, 0.06, \text{ and } 0.006$), but there was no interaction between treatment effects

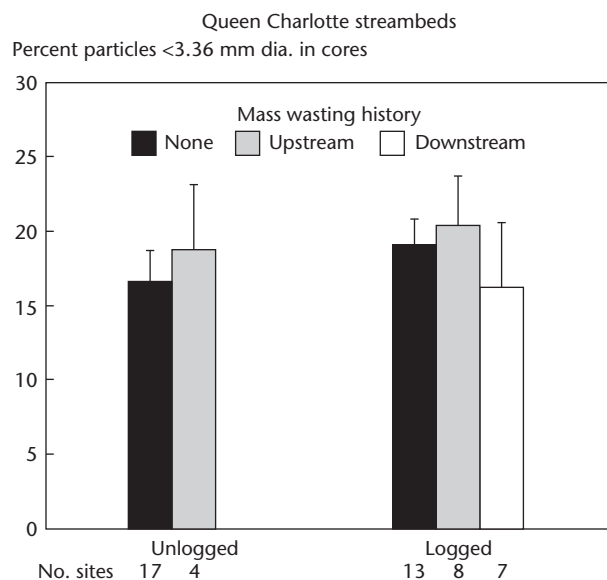


FIGURE 3 Mean percentage and error bars (± 1 S.D.) of sand and smaller size particles in spawning gravel obtained from streams on the Queen Charlotte Islands. Usually six samples were collected at each site with a McNeil sampler and sites were categorized as logged or unlogged and as watersheds with no mass wasting, with mass wasting, or with mass wasting at the site (instream).

($P = 0.43, 0.37$, and 0.73). Logging was the main factor influencing overall results ($P = 0.045$; Tripp and Poulin 1986).

Effects of Stream Sedimentation on Salmon Embryos and Other Biota

Survival rates from egg deposition to fry emergence declined for both juvenile chum (*Oncorhynchus keta*) and coho salmon (*O. kisutch*) after forest harvesting in the Carnation Creek watershed (Hartman and Scrivener 1990). Incubation survival was positively correlated with the geometric mean particle size of the top 15 cm of the streambed (Fig. 4). It declined 45% for chum salmon and 40% for coho salmon after logging was begun (Table 1). Dissolved oxygen and permeability declined in relation to mean particle size of the incubation environment (Scrivener and Brownlee 1981, 1989). Scouring also increased as the mean particle size of the bed decreased (Hartman and Scrivener 1990;

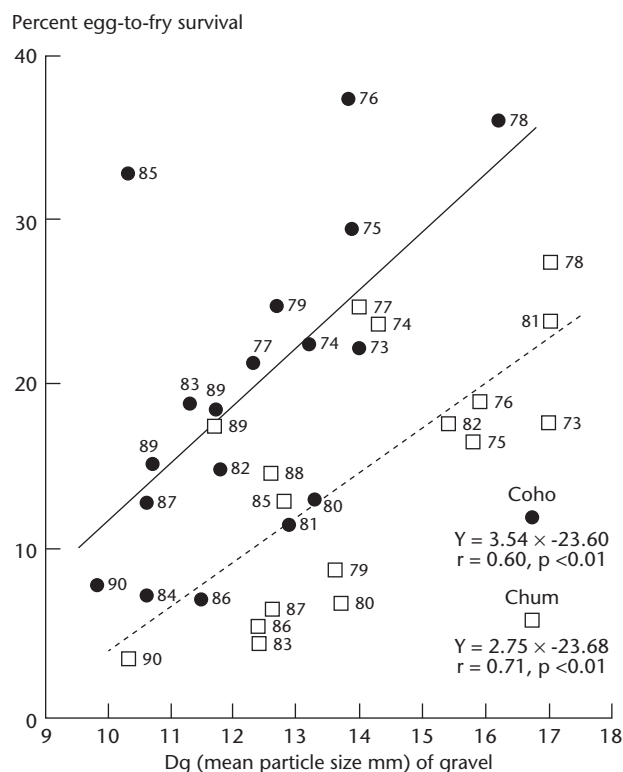


FIGURE 4 The relationships between survival to fry emergence and geometric mean particle size of gravel used by spawning coho and chum salmon in Carnation Creek (updated from Scrivener and Brownlee 1989).

TABLE 1 Estimated coho egg-to-fry survival rates for Carnation Creek and Queen Charlotte Island streams, using the correlation between survival and streambed composition obtained from Carnation Creek (% Sur. = Fredle Index \times 17.28 - 38.11, $n = 18$, $P < 0.01$). Mass wasting was not common in unlogged watersheds.

Logging history	Mass wasting history	Predicted coho survivals	
		Carnation Creek (%)	QCI streams (%)
Unlogged	None	25	55
	Upstream	—	39
Logged	None	19	36
	Upstream	15	34
	Instream	—	57

Scrivener 1991). Increasing proportions of pea gravel and sand have caused the decline of mean particle size (Scrivener and Brownlee 1989). These particles moved downstream on the surface of the bed during large freshets, filled pore spaces in the surface gravel, and caused a size-selective entombment of the salmon fry (Hartman and Scrivener 1990). Survival also appeared to decline for steelhead and cutthroat trout (*O. mykiss* and *O. clarki*; Hartman and Scrivener 1990) and macroinvertebrates (Culp and Davies 1983) because summer densities of both fish and benthic taxa declined after logging.

A reduction of incubation survival has limited the size of the chum salmon population, but it has not limited coho salmon production in Carnation Creek. Between 1971 and 1990, one-third of the 52% decline of chum salmon spawners was caused by forest harvesting and more than half of it was attributed to changes in incubation success (Scrivener 1991). The decline of incubation survival among coho salmon was partially ameliorated during later life stages (Hartman and Scrivener 1990). After logging, coho fry emerged earlier, thus became larger by autumn, and survived better over winter. During winter, they also used off-channel habitat that was little impacted by forest harvesting.

There was no direct measurement of egg-to-fry survival in either coho or chum salmon from streams on the Queen Charlotte Islands, but the relative importance of increased sedimentation and scouring on survivals can be implied. Coho survival rates can be estimated indirectly using the relationship between survival and streambed composition at Carnation Creek, and the data on gravel composition from Queen Charlotte streams. They showed the same pattern of decline as in Carnation Creek (Table 1). The relative decline in survival was also similar for both studies: 40% in Carnation Creek and 38% in the Queen Charlotte Islands. Absolute values for survival were predicted to be greater for Queen Charlotte streams than for Carnation Creek, possibly because sampling methods (McNeil vs. freeze-core samples; Figs. 1 and 3) and sample locations were different (pool-riffle breaks vs. cross-sections through riffles and glides). Fine sediments in the streambed are slightly underestimated when a McNeil sampler is used (Platts et al. 1983). Survival values from Carnation Creek also integrated other factors such as spawner density, redd location, and channel gradient <1% that were probably less influential in Queen Charlotte streams.

Effects of Scouring

Streambed scour likely had an important effect on egg-to-fry survival in some streams on the Queen Charlotte Islands, particularly where mass wasting loaded the channel with sediments and debris or where large woody debris was redistributed in high gradient reaches. Scour occurred regardless of logging condition in high gradient channels, although logging greatly increased the incidence of mass wasting (Tripp and Poulin 1986). It appeared to be a long-term problem for fish habitat in these streams. By comparison, logged streams with low gradients and no recent mass wasting had relatively little scour (Tripp and Poulin 1986). If the loss of salmon eggs due to scouring is assumed to be directly related to depth of the incubating eggs, mortality due to scouring alone could be $\geq 70\%$ for coho salmon in the most active streams. The strong relationship between depth of scour and actual spring densities of coho fry supports this possibility (Fig. 5). Densities were also lower in streams with mass wasting than without it (Tripp and Poulin 1992). On the Queen Charlotte Islands, egg losses

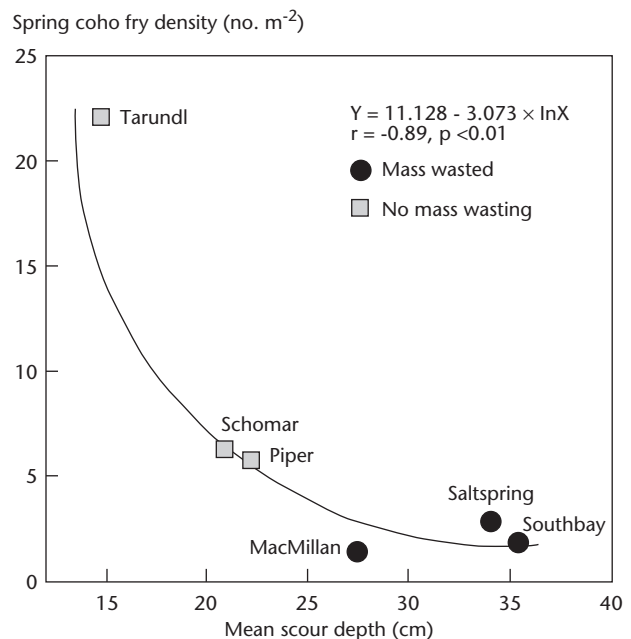


FIGURE 5 The relationship between mean depth of streambed scour during winter and fry densities next spring for coho salmon using logged streams in the Queen Charlotte Islands (redrawn from Tripp and Poulin 1992).

due to scouring could be even higher for species such as pink (*O. gorbuscha*) and chum salmon, which appeared to have shallower redds than coho salmon (Tripp and Poulin 1986; Hogan and Schwab 1991). Elsewhere, chum and pink salmon tend to spawn in lower gradient reaches that are affected less by scour, but these sites are more likely to accumulate fine sediments (McNeil and Ahnell 1964; Everest et al. 1987; Hartman and Scrivener 1990).

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Overwintering Habitats and Survival of Juvenile Salmonids in Coastal Streams of British Columbia

GORDON F. HARTMAN, DEREK B. TRIPP, AND TOM G. BROWN

Introduction

Foresters and biologists involved in harvest planning and logging operations make decisions that affect the survival and production of salmon and trout. Their decisions may, among other things, govern the quality and availability of winter habitat for juvenile fish. Because of low water temperatures and extreme conditions of streamflow during winter, fish are vulnerable if winter habitat is lost or degraded. Winter is a critical period for juvenile salmonids. Therefore, it is important for land use managers to understand some of the behaviour and habitat needs of young fish during the winter period.

This paper reviews the different life history strategies observed in young salmonids in Carnation Creek, and compares them to the life history patterns of coho salmon (*Oncorhynchus kisutch*) in the Clearwater River, Washington. It briefly reviews the seasonal changes in the behaviour of young coho salmon and steelhead trout (*O. mykiss*) and indicates some of the features of behaviour that help these two species survive winter conditions. We review information, particularly from Carnation Creek, on habitat use and timing of seasonal redistribution from one type of habitat to another. This paper compares overwinter survival of juvenile coho salmon, before and after logging, in the off-channel habitat of Carnation Creek. It also provides estimates of overwinter survival in the main channel after logging.

Information on survival of coho salmon and steelhead trout in logged and unlogged streams in Queen Charlotte Islands permits limited comparison of the two areas. Therefore, we compare conditions in streams on the Queen Charlotte Islands to those in Carnation Creek in an attempt to determine why responses to logging were different in some respects. We also comment on egg-to-fry survival of chum

salmon (*O. keta*). The spawning and incubation periods are the only times during which chum salmon depend upon freshwater habitats. Chum salmon fry emigrate seaward soon after they emerge from the streambed in spring. Because the life history of chum salmon is very different than that of coho salmon and trout, comparisons cannot be made between chum fry and the juvenile stages of the other stream-dwelling salmonids. However chum salmon must be discussed because they responded dramatically to logging as well as to changes in ocean conditions. Future logging practices must carefully consider potential impacts on chum salmon.

Behaviour

Background Behaviour Studies of Fish in Winter

The behaviour and habitat use of young salmonids is a reflection of their physiological capabilities and environmental pressures. The metabolic demands of poikilothermic animals are reduced as environmental temperatures decrease. Swimming speed is also reduced at lowered water temperatures. As a consequence, the behaviour and habitat requirements of fish are different at reduced temperatures. They need less food but depend more on cover for protection from predators and from displacement downstream by high winter streamflows.

That salmonids exhibit changes in behaviour and habitat needs at different times of the year has been long recognized. Shifts in behaviour and related changes in habitat use during winter were recorded many years ago for Atlantic salmon (*Salmo salar*; Lindroth 1955), brown trout (*S. trutta*; Hartman 1963), coho salmon and steelhead trout (Hartman 1965), and chinook salmon (*O. tshawytscha*) and steelhead trout (Edmundson et al. 1968; Chapman and Bjornn 1969).

The two principal types of response to winter conditions that have been observed for juvenile salmonids are:

1. selection of special habitat features that provide cover within a main stream channel; and
2. migration to ponds, sloughs, swamps, and small ephemeral tributaries, usually in floodplain areas.

While exhibiting one of these responses or the other, fish also make a number of microhabitat choices. Since 1975 there have been many studies dealing with microhabitat selection during winter by young salmonids. Among these are key studies on coho salmon and steelhead trout (Bustard and Narver 1975), brook trout (*Salvelinus fontinalis*) and brown trout (Cunjak and Power 1986), Atlantic salmon (Cunjak 1988), and coho salmon (McMahon and Hartman 1989). Bustard and Narver (1975) first demonstrated the use of small, ephemeral, floodplain tributaries by coho salmon. There have, since then, been many publications dealing with this behaviour for coho salmon and cutthroat trout (*O. clarki clarki*) (Cederholm and Scarlett 1981; Peterson 1982a,b; Tschaplinski and Hartman 1983; Brown 1985; Swales et al. 1986; Hartman and Brown 1987; Brown and Hartman 1988; Swales and Levings 1989).

Survival in High-energy Streams These patterns of behaviour and particular aspects of its timing are especially significant for juvenile salmonids that inhabit dynamic and high-energy stream environments such as those found in coastal British Columbia. The behaviour and microhabitat selection by such fish, in response to severe seasonal changes in streamflow, temperature, and associated conditions, are critical for their survival. Survival rates in different environments depend partly on how well the behaviour of each species is adapted to conditions in such environments, or conversely, how much the environment has been changed from that for which the species is best suited. Different species of salmonids have evolved different mechanisms of microhabitat use and different patterns of movement within a watershed in order to sustain their populations. For this reason there are distinct patterns of habitat use for various species and life stages within the streams of coastal British Columbia. Human activities that change habitat conditions have the potential to change fish survival, and even alter species composition.

Patterns of Behavioral Change Specific kinds of habitat, and behaviour suited to those habitats, are required during each season. This type of information illustrates why habitat-protection biologists must seek to retain certain conditions within a system if fish are to survive there. Underyearling coho salmon and steelhead trout (i.e., fry or age 0+ fish) exhibit a pattern of behavioral change and habitat use from the time of emergence onward (Hartman 1965). The young of both species are particularly aggressive during the first few months after emergence, and aggression levels increase with water temperature increase. In this period, coho tend to be distributed in pools and laminar-flowing runs (glides), and steelhead and cutthroat trout in shallow riffles and the downstream ends of pools. In small coastal streams like the Salmon River, spatial segregation of these two species is most pronounced when inherent levels of aggressive behaviour are highest (Hartman 1965). During early spring, a part of the population of recently emerged coho disperses downstream, and such fish either reside in the estuary (Tschaplinski 1987) or move beyond it and are lost at sea. Redistribution continues into the late spring and early summer and is partly driven by aggressive behaviour (Hartman et al. 1982). The coho, cutthroat, and steelhead juveniles that remain in the stream defend an area around themselves which is called a "territory." Territorial behaviour spreads the fish in whatever habitat they select.

Relationship Between Behaviour and Space Occupied The types of movements and aggressive displays that each species of fish exhibits fits them to certain kinds of environmental conditions better than to others. In defending territories, young salmonids display specific types of body postures and fin movements as signals to other young fish. These display signals are different for different species.

The behavioural displays of coho, steelhead, and cutthroat equip them to defend, most successfully, certain types of habitat. Juvenile coho display by tilting their heads down, erecting their fins fully, and swinging their bodies back and forth in an exaggerated fashion ("wig wag display"; Hartman 1965). This type of behaviour equips them well to defend space in the slow-moving water of a pool. Hartman (1965) reported that coho salmon displaced trout from pool habitat in this way. However, the same behavioural movement is unsuited to conditions in

riffles because fish performing it would be displaced from such fast-current habitat. Consistent with this notion, coho salmon did not displace either steelhead (Hartman 1965) or cutthroat trout (Glova and Mason 1977a, b) from riffles, and they lost in most aggressive encounters in this type of habitat. On the other hand, given the types of displays and movements that trout make, that is, lateral displays (Kalleberg 1958) and the chasing and nipping behaviour they use, trout are able to defend space in riffles with less risk of being displaced by current while threatening other fish.

Winter and Behavioural Changes As juvenile salmonids grow older, and when the season changes from autumn to winter, two different facets of behaviour develop:

1. coho and steelhead fry become less aggressive (Hartman 1965), the result of both age and lower water temperature during winter; and
2. some coho and cutthroat move from the main channels of streams to off-channel habitat (Tschaplinski and Hartman 1983; Brown 1985; Hartman and Brown 1987).

Coho and cutthroat that redistribute themselves to off-channel habitat require access that permits entry in autumn, and exit in spring (Hartman and Brown 1987). Steelhead do not redistribute as coho and cutthroat do, but remain dependent primarily upon habitat within the main channel of streams such as Carnation Creek (Bustard and Narver 1975).

Habitat

Distribution in Different Kinds of Streams Juvenile coho, cutthroat, and steelhead are distributed differently within stream systems of southwestern British Columbia (lower Fraser River drainage; Hartman and Gill 1968) and on Vancouver Island (Brown et al. 1989). Differences in distribution are not rigid. Among these three species, steelhead have been found to predominate in large rivers such as the Chilliwack, Puntledge, Squamish, and Alouette. Of the two species of trout, cutthroat is the dominant one in small tributaries near headwaters. It is almost exclusively the species of trout found in small streams that drain down through sloughs and swamps, and is the most frequent trout occupant of drainages < 6 km long. Steelhead often occur in

small steep tributaries that drain directly into a large river (Hartman and Gill 1968). Coho can overlap the distributions of cutthroat and steelhead, but they usually do not occur as far upstream in small tributaries as cutthroat do. On the Queen Charlotte Islands, D. Tripp has observed that steelhead do not occur in streams with drainage areas < 5 m², unless they were part of a larger system (Tripp Biological Consultants, Nanaimo; unpublished data). Coho, chum, and pink salmon, and Dolly Varden char have been found to be essentially the only salmonids that occur in small streams that flow directly into the sea. Cutthroat were distributed farther upstream than coho and steelhead in systems where the three species were found (D. Tripp, Tripp Biological Consultants, Nanaimo; unpublished data).

Habitats Used in Different Sasons Patterns of fish distribution and habitat use may differ seasonally if the stream system is diverse enough to accommodate these shifts. Where habitat conditions permit, young coho salmon exhibit a spectrum of different life history strategies that allow different individuals within a cohort (brood year) to occupy different habitats (Fig. 1). Following autumn redistribution in Carnation Creek, 75% of the age 0+ coho were in the main channel, 20% were in off-channel habitats, and 5% were in estuarine drainages (Fig. 1; see Scrivener

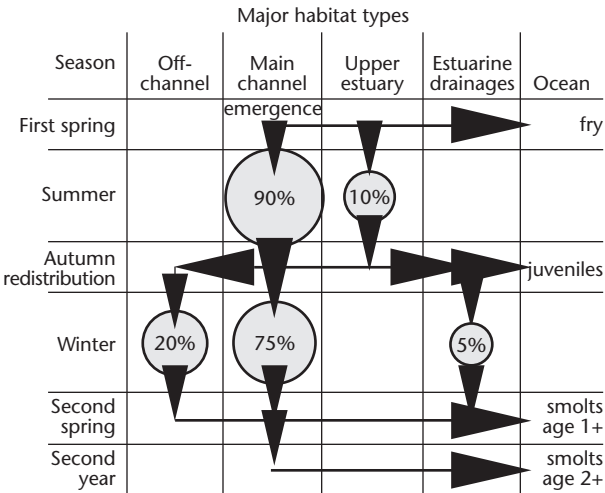


FIGURE 1 Coho use of different stream habitat components by season and stage of life history (from Scrivener et al., this volume).

et al., this volume). All of these fish originated from eggs that had incubated in the main channel. In Carnation Creek, most movement of age 0+ coho into off-channel habitats occurred during high flow periods in September, October, and November (Fig. 2). Most of the exodus of these fish occurred during March, April, and May the following spring.

Use of more than one type of habitat is important because fish that behave this way have a chance for a fraction of their population to survive in one part of the aquatic environment even if

severe losses occur in another. This broad distribution requires that managers protect a wide range of habitats rather than just the main channel.

The situation represented in Fig. 1 for Carnation Creek coho is more simple than that described by Lestelle et al. (1993) for the larger, more complex Clearwater River system in Washington (Fig. 3). In the Clearwater River, coho salmon eggs incubated in (or near to) five different types of habitat. However, the numbers of fish rearing in these same habitats in the summer and winter were not proportional to the

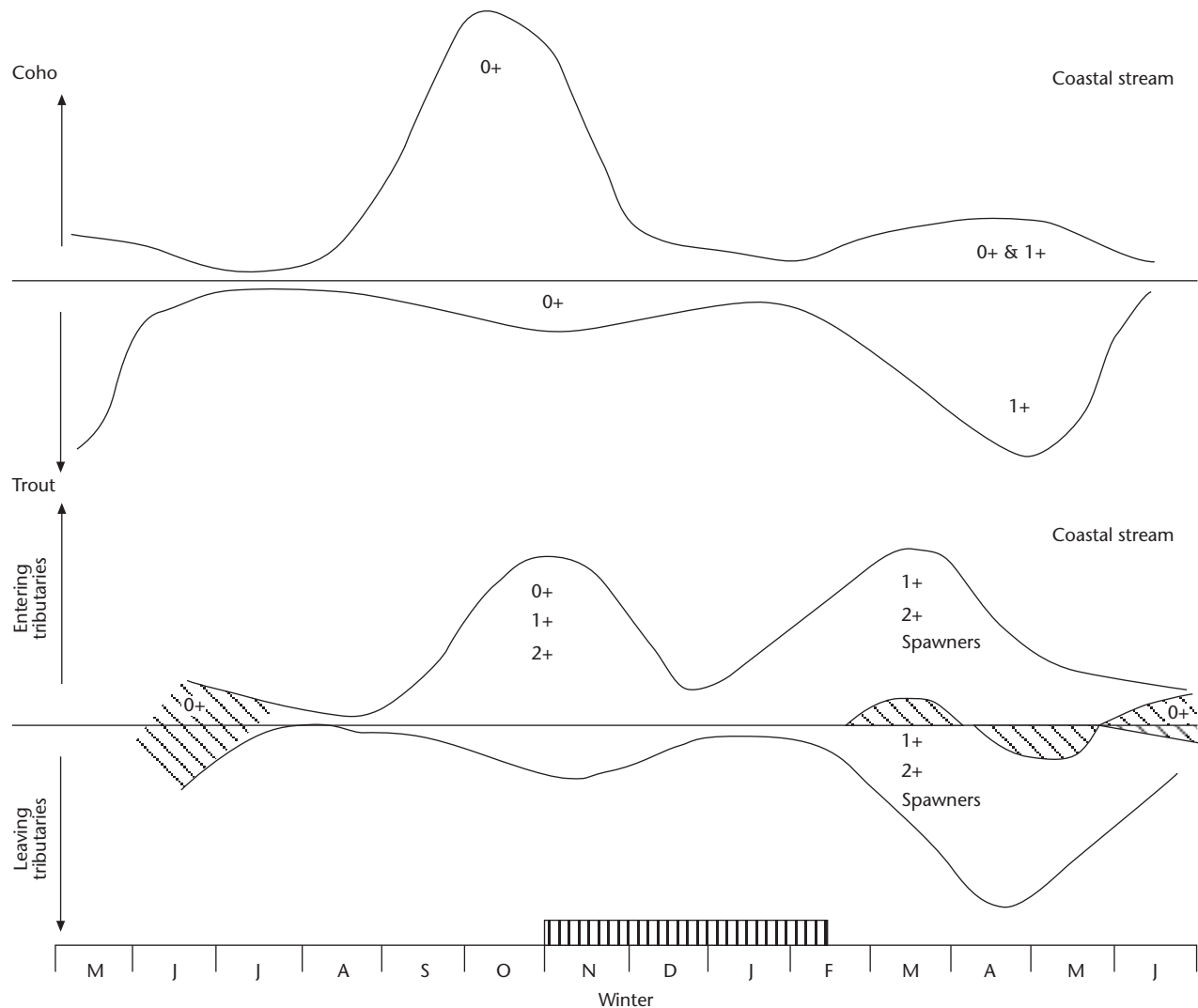


FIGURE 2 Generalized pattern of movement of coho salmon and cutthroat trout into and out of floodplain tributaries of a coastal stream such as Carnation Creek. The ages of non-spawning fish which are moving are indicated. The pattern of movement of cutthroat spawners during the March–May period is indicated by hatch marks.

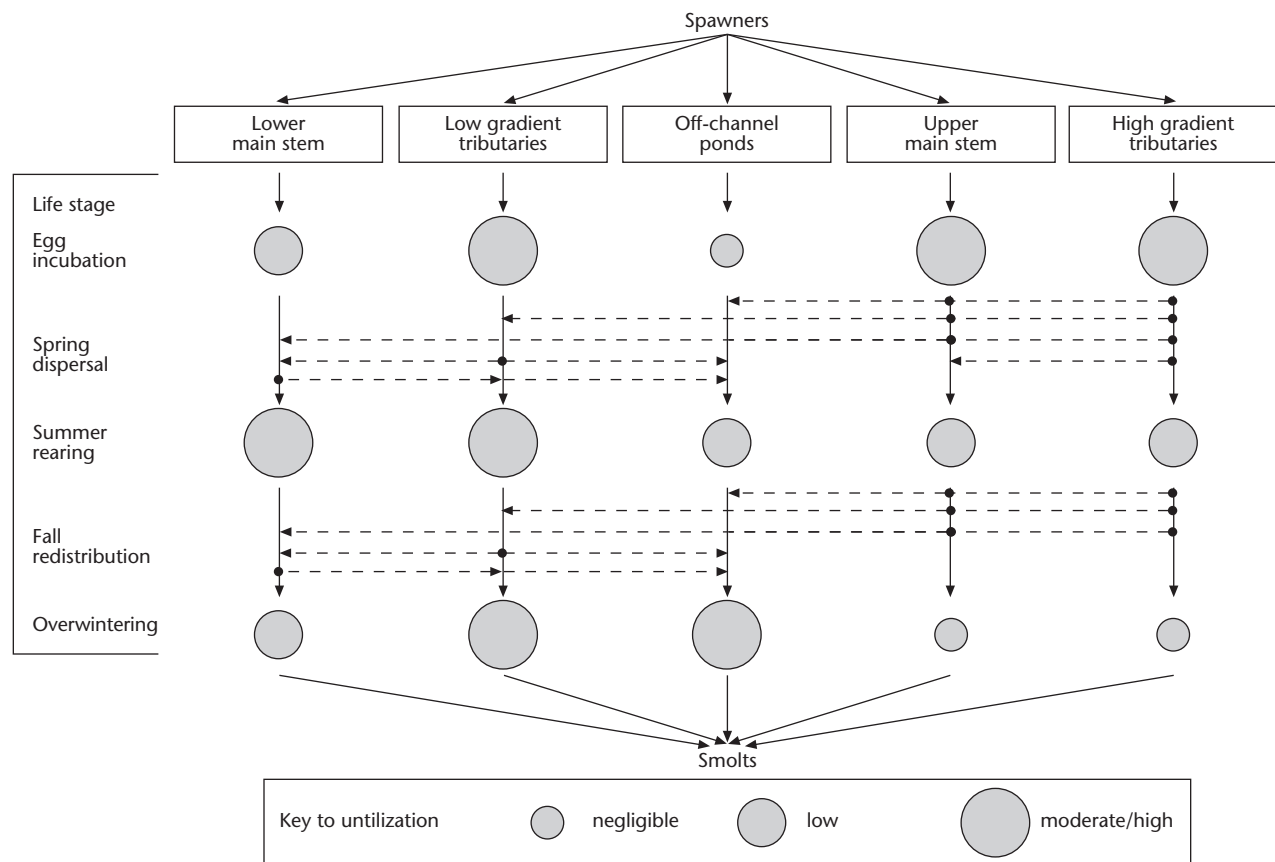


FIGURE 3 Coho use of different areas of the Clearwater River by life stage, and the amount of production occurring in each area (redrawn with permission from Lestelle et al. 1992).

numbers incubating in them. The low gradient tributaries were an exception to this observation. The work in the Clearwater system showed that there were essentially two main life history strategies, as well as major seasonal differences in the relative importance of different parts of the system for fish rearing.

The distances between incubation and rearing habitats may vary widely depending on stream size. In the Clearwater River, young coho salmon moved downstream as much as 32.6 km before entering off-channel habitat (Peterson 1982a). In Carnation Creek the distances moved were relatively short, from a few hundred metres to 2 km.

The seasonal movements of coho, cutthroat, and steelhead in Carnation Creek differed either in the age composition of fish or the fraction of the population that migrated. More year classes of cutthroat trout than coho salmon took part in

off-channel movement. Cutthroat migration patterns were the most complex: ages 0+, 1+, and 2+ cutthroat trout moved into off-channel habitats in the autumn, and spawners plus ages 1+ and 2+ fish moved there in the spring (Fig. 2). There was little evidence that steelhead used small ephemeral tributaries or ponds as winter habitat. Steelhead life history was more simple than that of coho: these trout overwintered almost exclusively within the main channel of the creek.

Cover and the Function of Large Woody Debris
 Coho salmon that remain in the main channels of streams in winter depend on large woody debris (LWD) for cover. The configuration and location of LWD in the channel are important during this critical period for fish survival. In Carnation Creek, young coho chose cover on the basis of several of its component features including overhead shade, low

water velocity, and spatial interstices (McMahon and Hartman 1989). A strong relationship has also been shown between the volume of LWD that is in the water during high flows and juvenile coho numbers (Tschaplinski and Hartman 1983).

The loss of such LWD, or even changes in its distribution, is detrimental to the maintenance of coho habitat. Torrents that deposit piles of broken wood or whole trees up on the stream bank or in large, high debris jams within the channel do not soon create ideal habitat in proportion to the volume of wood deposited. Many years are needed before fluvial processes can redistribute LWD from torrents to make a significant contribution to fish habitat.

Overwinter Survival

Egg-to-fry Survival in Carnation Creek Overwinter survival is a function of gravel quality and stability for incubating eggs, and of rearing habitat condition and fish behaviour for juveniles. Many studies tend to begin with post-emergent fish in their discussions of fish survival before and after logging. However, logging may have very important impacts on fish survival even before fry emerge from the streambed. In Carnation Creek, egg-to-fry survival declined following logging (Hartman and Scrivener 1990). Although survival of incubating eggs varied for both chum and coho salmon from year to year before 1978, a general decline became clear thereafter (Fig. 4). The causes of this decline in post-logging survival included lower oxygen levels in the streambed, egg entombment by deposited sand, and stream channel scouring (Scrivener and Tripp, this volume). Any one, or all of these impacts together, can have profound effects on the number of fry that emerge and their subsequent growth, behaviour, and survival. In Carnation Creek, the numbers of chum salmon returning to spawn have declined progressively since about 1980 (Hartman and Scrivener 1990; Tschaplinski et al., this volume), partly a result of conditions in the incubation environment altered by logging.

Egg-to-fry Survival in the Queen Charlotte Islands On the Queen Charlotte Islands, increases in fine sediments in streams related to mass wasting or logging were estimated to cause a 15–20% reduction in the survival of coho salmon eggs (Tripp and Poulin 1986). Logging alone accounted for as much of the decline in the quality of the streambed for egg

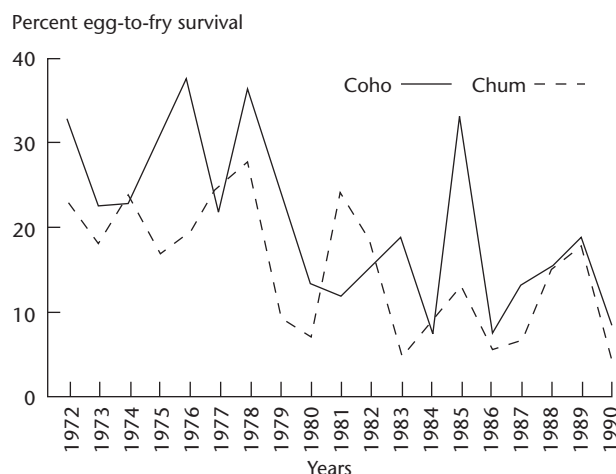


FIGURE 4 Percent egg-to-fry survival of chum and coho salmon in Carnation Creek, 1972–1990.

incubation as did mass wasting from locations upstream. However, high levels of egg mortality in the Queen Charlotte Islands were attributed to debris torrents and associated stream channel scouring (Tripp and Poulin 1986).

Egg-to-fry mortality in streams directly affected by debris torrents was estimated to vary between 66 and 86% for chum and 45 and 70% for coho salmon during a year of normal flows (Tripp and Poulin 1986). These estimates were based upon measurements of the depth of streambed scour during winter in selected streams and the depth distribution of chum and coho eggs in the streambed. Scouring in years of severe storms was suspected to result in egg losses of 90–100% for the same species, and is believed to be responsible for the loss of entire brood years. These catastrophic losses may have been the main reason that some torrented streams had juvenile coho during one year and not the next.

Survival of Juvenile Fish in Carnation Creek In Carnation Creek, high rates of coho survival in off-channel habitats were suggested from the numbers of coho that emigrated from them in spring compared with the numbers that entered them in the previous autumn. Bustard and Narver (1975) found that 64–71% of the fish that entered a small ephemeral tributary (“Trib-750”), left it the following spring. These estimates of survival were confirmed by those made later by Tschaplinski and Hartman (1983) and Brown (1985) (Table 1).

TABLE 1 *The percentage of juvenile coho salmon leaving off-channel habitat in the spring after entering in the fall and winter (i.e., percent "survival")*

Years	Percent survival	Source
1972–1973	64–71	Bustard and Narver (1975)
1976–1981	67	Tschaplinski and Hartman (1983)
1983–1984	64	Brown (1985)

Assuming that most coho that chose to enter off-channel habitat completed this migration by November 1, and began leaving by March 1, Brown (1985) may have provided the best survival information available for coho salmon in off-channel habitat in Carnation Creek. He reported a decline in juvenile coho from about 270 to 170, or a 64% survival (Fig. 5). Peterson (1982b), working in the Olympic Peninsula, recorded 78% survival for coho in one pond in the Clearwater River system, and 28% in another. He attributed the low survival in the second pond to its shallower depth and thus better conditions for avian predators. Timing of entry to the Clearwater River ponds was also important. Fish that entered in late November were

smaller and experienced lower survival than those that entered in the first week of November.

Calculations based on data from Brown (1985) also indicate different overwinter survival rates for coho using off-channel and main-channel habitats. In the winter of 1982–1983, coho survival in the main channel was 56%; in 1983–1984 it was 34%. Survival in the off-channel habitat showed an opposite pattern (Table 2).

TABLE 2 *Estimated percent survival of coho salmon during their first winter in main-channel and off-channel habitats*

Year	Off-channel survival (%)	Main-channel survival (%)
1982–1983	35	56
1983–1984	43	34

These differences in survival were related to hydrological conditions during spring. Twenty-three percent of the total number of coho smolts produced from Carnation Creek in spring came from off-channel habitat in the winter of 1983–1984, while 15.3%

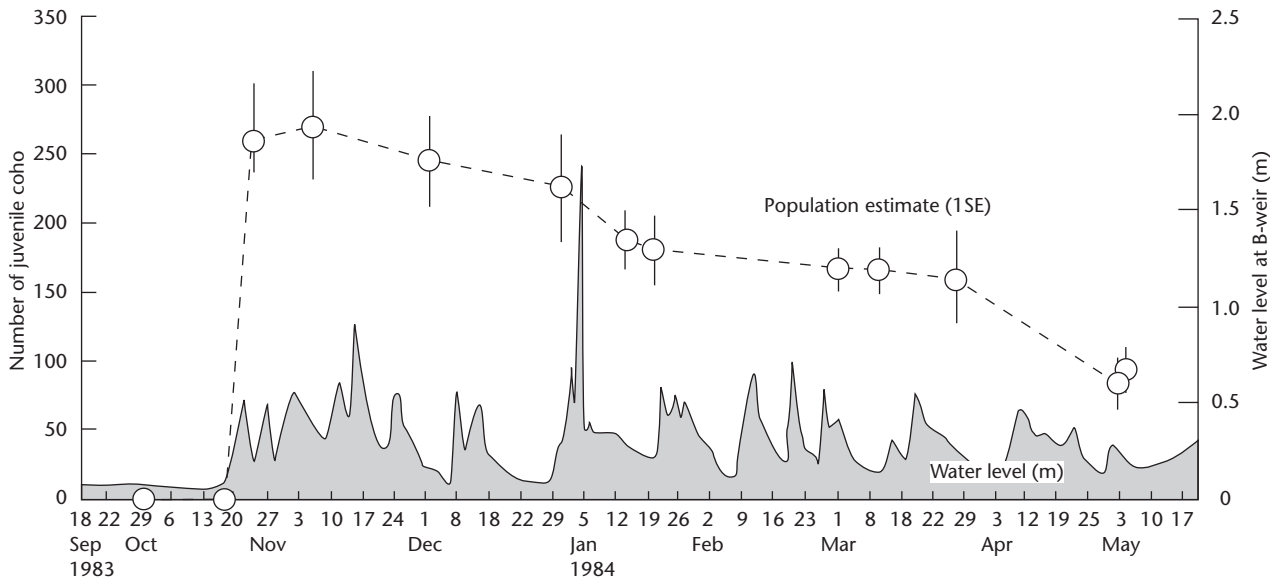


FIGURE 5 *Change in juvenile coho population over a winter period in one ephemeral swamp (R750m) (from Brown 1985).*

came from such habitat in 1982–1983. Brown and Hartman (1988) attributed this difference in production to water levels during the April–May period. During the spring, when the smolt contribution from off-channel habitat was high, the water level was 55% above the 13-year average for that time. When the smolt contribution was low, the water level was relatively low (Table 3).

TABLE 3 Relationship between percentage of coho smolts that come from off-channel habitat, and water level during April and May of the year of smolt transformation

Year	April–May water level compared to 13-year mean	Percentage of smolts from off-channel habitat
1983	37% below	15.3
1984	55% above	23.1

Juvenile coho salmon residing in off-channel habitat grew more during the winter than those remaining in the main channel. In the winter of 1983–1984, age 0+ coho at a site 2.7 km upstream from the mouth of Carnation Creek grew 3.8 mm on average from November 10 to March 10 (Brown 1985). Growth increments during the same period in various parts of the off-channel environment ranged from 6.8 to 12.8 mm (Brown 1985). Use of off-channel environments may not only have provided coho with the advantage of alternate habitats, but it may also have resulted in greater size and hence increased potential for survival later in life.

Survival of Juvenile Fish on the Queen Charlotte Islands D. Tripp measured changes in density of coho salmon and steelhead trout through the winter (September to April) in 27 reaches of 11 streams on the Queen Charlotte Islands during 1990–1991 and 1992–1993 (Tripp Biological Consultants, Nanaimo; unpublished data). Sixteen reaches in 8 streams, mostly logged, were surveyed over the 1990–1991 winter, and 11 reaches in 3 other streams were added to the survey for the following year (Table 4).

Eight logged and 3 unlogged streams were eventually examined. There were 16 reaches in the

TABLE 4 Number of logged and unlogged streams and stream reaches, studied on the Queen Charlotte Islands, 1990–1991 and 1992–1993

Year	Number of streams		Number of stream reaches	
	Logged	Unlogged	Logged	Unlogged
1990–1991	7	1	13	3
1992–1993	8	3	16	11

former and 11 in the latter. Twelve of the 16 logged reaches were on the east coast of the island and all of the unlogged ones on the west coast. Logging had occurred upstream of only two of the unlogged reaches.

In autumn, the densities of age 0+ coho in the logged stream reaches were much higher than those in the unlogged ones (Fig. 6). By the following spring, however, the differences in densities between the logged and unlogged reaches had largely disappeared: densities of age 0+ fish in the two stream types were nearly equal (Fig. 6). Although the effects of fry size on overwinter survival was unclear in these Queen Charlotte Islands streams, overwinter survival of fry in Carnation Creek was strongly correlated with fry size in the autumn (Holtby 1988).

The densities of the age 1+ coho in autumn were lower than those of the age 0+ fish and declined

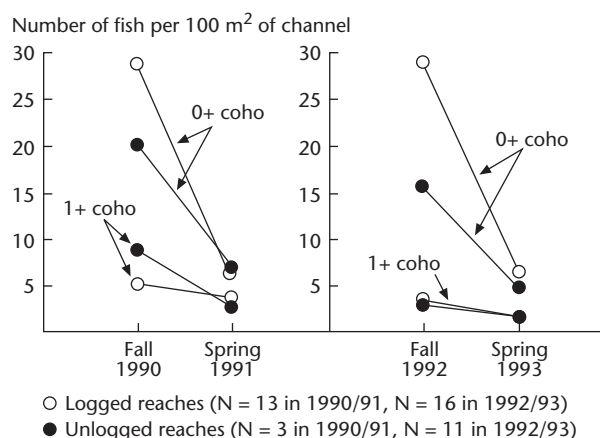


FIGURE 6 Juvenile coho salmon densities in logged and unlogged reaches of streams on the Queen Charlotte Islands.

much less through the winter (Table 5). Differences in the densities of age 1+ coho between logged and unlogged streams were smaller than those of the age 0+ fish. This relationship was most evident in the 1992–1993 winter when the largest number of each stream type was sampled.

TABLE 5 *Percentage of coho left in logged and unlogged stream reaches following the winter indicated*

Time period (Sep–Apr)	Age 0+ (fry)		Age 1+ (yearlings)	
	Logged	Unlogged	Logged	Unlogged
Fall 1990 to Spring 1991	23	35	71	29
Fall 1992 to Spring 1993	22	31	49	59

The differences between fish densities in logged and unlogged reaches, and the variation in the decline in densities overwinter, may have been largely due to differences between the east and west coast of the Queen Charlotte Islands. The influence of geography is indicated by patterns of overwinter survival of juvenile coho salmon that were similar in both the logged versus unlogged comparisons and the east versus west stream comparisons (Figs. 6 and 7).

The relationship between densities of age 0+ steelhead trout in logged and unlogged reaches, and the pattern of overwinter decline in their densities were similar to those of age 0+ coho (Fig. 8). The densities of age 1+ steelhead were also higher in the logged reaches than they were in the unlogged ones in both the autumn and the following spring. The densities of ages 2+ and 3+ steelhead were nearly the same in logged and unlogged reaches, and declined little or actually increased in some cases during the winter (Fig. 8). Like coho, all age classes of steelhead trout showed similar declines, regardless of whether they occupied east or west coast streams (Fig. 9), or logged and unlogged streams (Fig. 8).

The decline in densities of both coho and steelhead in winter was greater for the young fish than for the older ones. Table 6 summarizes the percentage of steelhead trout left in spring based on density changes from fall to spring. It indicates that the overwinter survivals for ages 2+ and 3+ fish were

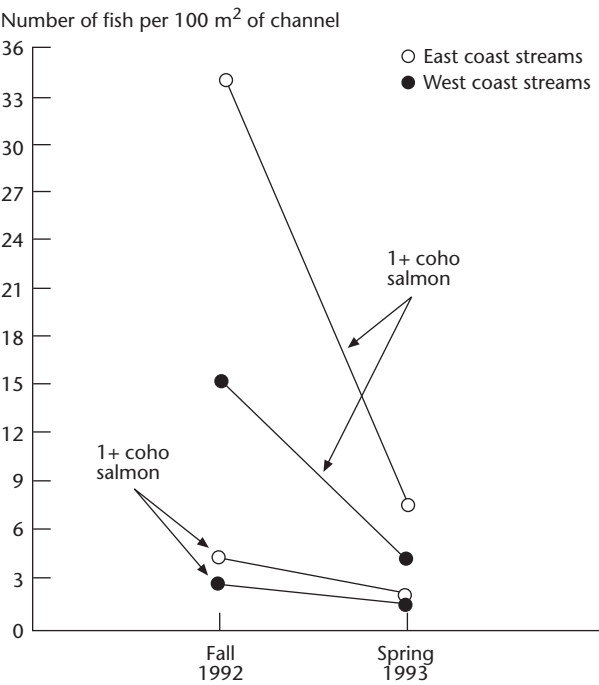


FIGURE 7 *Juvenile coho salmon densities in east and west coast streams on the Queen Charlotte Islands.*

higher than those for ages 0+ and 1+ fish. The densities of age 3+ fish actually increased over winter (due to immigration from other sites). The numbers in Tables 5 and 6, and the lines in Figs. 6–9 represent a combination of mortality and fish movements into or out of the various study reaches. Increased numbers of older fish after winter indicate that survival plus fish movements into the reach exceeded mortality plus fish movement out.

TABLE 6 *Percentages of steelhead left in reaches following the winter indicated in logged and unlogged stream reaches*

Fish age-class	Fall 1990–Spring 1991		Fall 1992–Spring 1993	
	Logged	Unlogged	Logged	Unlogged
0+	64	43	40	23
1+	69	50	85	57
2+	77	73	96	81
3+	175	75	225	163

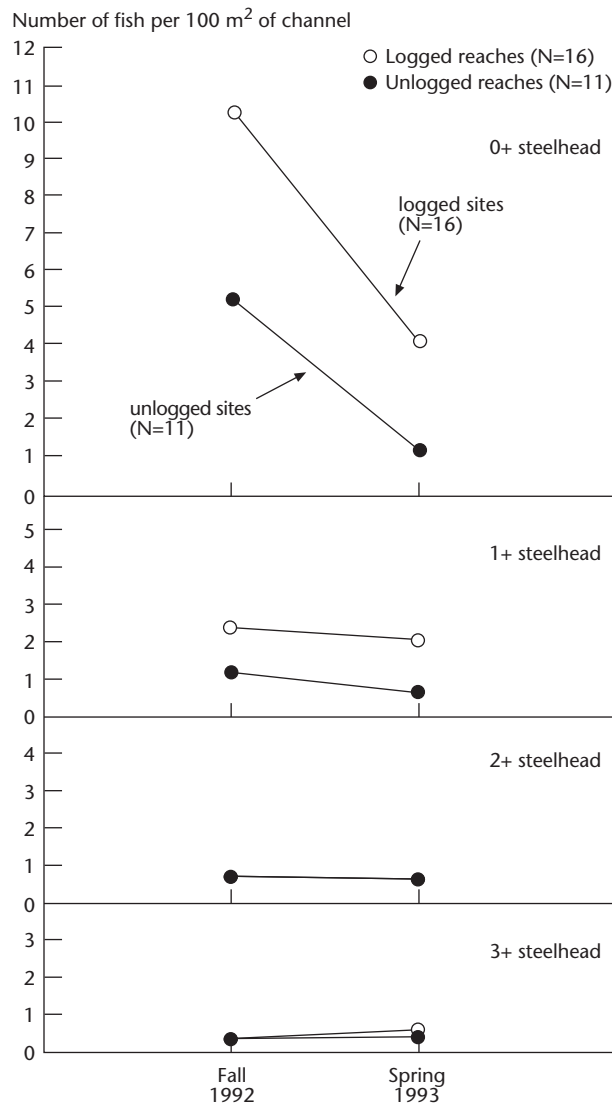


FIGURE 8 Juvenile steelhead densities in logged and unlogged reaches of streams in the Queen Charlotte Islands.

Within logged systems, the direct effects of debris torrents on fish production and survival were more clear. In an earlier survey (Tripp and Poulin 1992), overwinter survival of steelhead and coho in “logged” and “logged-plus-torrented” streams on the Queen Charlotte Islands varied from stream to stream. However, survival was lower in torrented streams than in logged streams. Overwinter survival of coho in three logged-plus-torrented streams ranged from 2.0 to 12.1%, and in three logged

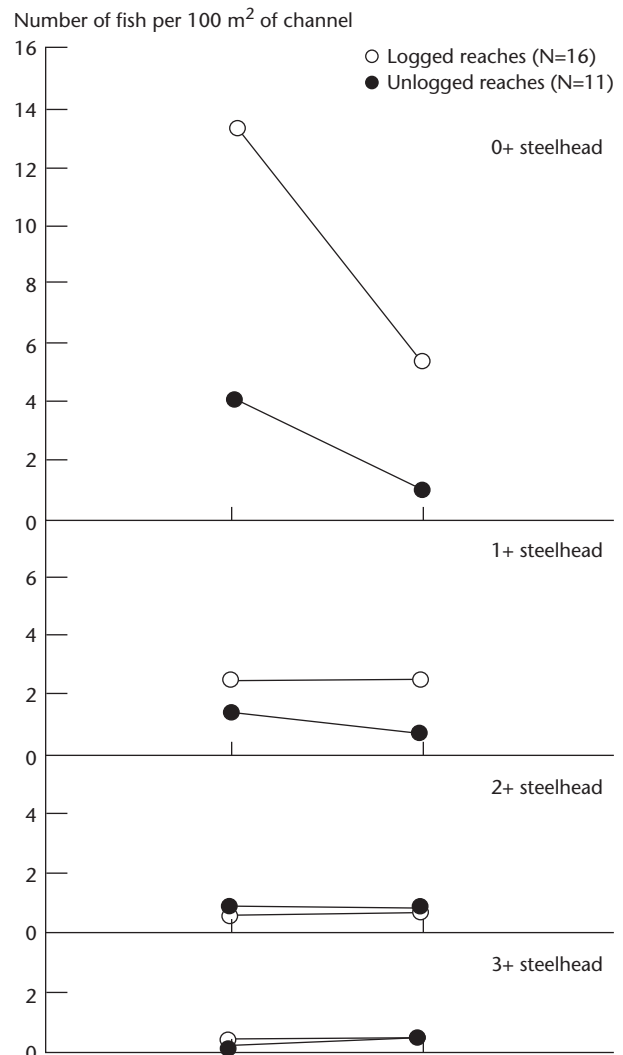


FIGURE 9 Juvenile steelhead densities in east and west coast streams on the Queen Charlotte Islands.

streams that had not experienced debris torrents it ranged from 3.6 to 34.7%. The overwinter survival of steelhead in one torrented stream was 7.0 %, while in two logged streams that had not had debris torrents it was 13.7 and 22.4%. These overwinter survival values are relatively low compared to those in Carnation Creek. These survival rates were minimal, however, because estimates were based on fence counts, and floods interrupted fence operations for 3–10 out of 40–80 operating days on the various streams.

Difficulties in Comparing Carnation Creek to Streams on the Queen Charlotte Islands At least six important differences stand out between the Carnation Creek drainage and those sampled in the synoptic surveys on the Queen Charlotte Islands:

1. The floodplain and estuary habitat in the Carnation Creek system was more extensive than in the streams typically sampled on the Queen Charlotte Islands. These habitats can buffer certain types of logging effects.
2. The streams sampled on the Queen Charlotte Islands were more likely to be directly affected by slides and debris torrents than was Carnation Creek.
3. The watersheds investigated on the Queen Charlotte Islands were logged earlier on average than was the Carnation Creek drainage. Cutting for the first phase of the Carnation Creek study occurred between 1976 and 1981. On the Queen Charlotte Islands, logging in the areas studied spanned 1948–1990 (cutblock age averaged 27 years in 1994). Logging in the Queen Charlotte Islands also extended further upstream, above the study reaches, than was the case in the Carnation Creek drainage.
4. Bedrock types and rainfall patterns varied from the east to the west on the Queen Charlotte Islands. Because logged and unlogged streams also tended to be split between the east and west coast, systematic variables such as rainfall and soil nutrients may have masked some logging effects. The effects of east versus west may confound comparisons of logged versus unlogged reaches.
5. Egg-to-fry survival in chum salmon could not be compared between Carnation Creek and the Queen Charlotte Islands. This limitation is unfortunate because chum salmon usually spawn in the lower portions of a drainage system and may thus reflect the cumulative impacts of fluvial disturbance more sensitively than coho salmon or trout.
6. There was a difference between the way juvenile steelhead numbers appeared to respond to logging in streams on the Queen Charlotte Islands and in the Carnation Creek drainage. This may have been caused by greater loss of deep pools in Carnation Creek than in Queen Charlotte Island streams, or it may have been due to the operation of a fish fence and, intensive work in Carnation Creek.

There were major differences among the life history strategies of coho salmon and steelhead and cutthroat trout when they occurred in complex habitat systems such as that found in Carnation Creek. Because there were also differences among the ways that these species responded to logging impacts, it is important to understand as much as possible about what impacts might occur in different types of systems. Evidence from Carnation Creek indicated that during the logging period of 1976–1981 and afterward, steelhead trout numbers followed a pattern different from that of cutthroat trout or coho salmon (Hartman and Scrivener 1990). The latter two species made use of off-channel habitat: steelhead did not. Steelhead survival may have declined because of the loss of deep pool habitat, a loss that would have had the most effect on ages 2+ and 3+ juveniles. We are unable to compare the effects of logging on pool habitat in the two areas and can not explain the apparent differences in steelhead survival.

The studies in both Carnation Creek and Queen Charlotte Islands provided information about processes and fish population responses from a range of streams. Winter was a critical period in which populations of young fish were reduced in both studies. Consideration must therefore be given to those activities that will affect the quality and quantity of winter habitats and fish access to these sites. Forestry activities must minimize debris and sediment release and transport, from the headwaters down.

We suggest that stream aspect, gradient, elevation, hydrological energy, and channel structure are primary features that determine fish responses to land-use treatments. Furthermore, if progressively higher proportions of terrain proposed to be logged in the future falls into steeper slope categories, the scale of impact associated with these features will be greater. In the absence of progressive refinement of management measures, impacts on overwintering habitat and survival will increase.

If we look for standardized ways of dealing with forestry impacts for all watershed ecosystems and fish species, we will fail in our efforts. It is an error to look for simple “formula-type” management for complex and varied systems that contain several fish species each of which is different in the way it responds to impacts. It is more important that managers try to understand the processes operating within stream ecosystems, processes that vary

according to differences in land characteristics, than to seek sets of rules for each perceived situation. This recommendation does not mean that forestry practices should not be related to impacts on fish. Rather, it means that in order to relate forest practices, impacts, and fish production, we must understand processes as much as possible. Knowledge of processes, and variability within them, must be regarded as key parts of the foundation of planning and regulation.

Summary

The management of Pacific Northwest salmon and trout requires an understanding of the processes which control their use of freshwater habitats, and their survival while in these habitats. Furthermore, managers must recognize that these processes may vary among watersheds and regions. To illustrate the complexity of fish-forestry interactions, the behaviour and habitat use of juvenile coho salmon, and steelhead and cutthroat trout are described briefly and compared for some of the different streams and regions of northwestern North America.

Coho salmon and cutthroat trout have life history strategies that include the use of small, floodplain tributaries, swamps, and sloughs during winter. Smolt numbers of these two species did not decline following logging in the Carnation Creek drainage because both species used these off-channel refuges which were little altered by forest harvesting.

The life history strategy employed by steelhead trout was apparently more limited. Steelhead trout made little use of off-channel refuges in winter, and their numbers fell for several years after logging in Carnation Creek. Differences in life history strategy among species may be reflected by the overwinter survival of their juveniles, but results of studies in different regions were not consistent. Steelhead smolt abundance declined for at least the first 10 years following logging in Carnation Creek. This decline appears to be anomalous with results from work on the Queen Charlotte Islands where numbers of steelhead juveniles, within stream sections, did not decline in response to logging. Densities of ages 0+ and 1+ steelhead trout were higher in logged stream sections than in unlogged ones, but this pattern was not apparent in older fish. Densities of age 0+ coho salmon were higher in logged sections in the autumn, but they were similar between logged

and unlogged sites by spring. Overwinter survival information for age 0+ coho salmon was more consistent between studies than it was for steelhead trout. Overall, coho and trout, especially cutthroat trout, appeared to be affected less by the impacts of logging than were chum salmon, which were severely reduced in numbers in Carnation Creek.

Acknowledgements

Many people have contributed to the fisheries-forestry work in both Carnation Creek and the Queen Charlotte Islands. All such work is appreciated. Much of the information in this paper is based on the original and unpublished work in the Queen Charlotte Islands by Derek Tripp and the thesis of Tom G. Brown. The senior author appreciates their permission to use this information.

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Long-term Patterns in the Abundance of Carnation Creek Salmon, and the Effects of Logging, Climate Variation, and Fishing on Adult Returns

PETER J. TSCHAPLINSKI, J. CHARLES SCRIVENER, AND L.B. HOLTBY

Introduction

The effects of forest harvesting on fish populations have been studied for over 23 years at Carnation Creek on the west coast of Vancouver Island, British Columbia. This intensive case study of a single watershed has generated the longest series of continuous data on fisheries-forestry interactions anywhere. The Carnation Creek Experimental Watershed Project was initiated in mid-1970 by the federal agency now known as the Department of Fisheries and Oceans. In the 1960s, resource managers and planners had to base their judgements about the effects of logging on fish populations on studies conducted elsewhere in North America, such as Oregon, Alaska, and as far away as New Hampshire. Both the forest industry and government resource agencies expressed concern that these extrapolations might not lead to the most appropriate planning decisions for areas on the west coast of British Columbia. Therefore, the Carnation Creek study was initiated to provide fisheries-forestry information on at least one type of drainage basin in coastal British Columbia.

After 1971, the Carnation Creek study greatly expanded into a multi-agency, multi-disciplinary program on the effects of forest harvesting on a coastal watershed and its salmon and trout populations. The objectives of this research and monitoring program were to: 1) provide an understanding of the physical and biological processes operating within a coastal watershed; 2) reveal how the forest harvesting practices employed in the 1970s and early 1980s changed these processes; and 3) apply the results of the study to make reasonable and useful decisions concerning land-use management, fish populations, and aquatic habitat protection. The project has achieved these goals despite the limitations typically associated with intensive studies

made only in a single watershed. Over 180 publications have been produced from Carnation Creek research. The results from this project have made major contributions to the British Columbia Coastal Fisheries-Forestry Guidelines (CFFG) implemented in 1987, and the legally binding provisions for aquatic habitat protection within the new British Columbia Forest Practices Code.

Fish populations have been studied at Carnation Creek virtually continuously since 1970. This project has thus provided researchers with a unique opportunity to examine the long-term changes in the abundance, growth, and survival of coastal salmon and trout under a regime of forest harvesting. The objectives of this review are to illustrate:

1. the changes in the abundance, growth, and survival of coho salmon (*Oncorhynchus kisutch*), chum salmon (*O. keta*), anadromous rainbow trout ("steelhead", *O. mykiss*), and cutthroat trout (*O. clarki*) in Carnation Creek from 1970 or 1971 (depending upon the species) to 1993 through 5 pre-logging, 6 during-logging, and 12 post-logging years;
2. the complex effects of forest harvesting and the way in which they vary among species and among the life stages within the same species; and
3. the dependency of salmonid production on biological and physical processes occurring not only within watersheds, but also in marine environments (e.g., climate-associated changes, predation, and fishing).

The following discussion also shows the value of long-term, multidisciplinary studies for clarifying the complex interactions among land-use practices and the natural processes occurring within watersheds, which together determine salmonid abundance and growth in coastal streams.

Methods

The design of the Carnation Creek Experimental Watershed Project and the methods employed for monitoring physical variables and biological processes before, during, and after forest harvesting have been thoroughly described by Hartman and Scrivener (1990). Those authors summarized all aspects of the project and provided a comprehensive bibliography of the publications generated from Carnation Creek research, current to 1990. The

following summary is condensed from the detailed descriptions in that work.

Carnation Creek is located approximately 20 km northwest of Bamfield on the south shore of Barkley Sound in southwestern Vancouver Island (49°N, 125°W; Fig. 1). The watershed occurs within the Coastal Western Hemlock Biogeoclimatic Zone, which spans the west coast of North America from the Olympic Peninsula in Washington State to the Queen Charlotte Islands and southeast Alaska (Krajina 1969). The stream drains an area of 11 km²

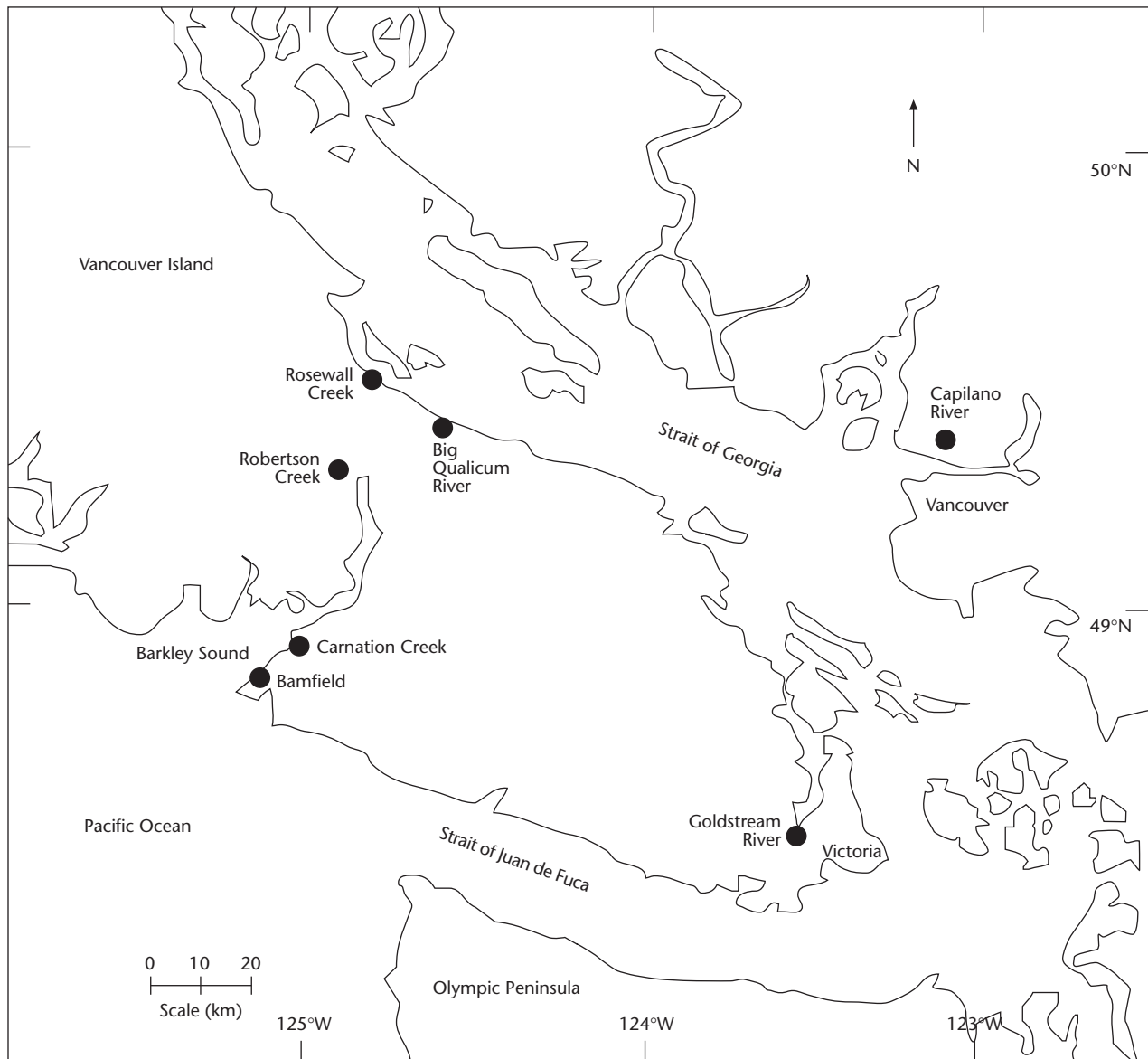


FIGURE 1 Location of the Carnation Creek study site in southwestern Vancouver Island.

and contains rugged terrain between 0 and 800 m elevation. The valley walls have gradients up to 80%. The main stream is about 7.8 km long, but only the lowermost 3.1 km extending from the stream mouth to the base of a steep-gradient canyon is inhabited by anadromous salmonids, including coho salmon, chum salmon, steelhead trout, and cutthroat trout. Much of this lowest stream reach contains a valley bottom of about 55 ha that is 50–200 m wide. The coarse, well-drained soils, forest cover, hydrology, and heavy annual precipitation ranging from 210 to over 500 cm/yr are typical of western Vancouver Island and many other areas of coastal British Columbia. About 95% of the annual precipitation falls as rain, primarily during autumn and winter. High variations in seasonal rainfall cause stream discharge to range from 0.03 m³/s in summer to 64 m³/s in winter. Stream discharge may increase by 200 fold within 48 hours because of the rapid runoff from rainstorms that produce up to 26 cm of precipitation within the same period.

The Carnation Creek study originally sought to determine the effects of three different types of streamside forest-harvest treatments on stream channels and fish populations. These treatments were applied along the lowermost 3 km of stream accessible to anadromous salmonids. A “leave-strip treatment” was applied from the estuary to 1300 m upstream. This treatment was designed to buffer the effects of clearcut logging from the stream channel by leaving a riparian strip of trees that varied from 1 to 70 m wide. An “intensive treatment” was applied along 900 m of stream channel immediately upstream from the leave-strip treatment. The intensive treatment involved clearcut harvesting simultaneously along both sides of the stream up to the channel margin. No riparian trees were left standing. Any activity within the channel that was considered operationally convenient, such as felling and yarding trees across the stream, was permitted. Economically valuable, windthrown trees lying within the stream channel were removed. Logging-associated debris was burned after the forest was harvested. The third treatment, called “careful clearcutting,” was applied over the 900 m length of stream immediately upstream from the intensively treated area. No activity within the stream was permitted in this treatment, with the exception that six trees leaning over the stream channel were felled across it and removed. Perennial vegetation on the

streambanks, such as salmonberry (*Rubus spectabilis*), was left alone; however, red alder trees (*Alnus rubra*) were removed.

The responses of a comprehensive set of biological and physical variables within the Carnation Creek basin were determined relative to forest harvesting over: (a) 5–6 pre-logging years spanning 1970 to 1975 (beginning in 1970 or 1971, depending on the variable measured); (b) 6 years spanning 1976 to 1981, during which 41% of the watershed was harvested (including almost all of the valley bottom); and (c) 12 post-logging years from 1982 to 1993. From 1987 to 1993, additional harvesting occurred in headwater areas remote from the main stream channel (<15% of the basin area).

Historical Data Collections Data collected historically have included comprehensive information on: climate; stream temperatures and discharge; ground-water levels (piezometers); water chemistry; stream channel morphology; large woody debris abundance and distribution (“LWD” which includes tree trunks, root masses, and large limbs); streambed particle-size composition (frozen-core methods); suspended sediment transport during high flows (automated sampling at one hydrological weir); streambed scour and deposition; ground disturbance, landslides, and post-logging revegetation; biomass of aquatic algae (periphyton); abundance and distribution of benthic macroinvertebrates; and fish populations. Details of all historic methods are given in Hartman and Scrivener (1990).

Fish population studies have examined, among other factors:

- abundance and distribution of adult salmonid spawners returning to the stream (autumn and winter);
- numbers of juvenile salmonids (smolts and young-of-the-year [fry]) migrating seaward in spring;
- abundance, distribution, age structure, growth, and survival of juvenile salmonids rearing in freshwater and estuarine habitats during summer and early autumn;
- seasonal movements of juvenile salmonids out of the main stream into “off-channel” overwinter habitats, and return movements in spring;
- main-channel and “off-channel” abundance, distribution, and survival of juvenile salmonids in winter;

- chum egg incubation, egg survival, and fry emergence (redds capped with trap nets); and
- fecundity for female chum and coho salmon for estimates of annual egg-to-fry survival.

See Andersen (1978, 1981, 1983, 1987), Andersen and Narver (1975), Andersen and Scrivener (1992), Brown (1987), Brown and Hartman (1988), Brown and McMahon (1988), Bustard (1991), Bustard and Narver (1975), Tschaplinski (1982a, b; 1988), and Tschaplinski and Hartman (1983).

Current Data Collections Many variables and processes continue to be studied. Work currently concentrates on fish populations and habitat, stream channel morphology, streambed movements, climate, hydrology, forest regeneration and growth, and hillslope processes.

Water temperature, depth, and discharge are monitored at permanent hydrological weirs installed on the main stream and on several principal tributaries. Climate stations are located in several sites at different elevations in the watershed. Some stations are co-located with the hydrological weirs. Air temperature, solar radiation, precipitation, relative humidity, and wind speed and direction are the climate variables monitored. Climate and hydrology stations have been updated by the installation of continuous-operation, electronic data recorders.

Channel morphology changes are determined annually in nine survey reaches of the stream (which incorporate the same sections used to determine seasonal fish population abundance and distribution). Standard survey and mapping techniques are employed (see Hartman and Scrivener 1990). Within each survey section: (1) all pieces of LWD are mapped and identified with numbered metal tags to observe changes in distribution and abundance; (2) textural distributions of surface sediments, especially fines, are described visually by using grid samplers and then mapped; and (3) cross-sectional and longitudinal profiles of the stream channel are obtained to describe its geomorphology. These ground-based techniques are supplemented with annual aerial surveys of the entire creek channel. Stereo aerial photographs are used to determine changes in channel structure in areas between study reaches and to generate an inventory of fish habitats throughout the stream. Aerial photographs will also be employed to monitor the rates of canopy closure over the creek as the new forest grows. Canopy closure and forest

growth will be studied relative to future water temperature changes in Carnation Creek.

Channel scour and deposition are studied in the same survey reaches by using scour-and-fill monitors (Haschenburger, this volume). Sediment (bedload) transport is estimated by studying the annual movements (distances and depths) of painted, magnetic rocks placed onto the streambed. These rocks represent the size distributions found in the streambed (Haschenburger, this volume).

Adult salmonids (coho and chum salmon, and steelhead and cutthroat trout) returning to spawn in Carnation Creek are enumerated at the main fish weir located near the mouth of the stream. Spawners are identified to species and sex. Ages are determined from scale samples and lengths are taken. Chum salmon that spawn downstream of the fence are enumerated visually each day by observers on foot.

Juvenile salmonids (fry and smolts) and sculpins (*Cottus asper* and *C. aleuticus*) migrating seaward in spring are also enumerated and identified to species at the main fish weir. Large samples of salmonid fry and smolts (up to 50 individuals per species per day) are measured for length and weighed. Scale samples are taken daily from up to 50 smolts of each species.

The abundance, habitat distribution, growth, and survival of populations of juvenile salmonids and sculpins rearing in Carnation Creek from spring to autumn are currently determined from three surveys conducted usually between June 15 and late September. During each survey, the two-catch removal method (Seber and LeCren 1967) is used to assess abundance within 9–10 representative study sections. Fish are captured by electrofishing and seining in each of two fishing trials. Barrier nets are employed to ensure no fish move between the surveyed section and adjacent stream reaches. Each fish collected is identified to species and measured for length (Andersen and Narver 1975). Large samples are weighed, and scales are taken to determine population age-size distributions and age-specific growth rates. The total abundance of fish in Carnation Creek is determined by extending the numbers of fish captured in the survey sections to the total length of stream inhabited by each species. Within each surveyed section, the total wetted surface area of the stream and its component pool, glide, and riffle areas are measured to determine densities of fish in specific habitats. Fish habitat is classified and quantified according to methods adapted from Bisson et al. (1982) and Hankin and Reeves (1988).

Overwinter survival of juvenile salmonids is determined from the difference between population abundances estimated in late summer (or early autumn) and the numbers of smolts migrating seaward from Carnation Creek in spring (plus any residual parr remaining in the stream in spring). Seasonal changes in distribution and habitat use between summer (rearing) and winter (shelter) are determined each year by a population survey in the main channel in winter, and by monitoring the movements of coho salmon and cutthroat trout between Carnation Creek and its valley-bottom tributaries through daily counts of fish at tributary weirs. Abundances of fish in specific off-channel sites are determined at intervals during winter by using large numbers of Gee traps baited with fish roe. Seasonal use of these off-channel sites by fish and changes in habitat characteristics are determined annually.

Results and Discussion

The principal trends in Carnation Creek fish population abundance, distribution, and survival over the past 23 years are discussed primarily for coho and chum salmon—the dominant species in the watershed.

Adult Chum and Coho Salmon Returns Adult chum salmon return to spawn in Carnation Creek primarily as 4-year-olds (usually >80%) and mainly in October and November (Hartman and Scrivener 1990). In most years, chum salmon has been, in numbers, the dominant salmonid spawning in Carnation Creek (Fig. 2). However, this species has shown the most drastic decline in abundance after forest harvesting. Before forest harvesting (1970–1975; Fig. 2), adult chum returns reached 4168 in one year, averaged 2188 (95% confidence interval: ± 1272), and never fell below 1000. (Variation associated with mean values are $\pm 95\%$ confidence limits in this report unless otherwise noted.) During 6 years of logging from 1976 to 1981, chum returns were not significantly different from the pre-logging mean: annual returns were 2042 ± 1102 (Fig. 2). Spawner abundance varied between a maximum of 3300 and a minimum of 450 during that period. Over the first 4 years of the post-logging period, average numbers returning exceeded 1600; however, sharp declines have been

observed in most years since 1986. Only 847 ± 497 chum have returned to spawn in Carnation Creek in the post-logging period between 1982 and 1993 (Fig. 2). Chum returns have thus averaged only about 39% of their pre-logging levels (Student's t , $p < 0.05$), and were less than one-sixth of the pre-logging average in 5 of 12 post-logging years.

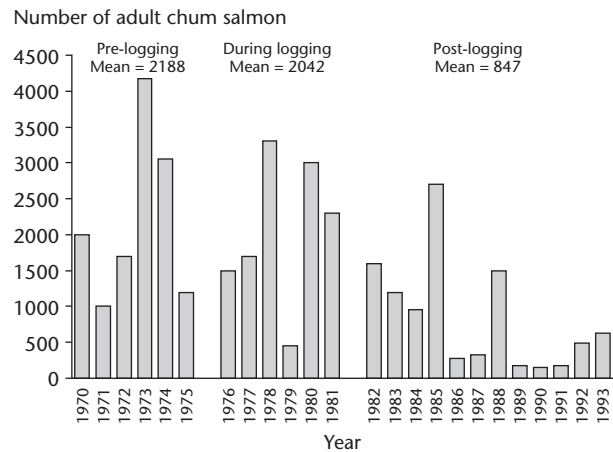


FIGURE 2 Numbers of adult chum salmon returning annually to Carnation Creek between 1970 and 1993.

Fisheries are thought to have had little effect on the numbers of chum salmon returning to Carnation Creek. Commercial harvesting for chum in Barkley Sound has been restricted since 1962 (Lightly et al. 1985). The fishing rate (proportion) has been <0.01 in 15 of 24 years examined, and usually <0.15 in most years since 1951 (Lightly et al. 1985). In 1971, 1973, 1978, and 1980, fishing took an estimated 20–43% of Barkley Sound chum, but the extensive fishery in those years reflected exceptional adult returns to the area and Carnation Creek (Andersen 1983; Lightly et al. 1985). The commercial gillnet and seine fisheries were concentrated in terminal areas far from Carnation Creek on the north side of Barkley Sound (Lightly et al. 1985), and suggest that few chum from Carnation Creek were caught.

Local aboriginal peoples have annually conducted a small food fishery for chum; however, this fishery often consisted of only one net-set during the peak of the adult run returning to the nearby Sarita River

(1.8 km away). Holtby and Scrivener (1989) noted that up to 300 fish are taken annually, and some are probably Carnation Creek chum. These investigators believed that the long-term decline in chum returns to Carnation Creek coinciding with the post-logging period are not likely due to fishing mortality.

Two patterns in coho spawner abundance have been observed, and each is associated with one of two types of coho returning annually to Carnation Creek. In most years, the majority of coho spawners are adults 3 or 4 years old that have spent about 18 months, including two summers, in the ocean (Hartman and Scrivener 1990). These fish are called “large adult coho” because most individuals are >44 cm long. Other coho, usually ≤44 cm long, return to spawn after spending only about 5–6 months in the ocean (Hartman and Scrivener 1990). These small fish are usually 2-year-old precocious males called jacks. Returns of large adult coho have declined significantly after logging in Carnation Creek (Student’s t , $p < 0.05$; Fig. 3); however, the decline has been less marked than that shown by chum. Before forest harvesting (1971–1975), 165 ± 17 large adult coho returned each year (Fig. 3). These returns decreased by about 31% to only 116 ± 34 in the post-logging period. In contrast with large adults, the numbers of jacks returning show no statistically significant trend among pre-logging, during-logging, and post-logging periods (Student’s t , all $p > 0.05$; Fig. 4). Therefore, when large adults and jacks are combined, the significant decline in the total coho

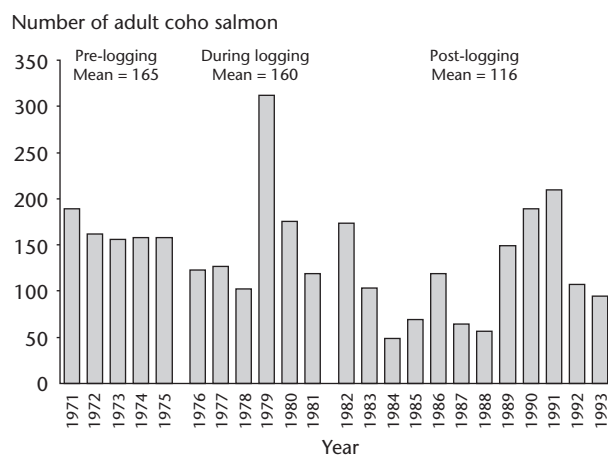


FIGURE 3 Numbers of large adult coho salmon returning to Carnation Creek annually between 1971 and 1993.

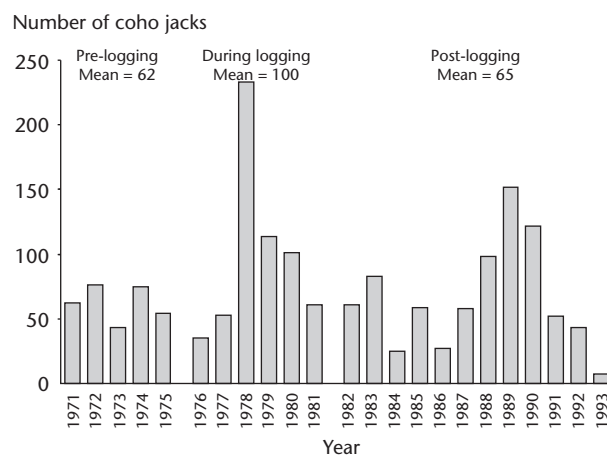


FIGURE 4 Numbers of coho jacks (small, precocious males) returning to spawn in Carnation Creek between 1971 and 1993.

return to Carnation Creek between pre-logging (227 ± 26) and post-logging (181 ± 50) periods is due to the decline in numbers of large adult coho alone (Student’s t , $p < 0.05$; Fig. 5).

The interannual variation in the abundance of both jacks and large adults has increased sharply since 1976, when forest harvesting activities were initiated (Figs. 3–4). The causes of the high interannual variability in jack returns are as yet unclear. However, the numbers of jacks actually exceeded the numbers of large adult coho in 1978,

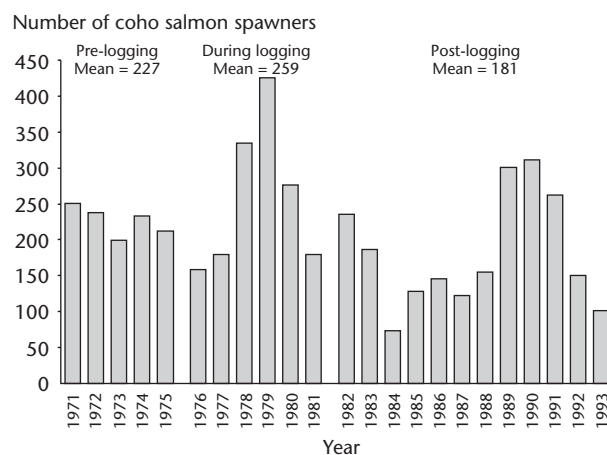


FIGURE 5 Total numbers of coho (large adults plus jacks) returning to spawn in Carnation Creek between 1971 and 1993.

1988, and 1989 when they made up respectively 69.6, 63.2, and 50.5% of the total numbers of coho returning to spawn. On several occasions, strong returns of jacks in a given year have been followed by strong returns of large adults in the next year (Figs. 3–4); however, this pattern was not consistent for all years.

The abundance of large adult coho was nearly invariant among years before logging (Fig. 3). However, the increase in variation in the during-logging and post-logging periods included especially low returns observed in 4 of 5 years spanning 1984 and 1988 when large coho averaged only 60 at Carnation Creek (Fig. 3). These depressed numbers occurred at roughly the same time during the mid-1980s when chum salmon returns also began to decline sharply in some years although there were species-specific differences in annual patterns (Figs. 2–3). In contrast with chum, coho spawner abundance increased dramatically between 1989 and 1991, during which time adult numbers returning exceeded the pre-logging average in each year (Fig. 3). However, these elevated returns reversed in the following 2 years when Pacific salmon stocks, including Carnation Creek coho and chum, were subjected to the simultaneous effects of forest harvesting, fishing, climatic warming, and poor conditions for marine survival caused by the northward extension of warm, nutrient-poor waters from southern latitudes (Konno 1992, 1993; Ware and Hargreaves 1993).

The warm-water phenomenon, termed the “El Niño,” was characterized not only by low ocean productivity, but also with elevated predator abundance (Karinen et al. 1985; Ware and Hargreaves 1993). A similar combination of conditions coincided in 1983 (Karinen et al. 1985; Holtby and Scrivener 1989) and contributed to the declines in adult coho and chum observed during the mid-1980s (Holtby and Scrivener 1989); however, the El Niño phenomenon at that time persisted for only about a year. El Niño-like conditions in the 1990s were first detected in 1992 and persisted beyond 1993 (Konno 1993; Ware and Hargreaves 1993). Because these conditions occurred throughout most of coastal British Columbia, low spawner returns were not unique to coho returning to Carnation Creek. Similar observations were made for coho and other salmon species returning to streams throughout the west coast of Vancouver Island and

elsewhere in south coastal British Columbia (Heizer 1991; Nelson 1993).

In contrast with chum, coho originating from Carnation Creek and several hundred other streams from western Vancouver Island, the Strait of Georgia, Fraser River, and the U.S. are subject to significant commercial (mainly troll) and recreational fisheries each year off the west coast of Vancouver Island. There is no direct measure of the number of Carnation Creek coho caught in various fisheries because smolts leaving Carnation Creek are not usually marked with coded-wire tags to study their patterns of ocean distribution and fishing mortality. The coho stock from the nearby Robertson Creek hatchery (Fig. 1) is the only one from the west coast of Vancouver Island that is tagged annually and has the data required to calculate harvest rates (Holtby and Scrivener 1989).

Fisheries scientists and managers have used Robertson Creek coho data to estimate fishing and natural mortalities for west coast Vancouver Island stocks including coho from Carnation Creek (Holtby and Scrivener 1989). Despite some untested assumptions (e.g., that hatchery and wild-stock smolts behave similarly in the ocean), the application of Robertson Creek information to Carnation Creek coho has been justified because: (1) the limited studies of coded-wire-tagged coho from Carnation Creek and other streams have shown that catch distributions are similar among west coast Vancouver Island stocks; therefore, coho from Carnation and Robertson creeks should be exposed to the same fisheries for similar periods of time; (2) temporal patterns of smolt-to-adult survival are significantly correlated between coho from Carnation and Robertson creeks; and (3) annual trends in adult escapements are generally similar between Carnation Creek coho and other western Vancouver Island stocks (Holtby and Scrivener 1989). From these statistical relationships, fishing mortality for Carnation Creek coho has been estimated to have ranged annually between 65 and 70% and averaged 67% throughout the period of the Carnation Creek study (Holtby and Scrivener 1989).

Holtby and Scrivener (1989) concluded that this fishing pressure has had little effect upon annual variations in adult coho returns to Carnation Creek. These investigators used a series of sequentially linked regression models to determine the relative effects of climate shifts, forest harvesting, and fishing

on the returns of adult chum and coho to Carnation Creek. The models predicted adult escapements based on correlations between fish population responses (e.g., survival and growth) at different life stages and (a) climatic, hydrologic, and physical variables, (b) indices of freshwater habitats affected by logging, (c) fishery exploitation rates varying from 0 to 0.50 for chum and 0.59 to 0.80 for coho. Simulations based on data available up to the late 1980s for Carnation Creek indicated that most of the variation in observed and predicted adult spawner returns for both species resulted from climate variations (warming) in both freshwater and marine environments (in roughly equal measure). Juvenile life stages appear to be the most affected by increased temperatures (see following discussion on juvenile salmonids).

Shifts in climate were determined from long-term trends in air and water temperatures from monitoring stations at Carnation Creek and other west coast Vancouver Island sites (to include data on ocean surface salinities and temperatures, and information prior to the start of the Carnation Creek study; Holtby 1988; Holtby and Scrivener 1989). Holtby (1988) used multiple regression analyses to partition the increases in stream temperatures observed after 1976 between the effects of forest cover removal and climate change. He determined that logging-associated increases in water temperatures varied from 0.7°C in December to ~3.3°C in August.

Fishing mortality generated little change in the interannual patterns in adult returns associated with climate variations. However, exploitation at the highest rates resulted in 2- to 3-fold increases in interannual variation in adult numbers relative to moderate levels of exploitation (Holtby and Scrivener 1989). The model predicted the collapse of salmon stocks when the effects of habitat disturbance (forest harvesting), adverse oceanic conditions, and high fishing rates coincided. This prediction appears consistent with the reduced coho returns to Carnation Creek and other Vancouver Island streams observed in 1992 and 1993.

Clearly, the cumulative effects of forest harvesting, climate shifts, fishing, low ocean productivity, and elevated marine predation may reduce small populations of coho (such as the one in Carnation Creek) to levels that approach year-class extinction. To conserve salmon stocks that are simultaneously

affected by these three factors, the only short-term option available to fisheries managers is to reduce fishing pressure to allow more adults to return to their spawning grounds.

The analyses by Holtby and Scrivener (1989) and Scrivener (1991) indicated that forest harvesting alone reduced the numbers of chum adults returning to Carnation Creek after logging by 26% on average. However, <10% of the decline in adult coho returns by the late 1980s was predicted from forest harvest effects (Holtby and Scrivener 1989). The authors noted that their results were counter-intuitive, given that the relatively long time spent by coho in fresh water suggests that this species would be more strongly affected by forest harvesting than would chum. Conversely, chum spend more of their life cycle in marine environments and thus might be expected to be more strongly affected by marine climate shifts than by freshwater habitat changes. These trends might become more clear with continued observations of life-stage-specific abundance and survival from Carnation Creek. Regardless of any refinements that would occur, researchers and natural resource managers must clearly be aware of biological and physical processes occurring within both watersheds and marine environments before interpreting observed patterns in salmonid production.

Effects on Juvenile Salmonids

Chum Salmon Forest harvesting is clearly one of several causes of the observed declines in chum salmon abundance at Carnation Creek and elsewhere along the south coast of British Columbia (Holtby and Scrivener 1989; Scrivener 1991). Two-thirds of the post-logging decline of Carnation Creek chum that was attributed to forest harvesting by Holtby and Scrivener (1989) is explained by reductions in egg survival due to sedimentation of spawning and egg incubation gravels (Scrivener 1991). Observed egg-to-fry survival for chum has declined by roughly one-half from a mean of 20.3% in pre-logging years to 10.9% after logging (Hartman and Scrivener 1990).

Most chum at Carnation Creek spawn in the lowermost portion of the system located downstream of the main fish weir. Between 68 and >99% of all chum spawn in this area, all of which is under tidal influence and most of which is regularly

inundated with saline water (Tschaplinski 1982b, 1988). The remaining spawners migrate usually only short distances (e.g., 100 m) upstream of the weir. Frozen-core gravel samples have shown that all of this area used by chum has been subject to increases in fine sediment deposition after forest harvesting (Scrivener and Brownlee 1982, 1989; Scrivener 1988a, b, c, 1991; Hartman and Scrivener 1990).

Much of the sediment added to the stream came from eroding banks in areas upstream where both careful and intensive streamside forest harvest treatments were applied (Hartman et al. 1987; Hartman and Scrivener 1990). Post-logging accelerations of bank erosion occurred in these clearcut areas in association with increased frequencies and magnitudes of seasonal freshets observed from 1978 to the mid-1980s (Hartman et al. 1987; Scrivener 1988b, c; Scrivener and Brownlee 1989). Freshets transported the eroded materials downstream into the leave-strip treatment area, including the sites used by chum salmon (Hartman and Scrivener 1990, Scrivener 1988b). Analyses of frozen-core gravel samples showed that most of the material that reached the chum spawning sites and accumulated in the streambed consisted of sand and pea gravel (i.e., fines) that increased at depths where chum eggs would occur (in the middle and deep layers of the cores representing streambed depths of 12–35 cm; Scrivener 1988b). Seasonal freshets cleared this material from the streambed in both the clearcut areas upstream throughout the history of the study and from the leave-strip sites downstream before logging (Scrivener and Brownlee 1989). However, after logging, the persistent source of sand and pea gravel upstream caused the rate and depth of their accumulation to increase in the chum salmon spawning sites to the point where seasonal floods were no longer able to clean the streambed of these materials (Scrivener and Brownlee 1989). Sixty percent of the variation in chum egg survival between pre-logging and post-logging periods were explained by volumes of sand and pea gravel that had increased by 5.7 and 4.6% respectively.

Egg survival is well known to decrease with increasing amounts of fine sediments in streambeds (Everest et al. 1987), and as the result of streambed scour during freshets (McNeil 1966). Accumulations of fines cause egg mortality by reducing intragravel water flow and dissolved oxygen concentrations around developing embryos (Everest et al. 1987).

Additionally, fine sediments can bury alevins and prevent fry emergence (Dill and Northcote 1970; Koski 1975; Sowden and Power 1985; Scrivener 1988c). The number of chum fry produced by each spawner in Carnation Creek has been reduced by about one-half after logging, principally by these mechanisms.

Coincident with the decline in adult chum returns to Carnation Creek, fewer chum have spawned upstream of the main fish weir after forest harvesting. Before logging, up to 32% of chum adults spawned upstream of the fish weir beyond any tidal (or saline water) influence (Andersen 1983; Andersen and Scrivener 1992). Most chum now spawn downstream of the weir in areas that include some deep pools where brackish water $\geq 12\%$ remains in the streambed after high tides (Scrivener 1988a; Groot 1989). Groot (1989) demonstrated that chum eggs thrived at a salinity of 6‰, but 100% mortality occurred when eggs were exposed to salinities $>12\%$. Proportionally more of the total number of chum eggs deposited annually in Carnation Creek are now in these areas influenced by moderately high estuarine salinities where increased risk of egg mortality occurs. For example, between 1990 and 1992, fewer than three female chum spawned upstream of the weir (no females spawned above tidal influence in 1990). Only eight females migrated upstream of the weir in 1993. This shift in spawner distribution might also have contributed to post-logging declines in chum fry production from the stream.

Alterations in stream habitat have had relatively little direct effect on chum fry after they emerge from the streambed in spring because they spend little time rearing in fresh water. They emigrate seaward shortly after they emerge (Andersen 1983; Andersen and Scrivener 1992). However, logging-associated increases in the sand content of the streambed and seasonal water temperatures have had effects on chum eggs, alevins, and fry in fresh water that are linked to post-logging reductions in the survival of juvenile chum in marine environments.

First, the size (length) of chum fry has decreased after logging in association with reductions in the mean particle size of the spawning gravel (Scrivener 1988b, c; Scrivener and Brownlee 1989). Fine particles in the streambed are known to reduce interstitial spacing and thus to selectively trap larger fry within redds (Dill and Northcote 1970; Koski 1975; Sowden and Power 1985). Second, beginning

almost immediately after logging, seasonal increases in stream temperatures occurred, which were approximately proportional to the area of basin harvested (Holtby 1988). Increases occurring during winter were relatively subtle (i.e., 0.7°C mean weekly increase in December, and 1–2°C between February and April). However, these increments allowed incubating eggs to develop more rapidly during autumn and winter and, consequently, fry to emerge and emigrate seaward earlier in spring (Holtby 1988; Hartman and Scrivener 1990).

Both reduced fry size and earlier seaward emigration were correlated with reduced ocean survival (Hartman et al. 1987; Scrivener 1988c; Holtby and Scrivener 1989). Increased mortality of chum fry early in their ocean life history was attributed to increased susceptibility to predation (small size), and early-season entry into near-shore waters during winter-like conditions of relatively low salinity and biological productivity (Scrivener 1988c; Holtby and Scrivener 1989). This explanation was supported by the observation that marine survival of chum was correlated positively with sea-surface salinities for April (and for the entire “spring” period between March and June; Scrivener 1988c). Survival was very low in years when El Niño conditions prevailed (Fulton and LeBrasseur 1985; Hartman and Scrivener 1990). In El Niño years, chum fry entered the ocean in conditions that combined high predator abundances with low sea-surface salinity, warm water, and correspondingly reduced plankton productivity that resulted from the suppression of coastal water upwelling (Fulton and LeBrasseur 1985; see following discussion for coho salmon).

Anadromous Rainbow (Steelhead) and Cutthroat Trout Anadromous trout populations in Carnation Creek have always formed a relatively minor part of its fish fauna. Twelve or fewer adult rainbow and 9 or fewer adult cutthroat are known to have returned to spawn in any year since the project was initiated (Andersen and Narver 1975; Hartman and Scrivener 1990). Because of these low numbers, interpretation of population trends relative to the effects of forest harvesting is difficult. Additionally, direct estimates of adult trout abundance are not available after 1990 because from that year onward, adult counts were discontinued for the winter months (after December 18) when some adult trout return. Before 1991, the accuracy of adult trout counts was often reduced as

a result of floods that allowed spawners to migrate upstream over the fish weir without being counted (Hartman and Scrivener 1990). Despite these problems, the long-term trends in the abundance of trout smolts at Carnation Creek are included in this review to demonstrate that both species continue to inhabit the lower 3 km of the stream regardless of the sensitivity that these small populations might have to habitat alterations (Fig. 6).

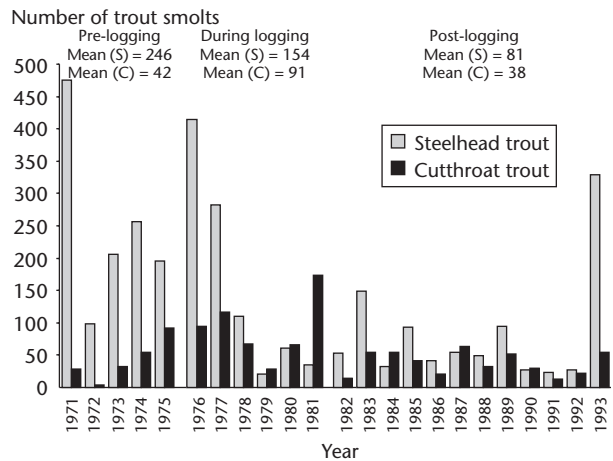


FIGURE 6 Numbers of rainbow (steelhead) trout (S) and cutthroat trout (C) smolts migrating seaward from Carnation Creek each spring between 1971 and 1993. The large number of rainbow smolts in 1993 may have been the result of good survival in a mild winter without strong freshets.

Very few cutthroat trout smolts have been produced annually from Carnation Creek. In no year have the numbers exceeded 174, and fewer than 95 smolts have been enumerated at the main weir in spring in most years (Fig. 6). No statistically significant changes in the numbers of cutthroat trout smolts produced from Carnation Creek are apparent after logging. The pre-logging mean of 42 (± 41) smolts is nearly identical to the post-logging mean of 38 ± 11 (Student's t , $p > 0.05$; Fig. 6). The trend to higher average numbers in the during-logging period is not significant, given the high variability among years ($p > 0.05$).

The abundance of rainbow trout smolts has declined on average at Carnation Creek from 246

before logging to only 81 between 1982 and 1993 (Fig. 6). Trout smolt numbers have thus fallen to about 33% of their pre-logging levels. However, variability among years has been so high that these trends are not statistically significant (Student's t , $p > 0.05$). Sharp reductions in some years are nevertheless apparent after 1978 when freshet-associated changes in the stream channel and consequent loss of rearing habitats were first observed in clearcut-logged areas of the stream (Hartman et al. 1987; Hartman and Scrivener 1990).

Rainbow trout may be more susceptible to main-channel habitat loss than either juvenile coho salmon or cutthroat trout, especially in winter when freshets are common. Rainbow in Carnation Creek are restricted to main-channel habitats, in contrast with coho and cutthroat which also occupy tributaries, especially in winter (Tschaplinski and Hartman 1983; Brown 1987). During winter, many young coho and cutthroat seek shelter from scouring freshets by inhabiting "off-channel" sites, including tributaries (Tschaplinski and Hartman 1983; Brown 1987). On the other hand, rainbow trout must find shelter in main-channel pools and undercut banks associated with logs and tree roots (Bustard and Narver 1975).

In some years after logging (e.g., 1984), low abundance of rainbow smolts in spring occurred after winters with frequent severe freshets (Fig. 6). With the loss of main-channel shelter habitats in clearcut sections of Carnation Creek (Hartman et al. 1987; Hartman and Scrivener 1990), the salmonid mortality associated with freshets was likely more pronounced in post-logging years. By comparison, winters without strong freshets were sometimes associated with high numbers of rainbow smolts in the following spring, even after logging. For example, the abundance of rainbow trout smolts in the spring of 1993 is the third highest on record (Fig. 6) and occurred after a relatively mild winter without strong freshets (unpublished project data). Despite these observations, patterns for rainbow trout are not consistent among years, and are obscured by the generally low abundance of this species in Carnation Creek. The effects of forest harvesting treatments on freshwater rearing habitats and fish populations are clearer for the relatively abundant coho salmon.

Coho Salmon The decline in the numbers of adult coho returning to Carnation Creek after forest harvesting might be explained at least partly if the

capacity of the stream to support populations of juvenile coho has decreased. Consistent with this notion, significant post-logging declines in the abundance of juvenile coho rearing in the stream during summer have been observed (Fig. 7; $p < 0.05$). Before forest harvesting, the freshwater habitats in Carnation Creek supported $11\,944 \pm 2117$ coho juveniles in late summer (late September–early October, fry and yearlings combined; Fig. 7). Between 1976 and 1981, when most of the valley bottom of the main basin was harvested, late-summer coho populations increased to $13\,656 \pm 5661$, but this increase was not statistically significant (Fig. 7; Student's t , $p > 0.05$). However, the total numbers of coho fry and yearlings rearing in Carnation Creek since 1982 have fallen on average to about 57% of pre-logging levels (Student's t , $p < 0.05$). Between 1982 and 1993, only 6826 ± 1586 juvenile coho inhabited Carnation Creek (Fig. 7).

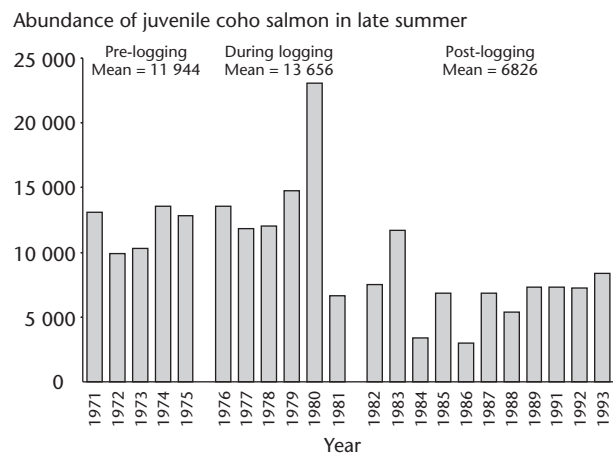


FIGURE 7 Abundance of juvenile coho rearing in Carnation Creek in late summer (Sep–Oct). These populations, consisting mainly of fry plus some yearlings, have declined by about 43% between pre-logging and post-logging periods (Student's t , $p < 0.05$). No data were available for 1990.

The post-logging reduction in juvenile coho abundance is due partly to marine survival variations that have reduced the numbers of adults returning to spawn in the post-logging period (Scrivener and Andersen 1984; Holtby and Scrivener 1989; Hartman and Scrivener 1990). The abundance

of adult females has declined on average by about 33% in the post-logging period, compared with numbers in pre-logging years (Student's *t*, $p < 0.05$). In pre-logging, during-logging, and post-logging periods, the mean numbers of coho females returning to spawn were 73 ± 6 , 74 ± 53 , and 49 ± 16 , respectively. This post-logging decline has resulted in fewer eggs deposited into the streambed. Consequently, fewer fry have inhabited the system during summer since 1982. However, the post-logging reduction in the abundance of juvenile coho in Carnation Creek was also due to logging-caused reductions in egg-to-fry survival and the quantity and quality of summer habitats.

After forest harvesting, coho egg-to-fry survival declined by about one-half in Carnation Creek from 28.8 to 15.6% (Hartman and Scrivener 1990). This trend was similar to that shown by chum salmon, and again was in part associated with increased amounts of sand and pea gravel in the streambed of the leave-strip area downstream of the clearcut portions of the creek ($r = 0.81$, $p < 0.001$; Scrivener and Brownlee 1989). However, reductions in coho egg-to-fry survival were primarily associated with increased rates of streambank and channel erosion after logging in both the intensively harvested and carefully harvested clearcut treatments (Toews and Moore 1982; Scrivener and Brownlee 1989). The proximal cause of increased mortality in coho embryos was increased streambed scour and deposition during freshets after logging (Holtby and Scrivener 1989).

Lower coho fry production at Carnation Creek after logging is thus the combined result of these processes in fresh water and reduced marine survival that resulted in fewer spawners returning to the creek. As well, the capacity of the stream to support those fry that survived to emerge from the streambed in spring also declined after logging. Most of this decline can be attributed to stream morphology changes that have occurred both in the intensively harvested and carefully harvested clearcut areas. Before 1982, Carnation Creek was able to support as many as 23 095 juvenile coho at the end of summer (including 20 953 fry; Fig. 7). This peak in juvenile abundance observed in 1980 exceeded mean population sizes in the pre-logging and during-logging periods by >1.9 and 1.7 fold, respectively, and was produced from the 23-year peak spawner return in the autumn of 1979 (312 large adults, including

176 females). The greatly elevated number of juveniles in Carnation Creek in 1980 suggests that habitat quantity in the stream did not limit their abundance in most years prior to the post-logging period. A >1.9 -fold increase in spawner abundance relative to pre-logging levels resulted in nearly doubling the population rearing in the system. Despite the elevated abundance of fry in 1980, strong density-dependent reductions in summer growth rates and mean size of fry were observed in that year, and indicate the upper limits of fry capacity for Carnation Creek had been reached (Holtby 1988; Tschaplinski 1987). The numbers of coho fry observed in the system before logging ($\sim 12\,000$ annually) may thus be a better indicator of the average rearing capacity of the stream.

In years other than 1980, whenever relatively high numbers of adults returned after logging, no corresponding increase in the abundance of juveniles rearing in the stream occurred in the following summer. For example, 189 large adult coho returned to Carnation Creek in 1990 and 210 in 1991 (Fig. 3). These numbers exceeded the pre-logging mean spawning escapements by 14.5 and 27.3% respectively. Additionally, the number of females returning in 1990 exceeded the pre-logging mean by nearly 33% ($p < 0.05$), while the number of females returning in 1991 (76) was essentially the same as the pre-logging mean ($p > 0.05$). Despite these relatively high spawner returns, the numbers of juveniles surviving in the stream by late summer throughout the late 1980s and early 1990s remained low and relatively invariant (Fig. 7). These patterns indicate that the quantity and quality of summer rearing habitats in Carnation Creek were reduced after logging and limited the numbers of juveniles the stream could support.

Of the 3070 m of Carnation Creek used by young coho upstream of the estuary, long-term post-logging reductions in the quantity and quality of available habitat have been observed primarily in the 1800-m portion subjected to clearcut harvesting (Hartman and Scrivener 1990). Habitat complexity in both the careful and intensive clearcut treatments decreased after logging as a result of reductions in the amount, size, and stability of LWD within the stream channel (Toews and Moore 1982; Hartman and Scrivener 1990). Stable pieces of LWD within the stream channel dissipate hydraulic energy and, in the fish-bearing reaches of Carnation Creek, are largely responsible for channel structure including

the diverse sequence of riffles, pools, glides, meanders, and undercut banks which are important habitat features for stream salmonids. The decrease in stable LWD altered fluvial geomorphic processes by increasing stream velocities, bank erosion, and channel scour and deposition (Toews and Moore 1982). As a result, the channel became wider by at least 2-fold and straighter (and thus shorter) when meanders were cut. The proportion of the stream consisting of shallow, fast-flowing riffles increased (Hartman et al. 1987). Favoured coho rearing habitat, consisting of deep pools with cover in the form of LWD, undercut banks, and overhanging vegetation (Tschaplinski 1987), became less abundant (Hartman et al. 1987). Those pools that remained became shallower through bedload deposition (Hartman et al. 1987). Long stretches of channel were filled with large deposits of gravel upstream of new log jams, thus creating ephemeral reaches and reducing stream wetted area and salmonid rearing habitat (Hartman et al. 1987).

Streamside clearcutting was partly responsible for some of these changes (see Hartman and Scrivener 1990). Logging activity around the streambanks resulted in killed or weakened tree roots in both the careful and intensive treatment areas. Large amounts of small woody debris (pieces <3 m long) were added to the channel, especially in the intensive treatment site, which destabilized LWD within the stream. Additionally, LWD in the intensive-treatment area was directly disturbed by machinery which broke or removed the pieces (Hartman and Scrivener 1990). The additions of woody debris initially increased habitat diversity and resulted in increases in fish density in the clearcut reaches of Carnation Creek early in the during-logging period (Hartman and Scrivener 1990). However, this habitat enhancement was short lived. Major freshets after logging soon removed much of this material. Coho densities adjacent to clearcut streamsides soon declined during both summer and winter relative to those observed in the leave-strip area downstream (Scrivener and Andersen 1984).

Although the Carnation Creek study intended to investigate the effects of different streamside harvesting treatments on stream channels and fish, the most pronounced changes to the stream channel have been associated with increased frequencies of landslides and debris torrents that occurred after logging. Over 80 small landslides and 3 major debris

torrents have been documented after logging in Carnation Creek (S. Chatwin, B.C. Ministry of Forests, per. comm.). All occurred in the logged portions of the watershed, and most have contributed sediment and debris into the creek channel.

No debris torrents occurred in the watershed in the pre-logging or during-logging periods. However, the three major torrents observed to date occurred early in the post-logging period in 1984. They initiated within the clearcut portions of three valley-wall tributaries (gullies) situated >1.5 km upstream of the portion of Carnation Creek containing anadromous fish (Hartman and Scrivener 1990; Hogan, this volume; Hogan and Millard, this volume). These rainstorm-triggered torrents deposited large volumes of logging-associated woody debris and inorganic sediments into the stream channel, where the materials were carried downstream into the carefully clearcut site inhabited by anadromous fish. Since 1984, the large log jams and associated sediments deposited by the torrents have moved progressively downstream into the intensively clearcut treatment and continue to cause major channel changes and fish habitat loss 10 years after their initiation. The post-logging widening of the channel, accelerated scour and deposition, and other changes have been largely due to the stream moving around these logjams and sediment deposits, and redistributing materials downstream (Hogan, this volume; Hogan and Bird, this volume).

So far, most of the woody debris and large sediments associated with post-logging landslides and debris torrents have not reached the leave-strip area of Carnation Creek. Stream structure and fish habitat characteristics remain much the same as observed in pre-logging years, with the exception of the fine sediment accumulations that have occurred in the streambed (Scrivener 1988c; Hogan and Bird, this volume). The majority of coho fry produced from Carnation Creek originate or rear in this lowermost portion of the stream. As excess sediment and debris move downstream into this area from the intensive and careful clearcut treatments, further reductions in the rearing capacity for coho will likely occur in the future. Therefore, the full extent of the harmful effects of logging on the stream channel and fish habitats are yet to be observed at Carnation Creek.

If data on smolt abundance from Carnation Creek were unavailable, one might reasonably speculate that

the numbers of coho smolts produced from this system would have declined after forest harvesting in parallel with the observed decrease in the numbers of fry and yearlings rearing in the watershed. However, the exact opposite has occurred. Both during logging and after, the numbers of coho smolts migrating seaward in spring have increased sharply (Fig. 8). Before logging, 2213 ± 424 smolts were counted on average at the main fish weir. Early in the during-logging period (1978), these numbers had nearly doubled to 4246 compared with the pre-logging mean (Fig. 8). Annual smolt production increased on average by nearly 1.7 fold to 3688 ± 813 in the 6-year, during-logging period. Numbers have remained high to the present. A 23-year peak migration of 5253 coho occurred in 1992. This peak exceeded the pre-logging mean by nearly 2.4 fold. Mean annual smolt abundance in the post-logging period up to 1993 has been 3327 ± 529 (Fig. 8).

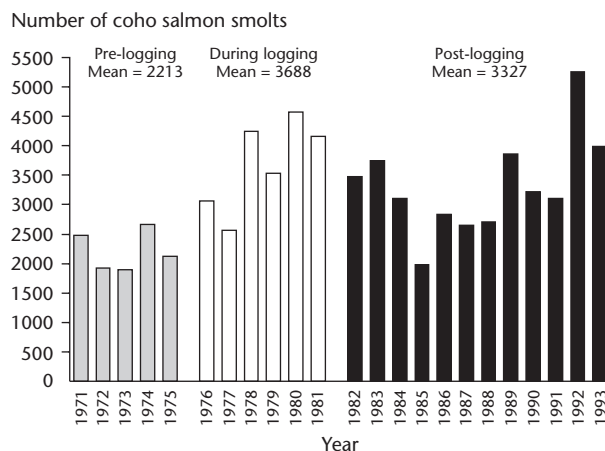


FIGURE 8 *Numbers of coho smolts migrating seaward from Carnation Creek each spring between 1971 and 1993.*

Therefore, in the post-logging period, Carnation Creek fry at about 57% of their pre-logging abundance have produced 50% more smolts compared with smolt production in pre-logging years. Smolt biomass has also increased after logging. The average weight of both 1-year-old and 2-year-old smolts has increased since 1977; for example, the mean weight of 1-year-old smolts increased by 1.5 g or one-third of their mean weight prior to logging (Holtby 1988). The reason for this phenomenon is that coho fry rearing in the stream in late summer are

surviving the winter at higher rates after logging as a result of the temperature-related effects of forest harvesting and climatic warming on coho emergence timing and seasonal growth (Holtby 1988; Scrivener 1988c; Hartman et al. 1990).

The multiple regression analyses which Holtby (1988) used to determine the effects of elevated water temperature on chum, and partition the effects due to climate change and forest harvesting, were also applied to coho. He demonstrated that the same logging-associated increases in winter water temperatures that allowed chum eggs to develop more rapidly, and chum fry to emerge earlier in spring, have had similar effects upon coho. During and after logging, coho fry were emerging from the streambed up to 6 weeks earlier in spring (Holtby 1988). Earlier emergence thus permitted these fish to experience a period for summer growth that was as much as 6 weeks longer than available to fry in pre-logging years. As well, the lower numbers of fry rearing in Carnation Creek after logging resulted in increased growth rates resulting from density-dependent reductions in competition for food (Scrivener and Andersen 1984; Holtby 1988). After logging, coho fry consequently grew 11 mm longer on average by the end of their first summer, compared with fry in pre-logging years (Hartman and Scrivener 1990). (For the same reasons, trout fry increased in mean length by 18 mm after logging in Carnation Creek [Hartman and Scrivener 1990].) This larger size was positively associated with improved overwinter survival in the stream after logging ($r = 0.91$, $p < 0.001$; Holtby 1988). Larger coho are apparently better able to survive winter conditions that include frequent scouring freshets (Tschaplinski and Hartman 1983; Brown and McMahon 1988).

The additional seasonal growth resulting primarily from post-logging increases in water temperatures has also radically changed the age structure of coho smolt populations (Fig. 9). Before forest harvesting, nearly one-half of all coho rearing in Carnation Creek required 2 years of growth before they were large enough to transform into smolts and migrate seaward (1971–1975; Fig. 9). During and after logging, increased growth made 2-year-olds relatively rare (Fig. 9).

Increases in water temperatures were observed almost immediately after clearcut harvesting removed significant portions of the streamside forest

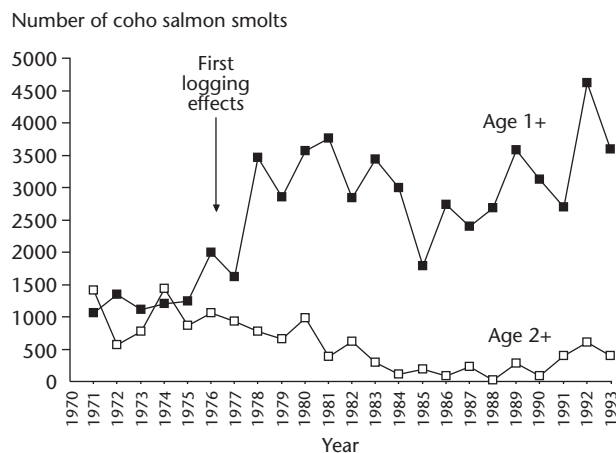


FIGURE 9 Age composition of coho smolts migrating from Carnation Creek each spring between 1971 and 1993. Since 1982, >91% of coho smolts have been 1-year-olds.

canopy (Holtby 1988; Hartman and Scrivener 1990). Coinciding with this rapid temperature shift was the dramatic increase, in 1976, in the numbers of coho fry able to grow to smolt size after rearing for only 1 year in the stream—1976 being the first year of forest harvesting (Fig. 9). The proportion of the annual smolt migration made up of 1-year-olds increased significantly from $55.3 \pm 13.8\%$ in the pre-logging period to $76.7 \pm 11.0\%$ in the during-logging period (Student's t , $p < 0.05$). This proportion increased again in the post-logging period ($p < 0.05$). From 1982–1993, 1-year-olds have formed $91.9 \pm 3.1\%$ of all smolts leaving Carnation Creek. Therefore, the temperature-related effects of forest harvesting on juvenile coho growth and age structure, established soon after streamside harvesting began, persisted in the watershed nearly 18 years later. These effects will likely continue for several years until a new riparian forest canopy is established at Carnation Creek, and pre-logging water temperatures and seasonal patterns of fish growth return.

Although smolt numbers have increased after logging, reductions in their marine survival are implied from the declining numbers of adults returning to Carnation Creek since 1982 (Fig. 3). The marine survival of coho smolts from Carnation Creek has decreased steadily since the 1970s, and the lowest survivals have occurred in the most recent years for which these data have been analyzed (Fig. 10).

Although larger size has allowed coho fry to survive the winter better in fresh water after logging, similar relationships have not been observed for coho smolts in the ocean (Hartman and Scrivener 1990; Holtby et al. 1990). The marine survival of coho smolts appears unrelated to (a) the size of either 1-year-old or 2-year-old smolts, or (b) smolt age (Fig. 11; paired t -tests, all $p > 0.05$; Holtby et al. 1990). After logging, the mean size of coho smolts migrating seaward has actually declined because most smolts are now 1-year-olds which are smaller on average than 2-year-olds, which have become rare (Hartman and Scrivener 1990).

Survival of coho salmon smolts

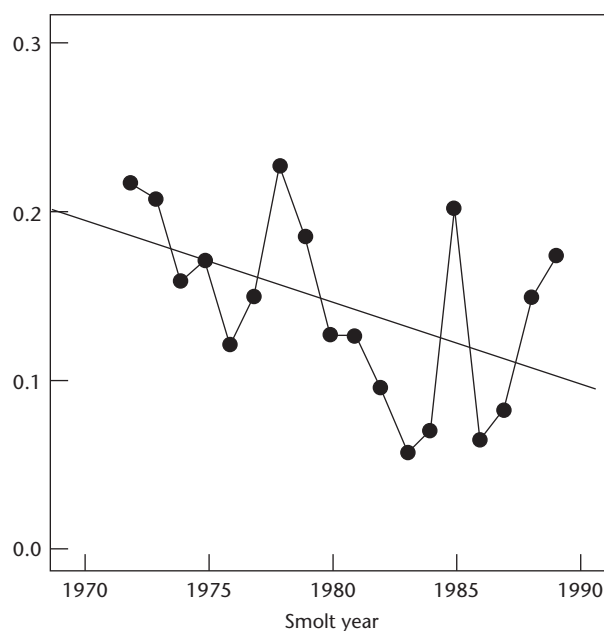


FIGURE 10 Survival of coho smolts in the ocean from the early 1970s to the late 1980s. Data on adult returns suggest that this significant ($p < 0.05$) long-term decline in survival continues in recent years. (Figure adapted from one provided by L.B. Holtby, Fisheries and Oceans Canada.)

The long-term decline in marine survival of smolts from Carnation Creek has occurred simultaneously in coho from other streams in southwestern British Columbia. For example, declines in smolt survivals have been recorded for hatchery-reared coho released from Robertson Creek, the

Big Qualicum and Capilano rivers (Figs. 1–12). These data indicate that long-term reductions in marine survival have been characteristic for the southwestern region of coastal British Columbia, and are largely associated with shifts in marine climate, decreased ocean productivity, and increased predator abundances (Holtby and Scrivener 1989).

Marine survival of coho salmon smolts

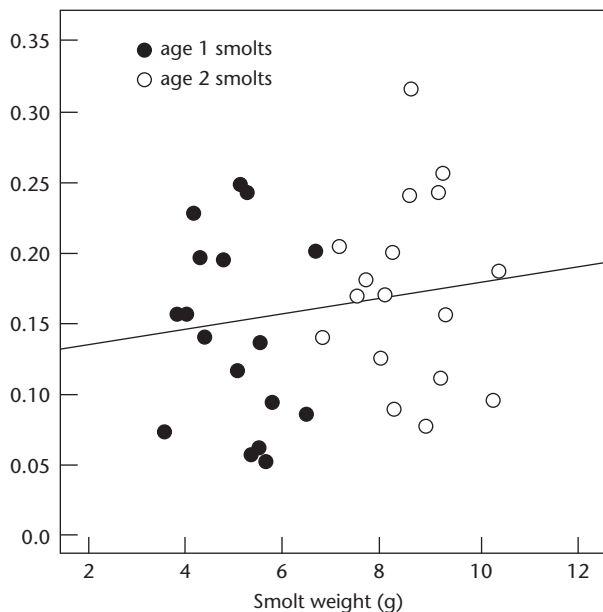


FIGURE 11 Marine survival versus size and freshwater age of coho smolts from Carnation Creek. (Figure adapted from one provided by L.B. Holtby, Fisheries and Oceans Canada.)

Despite the regional nature of these marine survival patterns, forest harvesting also appears to have contributed to the declines in marine survival of coho smolts leaving Carnation Creek. This linkage is again ultimately associated with the temperature-related effects of forest harvesting. Seasonal increases in water temperatures after logging have shifted the timing of the seaward migration of coho smolts from the stream to about 10 days earlier in the season compared with pre-logging migrations (Holtby et al. 1990). This shift appears trivial, but much information is available that demonstrates that most of the mortality in salmonids in marine environments occurs soon after they enter the ocean

(Healey 1982; Mathews and Buckley 1976; Holtby and Scrivener 1989; Holtby et al. 1990). Migration timing and ocean conditions in late winter and spring appear to be critically important in determining whether chum fry or coho salmon smolts survive to be adults (Healey 1982; Holtby et al. 1990). For example Thedinga and Koski (1984) demonstrated that coho smolts leaving a small Alaskan stream 1–2 weeks earlier or later than the median day of the migration had only 45–60% of the survival of smolts that left in the middle part of the migration period.

Consistent with these observations, Holtby and Scrivener (1989) found that migration timing in coho smolts (and chum fry) was a significant correlate of survival. From analyses of the “early-ocean” growth patterns on the scales of adult coho returning to Carnation Creek (spacing of the first five scale circuli), Holtby et al. (1990) determined that a strong and significant correlation occurred between marine survival and the growth rates of smolts soon after they enter the ocean (Fig. 13; relationship may be linear or stepped). Furthermore, strong and consistent correlations occurred between both early ocean growth and survival and sea surface salinities (Fig. 14). Years with high salinity (and low temperature) coastal waters were associated with the best years of coho survival and early ocean growth. A threshold salinity of 31.5‰ appeared to separate years in which growth and survival were poor with years when both population statistics reached relatively high values (Holtby et al. 1990).

The ocean conditions that promote the presence of cool, high salinity water at the time that Carnation Creek smolts enter coastal waters are created by the seasonal upwelling of deep water off the northwest coast of Vancouver Island (Fulton and LeBrasseur 1985; Holtby et al. 1990). Winter conditions are characterized by relatively nutrient-poor, warm, and low-salinity water flowing to the northwest from the Washington coast and out from the Strait of Juan de Fuca (Fig. 15). This pattern shifts in the spring and summer to a counter-current flow which is associated with the upwelling of deep, cold, and nutrient-rich water that promotes plankton growth and consequently high rates of salmonid growth and survival (Fig. 15). The post-logging decline in the ocean survival of coho smolts from Carnation Creek may thus be explained partly

Survival of coho salmon smolts

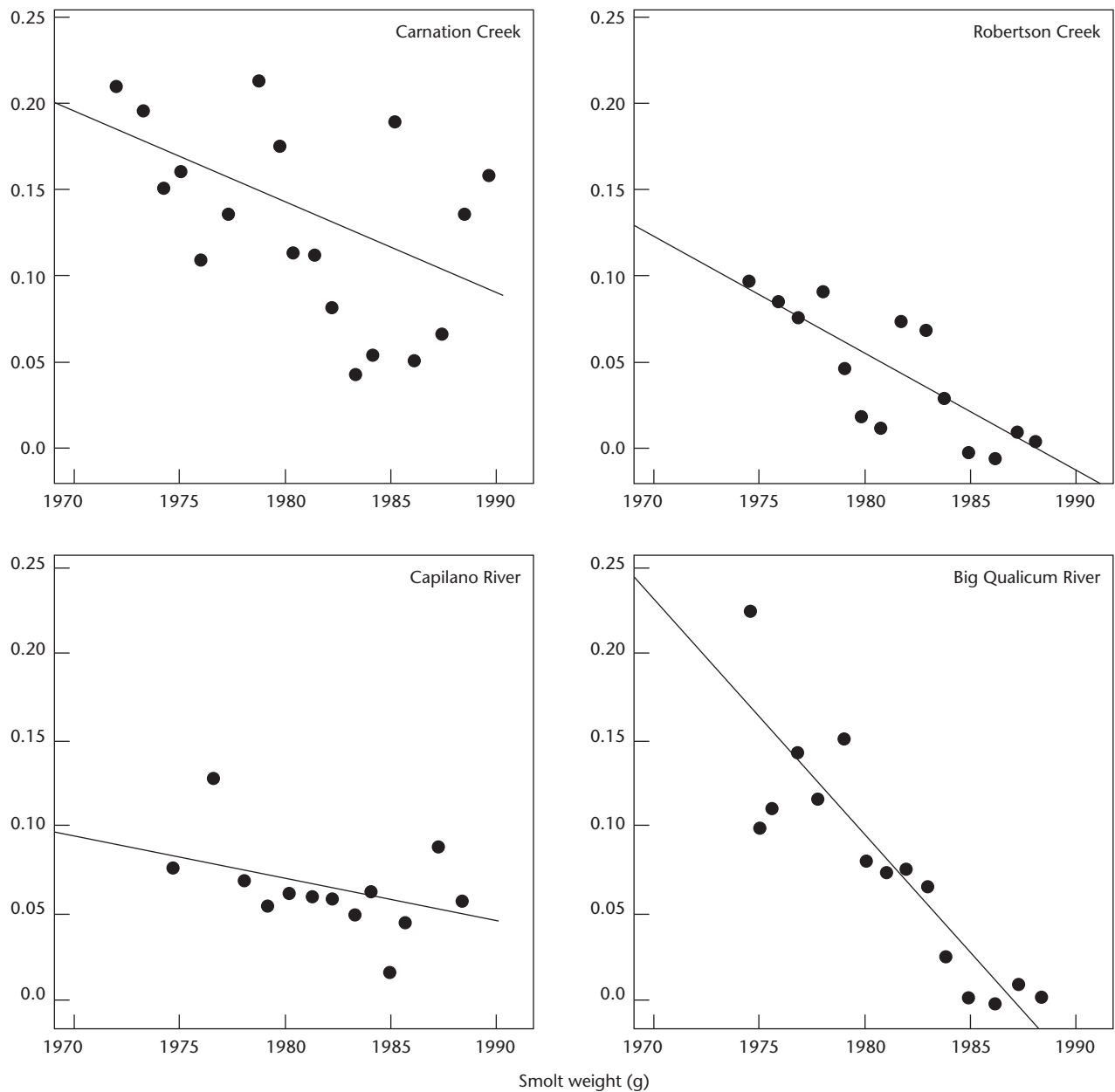


FIGURE 12 Long-term declines in the ocean-phase survival of coho smolts from Carnation Creek is reflected by trends observed elsewhere in southwestern British Columbia. Dates are brood years. (Figure adapted from one provided by L.B. Holtby, Fisheries and Oceans Canada.)

Marine survival of coho salmon smolts

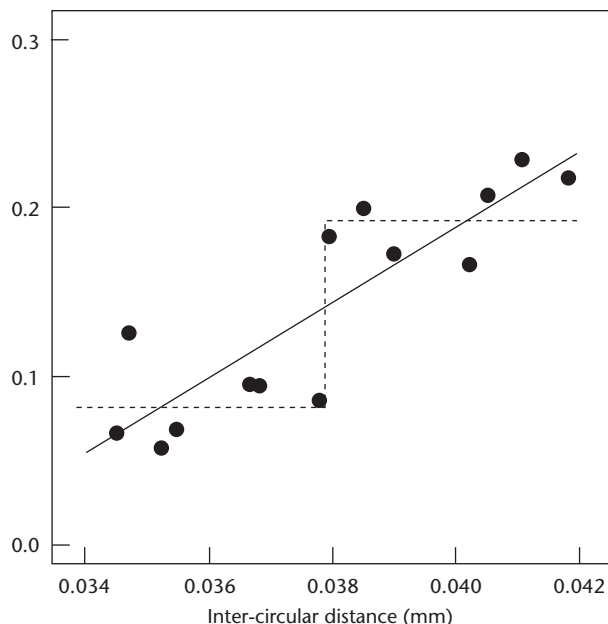


FIGURE 13 *Marine survival is a positive function of coho smolt growth rates soon after these juveniles enter the ocean from Carnation Creek ($p < 0.05$). An index of growth is determined from the spacing of early ocean-phase circuli measured from the scales of adults returning to the stream. Each point represents average inter-circulus distance for smolts leaving the stream in a given year. The dashed line represents a possible stepped model. (Figure adapted from one provided by L.B. Holtby, Fisheries and Oceans Canada.)*

by the shift to earlier smolt migrations, which has increased the risk that these smolts enter the ocean during winter-like conditions less favourable for growth and survival.

Notwithstanding the effects of forest harvesting, coho smolt survival in the past several years has clearly been depressed further by physical-regime shifts including the El Niño phenomenon. The northward shift of warm, nutrient-poor water suppresses seasonal upwelling, depresses ocean productivity, and is associated with low rates of survival for juvenile salmonids and other species such as herring (*Clupea harrengus pallasi*; Holtby et al. 1990). At the same time, large numbers of predators, mainly chub mackerel (*Scomber japonicus*) and

Marine survival of coho salmon smolts

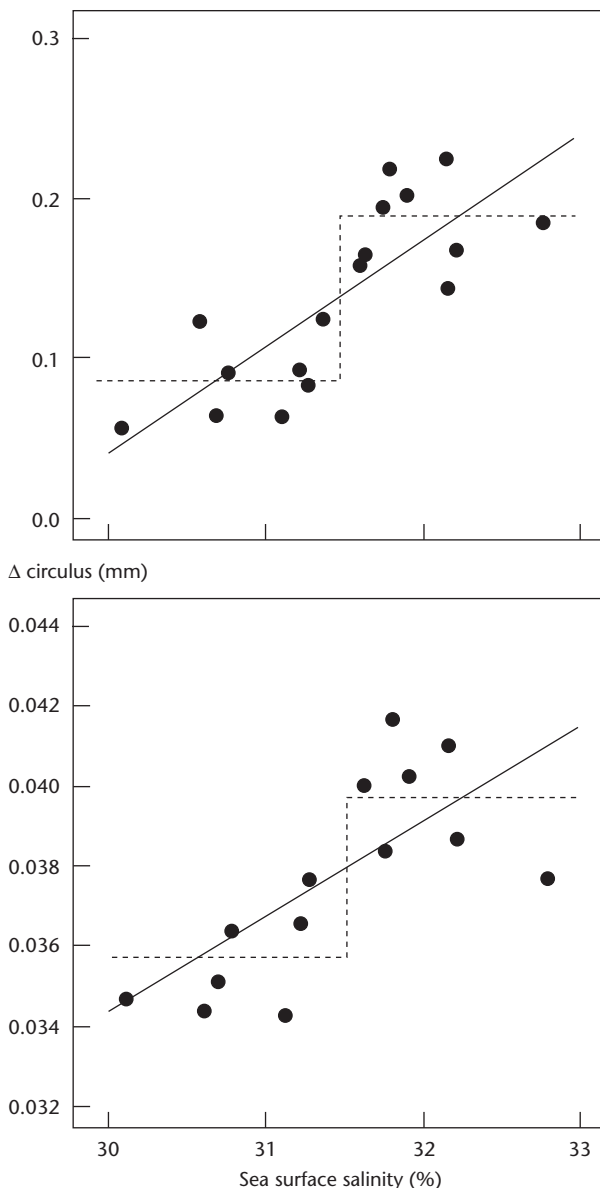


FIGURE 14 *Both growth (inter-circulus distance from scale analyses) and marine survival of Carnation Creek smolts early in their ocean-life phase are positive functions of sea-surface salinities. The dashed line represents a possible stepped model. (Figure adapted from one provided by L.B. Holtby, Fisheries and Oceans Canada.)*

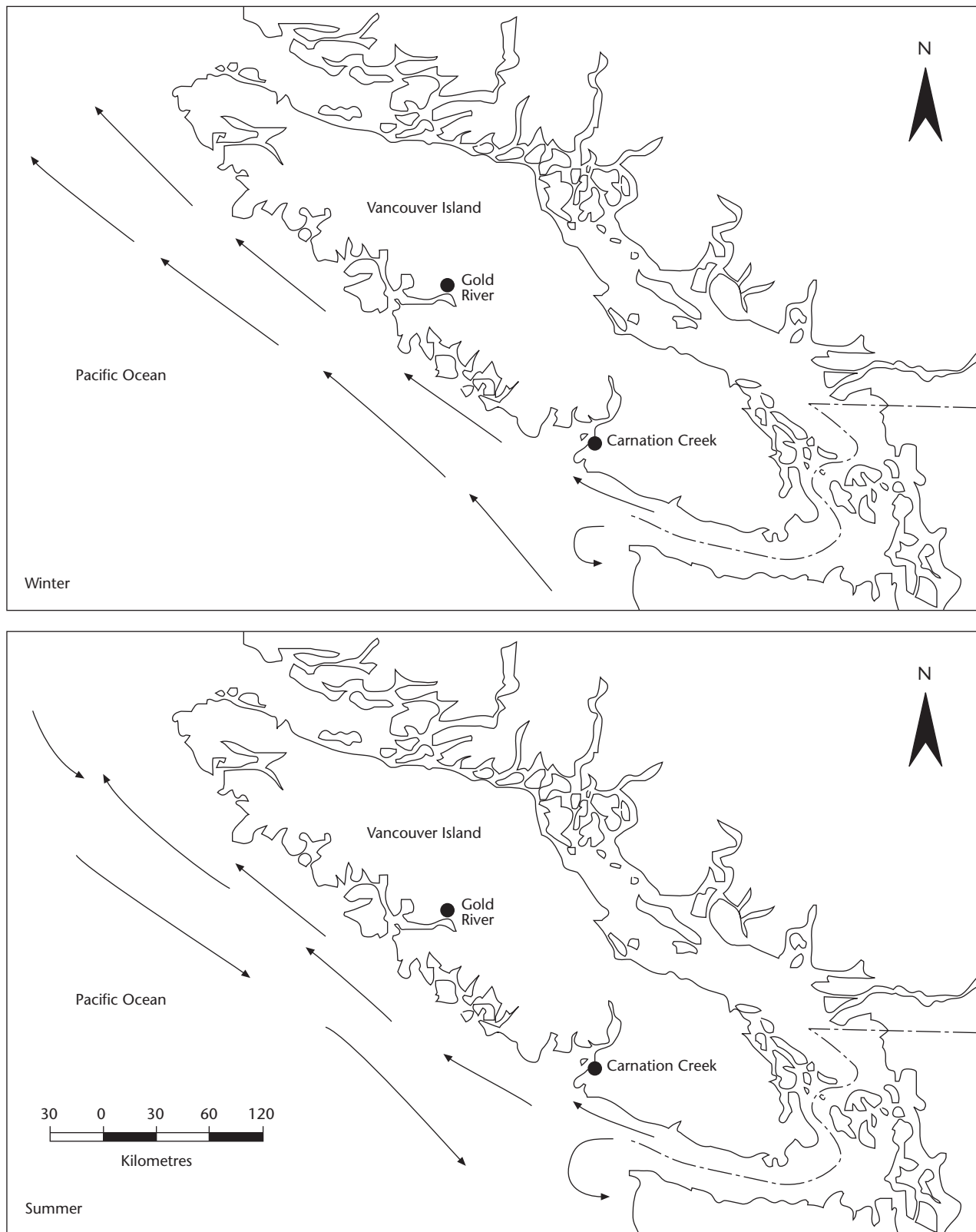


FIGURE 15 Seasonal shifts in the coastal currents off the west coast of Vancouver Island. Deep-water upwelling and high biological productivity is associated with the counter-current flows which fully develop by summer. (Figure adapted from one provided by L.B. Holtby, Fisheries and Oceans Canada.)

Pacific hake (*Merluccius productus*), move northward into the coastal waters of British Columbia, and are believed to consume large numbers of juvenile salmonids including coho (Fulton and LeBrasseur 1985; Holtby et al. 1990).

Ware and McFarlane (1988) concluded that changes in the abundance of herring off Barkley Sound are due primarily to changes in the intensity of predation. They have noted that the biomass of piscivorous predators such as Pacific hake have been sufficiently high to account for all of the annual mortality within herring stocks in some years. Holtby et al. (1990) have shown that the survival of coho smolts and 1- and 2-year-old herring co-vary (Fig. 16; $r = 0.6$, $p < 0.01$). They noted that coho smolts and herring between 1 and 2 years old are similar in size, have overlapping diets, and occur together in both Barkley Sound and other rearing areas in the coastal waters of western Vancouver Island. Although Pacific hake and chub mackerel prey primarily on herring (which usually greatly

outnumber coho), even incidental predation on coho can cause substantial mortality in their populations, including those from Carnation Creek. Predation probably increases in El Niño years when slow growth keeps juvenile coho small and susceptible to predators (Holtby et al. 1990). Holtby et al. (1990) suggested that most of the reduction in the ocean survival of coho smolts in recent years has likely been the result of predation.

The effects of forest harvesting upon coho and chum at Carnation Creek have been relatively small so far, (for each species, explaining respectively ~26% and < 10% of the post-logging variability in the abundance of adult returns) when compared to the effects of climate change in both freshwater and ocean environments (Holtby and Scrivener 1989; Holtby et al. 1990). The abundance of coho smolts leaving Carnation Creek has increased despite habitat disturbance, not only because of the effects of temperature on seasonal growth and survival, but also because important winter habitats consisting of seven ephemeral tributaries and side channels located on the valley floor remained largely intact after logging (Brown 1987; Hartman et al. 1996). Consequently, the maintenance of good-quality “off-channel” habitats have contributed to high rates of overwinter survival in juvenile coho after logging.

The effects of forestry practices upon both chum and coho would likely have been more severe had the network of forestry roads been more typical of those in most other coastal watersheds. Most of the forestry practices conducted at Carnation Creek, such as clearcut harvesting over progressively larger areas, were typical of those employed in the 1970s and 1980s. However, no roads crossed the main channel of Carnation Creek. Only one short-section of road entered the floodplain in the lower portion of the watershed inhabited by anadromous salmonids. The only stream crossed by this road was the main tributary to Carnation Creek (C Tributary). All other roads were located on relatively stable hill-slopes on both sides of the basin. This road network remains one of the limitations of the Carnation Creek study design. Reductions in the quality of streambed gravels and egg-to-fry survival were probably minimized in the absence of (1) the short-term peak of fine sediments from the construction of valley-bottom roads and stream crossings, and (2) the chronic introduction of fines into the stream from road surfaces and stream crossings.

Marine survival of coho salmon smolts

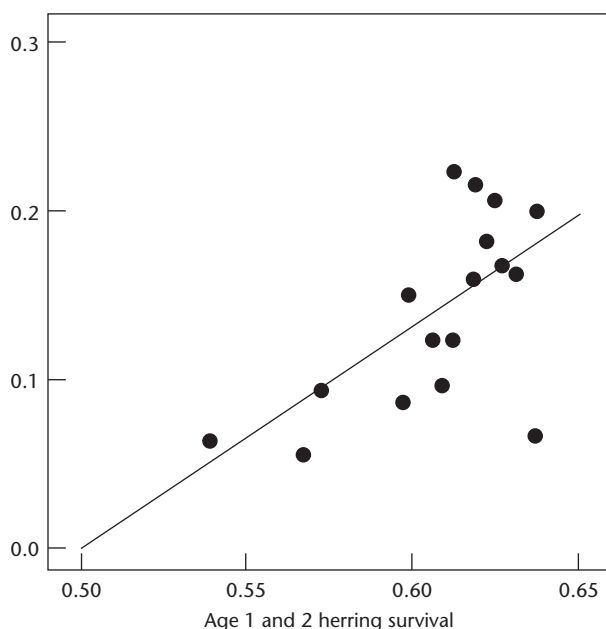


FIGURE 16 Marine smolt survivals of Carnation Creek coho salmon co-vary with an index of survival for 1- and 2-year-old herring off the southwest coast of Vancouver Island from 1971 to 1987 ($p < 0.01$). (Figure adapted from one provided by L. B. Holtby, Fisheries and Oceans Canada.)

Despite the limitations of this project such as the absence of an unlogged control watershed, much has been learned about the biological and physical processes operating within a small coastal watershed, and the effects of forestry practices on these processes. We will likely learn more as this project continues. The abundance of coho smolts leaving Carnation Creek remains high. However, the main-channel habitats at Carnation Creek continue to deteriorate: large portions of the stream will lack stable LWD for many decades. In several years, the forest canopy will be re-established over the stream and begin to reduce water temperatures. Some of the increases in fish growth and survival associated with elevated stream temperatures after logging will disappear. With poorer habitat quality and lower water temperatures, smolt production from Carnation Creek may then begin to decline.

Summary

Salmon and trout populations of Carnation Creek have been closely monitored for the past 23 years as an important component of multi-disciplinary, multi-agency research on fisheries-forestry interactions. This paper: 1) describes long-term patterns in salmonid abundance; 2) demonstrates that the production of salmonids from coastal streams depends on processes both within the watershed and the marine environment; and 3) emphasizes the value of long-term studies such as the one at Carnation Creek to clarify the complex interactions among land-use practices, fishing, climate change, shifts in marine conditions, and salmonid populations.

Studies of fish populations at Carnation Creek through 5 pre-logging, 6 during-logging, and 12 post-logging years have clearly illustrated that forest harvesting has complex and often variable effects on population processes at the different life stages of each species. The abundance of both adult chum and coho salmon returning to Carnation Creek has declined significantly after logging. Forestry practices appear to account for ~26% of the decline in chum, but <10% of that in coho salmon. Chum salmon populations have also declined the most sharply. Adult returns are now only about 39% of their pre-logging levels. Chum egg survival has declined by about one-half after forest harvesting, partly as the result of fine sediment deposition and other gravel quality changes in the lowest parts of

the stream. The numbers of coho fry rearing in Carnation Creek are about 57% of their pre-logging levels. The effects on juvenile coho associated with forest harvesting include a reduction in egg-to-fry survival by about one-half, and decreased quantity and quality of the rearing habitat because of stream channel changes associated with streambank damage, loss of LWD, and increased scour and deposition.

Loss of rearing habitat is associated with clearcut logging along streamsides and over steep-sloped terrain. Debris torrents and landslides from clearcut hillsides have introduced large volumes of sediment and woody debris into the stream channel, and this continues to cause pronounced changes to fish habitats 18 years after forest harvesting was initiated.

The Carnation Creek study has demonstrated the importance of managing forestry activities to minimize the risk of landslides and debris torrents. It has also demonstrated the importance of having forested riparian strips to “buffer” streams from forestry effects. Although the leave-strip treatment at Carnation Creek was located downstream of the clearcut treatments, and thus was partly impacted by activities upstream, the stream channel and the quality and amount of salmonid habitat in the buffer-strip area remain largely the same as in pre-logging years. The majority of anadromous salmonids now originating from Carnation Creek rear within the leave-strip portion (P. Tschaplinski, B.C. Ministry of Forests, unpublished project data). Major logging-associated changes will eventually be transmitted downstream into this area. Therefore, the full extent of forestry impacts on the stream channel and fish populations is yet to be observed at Carnation Creek. The time course of forestry effects demonstrates the value of long-term studies such as the Carnation Creek project.

After forest harvesting, slightly more than one-half the number of coho fry produced 1.5-times more smolts as a result of increased water temperatures associated with forest canopy removal and climate shifts. Increased temperatures allowed coho fry to emerge earlier in spring, grow larger by autumn, survive the winter better because of larger size, and migrate seaward, mainly as 1-year-old smolts. The post-logging increase in smolt abundance has not resulted in increased numbers of adult returns because early marine growth and survival has declined. Temperature increases in fresh water has shifted seaward smolt migrations earlier in

the spring, potentially into ocean conditions unfavourable for growth and survival. Additionally, marine climate changes have increased coho mortality in the ocean through reductions in biological productivity and simultaneous increases in predator abundance.

These results show that both freshwater and marine phases of salmonid life histories must be considered from the perspective of resource conservation and management. We must also note that our best forest harvest practices might not ultimately result in more salmon returning to our coastal streams in every situation, given climate changes and marine processes beyond our control. However, the application of the best practices for watershed stewardship is essential because the combination of forest harvesting, fishing, and climate change can together reduce salmon populations to levels so low that recovery is not possible. High-quality habitats for stream fishes after logging remain a high priority.

Acknowledgments

Many people should be thanked for their contributions to the Carnation Creek study. Much of the information in this paper is based on the original work of Charles Scrivener and Blair Holtby. The senior author is especially grateful for their permission to use this material. Both must be thanked for their data analyses, and Blair Holtby's provision of several figures noted within the text is sincerely appreciated.

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Watershed Hydrology: Forest Management Implications

ROBERT P. WILLINGTON

Introduction

Over the years, as hydrological information and knowledge have been developed from the Carnation Creek Watershed Research Program and the Fish/Forestry Interaction Program, our ability to build roads and harvest timber in ways that recognize these hydrologic processes has been enhanced. Unfortunately, hillslopes and stream channels continue to react negatively to some forest practices, suggesting there is still room for improvement.

While changes to operational practices continue to lag behind research findings, such will always be the case. This is due to the fundamental reality that any changes in forest practices which increase costs must be based on sound information developed from research. However, the lag between watershed hydrology research findings and operational changes is drastically shorter than it was 20 years ago, when watershed hydrology became a serious topic of discussion in British Columbia forest practices circles.

It is therefore timely to review the degree by which watershed hydrology principles are accommodated by present forest practices and possible opportunities for improvement.

Current State of Hydrologic Forest Practices

The best summary of the degree by which watershed hydrology principles have been captured by current forest practices is that which is contained in current forest practices guidelines. While most people involved in forest practices are fully aware of the contents of these various guideline documents, a few examples are illustrative.

The B.C. Coastal Fisheries-Forestry Guidelines (CFFG) contain many specific guidelines related to watershed hydrology. The more focused of these guidelines are those that relate to road drainage. Preferred practices with respect to planning,

construction timing and conduct, and ditch, culvert, bridge and road maintenance are clearly articulated. Also emphasized is the wisdom of operator training and the need for maintenance of inactive logging roads, inclusive of road deactivation.

The “Forest Road and Logging Trail Engineering” practices of the B.C. Forest Service complement many of the CFFG guidelines. They detail engineering *standards* for forest roads, logging trails, and drainage structures. The standards apply to all phases of forest access management, including pre-construction, construction, maintenance, and deactivation. While these standards allow flexibility of application for site-specific situations, it is likely that the Forest Practices Code will require the advice from a registered professional engineer or geoscientist where a proposed application deviates from the standard.

Further guidance for the management of road access to minimize adverse site-specific environmental impacts is also available from regulatory agency staff and publications such as “A Guide for Management of Landslide-Prone Terrain in the Pacific Northwest” (B.C. Ministry of Forests, Land Management Handbook No. 18).

In addition to the site-specific watershed hydrology guidelines, the CFFG recognizes “cumulative effects” and “rate of cut” considerations. A Level 1 assessment of Class A watersheds, described in the CFFG, specifies that if the past harvest area (since 1965) plus proposed harvest area exceeds 20% of the total watershed, or evidence exists of significant stream channel instability or landslide frequency, then a Level 2 analysis is required. The Level 2 analysis is outlined in the recently released “Coastal Watershed Assessment Procedure” (B.C. Ministry of Forests) and is intended to provide an understanding of the type and extent of current water-related problems in a watershed and the potential hydrologic implications of proposed

forestry-related development. If the Level 2 analysis identifies a high hazard watershed or sub-basin, a hydrologist carries out a detailed field-based investigation under a Level 3 analysis.

Potential Future Hydrologic Forest Practices

In British Columbia, it would appear that we have turned the corner in addressing the major hydrologic concerns associated with forest management and have now reached the fine tuning stage. Much of this fine tuning, because of its site-specific nature, defies being captured by forest practices guidelines. There are, however, a few examples of local operational improvements worth mentioning, because they provide the potential opportunity to further minimize watershed hydrology impacts from forest practices:

1. While the advantages of training have been recognized as an integral part of new forest practices guidelines and a great deal of effort has been expended on it, operator training at the field level has been wanting. Operators are “doers” and are more receptive to new information shared at the field level rather than in the classroom. Experience has shown that where, at the field level, the environmental objectives of a project are clearly understood by the operator, he or she will usually be able to achieve those objectives successfully, notwithstanding the constraints posed by available equipment, safety concerns, experience, and local conditions.
2. Many hydrologic problems associated with roads appear to be related to dry or snowpack season layout and dry season construction. While it is impossible to lay out all roads during wet, snow-free conditions, a quick check of roads laid out in snowpack or dry periods when surface water is

evident would likely yield a better road water management plan, particularly with respect to ephemeral creek-crossing culverts and ditch relief cross-drains.

3. In watersheds where rate of cut is, or is expected to be, a concern, consideration should be given to increasing silvicultural investments. Any silviculture investments that shorten the time required for a plantation to reach the height and canopy closure requirements for hydrologic recovery have the potential to increase the volume of timber available for harvest in a watershed or sub-basin.

Some Further Concerns

Unfortunately, no matter how much both current and future forest management practices improve, a large backlog of environmentally detrimental, hydrologic impacts still remains to be addressed. While we are currently experiencing an aggressive road deactivation program in British Columbia, a great many old roads still remain to be addressed. As well, some early road deactivation is not delivering the desired reduction in hydrologic impacts and needs upgrading to present deactivation standards.

Furthermore, additional work must be carried out on the rehabilitation of landslides and impacted streams. Although these projects can be very expensive, the hydrological stabilizing gains can be measurable and thus highly useful.

It is hoped that the recently announced Forest Renewal initiative by the Province of British Columbia will provide the opportunity for rehabilitating the backlog of hydrologic problem areas, to complement the energy being expended to avoid adding new areas to this backlog.

Gully Assessment Methods

D.L. HOGAN AND T.H. MILLARD

Introduction

Several papers in this workshop have stressed the importance of gully systems to hillslope geomorphology (Schwab, Bovis), to forestry practices (Rollerson, Krag), and to the formation of a critical link between terrestrial and aquatic ecosystems (Hogan et al., Tripp). Accordingly, the correct assessment of gully characteristics during the development of forest management plans, both before and after harvesting, is important. Among the many reasons that gullies should be properly assessed:

- Gullies are inherently unstable areas of a hillslope.
- Landslides starting within the gully system initiate debris flows that are often extremely destructive.
- Timber harvesting activities can accelerate the natural rate of landslide activity within gullies.
- Timber harvesting activities can increase the amount of debris and sediment stored within the gully.
- Large floods, generated by either high-intensity, long duration rainstorms or rain-on-snow events, can move large amounts of debris and organic materials.
- Due to the overall steepness of gully systems, debris and sediment moved along gullies are frequently transported downslope to productive forest sites on floodplains, fish habitats, domestic water supply intakes, major installations (e.g., logging camps, highways, pipelines, powerlines), and even human townsites.

As a result of these conditions, both worker safety and fish habitat integrity are commonly at risk.

A gully assessment procedure (GAP) has been developed and is currently being field-tested. The procedure has been presented and used in the British Columbia Coastal Fisheries-Forestry Guidelines training program, in a technical manual for the

British Columbia Watershed Restoration Program (Hogan et al. 1994), and will eventually be issued as a British Columbia Forest Practices Code guidebook. The procedure is summarized here; complete details are included in Hogan et al. (1994).

Gully Assessment Procedure

Gullies are defined as long, linear depressions incised or cut into steep hillslopes, with a channel usually confined in a V-notched ravine with banks higher than 3 m and sideslopes steeper than 40%. A gully system is composed of headwalls, transport zones and, in some cases a depositional fan (Table 1).

The GAP provides a framework for making site prescriptions, either before harvest or during post-harvesting inspections. It directs field staff to the most critical factors they need to consider when evaluating gully areas. Important to note, however, is that the procedure is not geotechnically rigorous; it cannot replace a thorough review by a geoscientist, especially in situations where gullies pose a substantial hazard to downslope resources.

TABLE 1 *Gully system components*

Headwalls	Includes source areas that commonly have very steep head- and sidewalls, are susceptible to extensive erosion and landsliding, and are often the zone where debris flows start.
Channels	Material transport zones that include steep gully sidewalls, confined channels with perennial or intermittent streams, unstable or partly unstable banks, and temporarily-stored woody debris and sediment.
Fans	Sediment and debris deposit zones that include gently sloping fans or cones with single or multiple channels ranging from deeply incised to fully unconfined.

The procedure has three parts (Fig. 1). First, it presents a series of questions to be answered during office and field investigations. Next, it requires users to rank the severity of the potential problem according to their answers in the first part. Finally, it describes management objectives and strategies to meet those objectives in a range of situations. These three parts are described in more detail below.

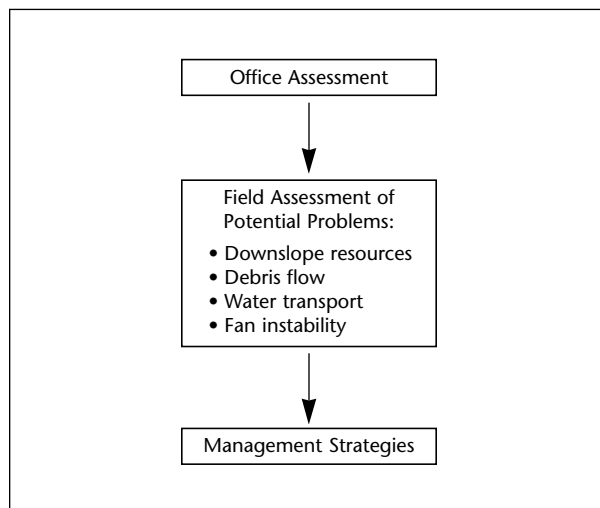


FIGURE 1 *Gully assessment procedure.*

Office Assessments The first step is to identify the gully system on 1:20 000 forest cover maps and on the most recent, largest scale aerial photographs. General characteristics can be determined from the photographs, including gully system size (drainage basin area), shape (single or multiple channels), steepness, confinement, sediment supply (actively failing side or headwalls), and the gully's position relative to other resources. The last point is particularly important. The appropriate fisheries officials should be contacted to determine the extent of fish streams connected to the gully. Also, in some cases, such as logging sites near human settlements, other officials should be contacted to determine if there are any domestic water supply licences held for any of the streams downstream of the gully.

Field Assessments The GAP is primarily a field-oriented task. Through the field work, the investigator answers a series of questions with the aim of

estimating the potential or likelihood of gully problems developing related to flooding, debris flow generation, fan destabilization, and downstream resource impacts. Estimation of risk is based on the seven field considerations considered below.

1. Upslope debris flow potential

The potential for debris flows and/or water floods (washouts) depends on conditions upslope of the assessment area. Debris flows are usually triggered by small landslides descending the steep sidewalls or headwall of a gully, or by landslides entering gullies from adjacent slopes. Large amounts of material are entrained or transported as the debris flow descends a gully. Because of their large volume, speed, and depth of flow, they are the most destructive events occurring in gullies. The upslope debris flow potential is determined from identification of specific terrain stability classes and field evidence of past landslides or debris flows in the gully system.

2. Water transport potential

Water floods can also transport large amounts of sediment and organic material down a gully. Both debris flows and debris floods depend on critical combinations of environmental factors: steepness of the gully catchment area sidewalls and the availability of loose, transportable material. The calculation of water transport potential is based on field measurements of gully channel width, depth and gradient, and estimates of the catchment area and the size of both sediment and woody debris moving along the gully.

3. Downstream impact potential

Gully impacts depend to a large extent on the resource values downslope. Assessments of downstream impact potential are done by considering the proximity of the gully to human dwellings, community water intakes, important fish species (salmon or game fish), or major installations (highways, bridges, powerlines, etc.).

4. Debris flow movement potential

Gully channel gradient, sidewall slope, and gully height all affect debris flow movement potential. In general, the steeper the sidewall slope, the more likely a failure is to occur. The higher the sidewall and the steeper the channel gradient, the more likely a slope failure on the sidewall will start a debris flow in and down the gully. A slope failure on the gully headwall will invariably start a debris flow in the gully channel.

5. Water movement potential

The movement and storage of both sediment and woody debris in gullies is controlled in part by the amount of water flowing down the gully, and in part by the presence of obstructions to water flow within the gully, such as large logs. Thus, steep gullies with high runoff and few in-channel obstructions have a much higher stream power than do lower-gradient gullies with lower runoff and many obstructions. Since runoff is controlled by climate conditions, only the woody debris factor can be managed.

In the procedure described here, gully catchment area, gully gradient, gully channel dimensions (width and depth), and the size and nature of sediment and debris present within the gully are used to estimate the water discharge potential of a gully.

6. Debris and sediment supply potential

The questions in this section are meant to give the investigator a sense of the possible magnitude of a particular event. Answers provide data so that management prescriptions can be refined to reflect the possible magnitude of a given event or impact. The sidewall angle and height and the volume of woody debris already in the gully are used as measures of the potential for introducing debris and sediment into the gully channel.

7. Fan destabilization potential

A fan is created by the deposition of sediment and coarse woody debris at the mouth of a gully. Since fan materials are unconsolidated, they may be subject to erosion following logging if adequate precautions are not taken. Of particular concern are fans that have several channels only slightly incised into the fan surface. In this case, debris obstructions may cause flowing water to be diverted from the regular channel, resulting in severe erosion and unacceptable downstream impacts. Where a single, well-incised channel exists, the problem of channel shifting is much lower; however, erosion of high streamside embankments is still a concern.

In assessing fan destabilization potential, the investigator should consider the number of channels on the fan surface, their dimensions (channel width, depth, gradient), the depth of channel incision into the fan, and other sediment-and debris-loading characteristics.

The complete field forms are not reproduced here. They can be found in Hogan et al. (1994).

Problem Potential Assessment The second part of the GAP involves assessing the gully problem and ranking its potential severity. A field assessment form has been created to allow ready evaluation of the potential for debris movement resulting from stream flow or debris flow activity, and assessment of the potential impact of that activity downstream.

To complete the form, the investigator reviews the appropriate answers for the series of questions and then determines the potential problem rank (high, moderate, low or none). These rankings are then applied to determine possible management strategies.

Management Objectives and Strategies In the third part of the GAP, management objectives are identified after the potential problems have been determined. Table 2 shows six management objectives ranked from most to least critical. The suggested management prescriptions to be considered for each forested gully site are included in Table 3.

Pre-logging Objectives Goal: The goal is to maintain natural rates of erosion, channel stability, and sediment and debris transport. To maintain the supply of LWD, either trees should be left or new LWD placed in the channel. No, or only minimal, disturbance of the gully sides (e.g., exposure of mineral soil, displacement of stumps) should occur. The development of innovative prescriptions that achieve these objectives is encouraged.

Methods: The falling and yarding methods used should be those that maximize the opportunity to achieve these six objectives. The GAP does not specify the falling and yarding methods that will best achieve these objectives, because that responsibility lies with the loggers, licensees and agencies involved in each cutting permit.

Potential problems: If there is a potential for a debris flow starting upslope or up-channel of the reach being assessed, this event should be allowed for in the management objectives. The size of the debris flow should not be increased (i.e., if the reach is logged, most small and large logging debris should be removed from the channel).

Safety considerations: A safety hazard is always present in gullies due to the potential for sidewall failures and down-channel debris flows. Landslides are a hazard even in unlogged gully areas. Falling and yarding operations should be avoided, as well as any rehabilitative work during high-intensity or long-duration rainstorms or rain-on-snow events.

TABLE 2 *Gap assessment procedure management objectives*

#	Objective	Abbreviation
1	Leave gully in a natural state.	NOLOG
2	Selective logging only. Clear logging debris from the channel following logging. ^{a,b}	SELECT
3	Leave unlogged buffer along steep gully sidewalls and headwalls. (Some gullies have a steep, V-notched form inset within a less steep, V-notched form. The inner part of the gully, at least, should be left unlogged when a buffer is recommended.) (See Hogan et al. 1994.) ^a	BUFFER
4	Log, minimize introduction of debris, and clear all logging debris after harvest. Do not disturb natural woody debris in channel. ^{a,b,c}	LOG/CA
5	Log, minimize introduction of debris, and clear small woody debris and some LWD after harvest. Do not disturb natural woody debris in the channel. ^{a,b,c}	LOG/CSWD
6	Log, minimize introduction of debris, and leave debris in the gully. ^{a,b,c}	LOG

^a Falling of trees (snags, heavy leaners) into or across the gully is permitted when faller safety is at risk. This safety measure includes trees outside the gully margins.

^b New, large logs (>0.5 m and at least three channel widths in length) should occasionally be left to provide a future supply of LWD for the channel. Where possible, anchor these pieces.

^c Where safety standards permit, saplings should be left along stream channels to help maintain channel stability.

TABLE 3 *Suggested pre-logging management strategies for forested gully systems^{a,b}*

Downstream impacts potential	Debris flow potential	Possible management prescription	Water transport (flood) potential	Possible management prescription	Fan destabilization potential	Possible management prescription
High	High ^c	NOLOG	High ^c	NOLOG, BUFFER	High ^c	BUFFER
	Moderate ^c	BUFFER, SELECT, LOG/CA	Moderate ^c	LOG/CA, SELECT	Moderate ^c	LOG/CA, SELECT
	Low	LOG/CA	Low	LOG/CA	Low	LOG/CA
	High ^c	NOLOG, BUFFER	High ^c	BUFFER	High ^c	SELECT
Moderate	Moderate ^c	SELECT, LOG/CA	Moderate ^c	SELECT, LOG/CA	Moderate ^c	LOG/CA
	Low	LOG/CA	Low	LOG/CSWD	Low	LOG/CSWD
	High ^c	SELECT, LOG/CA	High ^c	LOG/CA	High	LOG/CA
Low	Moderate	LOG/CSWD	Moderate	LOG/CSWD	Moderate	LOG/CSWD
	Low	LOG	Low	LOG	Low	LOG

^a All potential problems must be checked in the field. The most limiting condition determines the management prescription.

^b In these cases, large non-merchantable logs may be bridged between gully walls, leaving a vertical clearance of at least 1 m above the gully channel.

^c A geoscientist should be consulted before logging proceeds in the gully or fan segment assessed, or if windthrow occurs after logging and salvage is contemplated.

In general, these areas should also be avoided during fall and winter storms. Most debris flows can run faster than any forest worker.

Post-logging Objectives After logging, the gully system should be assessed to determine whether management objectives have been met and, if necessary, to prescribe rehabilitative action. Post-logging management strategies (gully rehabilitation prescriptions) are based on the same estimates of gully problems (see “Field Assessments,” above). These strategies include the following:

1. Gullies with high to low debris flow or water transport potential and high to moderate downstream impact potential; and gullies with high to moderate debris flow or water transport potential and low downstream impact potential.
 - a) For gullies with logging debris:
 - Large, natural woody debris should never be removed or cut. There is a risk that removing natural woody debris will result in destabilizing the stream channel and cause significant transport of sediment and debris downstream during peak flows.
 - In areas of new logging, most logging debris should be removed from the channel and scattered, large woody debris left (i.e., debris that is ≥ 0.5 m diameter and at least three channel widths in length). Debris should be removed well beyond peak flow limits. Slash accumulations should not be burned within the gully channel in areas where tree roots or natural woody debris act to stabilize the channel bed.
 - In areas of recent logging (≤ 5 years), with only scattered, woody debris in the channel, the debris should be left as is.
 - In areas of recent logging (≤ 5 years), with considerable woody debris in the gully channel ($< 20\%$ of the channel floor visible), the logging debris should be cleaned out and scattered, large woody debris left (i.e., debris that is ≥ 0.5 m diameter and at least three channel widths in length).
 - In areas of moderately old logging (> 5 years and < 10 years), most logging debris should be cleaned out when the channel is excessively full; otherwise, it should be left untreated. If there are very high resource values or safety concerns immediately downslope, the advice of a geoscientist should be sought.
 - b) For gullies that have been scoured by debris flows or debris floods:
 - The areas should be hydroseeded with a grass/legume mixture combined with fertilizer.
 - Conifers/hardwoods and/or shrubs should be planted (e.g., Sitka alder).
 - Rock check dams, log retaining structures, or other in-channel structures should not be built unless a geoscientist advises it. In general, such structures are not appropriate, especially where the channel is scoured to bedrock. Building dams may occasionally be appropriate in gullies where there are deep, surficial deposits and where the channel continues to degrade (erode deeper).
 - Any existing debris jams should be left in place unless a geoscientist advises otherwise.
2. Gullies with low debris flow or water transport (flood) potential and low downstream impact potential.
 - In general, these gullies should be left as they are.
3. Stream channels on fans, where the channels have destabilized after logging.
 - These channels should be left as they are unless a geoscientist advises otherwise. Possible options include:
 - cabling log structures to existing stumps or other stable debris outside the channel;
 - planting fast-growing hardwoods along the channel margin; and
 - excavating excessive sediment and debris accumulations.

4. Stream channels on fans where there is a moderate to high potential for channel destabilization, or low potential for channel destabilization but high to moderate downstream impact potential.
 - All logging debris should be removed except for occasional large pieces that span the channel and may be anchored in place using wire cable or other means.
 - If there is a significant amount of sediment stored behind the woody debris in the channel, the advice of a geoscientist should be sought. It may be prudent to leave the channel untouched if a rapid release of sediment could have significant consequences downstream.
 - Planting fast-growing hardwoods should be considered along the channel margin, if there is no streamside buffer in place or if the buffer is very narrow.
5. Stream channels on fans with a low potential for channel destabilization and low downstream impact potential.
 - These channels should be left as they are.

Summary

A procedure to assess the risk of gully problems associated with logging and rehabilitation has been presented. This procedure is currently being tested in British Columbia. It is intended to be used by field technicians who require an objective, systematic procedure to aid their evaluations of gullies. It is not intended to replace a geoscientist's appraisal.

The gully assessment procedure uses relatively simple field measurements to estimate the type of potential problem present in the gully system. Based on these, and also considering the environmental and operational objectives, logging and rehabilitation prescriptions are suggested. It is hoped that the procedure will accomplish several objectives:

- first, that it will provide the necessary background to field workers who do not have extensive previous training in hillslope processes;
- second, because there are so many gully systems present in coastal forest lands, that it will provide a mechanism by which a large proportion of gully systems can be screened out quickly and the relatively few gullies with serious problems

identified and given a rigorous geotechnical evaluation; and

- third, that it will lead to improved environmental conditions, without causing an unnecessary burden on forest management operations.

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Classification and Assessment of Small Coastal Stream Channels

D.L. HOGAN AND S.A. BIRD

Introduction

Large woody debris (LWD) is a fundamental structural element in small coastal streams found throughout the Pacific Northwest (see, for example, Keller and Swanson 1979; Marston 1982; Hogan 1987; Robinson and Beschta 1990). The influence of log jams on channel morphology, riparian areas, and fish habitat, both in Carnation Creek and in streams on the Queen Charlotte Islands, is reviewed by Hogan et al. (this volume). In the early phases of channel adjustment following jam formation, fish habitat is degraded as spawning areas (riffles) riffles are buried (upstream of the jam) or eroded (downstream of the jam), rearing pools are infilled, and egg incubation environments are smothered with fine-textured sediments. Over the long term (on the order of half a century), log jams deteriorate and create complex, diverse stream channels and riparian areas that become highly productive fish habitats.

Log jams are spatially prevalent in small coastal streams. Considering longitudinal surveys that included almost 44 km of channel in streams throughout the Queen Charlotte Islands, Hogan et al. (in prep.) found the median spacing of log jams to be 2.85 and 2.30 bankfull widths (W_b) in forested and logged streams, respectively. In Carnation Creek, individual log jams determine local channel morphology and control the pattern of channel evolution, both upstream and downstream of a jam (see Figure 5, Hogan et al., this volume). Because of the importance of log jams, it is therefore important that channel assessments in small coastal streams, documenting changes in channel morphology and associated impacts on fish habitat, use a consistent and repeatable classification of log jams and their related morphological features.

This paper presents just such a classification, one that is field-based and can be used to assess the

spatial and temporal response of a stream channel to disturbance. The objective of the classification is to assess current channel conditions and to consider the probable long-term temporal response of a channel following the development of a log jam. The classification is based on a description of log jams and their individual characteristics, an inventory of relevant field indicators of channel disturbance associated with each jam, and the identification of the stage of channel recovery following jam formation.

Identifying Log Jams in the Field

A successful classification of log jams requires that jam occurrence be consistently detected and differentiated from individual debris pieces, log steps, and any non-functioning LWD. The contemporary inspection of a small coastal stream channel will identify an abundance of LWD. In 18 forested sub-basins on the Queen Charlotte Islands, Hogan et al. (in prep.) measured average LWD loadings ranging between 0.025 and 0.238 m^3/m^2 (channels surveyed ranged from 0.006 to 0.083 in gradient and 9.4 to 32.3 m in W_b). A re-analysis of this data shows that, by volume, 66% of all in-channel LWD were found in log jams. The remaining LWD either occurred as individual LWD pieces, formed log steps, or was non-functional.

Individual pieces of LWD can have an important role in forming the morphology and habitat of gravel and cobble bed streams. Several different types of pools develop because of flow convergence associated with LWD (Bisson et al. 1982; Sullivan 1986), while bars form in areas where LWD increases flow divergence. This influence increases as the orientation of individual LWD pieces shifts from parallel to perpendicular relative to the channel banks (Hogan 1987). A log step (Fig. 1) develops when an individual LWD piece crosses a channel

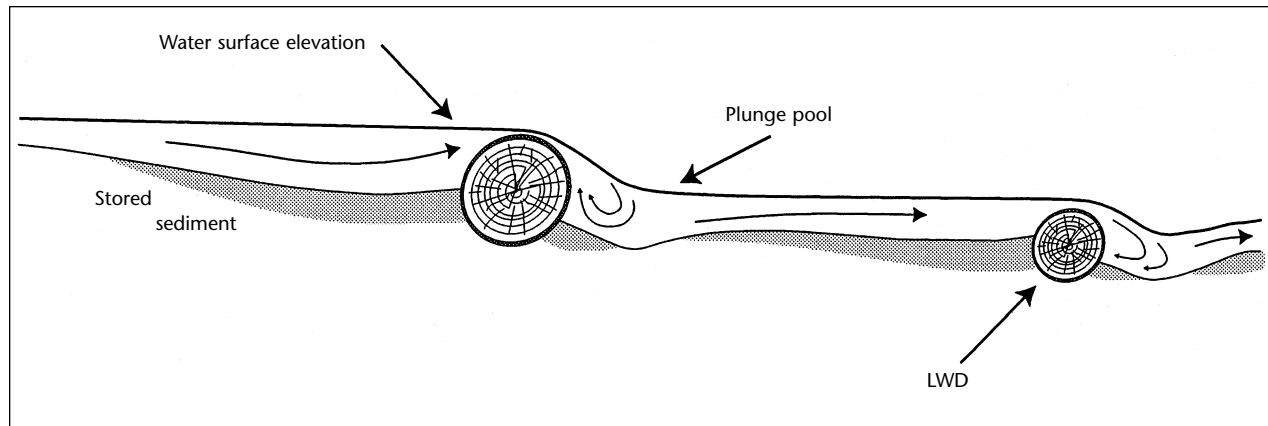


FIGURE 1 Sequence of log steps in a forest stream (after Keller and Swanson 1979). Individual LWD pieces create local variation in both the bed and water surface elevation.

and alters both the water surface and the bed elevation (Hogan 1987). Individual LWD pieces and log steps are important to channel morphology, stream flow, and fish habitat features at a relatively small scale (e.g., a maximum distance of several W_b), primarily between log jams.

Non-functioning LWD includes both individual pieces and accumulations of LWD that have no influence on sediment transport or channel morphology. This material is usually suspended above the channel banks and does not interact with bankfull stage streamflows. Non-functioning LWD on the streambed may be transient (i.e., it is transported downstream on a regular basis, usually several times a year) or may not have been present long enough to have been incorporated into the channel (e.g., LWD recently introduced to the channel by a landslide, bank erosion, or windthrow after the last major flood event).

A log jam consists of multiple, interacting LWD pieces that influence channel morphology by controlling sediment transport either at present or at some time in the past (see definition in Hogan et al., this volume). Recently formed jams are characterized by LWD oriented perpendicular and diagonally to the channel banks, often anchored by LWD pieces with large root wads (Fig. 2) or older, previously established jams. As log jams break down over time, debris pieces rot, break into smaller sizes, and get moved downstream by floods. Consequently, log jams older than 30 to 40 years become difficult to identify. In many cases, old log jams begin to

resemble a series of closely spaced log steps amongst individual LWD pieces. Remnants of old log jams often consist of weathered or decaying LWD oriented parallel or diagonally to the channel margin, with individual pieces incorporated into the surrounding bank materials (Fig. 2). Stable portions of the sediment wedge that cannot be excavated and transported downstream are colonized by vegetation and become part of the riparian area.

Log Jam Classification

The classification of log jams, modified after Hogan (1989), describes the current function of a log jam and how it influences sediment transport, channel stability, and stream morphology. The classification is based on a consideration of jam properties (e.g., type, shape, relative size, permeability) and associated characteristics (e.g., number of channels, size of sediment wedge stored upstream).

Type and Relative Size The spatial influence of a log jam on fluvial forms and processes is related to the type and relative size of each jam. Hogan (1989) identifies two fundamental types of log jams that develop in relation to valley bottom characteristics. The distinction is important because it determines the ability of a jam to control either the channel longitudinal profile or the disturbance of adjacent riparian areas. *Vertical* log jams exist as a longitudinal series of debris piles that occur where the channel is confined by non-erodible banks, usually



2a.



2b.

FIGURE 2 *Characteristics of young and old log jams. (a) A recently formed jam characterized by LWD oriented perpendicular and diagonally to the channel banks, with a sediment wedge stored upstream. (b) Remnants of an old log jam consisting of weathered or decaying LWD oriented parallel with and diagonally along the channel margin. Note that individual pieces are incorporated into the surrounding bank materials and the sediment wedge is difficult to identify.*

valley walls. Accumulations of sediment upstream of a vertical jam produce a stepped longitudinal profile as the upstream wedge fills the channel from valley wall to valley wall. As sediment and debris are added, the primary direction of growth of the jam and wedge is in the vertical direction. Similarly, as the jam deteriorates over time, the channel degrades vertically back through the wedge.

In contrast to the vertical structures, *lateral* log jams develop on unconfined, alluvial valley flats. In most cases, the stream is able to erode the channel

banks and move laterally around the log jam. Additional LWD is recruited from the riparian area as the channel migrates, leaving relatively stable alluvial deposits behind for riparian vegetation to colonize. As sediment and LWD are added to the channel upstream of the lateral jam, the jam and wedge grow primarily in the lateral direction. A single lateral log jam may actually be composed of several smaller jams (laterally dispersed LWD piles) that have formed as the channel erodes into the riparian area and migrates across the valley floor over time.

The relative size of a log jam is determined by comparing the volume and dimensions of a jam to a unit area of channel bed. (This paper uses the average bankfull area—that is, the area covered by the bankfull width squared). Four relative sizes of both vertical and lateral log jams are given here (Table 1, Fig. 3). Relative size defines the spatial scale over which a jam influences channel morphology and the adjacent riparian area. For example, a single *megajam* can control channel morphology and valley bottom development along an entire reach by regulating sediment transport and the tendency for the channel to aggrade or degrade. In contrast, a *microjam* may only influence channel morphology in the immediate vicinity of the jam, providing one of many sediment storage sites along a reach and an opportunity to initiate localized erosion of the channel banks and riparian area. Classification of log jams into relative sizes allows the comparison of jams in channels with different bankfull widths. The dimensions of a log jam must be scaled before the influence of a jam on channel morphology can be properly assessed.

Permeability In addition to the type and relative size of a log jam, the rate of sediment transport past the jam depends on its permeability. Jam permeability determines the sediment trapping efficiency of a jam by describing how “sieve-like” the structure is in relation to a cross-section of the stream channel. This is important because permeability controls the proportion of sediment stored in a wedge upstream of the jam compared to that allowed to pass downstream. A jam with relatively low permeability can lead to severe aggradation of the channel upstream, while the channel bed may be scoured to bedrock downstream (see review by Hogan et al., this volume).

To determine log jam permeability in the field, the structure’s span, height, and integrity must be

TABLE 1 Log jam size and dimension by jam type

Jam size	LWD Volume/ W_b^2 (m^3/m^2)	LWD Pieces/ W_b^2 (N/m^2)	Vertical jam		Lateral jam		Downstream influence ^b (W_b)
			Height (D_b) ^a	Width (W_b)	Height (D_b)	Width (W_b)	
Mega	>1	>1	>2 ^c	>1 ^d	>1 ^e	>2 ^f	>100
Macro	0.1–1	0.1–1	1–2	>1 ^d	>1 ^e	1–2	10–100
Meso	0.01–0.1	0.01–0.1	0.5–1	0.5–1.0	0.5–1	0.5–1	1–10
Micro	<0.01	<0.01	<0.5	<0.5	<0.5	<0.5	<1

^a D_b denotes bankfull depth.

^b The upstream influence of a jam on channel morphology cannot be specified, as it depends on channel gradient and sediment supply conditions.

^c Typically, does not exceed 10 D_b .

^d Typically, does not exceed 2 W_b .

^e Typically, does not exceed 2 D_b .

^f Typically, does not exceed 10 W_b .

evaluated. Span is defined by the width of a jam relative to the width of the channel, and includes consideration of breaches in the structure where preferred channels have established (Table 2). A jam that spans a channel from bank to bank forces water, sediment, and debris to pass either through, over (vertical jam), or around (lateral jam) the jam structure. Similarly, the height is defined by the vertical extent of a jam relative to the depth of the channel, and determines the magnitude of the step on the longitudinal profile (Table 3). The integrity of a jam considers the relative anchoring of a jam (i.e., its ability to resist rearrangement during high flows) and the spaces between LWD pieces in the structure (Table 4). A jam with high integrity forces the channel to pass over or around the jam.

The physical consequences of changing jam permeability are seen in the field as a series, or cycle, of aggrading or degrading channel segments. As permeability of a jam increases over time, the volume of stored sediment upstream is reduced while the number of channels around or through the jam generally increases. To determine the volume of stored sediment upstream of a jam, the height of the sediment wedge is compared to both the height of the jam and the width of the channel (Table 5). The number of channels associated with a jam (Table 6) is related to the characteristics of the channel upstream of the jam (e.g., braided) and the characteristics of

the channel as it passes through the jam structure (e.g., anastomosed around small islands of stable, vegetated portions of the sediment wedge).

Indicators of Channel Austment

Log jams initiate a series of morphological changes along the channel, which must adjust to changing sediment supply and storage conditions. Upstream of a jam, the channel aggrades and forms a sediment wedge as sediment transport is reduced through the jam. Typically, the banks erode in response to increased bar development, the channel changes from single thread to multiple branches or braids, sediment texture becomes relatively fine, pools are infilled, and LWD is buried. Downstream of a jam, the channel degrades as sediment supply is reduced. Sediment stored along the channel is scoured (occasionally down to bedrock), while the overall texture of any remaining stored sediment becomes relatively coarse. Individual LWD pieces are floated downstream during high flows.

Once a log jam is classified in the field, channel conditions associated with the jam are assessed from an inventory of field indicators related to channel disturbance. This includes a description of bed sediments, channel morphology, and bank and overbank characteristics (Table 7). Each characteristic is associated with both sediment supply and

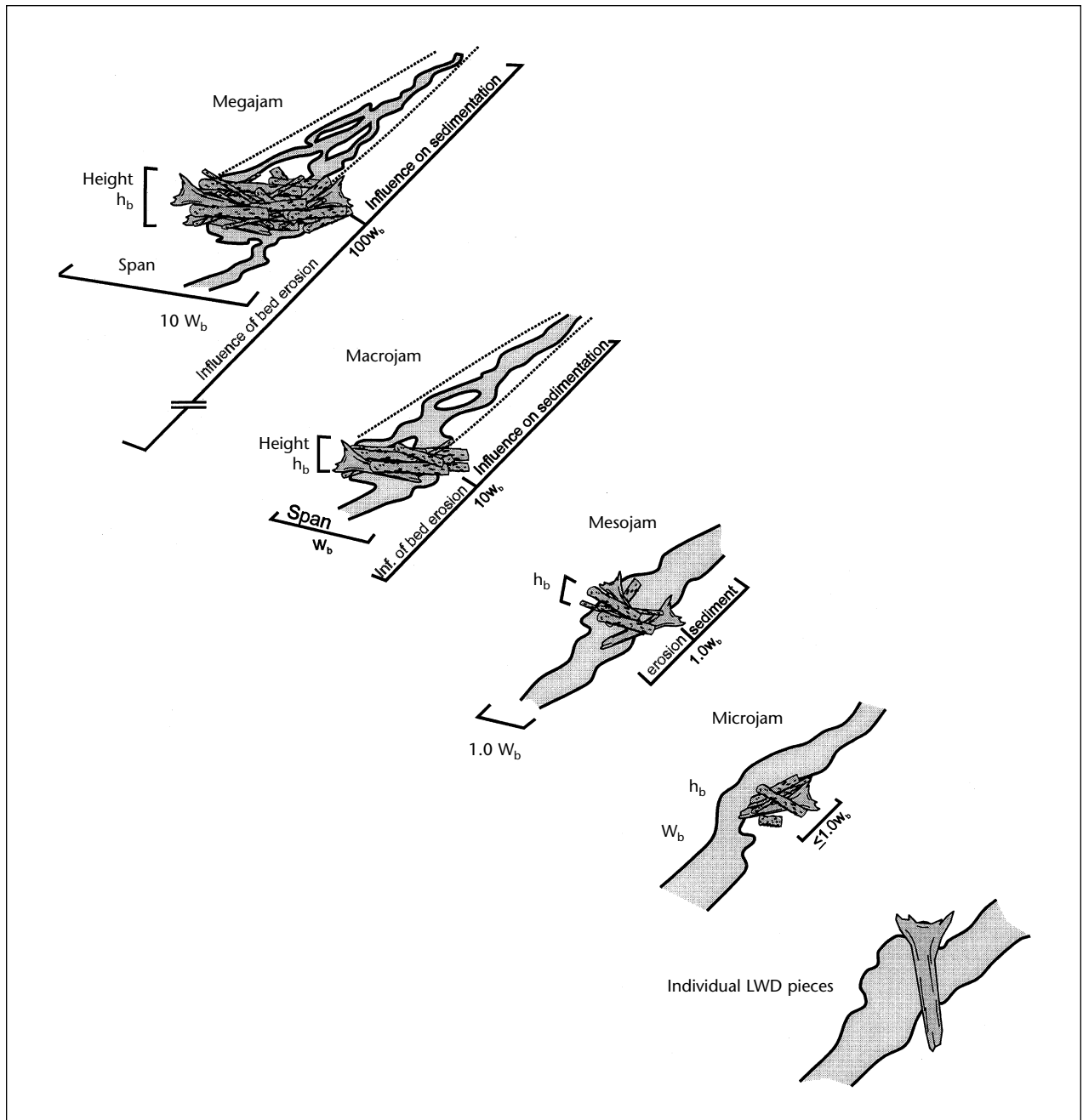


FIGURE 3 Relative sizes of vertical and lateral log jams scaled by bankfull width and height.

TABLE 2 *Log jam span characteristics (after Hogan 1989)*

Span (W_b)	Jam characteristics
<i>Complete:</i>	
> 1	Jam crosses the channel and forms a dam. Water flows over the top or passes through the jam.
<i>Incomplete:</i>	
$\frac{3}{4}$ –1	Jam crosses the channel but is breached in one part of its span. Water flows around one end or through the mid-section of the jam.
$\frac{1}{2}$ – $\frac{3}{4}$	Jam does not cross the channel and is usually breached more than once. Water flows around one or both ends or through the mid-section of the jam.
$\frac{1}{4}$ – $\frac{1}{2}$	Jam is typically anchored on one bank or in mid-channel. Water flows around one or both ends or through the mid-section of the jam.
< $\frac{1}{4}$	Jam is typically anchored on one bank or in mid-channel. Water flows around one or both ends of the jam.

TABLE 3 *Log jam height characteristics (after Hogan 1989)*

Height (D_b)	Jam characteristics
<i>Complete:</i>	
> 1	Jam is higher than local average bank height. The channel may be forced around the jam and into the riparian area.
<i>Incomplete:</i>	
$\frac{3}{4}$ –1	Jam does not exceed local average bank height (although individual LWD pieces in the jam may be resting on the channel banks).
$\frac{1}{2}$ – $\frac{3}{4}$	Jam structure is prominent in the channel.
$\frac{1}{4}$ – $\frac{1}{2}$	Bar tops may exceed jam top. Jam is usually not capable of forcing the channel into the riparian area.
< $\frac{1}{4}$	Bar tops exceed jam top. Individual LWD pieces in the jam may be buried by advancing bedload.

TABLE 4 *Log jam integrity characteristics (after Hogan 1989)*

Integrity	Jam characteristics
Very solid	Very compact, strong LWD pieces (no rot). Largest LWD pieces have diameter $\geq 1 D_b$ and lengths $\geq 1 W_b$. Stable and large anchors present (e.g., root wads and bedrock). Pieces are very tightly packed together and compact (with little if any void spaces between the pieces).
Solid	Compact, strong LWD, but smaller individual pieces (largest pieces have diameter $\sim \frac{1}{2} W_b$ and lengths $\sim \frac{3}{4} D_b$). Jam is anchored but overall stability is reduced. Minor voids exist between the debris pieces.
Weak	Predominantly small LWD pieces; larger LWD pieces are generally rotten. Jam has either a poor or precarious anchor. Large voids exist and pieces are loosely packed.
Very weak	Very small LWD pieces with no apparent anchor. Jam is in transition (i.e., it is difficult to determine if a jam exists). The pieces are very loosely packed and large voids exist between debris pieces.

TABLE 5 *Sediment storage characteristics upstream of a log jam (after Hogan 1989)*

Amount of wedge excavated	Wedge characteristics
None	The channel zone is full of sediment (e.g., sediment is filled to the top of the jam and extends completely across the channel). Sediment extends upstream as a function of channel gradient and sediment supply conditions, or until the next debris jam. Active overbank sedimentation in the riparian area is often apparent.
<1/4	The initiation of one or more preferred channels through or around a jam begins to excavate the wedge surface. Active overbank sedimentation in the riparian area may occur during moderate flows.
1/4–1/2	A channel has incised into the wedge surface. Relatively large volumes of sediment are stored near the jam or in areas of low shear stress. Active overbank sedimentation in the riparian area is unlikely except during high flows.
1/2–3/4	Preferred channels have developed and a portion of the wedge may be colonized by riparian vegetation (primarily <i>Alnus rubra</i> [red alder] in coastal British Columbia).
>3/4	Remnants of the wedge exist, but are difficult to identify and distinguish from the normal development of channel bars. Riparian vegetation may colonize any remaining stable portions of the wedge.

TABLE 6 *Channel characteristics associated with log jams (after Hogan 1989)*

Number of channels	Channel characteristics
1	A single, preferred channel has established through or around a jam and incised into the sediment wedge. There are no flood channels.
2	A single, preferred channel has established through or around a jam and incised into the sediment wedge. A secondary channel around the jam or a flood channel through the riparian area has also developed.
3	One or two preferred channels have established through or around a jam. A secondary channel around the jam or a flood channel through the riparian area have also developed. The channel may be anastomosed around stable, vegetated portions of the sediment wedge.
>3	Preferred channels have established through or around a jam. Secondary channels around the jam or a flood channel through the riparian area may have also developed. The channel may be anastomosed around stable, vegetated portions of the sediment wedge.

TABLE 7 Indicators of channel adjustment associated with log jams

Indicator	Description
<i>Bed sediments:</i>	
Bed texture	Sediment is relatively fine textured upstream of a jam (increase in sediment supply) and coarse textured downstream of a jam (decrease in sediment supply). In both cases, the channel bed and banks exhibit minimal sediment textural variability (i.e., sediment is similarly sized, regardless of actual texture).
Bars	Upstream of a log jam, areas of extensive bars (especially mid-channel bars) develop as the channel aggrades. Extensive bars often develop in association with a sediment wedge as the channel braids across the wedge surface. Mid-channel bars can have relatively steep downstream faces and bar-tops that reach or exceed elevations of surrounding bank-tops.
Scour	Downstream of a log jam, the majority of bed and bar material may be absent as sediment supply is reduced and the channel is scoured. Bedrock may be exposed along the channel margin.
<i>Channel morphology:</i>	
Riffles or cascades	Upstream of a log jam, riffles dominate the surface of the sediment wedge as pools are infilled by advancing bedload. Downstream of a jam, riffles or cascades dominate as bed structure is eliminated by scouring flows.
Pools	Pools are limited in frequency and areal extent, both upstream and downstream of log jams. Plunge pools may form in association with individual LWD pieces or immediately downstream of a jam.
Stone lines	Stone lines associated with step-pool channels can be disturbed. Upstream of a jam, stone lines may be buried by the sediment wedge. Downstream, stone lines may no longer be intact, with water now flowing around individual stones rather than cascading over actual stone lines.
<i>Bank characteristics:</i>	
Erosion	Upstream of a log jam, the channel banks may be eroded as the channel widens or buried as a sediment wedge builds vertically and then laterally into the riparian area. Downstream of a log jam, bank material may be recently exposed.
Undercut	Banks may lack an undercut as the bed and banks are scoured.
<i>Overbank characteristics:</i>	
Avulsions	As a sediment wedge aggrades, the channel can shift laterally around a log jam and spread onto the valley flat.
Channel abandonment	As a channel degrades through a sediment wedge, local base-level is reduced, often isolating back or side channels. Typically, abandoned channels show signs of colonization by riparian vegetation and have accumulated some forest litter.

transport limitations initiated by a log jam as it regulates the local sediment regime (see Hogan et al., this volume). The objective of the inventory is to document the adjustment of the channel in response to jam formation. A list of field indicators should be compiled upstream and downstream of individual log jams.

Stage of Channel Adjustment

The classification of log jams and the inventory of indicators of channel adjustment describe the current function of a log jam and how it influences sediment transport and channel stability. As a jam deteriorates over time, its influence on sediment transport decreases and the channel begins to

resemble the morphology associated with an undisturbed channel. The longevity of a log jam determines its temporal role in controlling channel morphology, while the specific pattern of channel adjustment is determined by the type of channel (e.g., riffle-pool, step-pool) the jam occurs in. A temporal model of channel adjustment following the initiation of a log jam is reviewed by Hogan et al. (this volume). Five stages of adjustment are identified, each with characteristic morphologies and LWD characteristics. The age of a log jam is determined in the field by both relative and absolute means. Individual LWD pieces in a jam exhibit certain characteristics as they age (e.g., branches are broken from the stem; stem-wood decays and discolours) and these can be used to establish the

relative age of a jam (jams being classified into ordinal-scale age classes). Within consistent biogeoclimatic and LWD decay conditions, temporal bounds can be established in association with each age class. For example, observations of log jams in the Queen Charlotte Islands suggest that LWD covered or partially covered in a moss and devoid of both branches and bark is usually older than 30 years. This method is often complicated, however, either by the addition of relatively new pieces of LWD to a jam during subsequent years after its initial formation, or by relatively old LWD being incorporated into a new jam. Using LWD decay characteristics to determine log-jam age is most reliable where individual LWD pieces are in a homogeneous stage of decay throughout the entire jam.

A more accurate method involves aging nursed trees growing on individual LWD pieces incorporated into a jam. In coastal British Columbia, red alder (*Alnus rubra*) can establish on a log jam shortly after the jam is initiated; counting tree rings of the oldest nursed trees establishes an absolute

minimum jam age. Additional botanical evidence is often available in the adjacent riparian area and may be required if nursed trees either did not establish or did not survive on a jam. Typically, the sediment wedge associated with a jam creates a fresh deposit of fine-textured sediments colonized by pioneering plant species (e.g., an even-aged stand of red alder) once the wedge is stabilized. Although the lag time between jam formation and wedge stabilization is usually unknown, the maximum age of the canopy can also be used to establish an absolute minimum jam age.

The presence of aging nursed trees is usually the most reliable method of establishing the age of a log jam. However, information derived from the riparian area and from decay characteristics of LWD pieces should be used for corroboration. Table 8 presents a summary of the common characteristics of a jam (including state of LWD decay and ages of nursed and riparian trees) associated with each age class. Age classes and channel characteristics coincide with those reviewed by Hogan et al. (this volume).

TABLE 8 Log jam age classes (after Hogan 1989). Five stages of channel adjustment following the formation of a log jam (and corresponding to the age classes below) are reviewed by Hogan et al. (this volume). Note below, however, that the <10-year stage of channel adjustment has been divided into two categories.

Time since jam formation (yr)	Characteristics of the jam, nursed tree, and sediment wedge
<2	Primarily new LWD pieces (bark, branches, etc., remain intact). Includes new debris from upstream and upslope, apparently formed during the last major storm or landslide event. No nursed trees; the wedge is unvegetated.
2–10	LWD pieces have lost some bark and few branches remain. Twigs are absent. Nursed trees (usually red alder in coastal British Columbia) are less than 5 m high and are aged in the field (cut and rings counted). Any stable portions of the sediment wedge support a dense pioneering canopy of red alder.
10–20	Bark is absent from some LWD pieces but remains intact on others. Branches are generally absent. Nursed trees are between 10 and 20 years old (aged by increment cores). Natural thinning of the riparian canopy growing on the sediment wedge is evident.
20–30	Sapwood is soft; moss may cover a portion of stable LWD pieces. Nursed trees are 20–30 years old. Stable portions of the sediment wedge support grasses, herbs, and mosses in the understorey.
30–50	Bark is absent or sloughing; LWD pieces are stained and discoloured. Nursed trees are 30–50 years old. The colonized portion of the sediment wedge is difficult to distinguish from the adjacent riparian area.
>50	LWD has no bark and may only be partially intact. Individual LWD pieces are uniformly dark and discoloured. Nursed trees are >50 years old, but occur infrequently. The riparian canopy supported by the sediment wedge has reached a maturing stage, with red alder in the overstorey and Sitka spruce (<i>Picea rubens</i>) establishing in any openings in the canopy.

Channel Assessment

Following a channel disturbance, such as the development of a landslide-induced log jam, the pattern of channel recovery is dependent on both the characteristics of the jam and the type of channel the jam occurs in. The permeability of a log jam determines the amount of sediment allowed to pass downstream, forcing the channel to locally aggrade upstream and degrade downstream. The magnitude of any net aggradation and degradation is determined by the type and relative size of a jam (spatial impact) and by the age of the jam (temporal impact). An assessment of channel morphology in small coastal stream channels must begin with a classification of these features that control channel morphology.

Typically, in unlogged watersheds on the Queen Charlotte Islands, there is a wide range of jam ages and associated levels of channel disturbance. The rate of log-jam formation is accelerated once a watershed is logged and the channel becomes dominated by relatively young, impermeable log jams. At the reach level, the assessment of channel morphology is based on the classification of log jams to identify specific impacts, and a record of their spacing throughout the reach. At a reconnaissance-level, assessment can proceed on a “walk-through” basis whereby features are classified along one-bankfull-width sections of channel, with minimal need for intensive measurements (e.g., pool-riffle spacings, sediment textures). The level of channel disturbance can then be assessed for each section, using Figure 4 as a reference.

Analysis of the results should be based on the temporal and spatial distributions of log jams and their characteristics. For example, a channel dominated by young, impermeable, vertical mega- and macrojams will be less stable than a similar channel dominated by old, permeable, vertical micro- and mesojams. A comparison of these distributions between forested and logged stream channels should also include watersheds similar in morphology and morphometry (see Cheong, this volume). Any increase in the relative frequency of recently formed, impermeable jams constitutes a fundamental impact relating to channel morphology, the riparian area, and fish habitat. The magnitude of this impact is indicated by any shift in the relative frequency in the type and relative size those jams.

Summary

Hogan et al. (this volume) review the importance of log jams as a control of channel morphology in small coastal streams. This paper describes a method of channel classification that considers the spatial and temporal distribution and the functional character (span, integrity, sediment storage, etc.) of log jams. The classification allows an assessment of current channel conditions and recovery potential, and enables a description to be made of channel resiliency to any potential upstream and upslope disturbances. For example, given similar reach characteristics and channel size, a channel containing frequent (short spacing lengths) micro- and mesojams with high integrity and low sediment storage ratings, frequent log steps, and stable, undercut banks should be more resilient to change than channels with infrequent, low-integrity macro- and megajams characterized by mid-channel bars, extensive riffles, and eroding banks. The former channel will likely respond much differently to altered sediment loading than will the latter, as sediment is stored in a relatively stable spatial and temporal channel configuration.

The channel classification and assessment procedure outlined here is in a preliminary state of development; it is presented to generate discussion and input from operational field workers. The underlying principles of the procedure are driven by our experiences gained from conducting extensive field surveys in small coastal stream channels. There are four main issues we attempt to deal with in the procedure:

- Channels undergo normal cycles of sediment erosion and deposition, so rather than measure all of the channel attributes of aggradation/degradation (e.g., changes in bed elevation, sediment textures, altered channel dimensions, sediment storage volumes) we key in on the overall effect on the channel.
- Many morphological measures are stage-dependent (particularly delineation of pools and riffles) and difficult to measure on a repeatable basis.
- Many field measurements are extremely time consuming to make because of sampling limitations (e.g., determination of sediment textures, volumes of LWD, volumes stored in sediment).
- Opinions about what constitutes a “stable” channel differ widely, the views of fisheries biologists, engineers and geomorphologist often being very different.

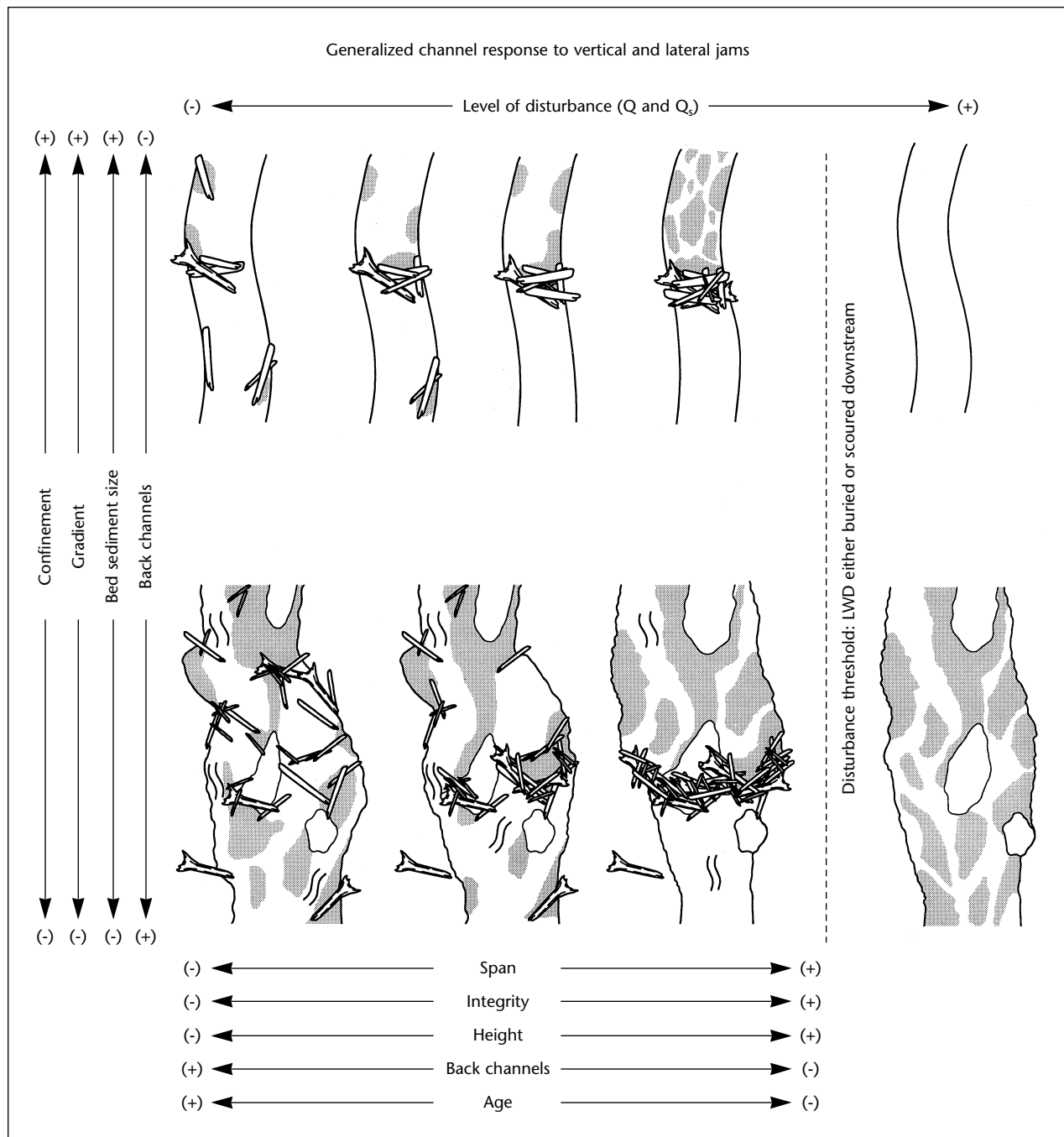


FIGURE 4 Disturbance matrix of lateral and vertical log jams. Note that as the level of disturbance increases, LWD can be completely buried as the entire reach aggrades.

We therefore use log-jam attributes—what we agree to be the primary factors that control these stream characteristics (sediment aggradation/degradation, pool/riffle densities, bed and bank characteristics)—as the basis of the channel classification and assessment scheme presented here. This is different approach than most other schemes that attempt to measure many individual channel attributes. We hope that this new approach provides a useful tool, one that is cost-effective to complete and provides the types of information needed for managing the forests and fish habitats. We intend to continue to revise this scheme in response to feedback obtained from field workers.

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Productivities, Costs, and Site and Stand Impacts of Helicopter-logging in Clearcuts, Patch Cuts, and Single-tree Selection Cuts: Rennell Sound Trials

RAY KRAG

Introduction

In 1992, a helicopter-logging trial was conducted in Rennell Sound on the Queen Charlotte Islands under the auspices of the Fish/Forestry Interaction Program. The purpose of the trial was to test the concept of using helicopters to selectively harvest timber from steep, potentially unstable hillslopes where the likelihood of logging-induced landslides precluded conventional cable-yarding and clearcutting. The Forest Engineering Research Institute of Canada (FERIC) monitored the trial to evaluate the operational feasibility of this concept. (Partial funding for FERIC's studies was provided by the Fish/Forestry Interaction Program and the South Moresby Forest Replacement Account.) This paper describes the trial and presents preliminary results on yarding productivities, post-logging stand and site conditions, and costs of the helicopter-logging operations.

In 1979, the federal Department of Fisheries and Oceans and the British Columbia Ministry of Forests and Ministry of Environment established the Fish/Forestry Interaction Program (FFIP), a multidisciplinary research program with the goal of identifying ways to manage and harvest mountain forests while maintaining stream integrity and fish habitat on the Queen Charlotte Islands. The program was initiated in response to concerns that the road-building and logging practices of the day were increasing the frequency and magnitude of landslides on steep slopes, resulting in loss of productive forest land and damage to salmon habitat. One of FFIP's stated objectives was "to investigate the feasibility and success of using alternative logging methods to reduce traditional environmental problems associated with logging. These methods include skyline and helicopter use, and improved planning of logging roads and logging layout in sensitive areas" (Poulin 1984).

In 1980, at the request of FFIP personnel, FERIC initiated a series of studies to address this objective. During the next 5 years, FERIC examined the causes of landslides in logged areas (Krag et al. 1986), studied conventional and alternative cable-yarding operations on steep slopes (Sauder and Wellburn 1987), and developed and compared alternative logging plans for two typical sensitive sites (Sauder and Wellburn 1989). These studies showed that on many logged sites the risk of landslides could be reduced through the use of improved planning and road-building practices and the innovative use of a variety of cable-yarding methods, including conventional as well as skyline systems.

On more sensitive sites, however, the risk of landslides precluded the use of conventional harvesting and silvicultural systems. The program therefore also examined the potential of using helicopters in combination with partial-cutting silvicultural systems to harvest such sites. Between 1986 and 1989, Husby Forest Products Ltd. and Canadian Air-Crane Ltd. successfully demonstrated the concept on gentle terrain in the Naden Harbour area by using a heavy-lift helicopter to selectively harvest timber in sensitive riparian areas (Moore 1991). As a result, part of FFIP's second 5-year research plan included a proposed operational trial to extend the concept onto steep slopes. FERIC monitored the trial, which took place between June and November of 1992 on two sites in Rennell Sound, to assess the operation's performance and feasibility.

Study Sites, Harvesting Treatments and Systems

Study Sites The two helicopter-logging sites are located in Rennell Sound on the west coast of Graham Island (Fig. 1). The Hangover Creek site occupies the midslope area of a mountain shoulder near the confluence of Hangover and Bonanza creeks; the Gregory Creek site, 5 km to the south-

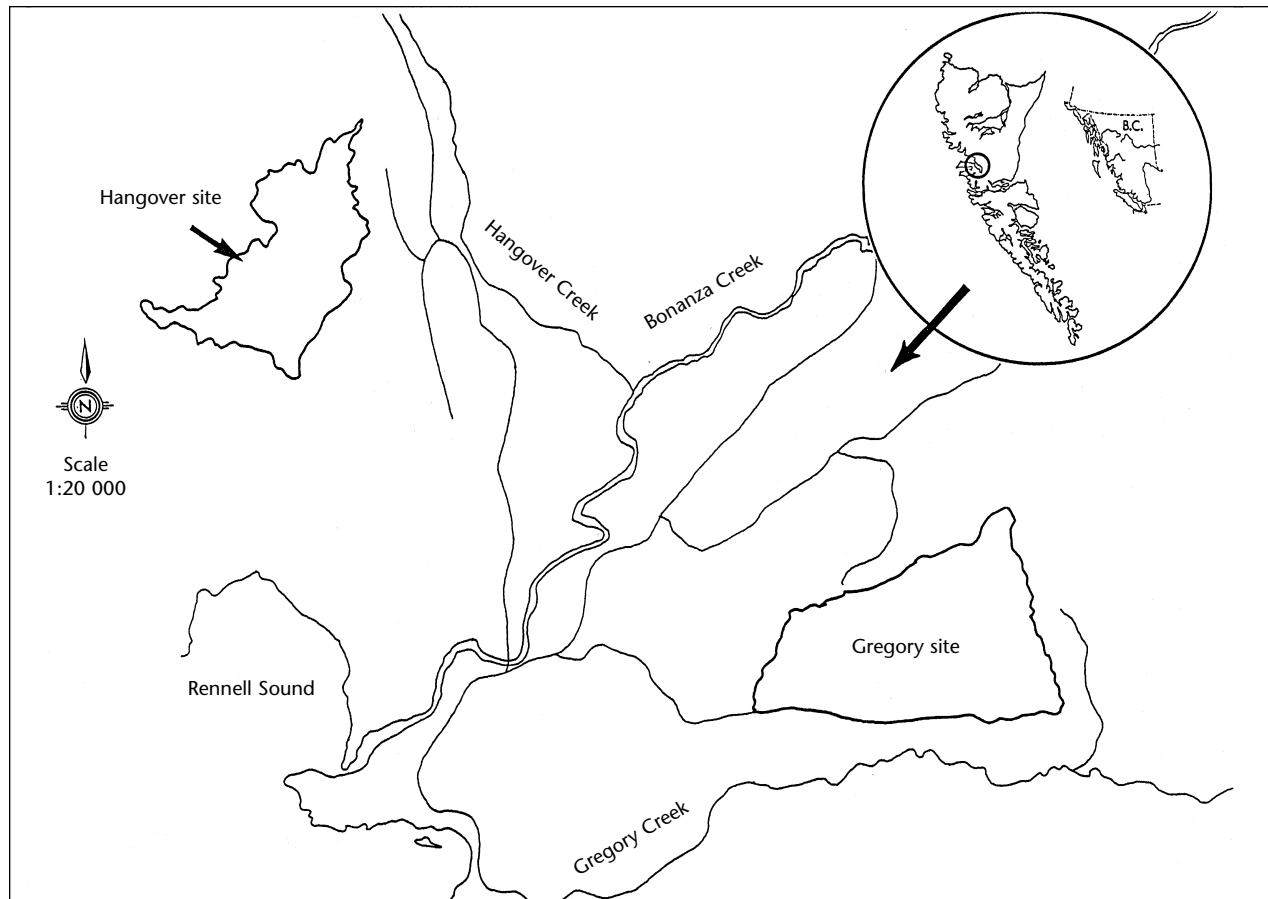


FIGURE 1 Location of study area in Rennell Sound on the west coast of Graham Island, Queen Charlotte Islands.

east, extends from the lower slope to the ridgetop along the north side of Gregory Creek. Both are on south to southeast aspects and are similar in terms of stand characteristics, aspects, slopes, and soils (Table 1). However, Hangover Creek consists mostly of steep, uniform open slopes while Gregory Creek is heavily dissected by numerous steep, bedrock-based gullies ranging from 2 to 15 m deep and 100 to 400 m long. Evidence of historic mass wasting is frequent on both sites.

Both sites are within the Very Wet Hypermaritime subzone of the Coastal Western Hemlock biogeoclimatic zone (CWHvh2) (Green and Klinka 1994), which is characterized by mild temperatures and heavy rainfalls. Forest cover is typical for rapidly drained slopes in this subzone. Hangover Creek contains an almost equal mix of western hemlock (*Tsuga heterophylla*) and Sitka spruce (*Picea*

sitchensis), with minor components of western redcedar (*Thuja plicata*) and yellow-cedar (*Chamaecyparis nootkatensis*); Gregory Creek is dominated by western hemlock with a lesser component of Sitka spruce and a minor component of western redcedar. The trees on Hangover Creek average slightly larger in diameter, height, and merchantable volume than on Gregory Creek. Net merchantable volumes average 816 m³/ha on Hangover Creek and 629 m³/ha on Gregory Creek.

The sites are representative of many marginally stable forested slopes on the Queen Charlotte Islands. Each site supports valuable stands of high-quality timber and contains a complex mosaic of terrain stability classes (B.C. Ministry of Forests 1995). Although sizable parts of each site are mapped as relatively stable (Classes I to III), a significant portion is mapped as unstable

TABLE 1 *Site and stand descriptions*

	Hangover Creek	Gregory Creek
Cutblock area (ha)	45.7	79.9
Ecological classification ^a	CWHvh2	CWHvh2
Site characteristics		
Terrain type	open-sloped, broken	gullied, broken
Slope		
Range (%)	20–120	20–100
Average (%)	65	55
Slope breaks	frequent	frequent
Soils		
Texture	silty loam	silty loam
Depth (m)	<1.0	<1.0
Slope stability class	IV, (V)	IV, (V)
Stand characteristics		
Species composition	51% hemlock 46% spruce 3% cedar/cypress	65% hemlock 28% spruce 7% cedar
Live trees		
Density (no./ha)	294	294
Average diameter (cm)	57.7	53.4
Snags		
Density (no./ha)	23	19
Average diameter (cm)	73.5	91.6
Merchantable volumes		
Per hectare (m ³ /ha)	816	629
Per tree (m ³)	2.77	2.14
Defect (%)	17.8	22.5
Average tree height (m)	41.9	41.1

^a Green and Klinka 1994.

(Classes IV and V), where experience has shown that traditional road-building and clearcutting practices have a moderate to high likelihood of inducing slope failures following logging. The stable areas are effectively isolated by unstable terrain units and are physically or economically inaccessible for conventional road development and cable logging. Currently such sites are excluded from the operable forest land base because of slope stability concerns, and therefore do not contribute to the allowable annual cut.

Harvesting Treatments

Four treatment units designated for helicopter yarding were established on Hangover Creek and each was assigned one of four silvicultural prescriptions: clearcutting; two levels of patch cutting (50% removal and 25% removal levels, in ~0.2-ha patches); and one level of single-tree selection cutting (25% by basal area, distributed proportionally among species and diameter classes). The same helicopter-yarding treatments were repeated on the Gregory Creek site, which also had two additional treatment units: a 15% single-tree selection unit that was designated for helicopter logging; and a clearcut unit designated for conventional grapple yarding. In addition, a no-logging control unit was established on or near each site.

Figure 2 shows the arrangement of the harvesting treatment units on Hangover Creek, with actual dimensions and shapes of patches after logging was completed. Each treatment unit was between 8 and 11 ha in size, and in most cases extended from the bottom to the top of the study site. Because of size limitations, there were no buffers between the harvesting treatments, so on both sites many of the patches in the 50% patch-cut units opened onto the adjacent clearcuts.

Harvesting System and Organization

Canadian Air-Crane Ltd. performed the helicopter-logging operations on the trial sites. The fallers and helicopter-logging crews were experienced in partial cutting in similar stand types before the start of this trial, having worked for Husby Forest Products Ltd. in its partial-cutting trials in Naden Harbour.

Equipment for the helicopter-logging operation consisted of one logging helicopter (a Sikorsky S-64E Skycrane) and on-site service trailer, one support helicopter (a Bell 206 Jet Ranger), and two log loaders (one front-end and one hydraulic). The support helicopter ferried fallers and ground crews to and from work sites and returned chokers to the hook-up areas. The two log loaders retrieved chokers and decked logs in the drop zone during helicopter-yarding operations, and occasionally loaded trucks during yarding stoppages. The 23- to 25-member workforce included one supervisor

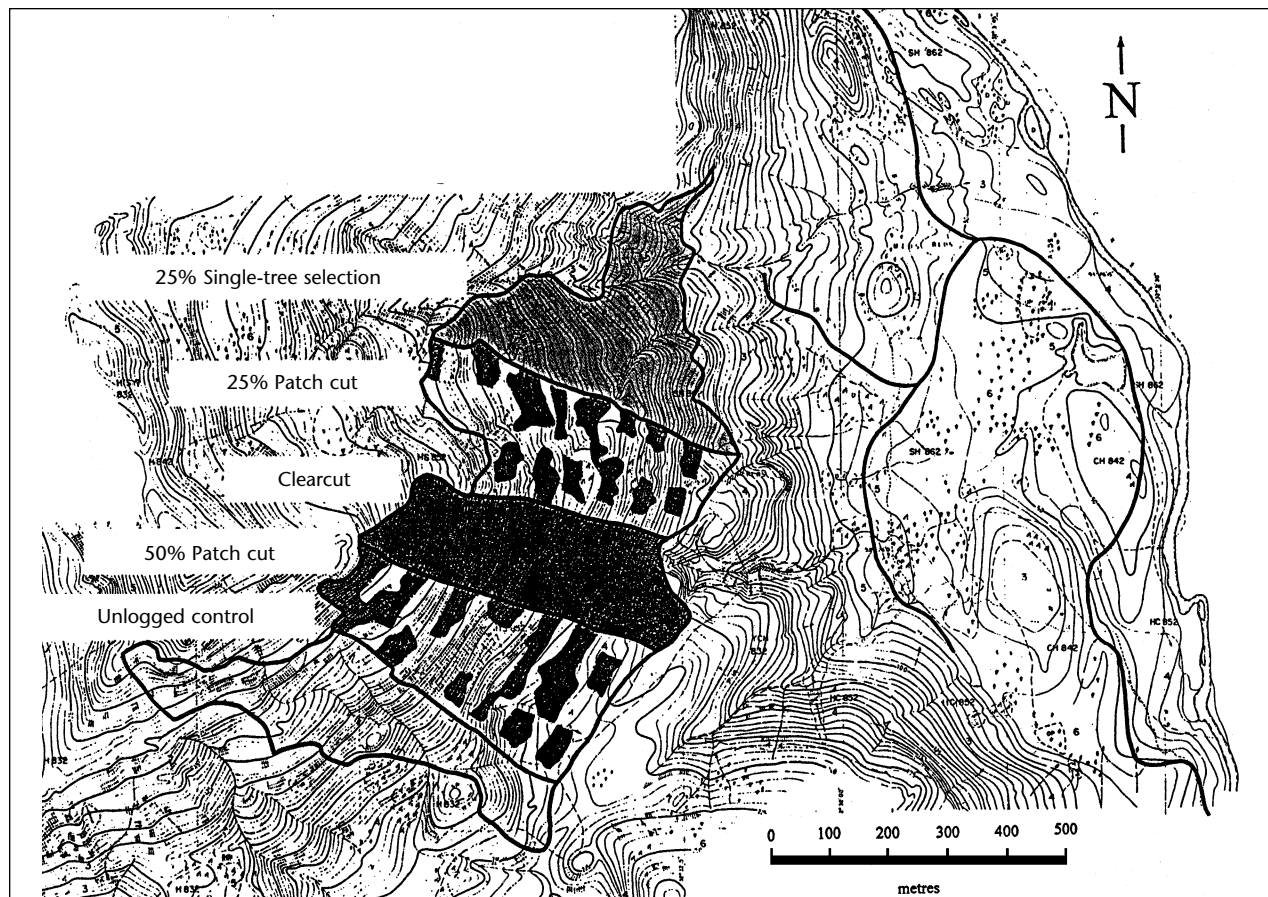


FIGURE 2 *Rennell Sound helicopter-logging trials: Hangover Creek.*

(occasionally two), a pilot and co-pilot, two or three mechanics, two loader operators, four chasers in the drop zone, and four rigging teams of one hook-tender, one strip-runner, and one chokersetter each.

The S-64E Skycrane, a heavy-lift helicopter with a rated lifting capacity of 9081 kg, used a two-hook system and a 60-m or 75-m dropline. A load cell located between the airframe hook and the dropline transmitted the turn weight to a cockpit display as the turn was lifted off the ground; if the turn was overweight, the pilot set the turn down again and released part (from one hook) or all (from both hooks) of the turn.

The Skycrane typically yarded 20–30 turns in a 55- to 60-minute flying cycle, with 5- to 10-minute visual inspection and refuelling breaks between cycles. The pilot and copilot usually switched tasks after every cycle. Shift lengths ranged from 2 to 12 hours per day, depending on available daylight and weather

conditions. Yarding began at the top of the harvesting treatments and progressed downhill. The four rigging crews were dispersed roughly along a level line across the width of the study site and were spaced as far apart as safety dictated. During a yarding cycle, the Skycrane rotated among the four hook-up points, taking two consecutive turns from one hooktender, then moving to the next hook-up point for two turns from the next hooktender, and so on.

Logs were landed on or beside existing roads along the bottoms of both sites. The loaders and chasers worked steadily back and forth along the road, always maintaining a clear zone for the Skycrane to land turns. The front-end loader kept the road clear and helped the chasers to unhook chokers, while the hydraulic loader followed behind and decked the unchoked logs on the downhill side.

On each site the harvesting treatment units were yarded concurrently to ensure that the yarding

operation progressed more or less uniformly downhill, thereby eliminating the risk of having rigging crews working beneath the Skycrane's flight path. On Hangover Creek, two rigging crews usually worked full-time in the clearcut unit, a third crew worked in the 50% patch-cut unit, and a fourth crew alternated between the 25% patch-cut and 25% single-tree selection units. On the Gregory Creek site, the treatment units were also yarded concurrently and rigging crews were similarly distributed, although crew placement was considerably more flexible because the harvesting treatment units were more dispersed.

Study Methods

Productivity and Cost A FERIC researcher was stationed on-site for the duration of the helicopter-logging operation. A combination of detailed-timing and shift-level data collection methods was applied to analyze the effects of harvesting treatment on helicopter-yarding productivity. The following information was collected during detailed timing: harvesting treatment and location (lower, middle, or upper third); start point (the drop zone segment where the previous turn was landed); end point (the drop zone segment where the current turn was landed); number of logs; time per turn element (Travel empty; Position and hook-up; Breakout; and Travel loaded); total turn time; and any delays with known or suspected causes.

Canadian Air-Crane Ltd. supplied the Skycrane's cycle data sheets, shift production summary, and operating report for every day of operation to supplement the detailed-timing data. This shift-level information provided a consecutive record of each turn yarded during a production cycle, including the turn number and location, estimated and actual turn weights, number of logs, and occurrences of partial or complete aborts, plus total numbers of cycles, turns and weight flown per operating shift, distribution of shift time, and maintenance activities. The detailed-timing and shift-level data were then correlated and compiled to determine average turn times, flight distances, number of turns, and total weight of logs yarded from each harvesting treatment. Husby Forest Products Ltd. supplied the final scale summaries for the trial, which were used to convert log weights to volumes.

Linear regression equations were developed to relate Travel empty and Travel loaded times to flight distances so that average turn times could be expressed and compared for common yarding distances.

Standard FERIC costing procedures were used to develop a preliminary estimate of owning and operating costs for the helicopter-logging operation, including the logging and support helicopters and the two log loaders. Standard union labour rates were used to derive labour costs. The hourly cost for the Sikorsky S-64E Skycrane was derived by updating costs presented in Guimier and Wellburn (1984) and including a standby allowance for weather delays. FERIC's costing excludes mobilization and demobilization costs, operating costs for the float camp, overhead, profit, and crew supervision and transportation. It is stressed that this costing is only preliminary and is not intended to represent the actual cost experienced by Canadian Air-Crane Ltd.

Residual Stand and Ground Surface Condition

Following the completion of helicopter-logging, both sites were resurveyed and mapped to establish final boundaries, locations, and areas of all treatment units and patch cuts. Within each treatment unit, 12.62-m radius (0.05-ha) plots were established in a staggered pattern on a 40-m \times 80-m (approximate) grid, yielding 20–30 plots per treatment unit depending on the size and shape of each unit. At each plot all live residual trees and snags 15 cm dbh and larger were cruised and species, height (above point of germination), and diameter were recorded for all stumps larger than 15 cm diameter at stump height. The dimensions and locations on the stem of all logging-related scars were recorded for all residual live trees in the patch-cut and single-tree selection cuts. Scars were measured directly if close to the ground; otherwise they were estimated.

Ground surface condition was determined by locating four 15-m transects at each plot centre. The first transect was established by selecting a random bearing; the second, third, and fourth transects were then oriented at 90°, 180°, and 270°, respectively, to the first. Point samples of ground surface condition were recorded at 1-m intervals along each transect, for a total of 60 points per plot.

Results and Discussion

Summary of Operations Falling, yarding, and loading operations were performed on the trial sites between June and November 1992. Falling began on Gregory Creek in mid-June and on Hangover Creek in early July. The fallers concentrated on Hangover Creek first and finished there in late August; they then shifted back to Gregory Creek. Falling was completed on most of the Gregory helicopter-yarding units by late September, but the decision to add the 15% single-tree selection unit extended falling operations into early October.

A few fallers remained on Gregory Creek during July so that the conventional clearcut unit could be logged before helicopter-yarding began on the other Gregory treatment units. This unit was grapple-yarded with a Madill 044 yarding crane between late July and mid-August, and the logs were loaded out between late August and mid-September.

The Skycrane began yarding on the Hangover Creek site in late August and finished in late September, then moved to Gregory Creek and finished there in mid-October. Helicopter-yarding operations on the two study sites were continuous except for a period of 3 days in early October, when a small blowdown patch was logged nearby.

One log loader and two log trucks remained on-site after the yarding phase finished. Loading and hauling operations were completed in late November.

Yarding Productivity for the Sikorsky S-64E Skycrane Table 2 summarizes the Skycrane's log production from the Hangover and Gregory Creek sites. The Skycrane yarded a total of 34 954 m³, distributed almost equally between the two sites, between August 31 and October 17. During that period, the Skycrane flew 219 production cycles in 40 operating shifts (20 at each location). The helicopter was grounded by low cloud or wind for six full shifts and parts of several other shifts as well.

The Skycrane averaged 5.7 cycles per operating shift at Hangover Creek and 5.3 cycles per operating shift at Gregory Creek. ("Cycle" refers to the 55- to 60-minute periods of yarding activity between refuelling breaks.) Yarding production averaged 22.4 turns, 97.1 logs, and 153.1 m³ per cycle on Hangover Creek, and 26.2 turns, 117.2 logs, and 166.6 m³ per cycle on Gregory Creek. ("Turn" refers to the sequence of activities required to transport logs from

TABLE 2 Summary of log production for the Sikorsky S-64E Skycrane

	Hangover Creek	Gregory Creek	Combined
Days with production	20	20	40
Full days lost to weather	5	1	6
Total number of shifts	25	21	46
Cycles flown (no.)	114	105	219
Turns yarded (no.)	2 554	2 746	5 300
Logs yarded (no.)	11 065	12 310	23 375
Volume yarded (m ³)	17 456	17 498	34 954
Cycles/shift (no.)	5.7	5.3	5.5
Turns/cycle (no.)	22.4	26.2	24.2
Logs/turn (no.)	97.1	117.2	106.7
Volume yarded/cycle (m ³)	153.1	166.6	159.6
Logs/turn (no.)	4.3	4.5	4.4
Volume yarded/turn (m ³)	6.83	6.37	6.60
Volume/log (m ³)	1.58	1.42	1.50
Average flight distance (m)			
Empty	751	370	—
Loaded	731	314	—

the hook-up site to the drop zone. A turn consists of four time elements: Travel empty, Position and hook-up, Breakout, and Travel loaded.) Average log size and number of logs per turn were slightly greater for Hangover Creek, so the average volume per turn was higher for Hangover than for Gregory Creek. However, the average yarding distance on Hangover Creek (740 m) was more than double that of Gregory Creek (340 m), resulting in longer average turn times and fewer turns per cycle. The longer turn times more than offset the slightly larger turn volumes, so average volume yarded per cycle was higher for Gregory Creek.

Effect of Harvesting Treatment on Helicopter-yarding Productivity It was hypothesized that, relative to the clearcut units, helicopter yarding from the patch cuts and single-tree selection cuts might experience longer average turn times, lower average turn weights (i.e., volumes), and higher frequencies of hang-ups or partial or complete aborts. The following analysis examines the effects of harvesting treatment on turn times and volumes.

Effect of Harvesting Treatment on Turn Times

More than 90% of the Skycrane’s 5300 turns were detail-timed during the study. After first eliminating occasional in-flight delays that were not related to the harvesting treatment (such as delays at the drop zone caused by hook malfunctions), times for Position and hook-up and Breakout were compiled and averaged for each harvesting treatment. Regression analysis was performed to relate Travel empty and Travel loaded times to flight distance for each site, resulting in the following equations:

Hangover Creek:

Travel empty time (min.)

$$= 0.24445 + (0.000297 \times \text{yarding distance (m)})$$

$$= 0.47 \text{ min. @ 751 m}$$

Travel loaded time (min.)

$$= 0.44528 + (0.000355 \times \text{yarding distance (m)})$$

$$= 0.70 \text{ min. @ 731 m}$$

Gregory Creek:

Travel empty time (min.)

$$= 0.22542 + (0.000270 \times \text{yarding distance (m)})$$

$$= 0.33 \text{ min. @ 370 m}$$

Travel loaded time (min.)

$$= 0.38849 + (0.000317 \times \text{yarding distance (m)})$$

$$= 0.49 \text{ min. @ 314 m}$$

Average total turn times were then generated for each site and treatment unit by adding average Position and hook-up and Breakout times to the

above predicted Travel empty and Travel loaded times for their respective average travel distances (Table 3). (Note that the flight distances were standardized for treatment units within each site, but not between sites.)

Table 3 shows very consistent trends and relative differences in average turn times between the harvesting treatments on each site. Average turn times for a given treatment unit were between 14 and 18% longer on Hangover Creek than on Gregory Creek because of the substantially longer average flight distance.

Within each site, average turn times for the clearcuts and the 50% patch cuts were virtually identical, indicating that average times for Position and hook-up and Breakout were essentially unchanged as well. On both sites, the clearcut and 50% patch-cut units were adjacent to each other and in both instances many of the patches in the 50% patch-cut unit opened onto the clearcut (Fig. 2). The Skycrane often extracted logs from these patches by flying into the adjacent clearcut rather than lifting them above treetop level, so in effect the patches became extensions of the clearcut.

Average turn times for the 25% patch-cut units were slightly longer than for the clearcuts. With only one exception, the patch openings in the 25% patch-cut units were surrounded by standing timber, so the Skycrane had to lift the logs high enough to clear the adjacent trees before beginning its descent to the drop zone. This resulted in slightly longer Breakout times for the 25% patch-cut units. Relative to the clearcut, Position and hook-up time was unchanged

TABLE 3 Average turn times for the Sikorsky S-64E Skycrane

Treatment unit	Hangover Creek		Gregory Creek	
	Turn time (min)	Change (%)	Turn time (min)	Change (%)
Clearcut	2.36	–	2.00	–
50% Patch cut	2.34	-0.8	2.00	n.c.
25% Patch cut	2.42	+2.5	2.12	+6.0
25% Single-tree selection	2.62	+11.0	2.22	+11.0
15% Single-tree selection	n/a	n/a	2.26	+13.0
Average yarding distance (m)	740		340	

on Hangover Creek and marginally longer on Gregory Creek, indicating that the small size of the patch cuts (~0.2 ha) did not materially affect the pilot’s ability to spot the hooktender.

Relative to their respective clearcut units, average turn times for the two 25% and one 15% single-tree selection units were substantially longer because of pronounced increases of 15–23% in Position and hook-up times and 18–32% increases in Breakout times. The slight difference in average turn times between the 25% and 15% patch cuts on Gregory Creek is not large enough to suggest a trend of increasing turn time with lighter removals.

Effect of Harvesting Treatment on Turn Weights

Table 4 summarizes average gross weights per turn (i.e., including logs, dropline, hook, and chokers) and net volumes per turn. (Turns could not be individually scaled during the study, so turn volume was estimated from weight-to-volume conversion factors derived for each site.)

Average turn weights were slightly higher for the 50% and 25% patch-cut units and marginally lower for the 25% single-tree units than for their respective clearcut counterparts. Although absolute

turn weights differed between the two sites, within-site trends between treatment units are surprisingly consistent. This consistency probably reflects the experience of the rigging crews and the skill of the hooktenders in accurately estimating log weights when making up the turns. Light slash levels in the 25% and 15% single-tree selection units may also have helped. Hooktenders reported that with less slash on the ground in the single-tree selection units, logs were more visible to the rigging crews and less likely to be missed when setting chokers, so clean-up yarding was reduced.

The 7.4% decrease in turn weight observed for the 15% single-tree selection unit may indicate that, at low removal levels, logs become too scattered for rigging crews to consistently achieve desired turn weights, despite crew experience and low slash levels.

Effect of Harvesting Treatment on Skycrane

Productivity and Cost Table 5 shows yarding productivities by treatment unit in terms of volume yarded per flight-hour. These yarding productivities, estimated from average number of turns per hour (derived from average turn times in Table 3) and average volume per turn (Table 4), express the com-

TABLE 4 Average turn weights and volumes for the Sikorsky S-64E Skycrane

Treatment unit	Hangover Creek		Gregory Creek	
	Gross turn weight (kg)	Change (%)	Gross turn weight (kg)	Change (%)
Clearcut				
gross weight (kg)	6712	–	6575	–
net volume (m³)	6.79		6.39	
50% Patch cut				
gross weight (kg)	6819	+1.6	6643	+1.0
net volume (m³)	6.91		6.46	
25% Patch cut				
gross weight (kg)	6841	+1.9	6687	+1.7
net volume (m³)	6.93		6.50	
25% Single-tree selection				
gross weight (kg)	6677	-0.5	6553	-0.3
net volume (m³)	6.76		6.36	
15% Single-tree selection				
gross weight (kg)	n/a	n/a	6088	-7.4
net volume (m³)	n/a		5.88	

bined effect of harvesting treatment on turn times and weights. (Average turn times were increased by 2.44% to account for minor in-cycle delays not related to treatment. This allows yarding productivity to be expressed on a per-flight-hour basis.)

Compared to the clearcut, the Skycrane’s yarding productivity in 50% patch cuts increased by 1.1–2.1%, mainly to slight increases in average turn volumes on both sites. Yarding productivity for the 25% patch cuts decreased by 0.5–9% because on both sites modest increases in average turn times more than offset slight increases in average turn volumes. Yarding productivity for the 25% single-tree selection units decreased by 10.2–10.4%, primarily because of substantial increases in average turn times and, to a lesser extent because of slight decreases in average turn volumes. Finally, yarding productivity for the 15% single-tree selection unit on Gregory Creek was 18.5% less than for the clearcut, because of a substantial increase in average turn time and a substantial decrease in average turn volume.

Stand and Site Conditions Following Logging

Scarring of Residual Trees Table 6 summarizes the incidence of falling- and yarding-related scars of any size on residual live trees in the patch-cut and single-tree selection units. Scarring levels for corresponding treatment units were consistent between the Hangover and Gregory Creek sites, which suggests that the observed patterns are probably treatment-related. Almost one- quarter (24.8%) of residual trees in the 25% single-tree selection units had logging-related scars, compared to 15% of trees in the 50% patch-cut units, 9.5% in the 25% patch-

cut units, and 6.6% in the 15% single-tree selection unit. The relatively high incidence and uniform distribution of scarring in the 25% single-tree selection units likely reflect the dispersed pattern of tree removal in this treatment. In contrast, the concentration of falling and yarding activities in the patch-cut units resulted in concentrations of scarring along the edges of the openings, especially on the lower sides. The lower incidence of scarring in the 25% patch cuts compared to the 50% patch cuts reflects the lower removal levels for these treatment units. The low level of scarring in the 15% single-tree selection unit may be due to two factors. First, the removal tended to be clustered rather than uniformly dispersed as in the 25% single-tree selection unit. Second, the actual removal level may have been much lighter than the target of 15% of basal area.

Snag falling was considered to be responsible for most of the scarring within the interiors of the leave areas on the patch-cut units, and therefore was probably responsible for some of the scarring within the single-tree selection units as well. However, although fresh scars were easily distinguished from older pre-logging damage during post-harvest surveys, it was difficult to reliably assign causes to the majority of logging-related scars, and the actual contribution of snag falling to scarring levels could not be determined.

Most logging-related scars were relatively small, with median sizes ranging from about 140 to 170 cm². Large scars, which for the purposes of this paper were defined as scars greater than 900 cm², constituted a small proportion of the total number of scars. Interestingly, within each site the percentage

TABLE 5 Volume yarded per flight-hour for the Sikorsky S-64E Skycrane

Treatment unit	Hangover Creek		Gregory Creek	
	Volume per flight-hour (m ³ /h)	Change (%)	Volume per flight-hour (m ³ /h)	Change (%)
Clearcut	168.5	–	186.9	–
50% Patch cut	172.2	+2.1	189.0	+1.1
25% Patch cut	167.7	-0.5	179.6	-3.9
25% Single-tree selection	150.9	-10.4	167.8	-10.2
15% Single-tree selection	n/a	n/a	152.2	-18.5

TABLE 6 *Scarring of residual trees^a in patch-cut and single-tree selection treatment units*

Treatment unit	Site	Residual trees surveyed (no.)	Trees with scars of any size		Trees with scars >900 cm ²	
			(no.)	(%)	(no.)	(%)
15% Single-tree selection	Hangover Creek	348	23	6.6	7	2.0
25% Single-tree selection	Hangover Creek	330	78	23.6	14	4.2
	Gregory Creek	276	72	26.1	5	1.8
	Combined	606	150	24.8	19	3.1
25% Patch cut	Hangover Creek	223	22	9.9	9	4.0
	Gregory Creek	178	16	9.0	3	1.7
	Combined	401	38	9.5	12	3.0
50% Patch cut	Hangover Creek	279	49	17.6	11	3.9
	Gregory Creek	208	24	11.5	4	1.9
	Combined	487	73	15.0	15	3.1

^a For trees >17.5 cm diameter.

of trees with large scars was similar for the 25% and 50% patch-cut and 25% single-tree selection units, ranging from 1.7 to 1.9% on Gregory Creek and from 3.9 to 4.2% on Hangover Creek. The higher proportion of large scars on Hangover Creek treatment units is probably due to the steeper, more broken terrain and therefore more difficult falling and yarding circumstances on this site as compared to Gregory Creek.

Ground Surface Condition Table 7 summarizes post-harvest ground surface conditions for all of the treatment units. Between 57 and 82% of the ground surface after falling and yarding consisted of undisturbed duff and litter layers and large woody debris such as old windfalls; from 5 to 11% consisted of natural non-soil components such as exposed rock, roots, trees, snags, and stumps. The occurrence of exposed mineral soil resulting from falling and yarding was very low. In all helicopter-yarded treatment units, this form of disturbance was less than natural or pre-harvest levels of exposed mineral soil (pre-harvest windthrow, exposed gully sidewalls, and occasional small debris slides contributed to natural soil exposure). Logging slash, the second largest component of ground cover on the helicopter-yarded units, was heaviest on the clearcut units (33.3–36.7% cover), intermediate on the 25% single-tree selection units (21.7–24.9% cover), and lightest on the patch-cut units (12.3–16.3% cover).

However, almost all of the slash cover on the patch-cut units was concentrated in the patch-cut openings, where slash loadings were similar to those of the clearcut units.

In contrast to the helicopter-yarded units, the conventional (grapple-yarded) unit had substantially higher levels of mineral soil exposure as a result of falling and yarding (8.0% vs. 0.1–2.4% for the helicopter units), as well as higher levels of slash cover and lower levels of undisturbed forest floor.

Estimated Costs of Helicopter Yarding

Yarding Costs Yarding costs per cubic metre for the Sikorsky S-64E Skycrane are presented for each harvesting treatment in Table 8. These costs are based on an estimated owning and operating cost for the Skycrane of \$6220 per flight-hour (see “Study Methods” for costing assumptions). Note that these costs are for the logging helicopter only, and do not include costs for falling, rigging, choker-retrieval, support helicopter, and chokers. The estimated yarding costs are calculated directly from the Skycrane’s yarding productivities (Table 5), so the explanations for relative differences and trends in cost per cubic metre are the same as for yarding productivities and reflect the effects of differing average turn times and turn weights for the various treatment units.

TABLE 7 *Ground surface condition following helicopter yarding*

Treatment unit	Ground surface condition					Total (%)
	Undisturbed (%)	Preharvest exposed mineral soil (%)	Disturbance resulting from logging (%)	Slash (%)	Other (%)	
Gregory Creek						
15% Single-tree selection	82.3	4.2	0.7	4.8	8.0	100.0
25% single-tree selection	65.8	2.6	1.1	24.9	5.6	100.0
25% Patch cut	80.5	1.7	0.4	12.4	5.0	100.0
50% Patch cut	80.0	1.8	1.1	12.3	4.8	100.0
Clearcut	57.2	1.1	<0.1	36.7	5.0	100.0
Hangover Creek						
25% Single-tree selection	60.8	3.6	2.4	21.7	11.4	100.0
25% Patch cut	75.6	3.0	0.5	12.5	8.5	100.0
50% Patch cut	67.4	3.9	1.6	16.3	10.7	100.0
Clearcut	56.5	0.9	0.9	33.3	8.3	100.0
Conventional yarding						
Clearcut	35.6	1.0	8.0	43.5	11.9	100.0

TABLE 8 *Yarding cost per cubic metre for the Sikorsky S-64E Skycrane (yarding phase only)*

Treatment unit	Hangover Creek		Gregory Creek	
	Yarding cost (\$/m ³)	Change (%)	Yarding cost (\$/m ³)	Change (%)
Clearcut	36.91	–	33.28	–
50% Patch cut	36.14	-2.1	32.92	-1.1
25% Patch cut	37.09	+0.5	34.64	+4.1
25% Single-tree selection	41.21	+11.6	37.08	+11.4
15% Single-tree selection	n/a	n/a	40.86	+22.8

Estimated Costs of Helicopter-logging for Gregory Creek To illustrate the typical magnitude of helicopter-logging costs, Table 9 shows preliminary cost estimates for Gregory Creek by treatment unit, for the complete helicopter-logging system used in this study. For the purposes of this example, costs per cubic metre for the rigging, choker retrieval, support helicopter, and choker categories are the average costs over the entire study period and are assumed to be the same for all harvesting treatments. The falling costs were derived using the following estimates of daily production (developed from

discussions with fallers): 120 m³ per shift in clearcuts; 100 m³ per shift in patch-cuts; and 85 m³ per shift in single-tree selection cuts. Falling costs also include the cost of helicopter transport to and from the falling sites, including standby time for the period of falling activity before the arrival of the rest of the helicopter-logging operation.

Under these assumptions, overall costs of falling and helicopter yarding are lowest for the clearcut (\$51.69/m³), intermediate for the patch cuts (\$51.99–\$53.71/m³), and highest for the single-tree selection cuts (\$56.84–\$60.62/m³). For the 50%

TABLE 9 Combined falling and yarding costs per cubic metre for the Gregory Creek study site (excludes loading and hauling phases)

Cost centre	Treatment unit				
	Clearcut (\$/m ³)	50% patch cut (\$/m ³)	25% patch cut 25% Patch cut (\$/m ³)	25% single-tree selection (\$/m ³)	15% single-tree selection (\$/m ³)
Helicopter yarding	33.28	32.92	34.64	37.08	40.68
Falling	5.86	6.52	6.52	7.21	7.21
Choker retrieval	4.10	4.10	4.10	4.10	4.10
Rigging	5.20	5.20	5.20	5.20	5.20
Chokers	0.84	0.84	0.84	0.84	0.84
Support helicopter	2.41	2.41	2.41	2.41	2.41
Total cost	51.69	51.99	53.71	56.84	60.62

patch-cut unit, the slight reduction in helicopter yarding cost partially offsets the higher falling cost, resulting in a cost per cubic metre that is only marginally higher than for the clearcut. For the 25% patch-cut unit, modest increases in both helicopter yarding and falling result in an overall cost increase of about 4%. Because many of the patches in the 50% patch-cut unit opened onto the clearcut, this unit is not considered representative for patch-cutting in general; the results for the 25% patch-cut unit are probably more representative. Overall costs for the 25% single-tree selection unit are about 10% higher than for the clearcut, while costs for the 15% single-tree selection unit are about 17% higher. These cost increases are probably realistic and may be slightly conservative.

Summary and Conclusions

In 1992, the Fish/Forestry Interaction Program conducted a helicopter-logging trial on two sites in Rennell Sound on the Queen Charlotte Islands. The goal of the trial was to evaluate the potential of using helicopters to selectively harvest timber from steep, potentially unstable slopes where conventional clearcutting and cable yarding operations were not permitted. Harvesting treatments common to both sites included clearcuts, 0.2-ha patch cuts at two removal levels (25% and 50%), and a single-tree selection cut with 25% removal by basal area. A 15% single-tree selection cut for helicopter logging and a

clearcut for conventional grapple-yarding were added to one of the sites. As part of this trial, FERIC studied the operational and economic feasibility of helicopter-logging on difficult terrain.

A helicopter-logging company with experience in partial-cutting operations in similar stands performed the logging operation. The two study sites were logged between June and November by a Sikorsky S-64E Skycrane with a rated lift capacity of 9081 kg. Approximately 17 500 m³ of wood was harvested from each site. FERIC timed more than 80% of the helicopter's turns and used data from the helicopter's cycle records and scale summaries to analyze the effects of clearcuts, patch-cuts, and single-tree selection cuts on the helicopter's productivity and cost.

Relative to clearcuts, average turn times were unchanged in the 50% patch cuts, and increased 3–6% in 25% patch-cuts, 11% in 25% single-tree selection cuts, and 13% in 15% single-tree selection cuts. Turn times increased in patch cuts because of the need to lift turns above the level of surrounding trees, while in single-tree selection cuts more time was required to sight the hooktender, lower the hook, and set and extract the turn from within standing timber. Average turn weights were very similar for all harvesting treatments except the lightest single-tree removal level, increasing slightly (relative to the clearcuts) in the 50% and 25% patch cuts and decreasing marginally in the 25% single-tree selection units. In the 15% single-tree selection

cut, turn weights decreased 7.4% compared to the clearcut. Trends and relative differences in turn times and weights for the different harvesting treatments were very consistent both between and within study sites. The consistency of the results is attributed to the experience of the rigging crews and helicopter pilots in partial-cutting operations in similar stands.

The combined effects of turn time and turn weight on yarding productivity for the Skycrane were increases of 1.1–2.1% for 50% patch cuts, and decreases of 0.5–3.9% for 25% patch cuts, 10.2–10.4% for 25% single-tree selection cuts, and 18.5% for the 15% single-tree selection cut. Relative to clearcuts, therefore, slight to moderate reductions in yarding productivity and corresponding increases in costs can probably be expected with the use of small, scattered patch cuts, while the use of single-tree selection cuts will result in larger productivity decreases and cost increases.

Damage to residual trees in the form of scars of any size was highest in the 25% single-tree selection units, intermediate in the 50% patch-cut units, and lowest in the 25% patch-cut units. Scarring distributions varied between treatment units as well. Scars were uniformly distributed in the single-tree selection units but concentrated around openings, especially on the lower edges, in the patch-cut units. However, the frequency of large scars (>900 cm²) was relatively constant for all treatment units, with 1.7–4.2% of residual trees affected. Disturbance to the forest floor, as expressed by exposed mineral soil, ranged from <0.1 to 2.4% on the helicopter-yarded units, while 57–82% remained undisturbed and slash covered 12–37%.

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Ten Years of Watershed Restoration in Deer Creek, Northwest Cascades of Washington State

JAMES E. DOYLE, GRETA MOVASSAGHI, AND ROGER NICHOLS

Introduction

A land ethic, then, reflects the existence of an ecological conscience, and this in turn reflects a conviction of individual responsibility for the health of the land. Health is the capacity of the land for self-renewal. Conservation is our effort to understand and preserve this capacity.

Aldo Leopold, Sand County Almanac, 1949

Over the past 2 years, watershed restoration has been one of the most popular environmental bandwagons flowing from watershed to watershed along the west coast of the United States and Canada. From British Columbia to northern California and to the east into the watersheds of the Southwest and Intermountain regions, governments, landowners, and public groups have been coming together and marshalling resources to make watershed restoration an ecologically and sustainably successful program. Expectations naturally are running high and much is at stake.

Up and down the West Coast, salmon and sea-run trout populations are in a dramatic, if not drastic, decline due in part to the deteriorating habitat conditions of coastal watersheds. As a result of these declines, for the past 2 years there has been a total salmon fishing closure along the coast of Washington, Oregon, and northern California. This translates into substantial economic losses to the commercial and recreational sport fishery. In 1988, these fishing industries generated about \$1.2 billion and supported up to 60 000 person-years of employment annually (Doppelt 1994). Currently, four anadromous fish stocks—Redfish Lake sockeye salmon (*Oncorhynchus nerka*), Snake River spring/summer and fall chinook (*O. tshawytscha*), and Sacramento River winter chinook salmon—are protected under the Endangered Species Act and numerous petitions for other anadromous fish stocks are being reviewed, including a coast-wide

petition for coho salmon (*O. kisutch*) and steelhead (*O. malma*). Such declines have forced management agencies to immediately begin to develop programs to help protect and restore these highly valued stocks and populations.

Along with the enthusiasm and positive energy for such a program comes apprehension and concern. Resource restoration at the watershed scale raises a plethora of questions: What is watershed restoration? And why, where, when, and how can it be planned and implemented?

Watershed restoration became an institutionalized federal program following the historic Forest Conference held in Portland, Oregon, April 1993, when President Clinton created three interagency working groups: the Forest Ecosystem Management Assessment Team (FEMAT), the Labor and Community Assessment Team, and the Agency Coordination Team. These groups produced a report, Forest Ecosystem Management: An Ecological, Economic, and Social Assessment. That report became the basis for the Record of Decision (ROD) and the Environmental Impact Statement (EIS) for Management of Habitat for Late-Successional and Old-Growth Forest Related Species Within the Range of the Northern Spotted Owl, made final in February 1994. President Clinton announced his proposed “Forest Plan for a Sustainable Economy and a Sustainable Environment” on July 1, 1994. That plan consisted of new strategies for forest ecosystem management, economic development, and agency coordination (FEMAT 1993).

A major part of this President’s Forest Ecosystem Plan is a section called the Aquatic Conservation Strategy. This strategy was developed to restore and maintain the ecological health of watersheds and aquatic ecosystems contained within them on public lands. The strategy was developed to protect salmon and steelhead habitat on federal lands managed by the U.S. Forest Service and the Bureau of Land

Management within the range of the Pacific Ocean anadromy (USDA & USDI 1994). One of the four major components of this aquatic conservation strategy is watershed restoration.

The legitimate object of government is to do for a community of people whatever they need to have done, but cannot do at all in their separate and individual capacities.

Abraham Lincoln

Identifying, developing, planning, and implementing an ecological and sustainable restoration program at a watershed or river basin scale requires both strategies and tactics. In watershed restoration it is important to keep in mind the differences in meaning between these terms. “Strategy” refers to the comprehensive, large-scale marshalling and allocation of resources; “tactics” refers to local, immediate, short-term activities (Frissell 1993). It is crucial in watershed restoration that tactics be defined and directed by an overall strategy and that the overall strategy be shaped by the limitations of the tactical capabilities. Ten years of watershed restoration efforts in Deer Creek have been carried out using this approach.

Watershed Overview

Deer Creek is a major tributary of the North Fork Stillaguamish River located in the western Cascade Mountains of Washington State. The watershed drains approximately 173 km (67 mi.) and is located north and northeast of the community of Oso, Washington, where Deer Creek enters the North Fork Stillaguamish River (Fig. 1). The geology is composed of volcanic and metamorphic rocks of the North Cascades system and the Eocene Chucknut Formation (Brown et al. 1992). Extensive glaciation occurred during the Pleistocene, leaving a veneer of till covering the upper watershed and a thick accumulation of up to 350 m (1148 ft) of glacial-lacustrine sediment, outwash gravel, and terrace deposits (Ryan et al. 1984). The present stream network was created by stream channel incision into these deep-seated glacial sediments (Eide 1990).

Sediments and landforms created by the last glaciation have shaped the watershed’s morphology and sediment production. About 3 km (1.9 mi.) of Deer Creek flows across the valley floor of the North Fork Stillaguamish River. The creek then rises 280 m

(978 ft) in about 11 km (6.8 mi.) through a canyon cut 60–180 m (197–590 ft) deep into glacial sediments and bedrock. This canyon area and the surrounding uplands account for one-fourth of the watershed. Upstream of the canyon area, the creek flows from a broad ice-sculpted valley having steep valley walls and tributaries. Glacial sediments in the steep lower slopes of the valley and its tributaries are prone to mass wasting and erosion (Collins et al. 1995). The mainstem of Deer Creek totals 39 km (24 mi.), with an elevation extending from 60 m (200 ft) at the mouth to 1600 m (4000 ft) to the headwaters. Major tributaries (Little Deer, Higgins, and Rick Creek) consist of another 40 km (25 mi.) of stream channel.

The watershed’s climate is generally moist with average annual precipitation ranging from around 2000 mm (79 in.) in the lower part of the watershed to 2800 mm (110 in.) or more at the higher elevations (Cummins et al. 1975). Precipitation occurs throughout the year with 75% falling between October and March.

The wide elevation range (60–1600 m) within the watershed exerts a strong influence on whether winter precipitation occurs as rain or snow. In the northwest Washington Cascades foothills, lower elevations (<490 m or 1600 ft) receive predominantly rainfall, while higher elevations (>900 m or 2900 ft) receive large amounts of snow and accumulate snowpacks of several feet or more. Middle watershed elevations are transitional; snow may build up and melt several times during a winter. Annual peak streamflows in Deer Creek generally occur between November and February (Williams et al. 1975), following heavy rainstorms that are often accompanied by snowmelt in much of this transitional elevational range, a process called rain-on-snow (Collins et al. 1995). Most of the watershed is classified as a temperate evergreen forest with a western hemlock and silver fir vegetation series dominating. Within these two vegetation series, dominant tree species include western hemlock, silver fir, western redcedar, and Douglas-fir (Henderson et al. 1992).

Approximately two-thirds of Deer Creek’s stream channel network is accessible to anadromous fish. Historically it contained high quality habitat ideally suited for adult holding and spawning and juvenile rearing. Based on historical accounts (Smith and Anderson 1921, cited in Haig-Brown 1946; Gray 1928; DeShazo 1974) the habitat consisted of a

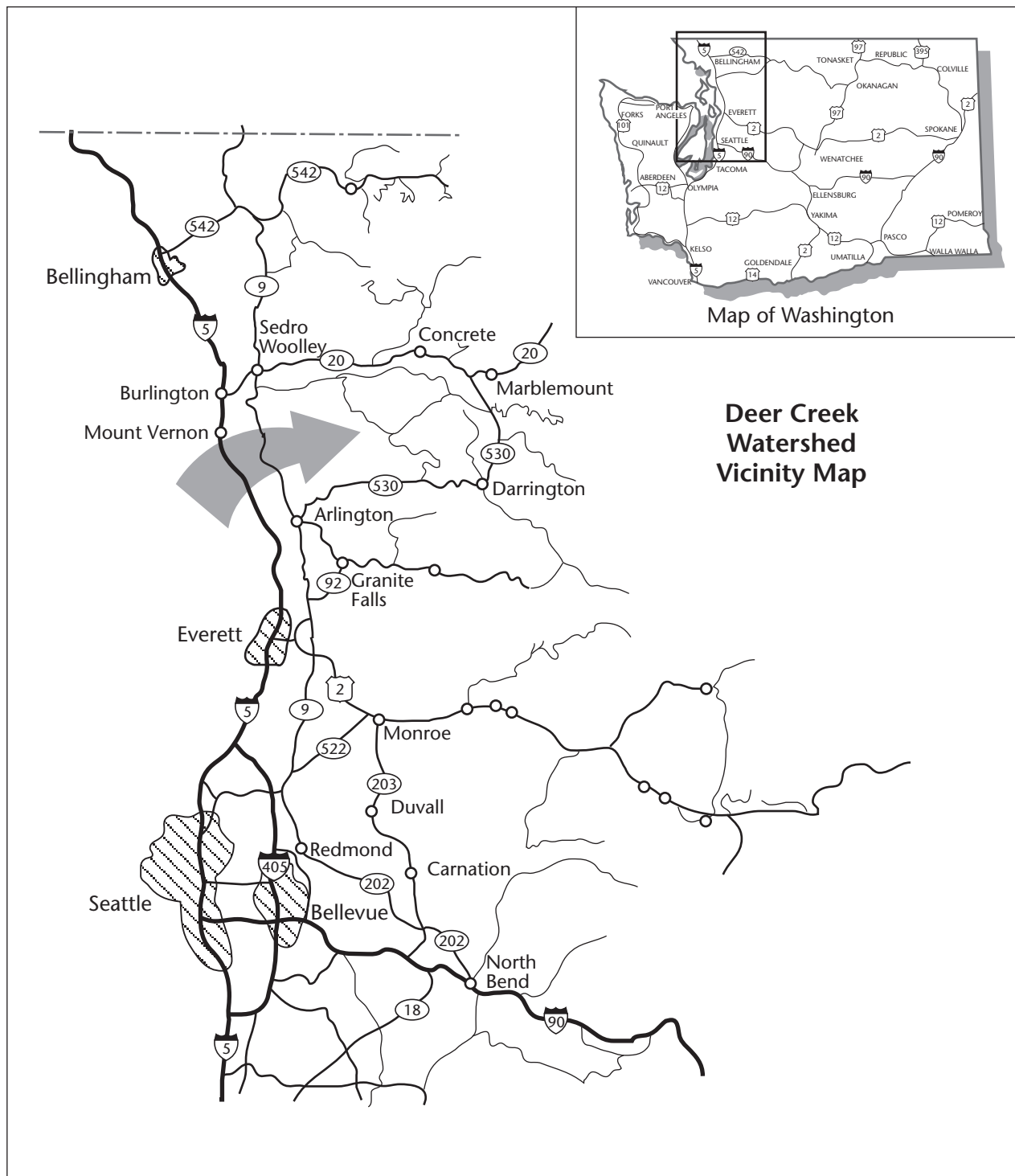


FIGURE 1 Location of Deer Creek Watershed, North Cascades Mountain Range, Western Washington.

variety of riffles, high quality pools formed by a multitude of huge boulders with deep, clear cold water. There was also an abundance of clean spawning gravel areas where fish could be observed. Large woody debris and large boulder complexes throughout the watershed created a foundation for these ideal habitat conditions. As well, Deer Creek supported healthy runs of summer-run steelhead (*Oncorhynchus mykiss*), coho salmon (*O. kisutch*), and Dolly Varden char (*Salvelinus malmo*) and resident rainbow trout in the upper watershed (Puget Sound Task Force 1970). Winter-run steelhead (*O. mykiss*), sea-run cutthroat trout (*O. clarki*), chinook salmon (*O. tshawytscha*), chum salmon (*O. keta*), and pink salmon (*O. gorbuscha*) have used the first 2.5 km (1.6 mi.) of Deer Creek (Puget Sound Task Force 1970; Williams et al. 1975).

The upper half of the watershed is National Forest land managed by the Mt. Baker Snoqualmie National Forest and the lower half is state and private land managed totally for timber production. Management of other forest resources such as salmon and trout in the watershed is the responsibility of the Washington State Department of Fish and Wildlife and two Puget Sound Treaty Indian Tribes (Tulalip and Stillaguamish). In the upper watershed, the U.S. Forest Service shares this resource management responsibility with the state and the tribes, as well as managing all the other forest resources and their associated uses.

Evolution of Watershed Restoration in Deer Creek

Early years (1920–1950): Significance of Watershed Resources It was the annual migration of summer-run steelhead that brought worldwide fame to Deer Creek. In 1918, while passing through Seattle on his way to Campbell River in British Columbia to fish for chinook (tyee) salmon, the famous Western novelist, Zane Gray, caught his first summer-run steelhead on a fly. In his famous *Tales of Fresh Water Fishing* (1928) Gray wrote:

“At last we descended to a point where from under giant cedars, we could look down upon Deer Creek. A beautiful green-and-white stream, shining here, dark and gleaming there, wound through a steep-walled canyon. It was worth working for. What struck me at once was the wonderful transparency of the water and the multitude of boulders, some of

them huge. Deer Creek was the most beautiful trout water I had ever seen. Clear as crystal, cold as ice, it spoke eloquently of the pure springs of the mountain fastness.”

His second day on the stream, Gray hooked the first steelhead of his life and it was the beginning of a long acquaintance with steelhead that later would take him to the Rogue River in Oregon, which he made famous with his writing (Raymond 1985).

Later in 1927, another famous outdoor writer, Roderick Haig-Brown caught his first steelhead in Deer Creek. He wrote, “The creek was beautiful, clear, bright and fast tumbled on rocks and gravel bars.” After his Deer Creek experience, Brown wrote for many years in great admiration of these great sea-going trout (Raymond 1985).

Notable Northwest steelhead writers and authors such as Enos Bradner, Ken McLeod, Steve Raymond, and Bob Arnold have followed Gray and Haig-Brown in recent years to chronicle the rich steelhead fishing history of Deer Creek.

In 1937, the Washington State Game Commission closed Deer Creek to all fishing to protect and maintain the natural production of steelhead within the watershed and, in 1943, designated fly fishing only in the North Fork Stillaguamish, downstream from Deer Creek. This probably was the first time ever a western river was restricted to fly-fishing (Raymond 1985).

According to the historical records, the steelhead run in Deer Creek was one of largest native runs of summer-run steelhead in Puget Sound, if not in the whole State of Washington (Puget Sound Task Force 1970). “No one knows the original size of this great native run, but there is little doubt that it was one of the finest summer runs in the world, perhaps the finest of them all,” wrote Steve Raymond in his *Year of the Angler* (1973).

By the early 1900s, the valley of the North Fork Stillaguamish had been logged and undergone other land uses. The valley had been cleared of timber and planted with crops and orchards. Railroad development pushed the logging operations farther up the river valley into watersheds like Deer Creek. Early logging activity in Deer Creek was restricted to lower elevation areas below the canyon section at stream mile 1.6. Timber harvesting operations probably had little or no significant impacts on the watershed (Collins et al. 1995).

Middle Years (1950–1980): Evolution of a Watershed Restoration Philosophy In the 1950s, the demand for Pacific Northwest lumber and wood increased as the country began to recover and rebuild from its involvement in World War II. Logging and the associated activities (road building and slash burning) in Deer Creek pushed farther and farther up into the watershed. Full-scale clearcut timber harvesting operations were carried out by all three landowners in the watershed during this 30-year period. Little or no documented, co-ordinated, or integrated timber harvesting plans or operations occurred among the three landowners during this time.

Although logging began within the watershed in the early 1920s, the scale of this activity was small during the next 3 decades; before 1950, most of the watershed was well vegetated by a mature conifer forest. This forest cover acted to moderate the impacts of large and frequent storm events and to hold the hillslopes and streambanks in place. The present Deer Creek channel system was created over time by channel incision into the thick glacial sediments of the valley floor (Eide 1990). Because of this, Deer Creek has always been subjected to a certain level of hillslope erosion and landsliding. Collins et al. (1995), in their watershed assessment, documented a cluster of larger-than-average floods between 1950 and 1960, which apparently eroded channel margins throughout the watershed. The effects of these events were also significantly influenced along the middle mainstem of Deer Creek by the effects of clearcutting the riparian areas in the 1940s and 1950s. This assessment estimated that by 1964 there had been a 60% increase in overall channel width from 1942. Channel bank erosion and aggradation of the mainstem of Deer Creek and in the tributary, Little Deer Creek, may also have been aggravated and prolonged by landslides from logging units and roads. Erosion, flooding, riparian logging, and channel widening and aggradation in the 1940s to early 1960s diminished the quality and quantity of salmonid habitat (Collins et al. 1995). Even during these years, fishermen themselves often mentioned heavy sedimentation in Deer Creek after major storm events (Raymond 1973), however, the magnitude of these events and their frequency were always low enough to enable the stream to recover and retain good to excellent channel and habitat conditions for summer steelhead. As of 1970, Deer Creek was still believed to be producing summer-

run steelhead at or near its natural capacity (Puget Sound Task Force 1970).

The riparian area along the main channel in the lower watershed was mostly all logged off by the mid-1970s. After harvesting, the landowner, Georgia Pacific, aerial-sprayed these riparian corridors for alder and willow control. The control agent was 2-4-D, with an application rate of 1 lb acid per 10 gal water per acre (DeShazo 1974). This riparian vegetation control operation was conducted by Georgia Pacific over the 1970s and into the early 1980s. Not documented is whether the U.S. Forest Service used similar vegetation control tactics on its riparian harvested units during this period. No known monitoring of this program was documented or published by the landowner.

The watershed experienced its one major forest fire in the summer of 1951, when approximately 2600 acres were burned.

The first recorded observations of summer-run steelhead escapement in Deer Creek were made in 1955 by Washington State Department of Game biologists, and were conducted again from 1956 to 1958 and in 1961 (DeShazo 1974). During the summers of 1970–1973, Washington Department of Game surveys were conducted in Deer Creek having two objectives: 1) to compare escapement of adult summer-run steelhead during the survey period to past observations, in an attempt to determine if there was a decline; and 2) to identify factors that could have already (or in future) adversely affect the summer-run population in the watershed (DeShazo 1974). The 4-year project concluded that this was a unique race of native summer-run steelhead, and probably the only remaining viable population of summer-run native steelhead in Puget Sound. During the 4 years of the inventory, the field biologists electrofishing Deer Creek had never seen a stream with the quality and quantity of steelhead juveniles as found in Deer Creek. The project concluded that every management effort should be made to protect and enhance this unique run of fish (DeShazo 1974).

Recent Years (1980–1990s): Justification for Watershed Restoration The U.S. Forest Service began to conduct stream and fish habitat surveys in Deer Creek in 1979 and early 1980s. Between 1979 and 1982, the mainstem of Deer Creek and its two major tributaries, Little Deer and Higgins Creek,

had become more unstable, with channel width to depth ratios increasing to 25 or greater in the Deer Creek mainstem and to a lesser extent in the tributaries (J.E. Doyle, Mt. Baker Snoqualmie N.F., unpublished data, 1983). These stream surveys also estimated that the percent of the mainstem channel reaches having fair to good spawning habitat had decreased from 1979 to 1982. The rearing habitat within these reaches was rated fair to good during this period, but the transitory nature and the reduction of many in-channel rearing habitat features was also noted, including pool quantity and quality (cover and depth) and the number and distribution of large woody debris jams and accumulations. Monitoring of summer low-flow water temperatures within the Deer Creek watershed also showed an increasingly alarming trend in the daily maximum temperature readings from the upper watershed areas to the mouth of the creek.

From 1920 to 1990, the total amount of forest clearcut harvested by the three landowners in Deer Creek was 25 730 acres. Over this 70-year period, 48% of the mature forest in this watershed had been harvested: on Washington State land, administered by the Department of Natural Resources, 91% had been cut; on private land owned by Georgia Pacific and later sold to John Hancock Insurance Company 88% was cut; and on national forest land, administered by the Mt. Baker Snoqualmie National Forest, 37%.

Common logging road construction practices before the mid 1970s in Deer Creek and other Western Cascades watersheds resulted in the material being excavated from the roadbed prism, to be used as fill material within the prism located usually on steep sideslopes. Much of this material was organic debris such as stumps and logs, and was subject to decomposition after a period of years. Over time, many of these road fills became saturated with water, eventually failing and creating or contributing to landsliding events within the watershed. In addition, before the 1970s, roads were constructed at constant grades, and were both undersized and deficient in number. As a result, the natural drainage processes (surface and subsurface) of the sideslopes where these roads were located was disrupted and significantly modified. These conditions triggered or contributed to numerous landslides, in the form of debris torrents, into numerous smaller tributaries. Much of this material made its way into the

mainstem channels of Deer, Little Deer, and Higgins creeks (Mt. Baker Snoqualmie N.F. 1990).

The combination of concentrated timber harvesting, road building on steep unstable sideslopes, and numerous flood events in Deer Creek over 70 years has impacted fish habitat in Deer Creek. Eide (1990) constructed a 48-year sediment budget for Deer Creek, spanning from 1942 to 1989, and showed that the increase in frequency and magnitude of disturbance events and associated sediment load to the stream was roughly proportional to the area logged during that period (Fig. 2). Collins et al. (1995) looked at the relationship between forestry activities (from 1942 to 1991) and landslide occurrence and frequency. They found there was a significant empirical association between forest practices and landsliding. Of the 240 landslides observed from the historical aerial photo files, 20% originated from areas with mature forest, 60% from clearcut harvest units, and another 20% from forest roads. These impacts led to an overwidened mainstem channel, lost or degraded rearing pools, deposition of sediments and fines in spawning gravel areas, higher stream temperatures during the summer low-flow season, and reduced benthic organism production. This was suspected to be affecting the freshwater life history stages of all salmonids in Deer Creek (J.E. Doyle, Mt. Baker Snoqualmie N.F., unpublished data 1983).

Then, in early 1984, an unusually large landslide in the DeForest Creek, located in the middle of the watershed on Department of Natural Resources managed land, began to move significant amounts of material (sediments) into Deer Creek. By 1991, this landslide had contributed 3 million m³ (85 000 ft³) of sediment into lower Deer Creek and the North Fork Stillaguamish River (Eide 1990). To state this sediment load another way, Kennard (1992) estimated that the number of standard-size dump trucks required to hold this volume of sediment would form a bumper-to-bumper line 1700 miles long. About 60% of the sediment was sand and fine gravel that partially filled pools and covered riffles downstream of the slide in the middle and late 1980s. An additional one-third of the sediment was silt and clay that caused Deer Creek and the Stillaguamish National Forest downstream to be highly turbid year-round. This probably caused decreased salmonid fish feeding and invertebrate production (Collins et al. 1995). Another impact due

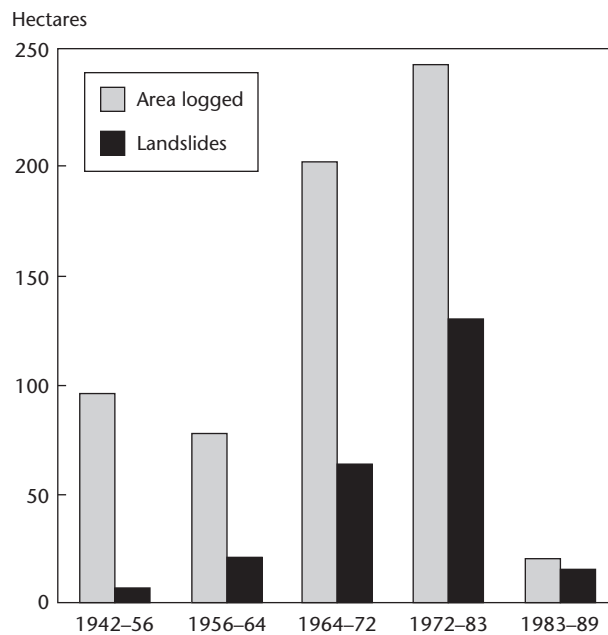


FIGURE 2 Relationship between the number of landslides and the area of Deer Creek logged within a 48-year period (from Eide 1990).

to high turbidity within the Stillaguamish National Forest below Deer Creek was the economic loss to the fishing industry, estimated to be \$3 million per year (Brown et al. 1992).

Watershed Restoration Efforts

Early Watershed Restoration Efforts (1984–1990)

Concerned with the continued decline in the health of the Deer Creek watershed (as indicated by the fish habitat surveys and stream temperature monitoring findings from 1979 to 1982), and with the present and future timber harvesting plans of the three landowners, the fish biologist and a hydrologist from the Mt. Baker Snoqualmie National Forest wrote a briefing report in the summer of 1983, describing the watershed's status. The report called for the U.S. Forest Service managers to develop both an integrated strategy to monitor key watershed parameters, and site-specific management prescriptions to protect and maintain critical watershed features; and to plan an extensive multi-year watershed restoration program. The report emphasized that the U.S. Forest Service take a lead in this watershed strategy on its land and at the same time actively promote a

similar effort by the two other landowners and agency resource managers. Also recognized was the need to coordinate such a strategy and tactics with the various fishery user groups concerned with the existing and future health of the Deer Creek summer-run steelhead (J.E. Doyle, Mt. Baker Snoqualmie N.F., unpublished report 1983).

Other Landowner Restoration Efforts In late 1984, the Department of Natural Resources began initial efforts to control the DeForest Creek landslide. At first several diversion structures and sediment dams were constructed within the slide cavity and along the west bank of Deer Creek. By the spring of 1985, however, the volume of sediment eroding from the slide had overwhelmed the structures and only an occasional remnant gabion and a few sandbags were all that remained. The next effort made was to regrade the slide headscarp in September of 1985. Within 1 month after the project was completed, the regraded soils began to fail and were soon carried from the slide cavity into Deer Creek by groundwater emerging from the slide headscarp. Since 1985, no further management attempts at remediation have been made on the DeForest Creek landslide (GeoEngineers 1992).

Concern over the fate of the Deer Creek fishery values led to the formation of the Deer Creek Group in early 1985. This coalition of landowners, agency and tribal resource managers, and resource user groups adopted a process modelled after that of the Soil Conservation Service's Coordinated Resource Management Plan. One of earliest actions of the group was the development and implementation of a watershed scale inventory and monitoring effort. Each of the landowners agreed to conduct road inventories on their land to determine existing and potential road failure sites and to identify and prescribe road repair or treatments. Resource management agencies and two treaty tribes were assigned various monitoring tasks: fish population (adult escapement and juvenile rearing density), Washington Department of Game; stream temperature monitoring, Tulalips Tribe; fish habitat surveys and channel cross-sections, U.S. Forest Service. This inventory and monitoring was done with no special funds allocated for such an effort. Instead, each landowner and resource manager absorbed the costs on an annual basis. Road inventories were completed by the three landowners by the early 1990s and road

restoration was eventually implemented by all landowners. Monitoring efforts, without stable funding, have diminished since the late 1980s, but water temperature and fish population evaluations have continued on an annual basis.

U.S. Forest Service Restoration Efforts Before any major watershed restoration was implemented by the U.S. Forest Service in Deer Creek, the Mt. Baker Snoqualmie National Forest began to re-evaluate its short- and long-term timber management plans in the watershed. This included the cumulative effects of forest practices on downstream aquatic resources. A modified version of Klock's cumulative effects model (Klock 1982) was applied to a future timber sale planned in the Higgins Creek subwatershed (Pintail Sale), and an existing timber sale (DeForest Bottom Sale). The findings of this cumulative effects analysis demonstrated that, with the number of existing U.S. Forest Service acres already harvested, plus the potential watershed disturbance with planned new harvesting, the impacts (existing and future) to downstream fish habitat below the National Forest boundary would exceed the acceptable threshold.

Because of these findings and the amount of public response to the Pintail Timber Sale Environmental Assessment, the Forest Supervisor chose the "No Action" alternative. Thus, the U.S. Forest Service deferred a planned 115 million bd ft and 16 mi. of new road construction (Mt. Baker Snoqualmie N.F. 1987). In addition, the Forest Supervisor stated that, beginning in late 1984, the U.S. Forest Service would defer all timber harvesting in the watershed until the stream channels and fish habitat conditions recovered to their former "natural conditions." For that time period, this controversial and timber industry-contested decision, validated the restoration planning and implementation that was to follow. With time then set aside for the watershed to begin to naturally heal, the U.S. Forest Service began a decade of watershed restoration in Deer Creek.

Inventories and Assessments

Beginning in 1984, the Mt. Baker Snoqualmie National Forest took the lead in conducting watershed-wide resource inventories and assessments with the following two objectives: 1) to develop a monitoring strategy to assess the overall aquatic health of the watershed (to include what, how, when, and

where to monitor); and 2) to identify and prioritize watershed restoration treatments on National Forest land within the watershed.

Through these assessments and inventories, several major natural upslope and channel physical and biological processes suspected to be influenced by forest management operations and activities were identified:

- Coarse sediment was being deposited in fish-bearing stream channels as a result of the flushing of the smaller, steeper gradient channels. This deposition both filled pools and reduced the channel's capacity to provide quality spawning and rearing habitat.
- Coarse sediment/bedload movement through the entire stream channel network caused extensive channel bank scour and the mobilizing of fine sediments that were transported downstream.
- Increased peak flows associated with rain-on-snow events, coupled with a decreased forest canopy interception, contributed to channel widening.
- Shallow, wide, mainstem channels and the lack of riparian vegetation contributed to increasing water temperatures, with salmonid tolerance limits and state water quality standards being exceeded on some days.

An assumption inherent in these assessments and inventories was that concentrated timber harvesting and associated road building modified the natural hydrologic structure and function, resulting in upslope and channel failure.

These natural processes, and the management operations and activities suspected of altering these processes, were used to determine and identify the appropriate restoration application and treatment. In addition, when road, landslide, and stream channel stability and fish habitat inventories were evaluated and the information synthesized, the following was found:

- Increased landsliding was associated with timber harvesting and road building. Later this finding was documented with Eide's 1990 48-year sediment budget study. He found that 87% of the landslides initiated during 1942–1989 occurred in managed portions of the watershed.
- Most of the sediment produced from hillslopes in the watershed was transported from the smaller, steeper first-order channels, through the

downstream second- and third-order channels, and eventually deposited in the larger, lower gradient fourth-order channels. This was later documented by Eide (1990).

- Most of the roads in the watershed were constructed using sidecast materials on steep slopes before 1970. The rotting of organic matter in these sidecast road fills could lead to road failure.
- Road drainage structures were under-sized and spaced too far apart to handle annual peak runoff, and most were not properly maintained and repaired.
- Some roads in the watershed were completely “abandoned.” These roads received no management action and some were considered “potential triggers” for initiating or contributing to landslides.
- Timber harvesting of the riparian areas reduced the potential for large woody debris recruitment to channels. This also could have inhibited the vegetative stabilization of aggraded gravel bars and the reformation of off-channel habitat (along the lower and third- and fourth-order channels), and reduced the amount of canopy cover over channels, dramatically raising summer low-flow stream temperatures. These suspected impacts were later documented in the watershed assessment done by Collins et al. (1995).
- Timber harvesting practices included large woody debris removal from stream channels as part of most timber yarding operations.
- Stream channel widening may have occurred as a response to riparian timber harvesting and periodic flooding. This was later documented by Collins et al. (1995).
- The quality and quantity of fish has declined as a result of stream channel and riparian forest structure and function changes. This was later documented by Collins et al. (1995).

Based on the findings from these early inventories and assessments, the restoration strategy in the Deer Creek watershed focussed on modifying or altering the sedimentation process. The strategy was to reduce the coarse sediment delivery to the stream channel network and to mechanically stabilize the riparian sideslopes and streambanks. This was intended to lead eventually to riparian area revegetation, stream channel recovery, and fish habitat improvement. This strategy employed two tactical operations:

1. restoration efforts that involved road, upland, and in-channel projects. Initial project emphasis was on the reduction of sedimentation from roads and upslope sources, based on the finding of roads being the major source of sediment to downstream fish-bearing channels. In-channel treatments would follow.
2. restoration efforts that would be carried out over a multi-year period and would cover the entire watershed. Initial restoration would be on sediment reduction and stream channel bank stabilization in the headwater areas of the watershed. Later on, projects would focus on improving the quality of anadromous and resident fish habitat, as well as on the vegetative stabilization of portions of the floodplains and riparian areas. Maintenance and monitoring needs were identified as part of the project cost for each treatment site; this assured proper project implementation, identified any necessary modification following construction, and allowed feedback as to the effectiveness of the restoration design and technique.

The specific restoration objectives for each treatment were:

- road and upslope
 - reduce coarse sediment transport into the larger, lower gradient stream channels;
 - reduce the risk of major landslide failure at as many sites as possible.
- in-channel
 - reduce coarse sediment movement to the stream channel by isolating unstable stream-banks to prevent them being undermined and eroded, and by promoting stream channel downcutting, thereby prompting a return to a natural balance of coarse sediment supply, transport, and deposition;
 - promote stream channel downcutting to encourage formation of more and deeper pools for fish habitat;
 - reduce the chronic fine sediment transport that results from streambank scouring, by isolating active sediment sources from active stream channels;
 - in the short-term, improve fish habitat rearing areas in the larger, lower gradient channels through the placement of in-channel structures.

Treatment Priorities

Prioritization for restoration treatment for each project site was based on factors of accessibility, achievability, cost, and risk of failure. In addition to using the road, landslide, and in-channel inventories to assist in prioritizing project sites, the Forest Service videotaped the watershed during a low elevation helicopter flight in the winter of 1987. The video provided a diagnostic overview of the watershed condition and visually displayed the spatial relationship of the various treatment sites. It also supported the restoration strategy because it showed the relationship between upslope sediment source areas and downstream channel transport and deposition areas.

Project and Program Implementation: Road Treatments Successful implementation of the Deer Creek restoration program required a diverse group of talented individuals working independently on program components and collectively to accomplish group project tasks. Individual champions stepped forward to move both the projects and overall program forward. Individuals who had knowledge of the watershed's major physical and biological processes, and experience with the watershed's changing conditions over time, were vital to the interdisciplinary restoration team. In Deer Creek, such a team was willing to test some unique tools and techniques in order to implement restoration work within the confines of the federal budgeting and planning timeframes.

During field layout, data were collected for preparing contracts, including linear distance information, estimates of sizes and quantities of material, and site surveys for later, more detailed designs. Often treatments were designed and prepared in a different season from the one in which the actual work was performed, complicating project design. This was usually due to administrative or budget-driven constraints. Because of this, contracts typically included a provision for flexibility (e.g., an hourly rate clause) so that adjustments could be made for unforeseen or unknown circumstances.

Some assumptions made in the early years of Deer Creek restoration planning led to conservative treatments. For example, it was assumed that waterbarring would take care of the water and road fill problems of most roads; that dipping road fills

over major road and stream channel crossings would adequately handle water and organic debris passage; and that outslowing would work on any road grade or road fill type. In the initial years (1985–1987), treatments were small scale and involved putting roads into a lower maintenance standard category. Where roads were identified as having a future use, relatively small equipment (a D-4 bulldozer and rubber-tired backhoe) was used to inslope and waterbar them; where they were identified as having no future use, larger excavators and bulldozers were brought in.

Up until the 1990s, most road decommissioning contracts were still on an equipment-with-operator hourly time scale and a contract inspector or representative was on-site during all operations (usually watershed personnel with engineering staff assistance). This type of service contract allowed for a great deal of flexibility in getting the job done. In a service contract, the government rents the equipment and the operator, and assumes all responsibility for the direction and supervision of work.

Recent road treatment restoration has been accomplished through construction contracts with fixed-unit costs for work items detailed by contract drawings and specifications. Most of these contracts are administered by engineers. Watershed and fishery personnel are usually involved at the planning and design stage and, on a more limited basis, during contract administration. This has resulted in some loss of control over the project and the end results. Such large-scale reconstruction projects in Deer Creek were carried out on the permanent road system in the watershed. The work involved the installation of bridges, hardened crossings, and additional larger culverts.

Roads were also reconstructed with unstable road fill replacement and improved ditch line design. Contracts such as these are often high dollar contracts and, because of the narrow operating season, they may take up to 2–3 years to complete.

Road work is now scheduled for completion during late summer, from July to October. Where seasonal timing restrictions are imposed by protection guidelines for federally Threatened and Endangered Species, such as in Deer Creek, contracts have an operating season from early August to October. Additional timing restrictions are applied when salmon and sea-run trout come in to spawn in late summer and daily operations may be suspended

if the weather creates a high forest fire danger. As a result of all of these timing restrictions, road work is sometimes pushed into the late fall or following spring, normally wetter seasons that can lead to undesirable results.

Road management objectives and restoration priorities in the past few years have been addressed through the Forest Service's Access and Travel Management Plan and planning process (ATM). In 1992, the Mt. Baker Snoqualmie National Forest began updating the road management objectives for all road systems, because of declining U.S. Forest Service road construction and reconstruction budgets within the Pacific Northwest. As a planning tool, ATM has given the Forest Service a way to interact with the public on issues and concerns related to the Forest Service's transportation system (roads and trails). Through the identification of current and future access needs from the public, preceded by an analysis (part of watershed analysis) of resource conditions that recommend management actions, individual road management objectives are modified and an overall transportation plan is developed for that area. Since 1992, a number of Forest Service roads have been identified for decommissioning. Final decisions about road treatments usually require an environmental assessment.

Over the past 10 years on National Forest land, 24 km (15.8 mi.) of road have been decommissioned and 93 km (58 mi.) storm-proofed and upgraded.

Project and Program Implementation: Upslope Treatments Several upslope treatment sites were identified from field inventories documenting coarse sediment deposition as a result of road failures. These depositional sites had the potential for delivering large quantities of coarse sediment to downstream, larger, lower gradient channels and eventually to the mainstem of Deer Creek. Some site conditions presented opportunities for coarse sediment storage and stabilization.

The upslope treatment objective was to reduce coarse sediment input into the larger, lower gradient stream channels in Deer Creek. The main technique for doing this was to use sediment fences. In addition to attempting to stabilize the storage of coarse sediment, the source of such sediment was also treated to reduce future sediment deposits. These sediment fences were designed to last long enough

for sediment storage to stabilize, allowing for natural seeding and revegetation to take over and consume the fences.

Fence installations were similar to standard erosion control fence procedures, except that the design was modified because of the coarse nature of the sediment and to accommodate expected high flows. A wire fence was used without filter fabric. In the original installation, the fence was laid out in a U-shape, with the trough intended to be a focal point for streamflows. The materials first used proved to be lightweight, and a year later the fences were rebuilt with heavy-weight materials and supports. Sediment fences were primarily installed in areas of lower gradient, areas where coarse sediment had already been deposited. In these areas, downed large woody debris was already providing a series of check dams to hold back these coarse sediments. The fences were intended to mimic this action.

In 1986 and 1987, these fences were installed at two sites in the watershed, in upper Deer and Little Deer creeks. The fences were relatively simple to build; construction on one site was contracted to a small business using a government purchase order for a fixed sum, and the other site was done by a Federation of Fly Fishermen volunteer group. In both cases, work involved packing materials and equipment in by hand to relatively remote sites. Both projects were closely supervised and administered by watershed personnel. This was important since this technique was new and the design and details of the construction were critical to the success of the project. A total of 12.1 ha (30 acres) of hillslope were treated.

Other labour-intensive vegetative treatments to control or stabilize upslope areas were not identified in these early stages (1985–1990). Based on the results of restoration work completed in the Redwood National Park and of several ranger district trials, a decision was made to limit the use of bioengineering vegetative techniques. Project emphasis in Deer Creek on National Forest land was to stabilize these large waves of moving coarse sediment through the use of heavy duty mechanical control structures (the sediment fences) and then to let natural revegetation take over each site. Bioengineering vegetative treatments were identified for use at other sites within the watershed at a later time.

Project and Program Implementation: In-channel Treatments Inventory and survey results for Deer Creek from 1979 to 1984 indicated that most of the fish habitat was seriously being displaced or degraded because of catastrophic and chronic channel stability problems (Doyle 1984). Specific habitat features noted were high levels of sand and silt, high width-to-depth ratios, and decreasing pool quality and quantity.

In-channel treatments began in 1987 and initially focussed on the upper sections of Deer and Little Deer creeks. The channel was divided into project reaches, with treatment objectives developed for each reach. When channel reaches were selected and prioritized for treatment, the entire stream channel length was considered. This was done to avoid or reduce the chance of affecting the response of channel sections outside the project reach. While budget restrictions made it possible to treat the worst reach sites only and not the entire channel, treatments were carefully planned and designed to result in the desired channel response. In addition, most of these project sites had follow-up maintenance needs identified as a result of the stream channel's response to the addition of these in-channel structures.

The specific in-channel treatment objectives were: 1) to reduce the erosion of channel banks and thereby reduce sediment delivery to the channel; and 2) to promote downcutting through the channel bed of stored sediments. Design factors considered for these in-channel treatments included:

- sources of sediment input to the channel;
- the sediment regime of the stream channel system (zones of aggradation and scour);
- large accumulations of in-channel and adjacent riparian area woody debris;
- location of control elevation points for each project reach;
- location and profile of the original channel.

Treatments were designed to add structural components or roughness elements missing or lacking in the channels and to allow for the channel to adjust to these structures. There was little or no mechanical reshaping or regrading of these channels. Large wood was used as the structure to focus streamflows (stream energy and power) into adjacent or downstream coarse sediment deposits to promote both the channel downcutting and transporting the sediment to downstream storage sites, and the

continued deposition of coarse sediment. In the long term, the design was intended to mechanically stabilize these large deposits of coarse sediments, allowing for natural revegetation to take over. As these channel gravel bars and unstable banks were stabilized, it was expected that vegetation would eventually surpass the in-stream wood in importance for providing channel stability. As the adjacent riparian stand matured, it would gradually supply large wood to the channel and provide the root strength so critical to providing and maintaining channel bank stability.

In Deer Creek, through the various field inventories, surveys, and historical aerial photographic records, it was hypothesized that the natural process of sediment storage and transport had been altered and modified a substantial degree by forest management. Both excess sediment input and a sediment transport deficit existed. The majority of in-channel work involved repositioning and anchoring large woody debris already in the stream channel or lying on the adjacent gravel bars. At first, the in-channel work was done with other Forest and National Park Service crews. Most in-channel projects sites were difficult to access with heavy equipment; tools and equipment had to be portable for distances up to 1 mi. At the remote sites, work crews rigged cables to reposition the large wood. At sites accessible by road, a large bulldozer was used for this task. Large wood was then anchored with either cables or rebar to the large boulders. Most of this work was done by in-house temporary work crews because there were few contractors with this type of experience. Over the past 10 years, approximately 5 km (3 mi.) of stream channel in Little Deer and Upper Deer creeks have received large woody debris placement.

TABLE 1 *Summary of 10 years of watershed restoration in Deer Creek on National Forest lands, 1984–1994*

Restoration treatment	Length	Area
Road decommissioning	24 km (15.8 mi.)	
Road upgrading/ storm-proofing	93 km (58 mi.)	
Hillslope stabilization		12.1 ha (30 acres)
Large woody debris placement in channels	5 km (3.0 mi.)	

Monitoring and Evaluation: The Results

Monitoring and evaluating the results of watershed restoration in Deer Creek requires examination at the project site level, as well as at the watershed scale over a period of years. The watershed-wide approach to monitoring Deer Creek started with the in-channel and fish habitat surveys in 1979 and the early 1980s. In 1984, the interagency effort attempted to evaluate the current conditions at the time and to speculate as to the causes of fish habitat loss or degradation. Some of the physical and biological parameters measured in 1984 continue to be measured on regularly.

The Mt. Baker Snoqualmie National Forest's monitoring efforts to date in Deer Creek have been focussed on the effectiveness of a particular treatment at a specific project site. This focus as a feedback for project maintenance has been essential, and has resulted in modification of existing projects and corrections for future project design. All projects require modifications, particularly in the initial years of a new restoration program, when tools and techniques need to be corrected and calibrated to local site conditions or because of untested treatments. Most types of watershed restoration require periodic, if not annual, maintenance in the years following implementation. The recovery period for a watershed like Deer Creek, especially for channel and fish habitat recovery, is one or more decades. To see or demonstrate effectiveness or success of management-induced restoration, both short- and long-term monitoring is required. Monitoring is also needed by management to show when the most feasible "managed restoration" opportunities have been completed and further restoration should be left to nature.

Efforts of Other Landowners and Management Agencies

In order for restoration treatments to be fully effective in a watershed restoration effort, the restoration strategy and tactical operations and treatments must be applied over the entire watershed. This presents problems when there are multiple landowners in a watershed, each having different forest management philosophies and objectives. Such is the case in Deer Creek, where the lower half of the watershed is owned and managed by the Washington State Department of Natural Resources and a private

timber landowner, while the upper half is National Forest land. Up to 1994, the two lower section landowners did not participate with the U.S. Forest Service in the development and implementation in the Deer Creek watershed restoration program. The reason for this, though not documented, lies probably in the differences in land stewardship, forest land management philosophy, and mandates.

For example, during the 1980s, after field inventory and resource information was assessed and evaluated, the U.S. Forest Service decided to curtail timber harvesting operations at that time and forgo any future timber harvesting operations because of the declining aquatic health of the watershed and the growing demise of the Deer Creek summer-run steelhead. As well, the Forest Service began in 1994 to develop and carry out an ambitious multi-year, comprehensive watershed restoration program on National Forest lands within Deer Creek. The other two landowners took a different approach. After the failed attempt of the Department of Natural Resources to fix the DeForest Creek slide in 1985, timber harvesting continued on state and private lands within the watershed. There was a minor curtailment of timber harvesting on state-owned land, but little or none on the private land. In fact, timber harvesting continues on these lands in the lower portion of the watershed to the present time. Up to this point, neither landowner has developed a similar restoration strategy or co-ordinated restoration efforts with the U.S. Forest Service in Deer Creek.

Collins et al. (1995), in their *Watershed Assessment and Salmonid Habitat Restoration Strategy for Deer Creek, North Cascades of Washington*, recommend in great detail the need for such a multi-landowner watershed restoration program for this watershed. They have shown that a significant amount of landsliding and stream channel impact occurred from roads and timber harvest units in Deer Creek. Of the 175 mi. of road in the watershed, 65 are owned and managed by the state and private landowner. Many of these roads, built before 1956, have failed or will fail in the future. Another 41 mi. of road were built in the lower watershed in the 1950s and 1960s and were "abandoned" before the rules in the 1974 state Forest Practice Act required long-term erosion control measures as part of the timber harvesting operations. Recent inventories (such as that of Zander 1993) have identified the

location and restoration needs of these abandoned roads. Collins et al. (1995) describe and prioritize various road treatments for the entire watershed. This is the initial focus of their restoration strategy for Deer Creek. The second stage of their strategy is to improve certain aspects of the in-channel fish habitat by treating the riparian forests and emphasizing the natural recruitment of large wood.

Linking this new watershed restoration strategy with the 10-year-old U.S. Forest Service program is critical to the further recovery of Deer Creek. To be successful, such a combined effort requires the full participation and commitment of all three land-owners. With the initiation of the 1994 federal and state Watershed Restoration and Jobs-in-the-Woods program, a multi-year, multi-landowner, and agency watershed restoration program in Deer Creek is closer to reality.

Fish and Fish Habitat Monitoring

Since the 1984 watershed-scale interagency monitoring effort in Deer Creek, the Washington Department of Fish and Wildlife has been conducting juvenile salmonid population estimates at seven sites in the watershed. With the use of a three-pass electrofishing method at each site, juvenile fish of all species were captured. The population of each species and age class were estimated and rearing densities were calculated for each species and age class.

From 1984 through 1992, steelhead parr densities declined at the rate of 30–50% per generation. For the first time since the annual juvenile population estimates have been monitored, the juvenile densities for the past 2 years (1993 and 1994) have increased over the juvenile densities estimated in their parent year (Kraemer 1994) (Table 2).

Adult summer-run steelhead abundance is monitored by conducting spawning surveys and estimating the number of adult fish returning to spawn. The preferred method of doing this in Deer Creek is to do a helicopter survey soon after the first fall rains, when the majority of the adult steelhead have moved up into the watershed above the canyon areas at channel mile 8. This type of adult steelhead survey has only been done twice since 1984, because in other years Deer Creek was too turbid and resulted in poor visibility of the channel features from the air or ground. In 1989, 88 adults were observed in the upper watershed above the canyon. In 1994, the same flight was made. Because of the large number of fish in some of the pools, these same areas were revisited with ground surveys a day later. An estimated 460 steelhead adults, 480 coho salmon adults, 50 sockeye salmon adults, and 2 Dolly Varden/bull trout adults were observed in upper Deer Creek. The count of 460 adults was done under ideal conditions and is considered to be as accurate a count as possible of those fish in the pools surveyed (Kraemer 1994).

Population estimates of juvenile salmonids have been made in the same six index areas in the watershed during the summer/fall low-flow period annually since 1984. Three index areas are located in mainstem Deer Creek: one at the mouth of Rick Creek and two in Little Deer Creek. Each year the area sampled in each index was at the same approximate location. A 75–100 m section of stream representative for that sample area is selected. Juvenile fish abundance is estimated using a two- to three-pass removal method. Separate estimates are made for coho, age 0 steelhead, and age 1+ steelhead. Since steelhead juveniles stay 2 years in Deer Creek to rear following fry emergence from the gravel in the early summer, juveniles must survive

TABLE 2 *Average density (fish per m2) of age 1+ steelhead for six index sample sites in the Deer Creek watershed (from Kraemer 1994)*

Year	Brood year 1	Year	Brood year 2	Year	Brood year 3
1984	0.111	1985	0.606	1986	0.165
1987	0.073	1988	0.150	1989	0.102
1990	0.059	1991	0.047	1992	0.071
1993	0.095	1994	0.094		

two winters before outmigrating in spring to saltwater. Because of this 2-year overwintering need, density of age 1+ steelhead juveniles provides the best available measure of the capability and condition of the freshwater habitat in Deer Creek for this fish species (Kraemer 1994).

Since most of the Deer Creek summer-run steelhead population spawns at age 3 after 2 years in freshwater and 1 year at sea, juvenile densities for different brood years provide a measure of the trend in the population. The steelhead population has consisted of 3 brood years since juvenile population estimates began in 1984. As already noted, steelhead age 1+ (parr) densities declined at the rate of 30–50% per generation from 1984 to 1992 (Table 2). The increase in fish densities over the past 2 years (1993 and 1994) is a reversal of the decade-long decline in steelhead juvenile densities. Following the large fall floods of 1990, there appears to have been annual improvements in the available steelhead habitat, according to fishery biologists with decade long experiences in Deer Creek (Kraemer 1994).

Conclusions

A conclusion is a place where you get when you're tired of thinking...

Anonymous

The increase in the number of steelhead summer-run adults from less than 100 in 1989 to more than 460 in 1994 represents a significant increase in the population. This increase is due mainly to the increase in freshwater survival of 1-year-old steelhead juveniles (parr). The adults counted in 1989 were produced from the parr counted in 1987, while the adult fish counted in 1994 were produced from the parr counted in 1992. The density of these 1+ steelhead in 1987 was 0.073 fish/m² and the density in 1992 was 0.071 fish/m². With the 1992 parr densities producing many more adult steelhead than similar parr densities did in the past and the parr densities of both 1993 and 1994 being greater than the densities of their parent year, there are 3 consecutive years of increasing production for steelhead in Deer Creek.

With the improvement of the fish habitat since the 1990 floods, there has been a consistent improvement in steelhead production. It is expected that parr densities measured during 1993 and 1994 will produce adult-run sizes of about 500 wild

steelhead over the next several years. If the trend in improving habitat and juvenile steelhead carrying capacity continues, run sizes could possibly be larger than 500 adults. Recent parr densities and an adult-run size of 500 steelhead represents a significant improvement from the low steelhead abundance observed in Deer Creek just a few years ago, and are cause for optimism (Kraemer 1994).

This increase in steelhead production from essentially the same parr densities can only be explained by the combination of two factors. One factor is increased overwintering survival from parr to smolt; the other factor is increased survival from smolt to adult. In view of the general poor smolt-to-adult survival of steelhead in the general Puget Sound area for the past few years, and the apparent improvement in the freshwater habitat, it is suspected that most of the increase in adult production can be accounted for by the improved capability of the habitat in Deer Creek to produce juveniles (Kraemer 1994).

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The Fish/Forestry Interaction Program Simulation Model (FFIPS)

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Goals

The Fish/Forestry Interaction Program (FFIP) has completed over a decade of applied research into the effects of climate and logging on fish habitat in coastal watersheds. One of the main objectives of FFIP is to study the extent and severity of mass wasting impacts on fish habitat and populations. As part of this goal, FFIP has begun a process to develop a watershed-scale simulation model (FFIPS) to assess how forest harvesting activities alter mass wasting, erosion, and channel processes, and ultimately fish production. The long-term goal of this project is to synthesize research on fish/forestry interactions into a tool for the integrated management of watersheds throughout coastal British Columbia. This tool would both build on and supplement other tools such as handbooks, training courses, the Forest Practices Code, the watershed assessment procedure (Watershed Restoration Program 1994) and the Gully Assessment Procedure (Hogan et al. 1994).

The short-term objectives of the FFIPS project are to: 1) improve scientific understanding by exploring hypotheses, developing integrated models at a watershed scale, and visualizing the impacts of logging on fish in the context of natural processes and stresses; 2) improve interdisciplinary communication among researchers and managers by forging explicit, quantitative links between management actions, watershed subsystems and “bottom-line” concerns; and 3) identify priorities for research, monitoring and adaptive management. This paper summarizes the work we have completed so far. These systems are very dynamic and very complex. Attempting to build a model teaches us as much about what we don't know as what we do. We hope the lessons we have learned are of general interest to practitioners of the science and art of fish-forest interactions.

Background

The FFIPS model was developed with the expertise and enthusiastic participation of numerous scientists having expertise in fish-forestry interactions (Table 1), many of whom contributed to a series of structured workshops, meetings, programming activities, and reports (Table 2). The project was implemented by a team from ESSA Technologies Ltd., under the direction of Steve Chatwin and Dan Hogan of the Ministry of Forests.

Initial Design Workshop

At the first workshop (December 1991), we developed an initial design with three submodels (Figure 1):

- a forest/upslope model, describing important mass wasting and erosion processes occurring throughout the watershed, except within channels;
- a channel submodel, describing the movements of sediment and large organic debris (LOD) through a river system; and
- a fish submodel, describing the important processes influencing growth and mortality as affected by changes in habitat.

We bounded the problem by determining the critical indicators of system status, the management actions that the model would be able to accommodate, and the key linkages among subsystems. We also determined the spatial and temporal resolution of the model. The spatial horizon is defined by those watersheds on the Queen Charlotte Islands up to 100 km² in size which contain fish populations or have habitat that could potentially support fish populations. Watersheds are subdivided into sub-basins and further subdivided into polygons. These polygons may be terrain units, large gullies, gully reaches, or stream reaches, determined according to commonly used methods (e.g., terrain stability

TABLE 1 *Participants in FFIPS. (*) indicates those participants most closely involved in channel model development*

Name	Affiliation
G.F. Hartman	
Jim Schwab	B.C. Forest Service
Pete Bruce	Consultant
Dave Bustard	Consultant
Derek Tripp	Consultant
J. Charles Scrivener, Al Cowan	Department of Fisheries and Oceans
Allan McDonald	District Habitat Officer
Josh Korman, Werner Kurz, David Marmorek, Ian Parnell, Claire Trethewey, Michael Z'Graggen	ESSA Technologies Ltd.
Pete Lewis, Laurence Turney, Sylvia von Schuckmann, Bruce Ward	B.C. Ministry of Environment, Lands and Parks
Mike Brownlee, Steve Chatwin (*), Terry Dyer, Dan Hogan (*), Terry Rollerson	B.C. Ministry of Forests
Ken Rood (*)	Northwest Hydraulic Consultants Ltd.
Jonathan Fannin Engineering	UBC, Forestry and Civil
Michael Bovis, Michael Church (*)	UBC, Geography
Olaf Niemann	Univ. of Victoria, Geography
Bill Dumont	Western Forest Products

classes or the stream classification system of the B.C. Ministry of Environment, Lands and Parks). The temporal horizon is at least two managed forest rotations (150–200 years) so that 100-year storm events are captured and the ecosystem recovery time period after logging is covered. This time horizon is compatible with harvest planning which is commonly based on 200-year projections. The temporal resolution varies from daily to annual time steps, depending on the component being simulated. Korman et al. (1992) report the results of the workshop in considerable detail, listing data and assumptions identified during the workshop.

TABLE 2 *A brief history of FFIPS*

Date	Event
December 1991	Model design workshop (Mesachie Lake)
August 1992	Korman et al. (1992) distribute detailed model design report. Channel submodel designated as first component to be completed
1993–94	Working prototype of Channel submodel completed (Webb et al. 1994)
May 1994	Prototype model and initial results presented at conference in Queen Charlotte City

Overall Model Structure and Links

Figure 2 illustrates the relationships and linkages between the three submodels. These links were established through a “Looking Outward” exercise in which specialists described the inputs they required from other subsystems. All three submodels have specific needs for climatic inputs. We briefly describe the design of the forest/upslope and fish submodels below; the working channel prototype is discussed below.

The forest/upslope submodel provides information about the input of organic and mineral material from hillslopes into the channel and stream component of the model (primarily LOD and sediment) in response to various forest management activities (Figs. 1 and 2). Information flow from this submodel to the fish submodel includes a description of the stream-side vegetation, from which the fish submodel can draw inferences about water temperatures for simulating fish population dynamics.

The design of the fish submodel incorporates the effects of mass wasting events, erosion, and forest harvesting activities on the freshwater survival and population dynamics of anadromous and resident fish species (Figs. 1 and 2). The fish submodel uses climatic information and output provided by the channel submodel to predict the numbers, sizes, and age structure of juvenile fish populations. Such information could be used in conjunction with current marine survival models to estimate returning adults. The submodel design synthesizes understanding gained in both the Carnation Creek and FFIP research programs.

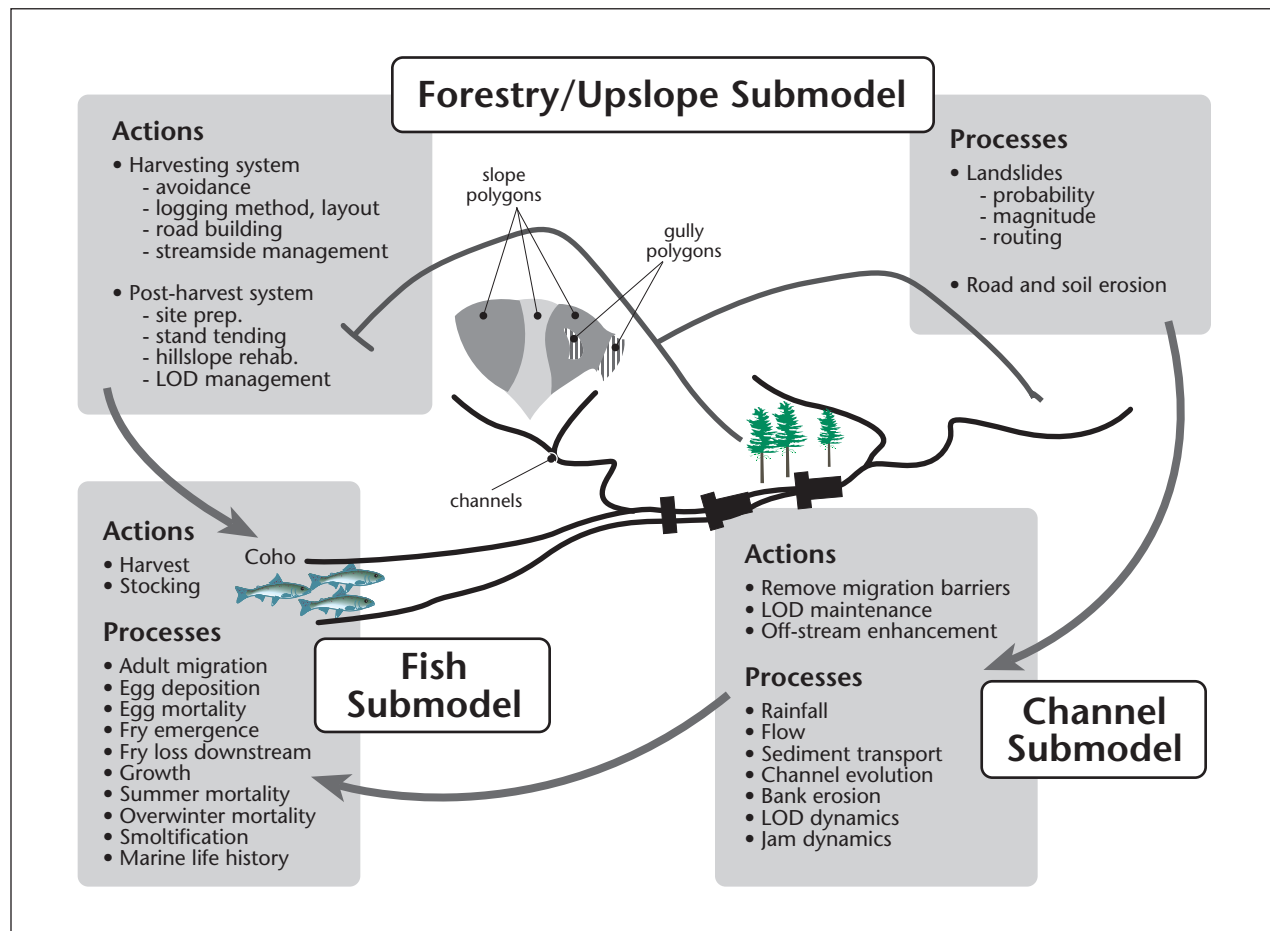


FIGURE 1 Management actions and processes included in the design of the Fish/Forestry Interaction Program Simulation Model (FFIPS).

Research Needs

A useful outcome of the workshop model design process was the identification of future research requirements. We summarize a selection of these research needs below, grouped by the subsystem and submodel to which they apply.

Forest/upslope:

- quantification of the yield of slide material from failures in open slope polygons;
- quantification of sediment storage in various types of gully reaches and the rate at which gullies recharge after debris torrents;
- better understanding of the role of log jams in gullies and the contribution of logging slash to such log jams;

- effects of partial cutting on the rate of landslide initiation;
- modelling rules for predicting slide frequency, behaviour, and size; and
- potential for using derived slope stability classification algorithms in conjunction with the submodels designed at the workshop.

Channel:

- methods of estimating flow at different periods for different parts of a drainage network (i.e., reaches);
- rules for moving LOD and changing the character of log jams;
- location of sediment storage within reaches;
- rules for moving gravel and sand; and
- harmonization of habitat indicators computed in the channel submodel with those required by the fish submodel.

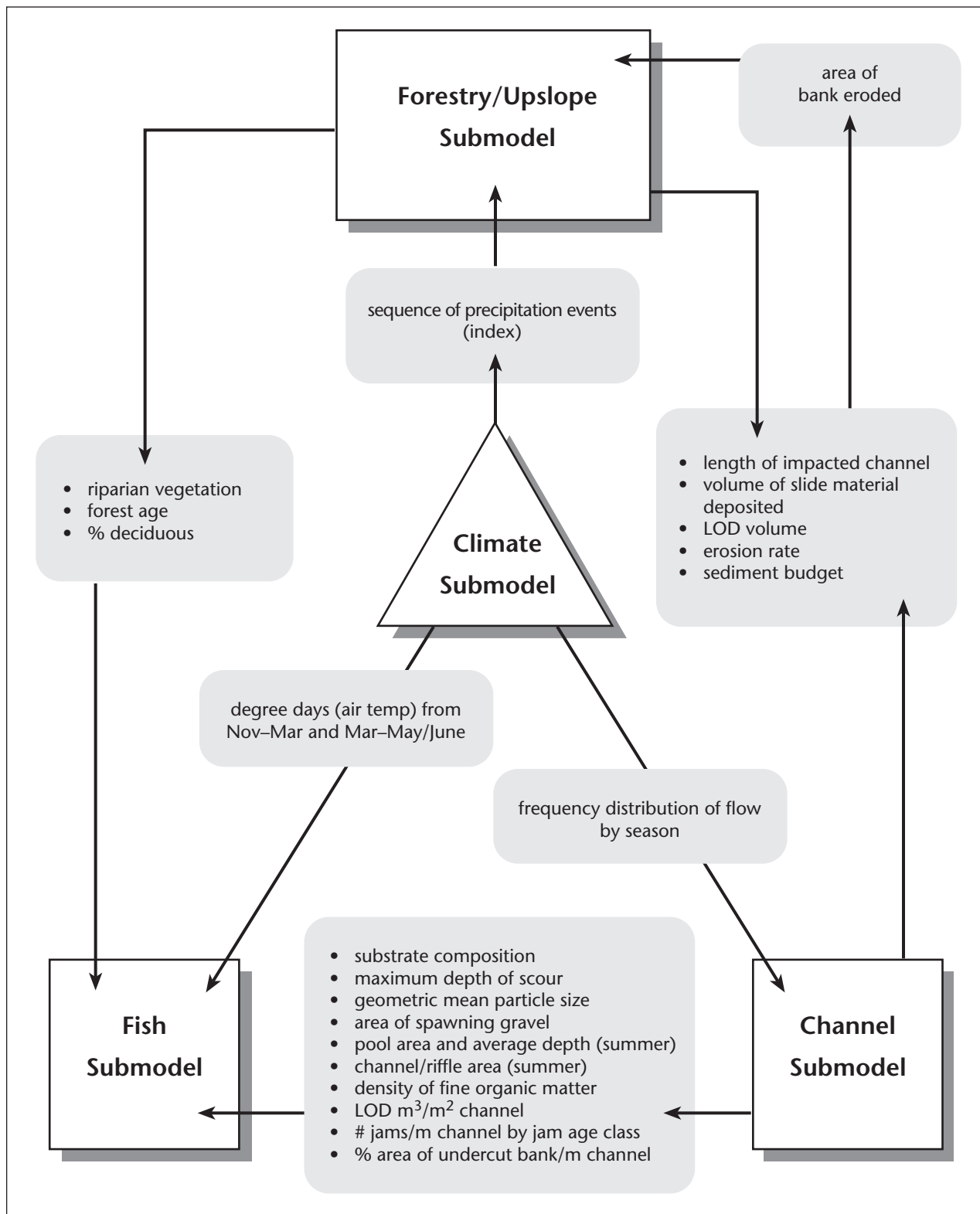


FIGURE 2 Schematic representation of the linkages between the three submodels conceptualized at the December 1991 model design workshop.

Fish:

- sediment aggradation effects on fry entombment, egg desiccation, upstream fish movements, intragravel water temperatures, and emergence times;
- effect of logging on winter thermal processes affecting early emergence;
- reasons for impact of logging on coho 1+ parr growth being different than its impact on younger juveniles;
- suspected increases in the trophic status of Queen Charlotte Islands streams resulting from mass wasting;
- effects of logging on salmonid predators, including birds and aquatic mammals;
- effects of variability in important ocean climate indicators on marine survival;
- review existing models simulating salmonid marine survival and growth;
- negative effects of dewatering on upstream fish migration and pre-spawning survivals;
- estimates of the proportion of resident spawners, steelhead and anadromous cutthroat trout and Dolly Varden which survive spawning (needed to calculate the proportion of repeat spawners in the following year); and
- percent mortality/scour depth curves for steelhead, cutthroat, sockeye, and Dolly Varden based on their respective depths.

Prototype Channel Submodel

Because channel processes have never before been successfully modelled for coastal streams, FFIP scientists agreed that model development should follow a staged process, with the channel model being developed first. There was no point in building the upslope and fish submodels if the channel hurdle could not be cleared. The following sections outline the current channel submodel we developed through intermittent contracts following the model design workshop. A detailed account of this submodel is provided in Webb et al. (1994).

The main objective of our work on the channel submodel has been to develop a working prototype based on the conceptualization developed at the December 1991 workshop. The participating scientists have found the process of model building very useful in testing and revising rules developed at the design workshop. In building the model, we synthesized available knowledge covering the effects of mass

wasting on the dynamics of sediment and LOD in stream systems and completed initial work on integrating the channel model with an upslope component. The model has a very open, modular structure that facilitates exploration of scenarios and hypotheses.

Major Processes and Indicators

We have simulated the following key processes that govern the aggregate behaviour of the stream:

- precipitation and flow estimation, including daily rainfall and flows (see climate submodel, Fig. 2);
- channel structure changes, including changes in stream width and depth over time in response to storm events and sediment movement;
- sediment aggregation and transfer, including short-term processes (bedload movement episodes during storms) and jam storage that generate long-term (50–100 years) patterns of sediment distribution within the watershed;
- LOD, including movement among jams, additions from eroded banks, and loose debris movement during storms;
- log jams, including jam formation and decay rules, debris interception, effects on sediment storage and fish habitat, and distribution of LOD; and
- upslope additions, including addition of sediment and debris caused by slides and streambank erosion.

Since one of the major objectives of FFIPS is to simulate the effects of mass wasting events on fish habitat, we have included the following indicators to track stream characteristics over time:

- sediment storage zones (area, volume of sediment, number, and location)
- channel depth and width
- flow
- loose debris volume and composition in each stream segment
- jam number and characteristics (size, age, and integrity)

We keep track of these data within the model both temporally and spatially. We have not included other habitat indicators such as maximum scour depth, pool/riffle ratios, usable pool area, or gravel quality in the current model. Further discussion with fisheries specialists is required before these criteria can be appropriately quantified, given the structure of the submodel.

The model user interface (programmed in Visual Basic) displays model results in both tabular and graphic form to give the user rapid feedback on model scenario results. For example, the user can compare reaches spatially at a specific point in time, observe trends in a single reach over time, observe changes in jam location and characteristics over time, and summarize data for all jams and reaches.

Spatial Structure

We represent a stream by dividing it into smaller units that differ from one another, but are uniform each within themselves. The primary division is made along reach boundaries (Fig. 3). Each reach is further subdivided into reach segments representing stream zones that may be influenced by the presence of log jams or sediment accumulation (wedges).

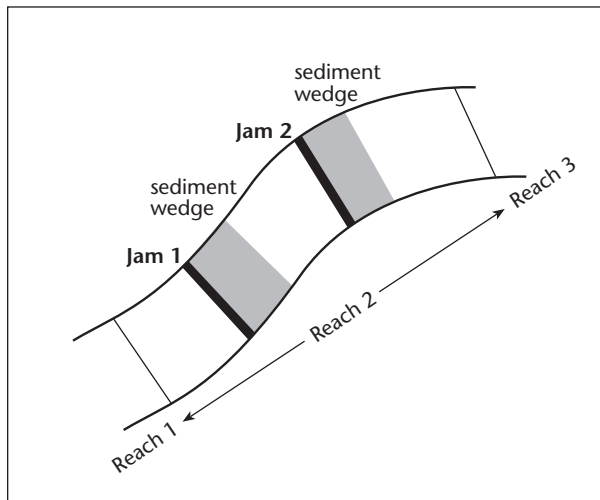


FIGURE 3 General spatial structure of the channel submodel.

Each *reach* has a number of properties that identify its spatial structure and contents: slope, length, channel size, drainage area, and relative position. Some properties are defined beforehand and remain constant throughout the simulation; others are dynamic and updated continuously. Reach boundaries are defined at tributary junctions and between stream regions having marked differences in slope, channel size, or other characteristics. Stream components within a reach are *reach segments*, *LOD*, and *log jams*.

Reach segments are subunits of reaches, used to differentiate sections of a reach influenced by a log jam (the ability to accumulate sediment) from those sections unaffected by a jam. In the simple case of a single jam (Fig. 4), a reach will consist of three reach segments: 1) the segment downstream of the jam; 2) the segment upstream of the jam and incorporating the maximum extent of the sediment wedge; and 3) the segment upstream of the sediment wedge that is unaffected by the jam. If there are no jams present, the reach will not be subdivided into smaller reach segments. The situation becomes more complex when there are multiple jams close together or if a sediment wedge extends across a reach boundary. Reach segments properties include their length, bankfull width, bankfull depth, sediment wedge volume, loose debris, slope, and various location pointers (such as jams within a segment, previous segment, and position).

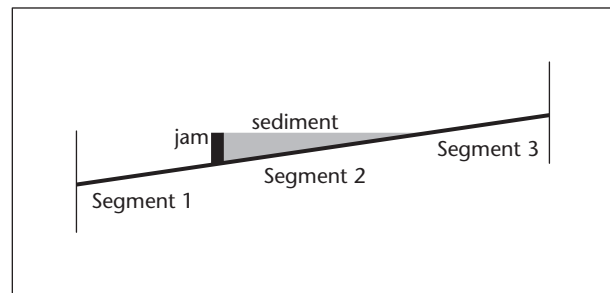


FIGURE 4 Separation of a reach into three reach segments as a result of the presence of a jam.

Large organic debris is woody material deposited in streams through slides or riparian erosion. Continued input of this material is required to ensure the long-term functioning of coastal stream fish populations. It can be either incorporated within log jams or loosely distributed. Loose LOD is free to move downstream if flows are sufficient, is separated into three size categories: small, $<0.1 \text{ m}^3$; 0.1 < medium, $<1 \text{ m}^3$; large, $>1 \text{ m}^3$. Each of these size classes has unique properties such as movement rate and the ability to be intercepted by existing jams. The volume of loose debris within a reach segment is assumed to be evenly distributed.

Log jams are large accumulations of woody debris that have the ability to store sediment and alter downstream sediment transport (Hogan 1989). For this reason, they are important factors influencing

the overall sediment budget of streams. We assume that if no jams are present, sediment will be washed out of the system unless continuous inputs occur. Jams are defined by their: span, height, volume, age, length, integrity, maximum wedge volume, sediment, and location.

Temporal Dynamics

Channel dynamics are complex. Events occur at many different spatial and temporal scales, requiring a number of different time scales in the model. We use an annual time step to model jam and debris dynamics, and finer time steps to simulate precipitation, flow, and the movement of sediment material. Figure 4 shows the sequence of events performed by the model and the time scales at which they operate.

Precipitation: To link precipitation to flow, we incorporated a stochastic rainfall generator in the channel model to predict flow in the various stream reaches (based on Woo, 1972). The precipitation model simulates daily rainfall using probabilities of rainfall occurring on a given day as well as the average quantity of rainfall that falls in a precipitation event. The precipitation model is an important component of the channel submodel because it affects a number of key processes such as upslope sediment input, probabilities of debris torrent or landslide occurrence, and channel flows and velocity. The effect on flow is particularly important because we use flow to drive debris and sediment movement.

Debris dynamics: We simulate organic debris in two forms: that which is loose and that which is associated with jams. Debris can be added laterally from upslope sources and from upstream reaches. It can enter the stream either continuously or as a result of episodic events such as landslides or debris torrents.

We divide the lateral input of LOD into continuous (i.e., bank erosion) and event-driven processes (i.e., slides or torrents). Bank erosion can lead to significant inputs of LOD, as woody material falls into the stream when channel banks collapse. The quantity of LOD entering a stream is a function of the channel confinement, sediment aggregation rate, and density of LOD on the banks. If a reach is highly confined (e.g., a narrow rocky gorge), it is more resistant to bank erosion than if it is unconfined (e.g., floodplain). Accumulation of

sediment in a stream segment can result in accelerated bank erosion as the stream course moves laterally to traverse the sediment wedge. The higher the density of woody debris on the banks, the greater the rate of LOD input.

The size characteristics of woody debris on the banks are also important. These are influenced by the type and age structure of the forest cover. We keep the density and size characteristics of this matter fixed. However, when the channel model is linked to the upslope model, in the future it may be possible to vary these parameters as forest structure changes due to forest succession or logging. Event-driven processes such as landslides and debris torrents can also be major sources of LOD. At present, we have arbitrarily fixed the quantity of debris that is added to the stream during one of these events at 100 m³ per event.

Movement of loose debris: We assume that small debris moves at a fixed annual rate. Medium debris moves only if the peak flow event of the year is greater than the mean annual flood, and then varies with size of the flood event and stream width. We also assume that large debris moves only if the peak annual flow is larger than a 20-year flood event, and then travels a distance dependent on stream width.

Jam dynamics: Many jam characteristics are correlated with the age class of the jam (Hogan 1989). We simulate jam formation, aging and removal using relationships we derived to mimic the observed structure of jams in the field. These are only one set of possible rules that could match field observations. Jams are assumed both to form where a slide event occurs or where a debris torrent stops, and to incorporate all medium and large loose debris associated with the slide and already present in the reach segment. In the absence of loose debris accumulating on a jam, jam characteristics such as span, height, length, and integrity decay at fixed rates. The capacity to store sediment and the ability to intercept woody debris are functions of jam integrity. A jam integrity of 1 indicates a very recently formed jam. Jams are removed when their integrity falls below 0.1, or when debris torrents occur. They intercept loose debris and grow as a function of their integrity and the size of the debris. As material is intercepted, the size, volume, and integrity of the jam increases.

Sediment dynamics: Sediment input occurs through upslope erosion, which is proportional to

rainfall intensity above a threshold of 50 mm per day. We calculate this on a daily time step. During high flow events, when bedload movement occurs, this daily time step is broken down into finer time steps to maintain numerical stability. We determine the potential for bedload movement each day. Once the total potential transport for each reach is estimated, we move sediment down the stream network by examining each reach segment in a downstream sequence. The channel shape is reset after each high flow event. To control the size of the channel, we use a relationship that annually moves the channel shape back towards its equilibrium size.

Debris torrents and slides: These events transport debris from upslope regions to the stream. A debris torrent enters a particular stream reach segment and proceeds downstream, removing jams and moving debris until stream gradient falls below a certain value, the stream becomes unconfined, or it reaches the most downstream reach segment. A large jam is created in the reach segment where the debris torrent stops. Landslides do not move downstream, but a jam is formed in the reach segment where the slide event originally occurred. We currently use a very simple method to initiate these events. The probability of a debris torrent or slide occurrence depends on the maximum daily precipitation for the year: these events only occur if peak rainfall is greater than 100 mm. When the forest/upslope submodel is developed, more defensible approaches will be used, incorporating recent advances.

We emphasize that the channel model is a prototype, not a tested management model. Since there is considerable uncertainty concerning some key processes (e.g., jam creation and movement of large organic debris), further model additions and revisions will be required in the future. One of the valuable features of the model is that it helps scientists and managers examine the defensibility of their hypotheses about how these streams operate, and to identify gaps in knowledge. In examining the model's behaviour under different scenarios, we have highlighted key areas of data gathering required to further our understanding of the system's complexities and to test our predictions. We have developed the channel model with flexibility in mind; its modular structure can easily be modified as new data and understanding are generated.

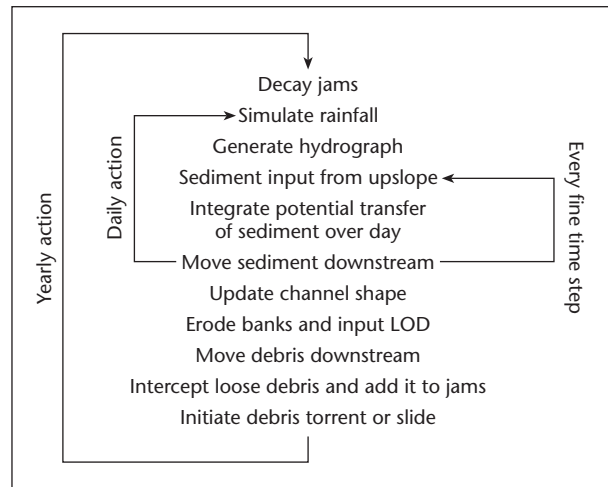


FIGURE 5 Order and frequency of events performed by the channel submodel.

Preliminary Results

The prototype channel model currently uses data from the Government Creek watershed in the Queen Charlotte Islands. To demonstrate the behaviour of the main components of the model, we ran the model for 50 years using three scenarios. For the first scenario, we set the model up so that no jams form over the simulation. This allows us to examine the behaviour of loose organic debris over time. In the second scenario, we initialize the model with no jams, but allow them to form over time so that we can view the interaction between loose LOD and jam LOD. Our third scenario runs with the model initialized for the current state of Government Creek (data provided by D. Hogan, B.C. Ministry of Forests). For each scenario all settings but the formation of jams are the same. We set the probability of slides or torrents to zero to examine how the system would behave without these major disturbances. To facilitate comparison between scenarios, we present data from a single reach of Government Creek on time scales ranging from days to 50 years.

Precipitation and bedload movement occur on fine time scales, during large storm events. Figure 6 illustrates the relationship between precipitation and bedload movement (as well as sediment wedge volume) over the course of a year. Precipitation is

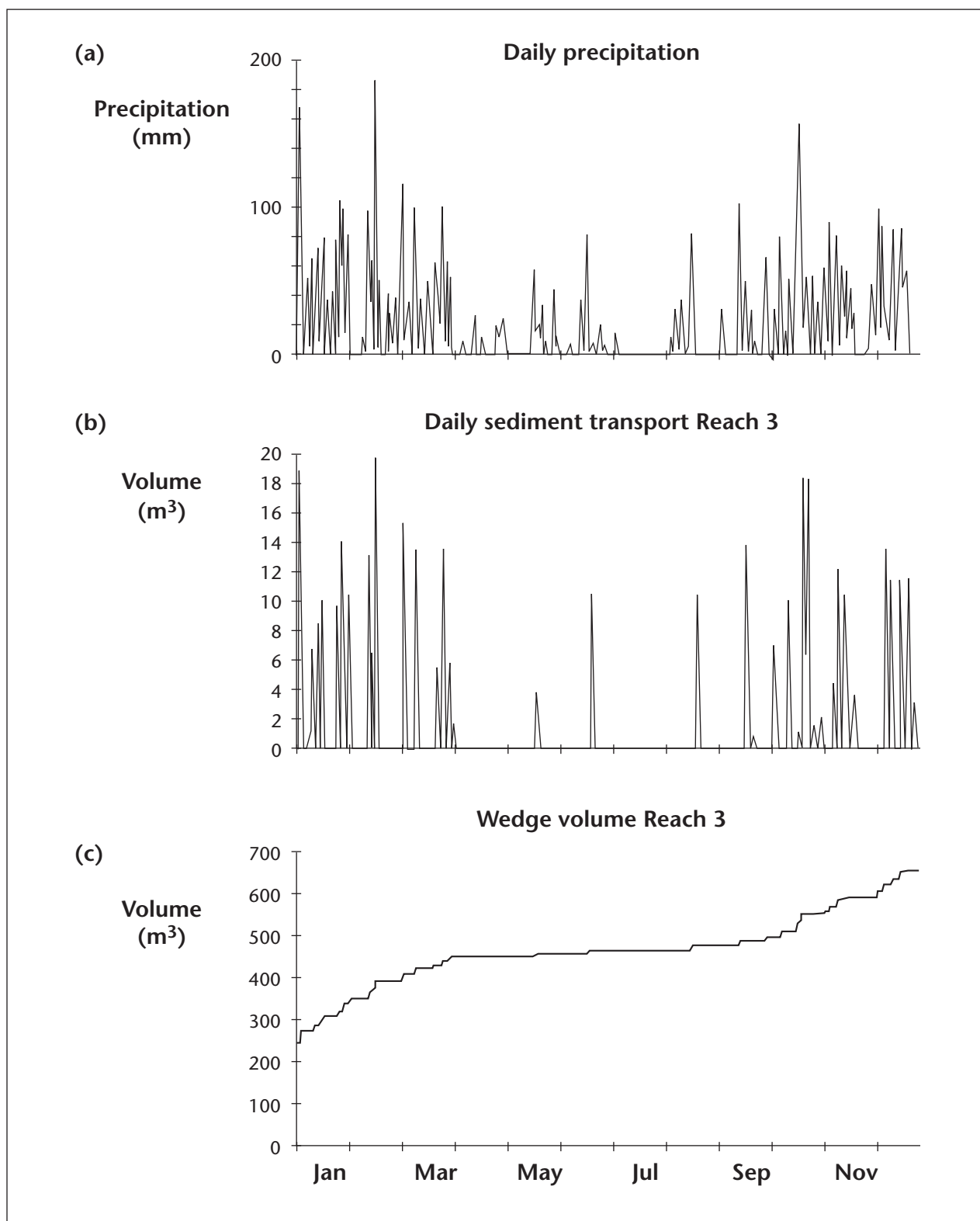


FIGURE 6 Comparison of (a) daily precipitation, (b) daily sediment transport, and (c) wedge volume in a single reach for 1 year.

generated from the stochastic rainfall generator and then converted to flow using a hydrograph. Bedload movement only occurs when there is sufficient stream velocity, channel gradient, and grain size. In this reach segment, the flow is only large enough for sediment transport about 10% of the year. Because there is both little erosion and little sediment transport in summer when precipitation is low, stored wedge volume remains relatively constant. Fall and winter storms, however, erode and transport more material.

We used the model to explore how jams control the distribution of LOD. Figure 7 compares the behaviour of LOD in one reach under the three jam formation scenarios. Figure 7a shows the volume of LOD as total loose LOD and partitioned into the three LOD size groups. The model is initialized with no LOD and no jams are permitted to form. Bank erosion gradually increases LOD to just under 300 m³, about 80% of it in the two smallest size categories. Figure 7b shows the behaviour of LOD as jams form over time. For the first few years the situation in the second scenario is identical to that in the first. Then jams begin to form when loose LOD is greater than a threshold value. The amount of loose LOD drops dramatically when jams form, and the amount removed equals the amount in jams. As the model continues, the jams increase in their ability to trap LOD and a greater percentage of total LOD moves into jams. Figure 7c shows the third scenario, where the model is initialized with the jam characteristics of Government Creek. Note that there is about 5 times as much total LOD as in the first two scenarios. This reflects the historical, cumulative effect of landslides and debris torrents in Government Creek, which have created over 20 jams in this reach alone. Virtually all the LOD is trapped in these jams.

Sediment and LOD dynamics are inextricably linked. As the volume of jam LOD increases, more sediment is stored behind jams (Fig. 4). Sediment storage leads to the widening of the stream channel as water moves around jams. As banks erode, more LOD is added to the system, which in turn leads to more jams holding more sediment. This is not an infinite process; the channel has an equilibrium width to which it converges, and it is always attracted back to that width. With no jams initially, the stored sediment volume gradually increases and then declines as jams decay (Fig. 8b). The fully jammed system gradually stores more and more sediment (Fig. 8c–d), moving towards an equilibrium value appropriate for

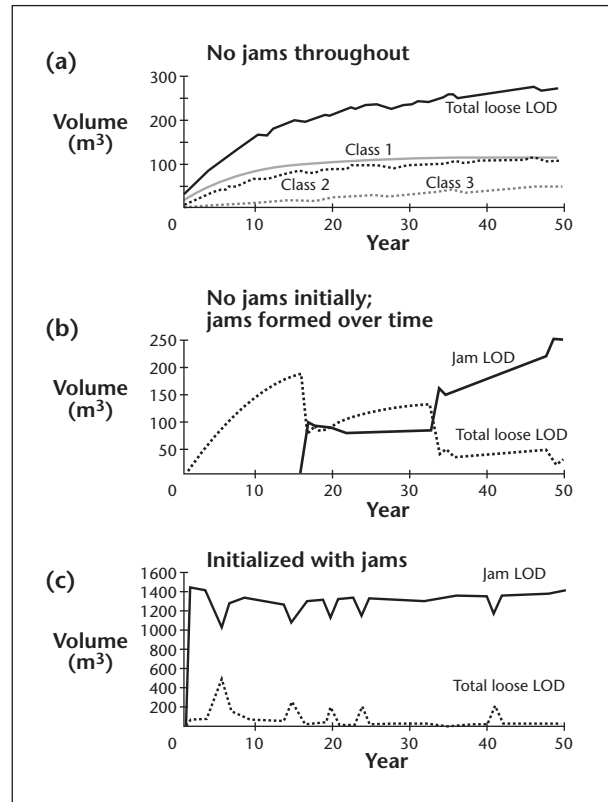


FIGURE 7 Large organic debris (LOD) behaviour in Reach 3 of Government Creek, Queen Charlotte Islands, under three scenarios of jam formation: (a) no jams, (b) no jams initially, but jams form over time, and (c) jams initialized as in Government Creek. Class 1 = small LOD (<0.1 m³), class 2 = medium LOD (0.1–1 m³), and class 3 = large LOD (>1 m³).

the number of jams. Torrents (or higher jam decay rates) are required to “reset” the system and move out sediment.

Without landslides, the age structure of the jam population shifts over time. The shift leads to smaller volumes of LOD per jam. Figure 9 shows “snapshot” frequency distributions of jam age and jam LOD at 5, 25, and 40 years over the course of a 50-year simulation in a single reach. The model is initialized with the jam structure of Government Creek. Over the 50-year simulation, the LOD stays more or less constant (Fig. 8c) but gets distributed over twice as many jams. The stream gradually evolves towards a bimodal distribution, with a higher proportion of young, low volume jams, and

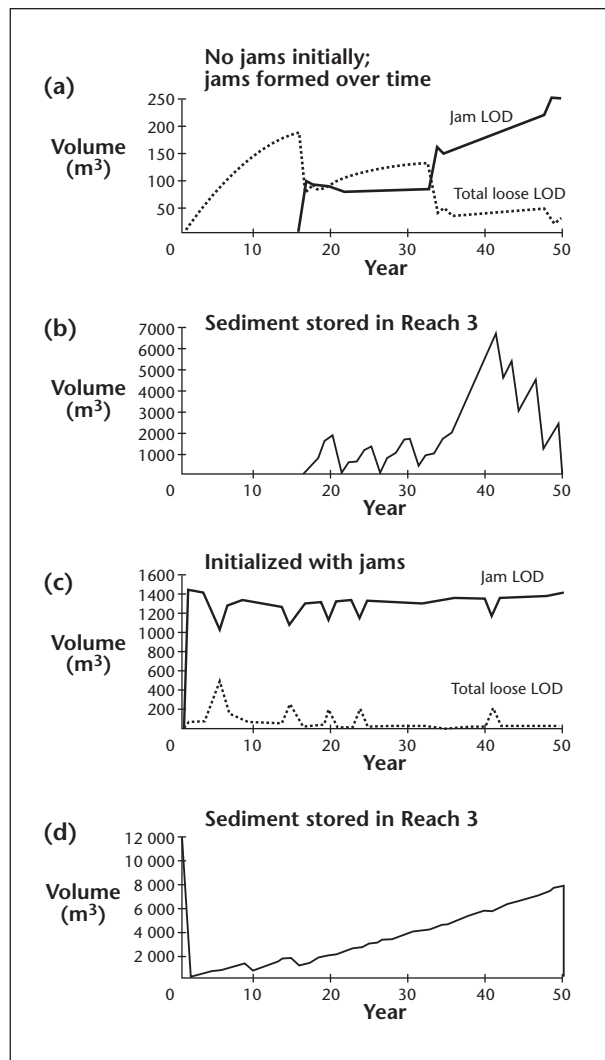


FIGURE 8 Loose LOD, jam LOD, and sediment storage in a single reach for two scenarios of jam formation: no jams initially, but jams form over time (a, b), and jams initialized as in Government Creek, Queen Charlotte Islands (c, d).

the remnants of older, larger jams present at the beginning of the simulation. It appears that the absence of landslides creates a deficit of large volume jams. It may be possible to set landslide rates within the model to maintain the equilibrium of jam dynamics within the stream, and then to compare model estimates of landslide frequency to field estimates. In future, we could also use a forest/upslope model to predict landslide rates and see if equilibrium is maintained. The latter scenario has an advantage in that we could simulate logging.

Future Directions

Short-term improvements: The next steps in model development are to adjust the channel submodel rules so that the model properly handles sediment movement, and to add a simple forest/upslope submodel to permit exploration of different upslope treatments. There are two main problems with the current channel submodel. First, high deposition of sediment in the lower unconfined reaches causes rapid widening of the stream to compensate for this increase in storage. The resulting erosion of the banks causes high inputs of LOD into these reaches. This model representation is incorrect because, in nature, sediment wedges can overflow channel banks. Second, we assume that all of the sediment stored behind a jam can be moved downstream once the jam is removed. This may be correct in confined reaches, but in unconfined reaches a large proportion of the stored sediment can end up on the floodplain. In this situation, the new channel that incises the jam can move only a fraction of the total stored sediment.

Several rule changes could be made to represent processes more realistically in unconfined reaches:

1. Let sediment wedges overflow streambanks, but constrain them by the width of the floodplain.
2. Limit bank erosion in reach segments with a sediment wedge.
3. When jams break down, reconfigure the new channel shape incised through the sediment wedge and jam to the shape that existed before to jam formation.

At present, the channel submodel has the simplest possible representation of the forest/upslope component (e.g., fixed volumes of LOD and debris associated with debris torrents and landslides). The logical next step is to develop a simple user interface which allows specification of different terrain sensitivities for different sub-basins of the watershed. This would allow some of the consequences of spatial variability to be considered, without the time and computer requirements of implementing a full GIS version of the forest/upslope submodel.

Medium term improvements: We recommend four medium-term improvements in the following order of priority. First, the group needs to further develop fish habitat indicators conceptualized in the December 1991 model design workshop. These need to be re-examined in light of the current channel

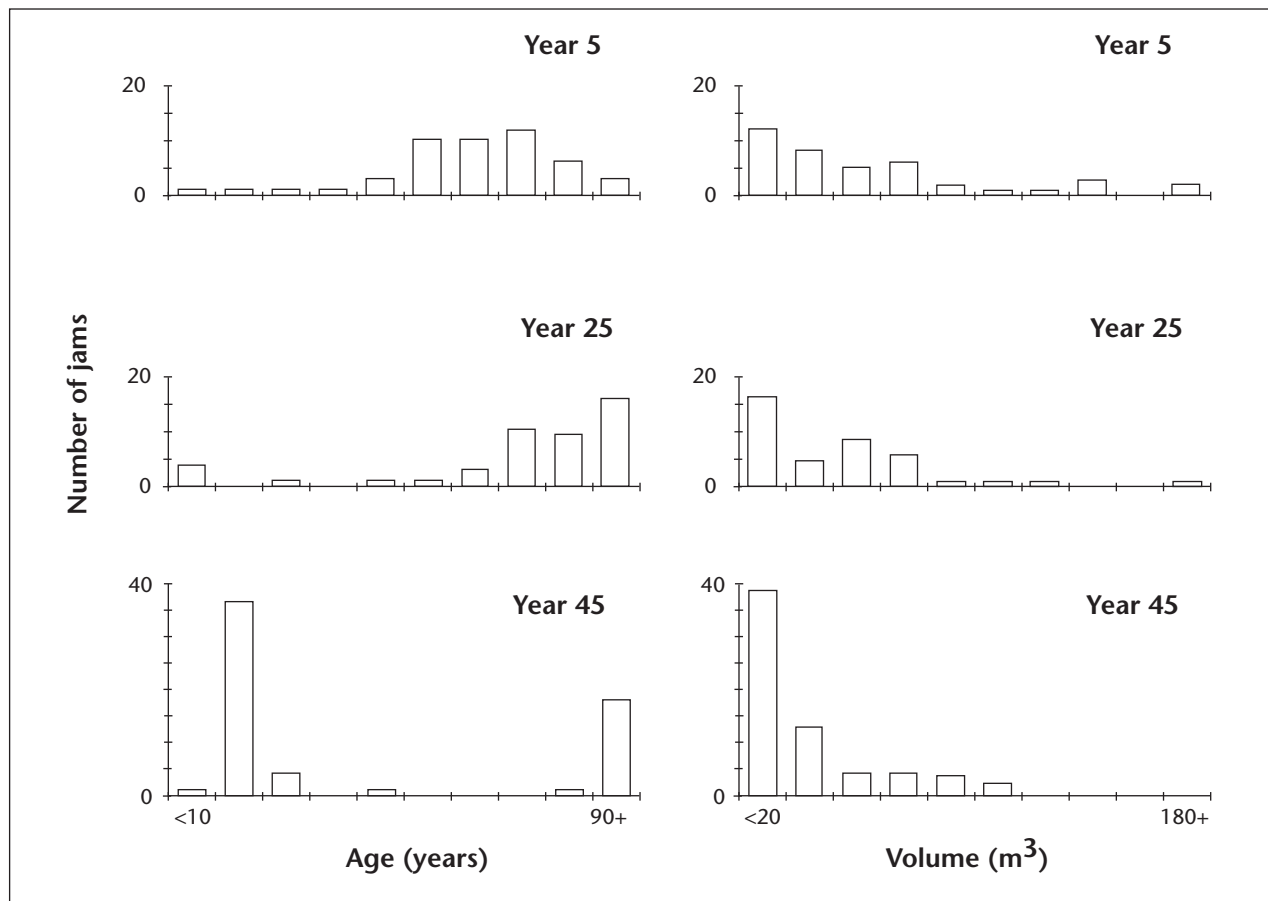


FIGURE 9 Frequency distributions of jam age structure and jam LOD (m^3) in a single reach after 5, 25, and 40 years. Jams initialized as in Government Creek, Queen Charlotte Islands.

submodel structure. Fisheries scientists and channel morphometry experts need to work together on formulating appropriate rules. Second, we need to conduct further model calibration and testing using the Government Creek data. Scenarios could include alternative management actions (e.g., simulating logging case histories) and the adaptation of input data to reflect conditions at other sites. It is particularly important to explore not only the effects of logging on pristine watersheds, but also the rate of recovery of systems with damaged habitat. The intent of this step would be to expose the model to a wide array of conditions, discovering when and where unexpected results are produced. The third step would be construction of the forest/upslope submodel conceptualized at the December 1991 model design workshop. The model would interact with a GIS or data base representation of open slope

and gully polygons. Linking the channel submodel to a complete forest/upslope model will allow users to explore the habitat effects of different logging plans. Finally, we should explore development of the fish submodel conceptualized at the December 1991 model design workshop. Though it may be possible to use the forest/upslope and channel submodels by themselves to guide logging plans (and therefore assume, for example, no loss of habitat), the inclusion of a fish submodel is necessary to allow us to assess the ultimate effects of habitat change on fish populations. The fish population responses to changes in fish habitat are often non-linear.

Longer-term improvements: Once we have confidence in the behaviour of the integrated FFIPS model, it could be used to contribute to the development of three useful products: 1) a constraint-mapping GIS tool for developing logging plans;

2) data to supplement the FFIP guidelines and Forest Practices Code; and 3) a tool for assessing the benefits of different types of watershed and habitat restoration work.

A constraint-mapping tool for developing logging plans could combine upslope terrain sensitivity ranking with fish habitat and channel sensitivity, using FFIPS results, Forest Practices Code regulations, or Clayoquot Science Panel recommendations (Clayoquot Sound Scientific Review Panel 1995). It would therefore bring together the key criteria necessary to assess what areas of the watershed could be safely logged and at what rates; and would focus on the upslope component, but contain within it the implications over time of upslope changes for channel fish habitat (such as which upslope areas exert the greatest influence on fish habitat). The FFIP guidelines developed to date have been very useful in guiding timber management. Once a linked channel-forest/upslope model has been tested, it will generate some additional useful guidelines to be used in the field for planning logging operations. Specific mapped recommendations are more likely to be used in the field than computer models or handbooks, so it's vital that the lessons learned from this research be translated into on-the-ground instructions.

The FFIPS model could also be a useful tool for assessing the benefits of watershed and habitat restoration work, especially the stabilization of roads and restoration of riparian habitat. FFIPS could be also used to interpret the results of ongoing Watershed Restoration Program projects. Those projects each represent experiments that can be used to improve understanding. Consolidation of this knowledge in a model would leave a lasting legacy of the program.

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Problems, Prescriptions, and Compliance with the Coastal Fisheries-Forestry Guidelines in a Random Sample of Cutblocks in Coastal British Columbia

DEREK TRIPP

Introduction

The 1988 Coastal Fisheries-Forestry Guidelines (CFFG) were developed to help forest companies and regulatory agencies integrate with consistency the needs of the coastal fisheries resources with those of forest harvest and silviculture activities. While most Forest Districts had some form of guidelines, they varied from district to district. Other earlier guidelines or handbooks for protecting fish habitat were available, but these were either not specific enough to coastal operations or in need of some updating. In particular, new information was required on such issues as: the importance of large woody debris in streams; the processes that influence water temperatures and the emergence, growth, survival, and migration patterns of juvenile fish in streams; and the effect of upslope events on fish resources downstream.

As with any guidelines, it was anticipated that the CFFG would require regular revisions as our knowledge of fish/forestry interactions continues to increase, and our ability to successfully integrate fisheries and forestry resources improves. Until then, however, apparently few people were comfortable that the level of fish habitat protection implied by the 1988 guidelines was being achieved in the field, with or without the continued input of site-specific recommendations by the regulatory agencies on road locations, cutting boundaries, leave areas, or harvesting techniques (Moore 1991). Indeed, there was some question about whether or not site-specific prescriptions themselves were effective in mitigating some of the negative aspects of logging on streams. Problems continued to occur in the field, though there was no consensus as to what the main causes of the problems were.

Summarized here are the types of site-specific prescriptions provided by the agencies to help reduce or eliminate the effects of logging on streams

in cutblocks in coastal British Columbia. Also provided is an assessment of how effective the prescriptions were, how well logging companies in coastal British Columbia applied the CFFG generally in cutblocks logged between 1988 and 1992, what the principal impacts were on streams, and what problems caused the impacts.

The findings are based on a series of field audits initiated in 1992 on 126 randomly selected cutblocks in eight different Forest Districts or regions (Vancouver Island) of coastal British Columbia. They include work on 26 cutblocks that was in progress when this paper was originally presented, though few of the results changed with the additional cutblocks. Since all of the cutblocks inspected were logged before mid-1992, the findings presented here reflect logging as it was practised from 1988 to 1992, and not necessarily as practised today.

Methods

The specific methods used to assess the application and effectiveness of site-specific prescriptions and the CFFG in each cutblock inspected are described in detail in a series of reports that cover the use and effectiveness of the CFFG over most of coastal British Columbia (Tripp et al. 1992; Tripp 1994, 1995). Methods for determining overall percent compliance with the CFFG are also described, based on a checklist of 25 expectations of the CFFG. Scoring took into account the number of streams, road types, and bridges affected in each block. Variances of 10–20% were also allowed for on the length or number of drainage structures present (e.g., ditches, culverts, and cross ditches), and the proportion of those structures that were functioning properly. Scoring in general was conservative. It was also unrelated to the presence or absence of impacts on streams.

Only blocks with fisheries concerns were inspected. These were blocks that encompassed or impinged on Class I or II streams, or blocks that included Class III or IV streams that could affect Class I or II waters downstream. Stream reach classification was based primarily on fish use as defined in the 1988 CFFG. Class I stream reaches included any reaches with anadromous salmonids or better than low levels of resident sport fish at any time of the year. Class II streams were reaches with low levels of non-anadromous sport fish. Class I and Class II streams are now referred to as Class A streams in the 1993 edition of the CFFG.

A Class III stream reach was a reach with resident non-sport fish only; a Class IV stream reach was a reach with no fish, nor any likelihood of fish use in the future. These streams are now called Class B and C streams, respectively. A stream itself was defined as any water channel with definable, continuous channel boundaries formed by fluvial processes. A stream did not have to have any water at the time of the survey, nor was there a minimum width.

The first step in the audit after selecting the cut-blocks was to compile the relevant correspondence available for each. This included the 5-year development plans submitted by the logging companies, the specific comments on the plans by the environmental agencies (Ministry of Environment, Lands and Parks and the Department of Fisheries and Oceans), the results of on-site field reviews before logging, consultant reports, the Pre-Harvest Silvicultural Prescriptions, the Logging Plans, the Cutting Permits, falling approvals, Harvest Inspection Reports, and all maps. The material was reviewed to determine what the logging companies and agencies felt were significant concerns in each block, and what the recommendations were, if any, to mitigate the concerns. The material was then ground-truthed in the field to assess the accuracy of the material, determine if all environmental constraints specified were followed, and describe what the condition of the roads and streams were generally.

Field inspections averaged 2 person-days per block. During the inspections, usually all of the road would be walked or driven. All fish-bearing streams would also be walked, along with most non-fish-bearing streams that had the potential for affecting fish-bearing streams downstream. During road inspections, records were kept of road length, road gradients; hillslopes; numbers of streams and watercourses; numbers and dimensions, condition,

and effectiveness of all drainage structures (ditches, water bars, culverts, cross ditches, bridges); surface erosion, road failures, and so on. During stream inspections records were kept of gradient, channel width, channel depth, side hillslopes, stream length, leave strip widths, and windthrow. The length and depth of the stream channel affected by logging debris or sediment aggradation present was also recorded, along with the length of streambanks or streambed scoured, and any changes in stream flow patterns. If possible, the cause of any impacts was also noted.

Results

Proportion of Blocks Logged with Fisheries Concerns

In some areas (e.g., Vancouver Island, Kalum District, and the Queen Charlotte Islands), a relatively high proportion (>85%) of the blocks logged between 1988 and 1992 had fisheries concerns. In these areas, the results of the audit apply generally to most blocks. In other areas, only 22–55% of the blocks had fisheries concerns; the results here apply only to this proportion of the blocks. Various Forest Districts had fewer blocks with fisheries concerns than other Districts because:

1. some districts had a much longer history of logging, and many areas currently being logged were located well upstream of the main areas with fisheries concerns;
2. some districts had a disproportionate number of non-fish-bearing streams that flowed directly into the ocean, or into large lakes where the impacts were difficult to quantify;
3. some districts had significantly smaller blocks than others, and the blocks therefore “fit” between streams better than large blocks in other districts, with more room for large leave areas beside streams; and
4. parts of some districts were quite dry and the distribution of fish was more restricted than in other wetter areas.

Stream Impacts Approximately half (48.2%) of the stream reaches inspected with fisheries concerns had a major or moderate impact, as defined in this survey. The lowest percentage of streams affected was in the Queen Charlotte Islands (23.6%); the highest percentages were in the Kalum, North Coast, Mid-Coast, and Chilliwack Forest Districts (65–70%).

Differences among districts in the percentage of specific stream reach classes affected tended to be greatest for Class I–II streams, and smallest for Class IV streams (Fig. 1). The best performance on Class I–II streams was on the Queen Charlotte Islands where only 8.3% of the Class I–II reaches inspected were affected. Mid-Coast had the poorest record for avoiding impacts on Class I–II streams (56% of the streams), while Chilliwack had the poorest record on Class III streams (60% of the streams). No district fared particularly well on Class IV streams, where 56–100% of the streams inspected with moderate to high transport potential had a moderate to major impact.

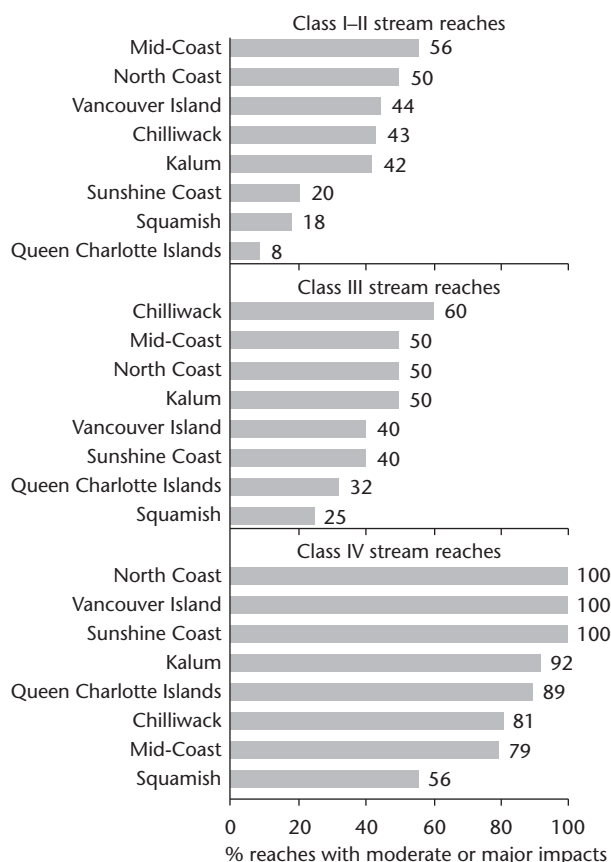


FIGURE 1 Percent of streams with a moderate or major impact, by Forest District and stream class. Class IV streams refer only to Class I–III tributary streams with a moderate to high transport potential.

Salmon (Class I) and other sport fish streams (Class II) were less affected than resident fish (Class III) or non-fish-bearing (Class IV) streams. For all districts and all streams combined, including streams with minor or no impacts, average net stream area affected was 3% on Class I streams, 11% on Class II streams, 16% on Class III streams, and 55% on Class IV streams. Most of the streams affected were the smaller, first-order streams or side channels evident on 1:5000 scale maps. This was particularly true of Class I and II streams, where the difference between “large” and “small” streams was substantial compared to most Class III or IV streams.

Larger streams were less affected by logging than small streams, partly because larger streams were usually better protected with Streamside Management Zones (which included leave strips, buffer strips, and machine-free zones) and partly because of the conservative nature of the methods used to estimate impacts. Since assessments of major or moderate impacts were based on both the proportion of stream area affected and the degree of the impact within the affected area, larger streams were less likely to be considered impacted. With the methods used here, up to 40% of the channel cross-sectional area could be filled with sediments over 40% of its length and this would still be deemed a minor impact. Because the larger mainstem streams were invariably bordered by other blocks upstream, impacts due to logging in the block being audited were also sometimes difficult to distinguish from the effects of logging upstream.

Source of the Problems If the amount of work currently being directed at roads is any indication, there is a widespread belief that roads are the main source of fisheries-forestry problems. This may be true in terms of the degradation of plantable sites. It may also be true in terms of the amount of fine sediments introduced to streams, but there was no attempt to quantify either of these parameters in the present audits. What was quantified in the three audits was the overall net stream area affected by increases in LOD and sediment loads, stream bed scouring, and channel scouring. The results clearly indicate that roads were much less of a problem than the harvest operations themselves (e.g., falling, bucking, yarding, and clean-up). Coast-wide, poor harvest practices affected 7.5 times more net stream area (120 000 m²) than poor road practices (16 000 m²).

Post-harvest failures (mainly torrents) were the most significant problem overall, accounting for 39% of the total net stream area affected by all problems combined (Fig. 2). A combination of inappropriate streamside activities such as over harvesting, trespasses, machinery or trails in streams, burn piles in streams, stock piling gravel in a stream, or excessive clean-up on streams accounted for another 20% of the total area affected, all on fish-bearing streams. A lack of clean-up where clean-up was possible and poor falling and yarding practices represented another 17% and 11% of the area affected, respectively.

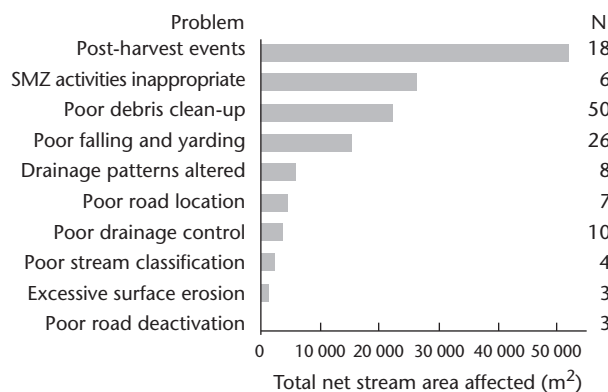


FIGURE 2 Total net stream area (m^2) affected by each of the 10 main problems observed in coastal Forest Districts of British Columbia. Numbers arranged vertically on the right are the number of times each problem was observed. SMZ – Streamside Management Zone.

With an average net stream area of $4400 m^2$ affected, inappropriate streamside activities were individually the single most damaging problem. This was followed by post-harvest failures at $2900 m^2$ of net stream area per event. With the exception of poor road deactivation work, individual differences in the amount of stream area affected by all other problems were small, ranging from approximately 350 to $760 m^2$. Road deactivation work accounted for the least area affected per incident ($70 m^2$), however, this may underestimate the potential for problems since the only evidence of a problem encountered (large accumulations of fine sediments) was only visible until the next heavy rain.

Site-specific Prescriptions The large majority of site-specific prescriptions recommended by Department of Fisheries and Oceans and BC Environment to mitigate the impacts of logging focused on logging beside streams. Before 1992–1993, very few specific prescriptions were noted for roads or bridges (in some cases because roads were already constructed before the blocks were laid out) and thus they did not go through the same referral process as the cutblocks. In other cases, many people involved in environmental protection lacked the expertise to comment on specific engineering problems. After 1992–1993, there was an abundance of road-related prescriptions by Ministry of Forests personnel on Harvest Inspection Reports, mainly to clean out ditches and culverts or deactivate roads.

Site-specific recommendations for mitigating the impacts of logging were provided for approximately 70% of all fish-bearing streams inspected, and about 30% of all non-fish-bearing streams. The average number of prescriptions per stream was 1.9 (range 1–5). Some common prescriptions such as “maintain water quality” were not considered a prescription because it was impossible to determine whether it was applied in the field. Others had to be interpreted fairly liberally. For example, “fall and yard away, but okay to fall across where unavoidable according to the company’s discretion” reflected a very casual concern that was interpreted as permission to fall and yard across the stream.

There were 15 basic types of stream prescriptions recommended throughout the coast. Typically, however, only five or six were used in any one district. Agencies on the Queen Charlotte Islands and Vancouver Island (primarily north Vancouver Island) had the greatest range of recommendations, but these two districts, along with North Coast, also relied on two prescriptions more than other areas—fall and yard away from the stream, and clean out the logging debris after falling. Two districts emphasized leaving only non-merchantable trees along streams, while two others gave specific approvals to fall and yard across relatively large streams in the block.

There were few differences in the prescriptions recommended on fish- (Class I–III) and non-fish- (Class IV) bearing streams (Fig. 3). In both stream types, the two recommendations to fall and yard away from the stream and clean out the logging

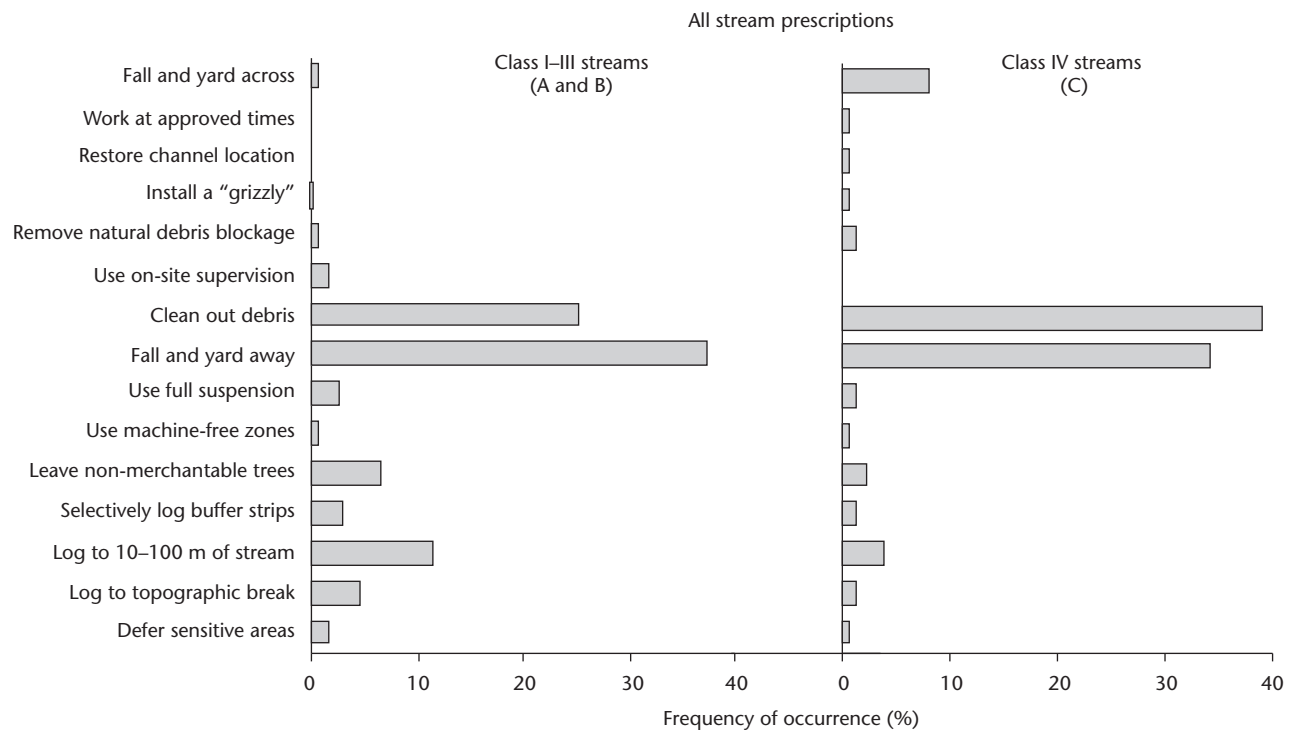


FIGURE 3 Frequency of occurrence of different site-specific prescriptions used on Class I-III streams and Class IV streams.

debris were by far the most widely used prescriptions to mitigating the effects of logging. Fish-bearing streams received a slightly greater emphasis for leave strips, while non-fish-bearing streams got more approvals to fall and yard across the streams, plus slightly more recommendations for in-stream work. The latter included relocating a stream back to its original channel, constructing large debris catchers ("grizzlies") at road crossings, and removing natural debris blockages. Recommendations to clean out debris also predominated in Class IV streams.

There were more prescriptions for a leave area on large, steep Class IV streams with a moderate to high downstream transport capability. The use of site-specific prescriptions on Class IV streams was otherwise not always clearly related to the transport capability of the streams (Fig. 4). Of the Class IV streams with site-specific prescriptions, approximately half were rated low to low-moderate in their ability to transport debris and sediments downstream; the other half were rated moderate or higher. Similarly, among the Class IV streams that lacked specific recommendations for logging, about half had a moderate to high rating for transporting

debris downstream. Without any recommendations to the contrary, the timber was cross-stream felled and yarded on most Class IV streams lacking prescriptions, with no clean-up after yarding.

Effectiveness of Site-specific Prescriptions Specific prescriptions on logging beside streams were more effective in reducing impacts to streams than the CFFG for two reasons: they generally focused on specific problem areas in a cutblock and they usually left little room for interpretation. The most effective prescriptions were those that specified a specific leave strip width alongside streams, with a clearly achievable understanding of how timber was to be harvested within portions of the leave strip if this was the case. Prescriptions that recognized the need to protect, limit, or defer harvest in upslope areas that were unstable, or which had a realistic possibility of affecting downstream resources, were also very effective.

Prescriptions that were not effective were those that did not appear to deal with a specific problem (e.g., fall and yard away on non-fish-bearing streams with little potential for erosion on-site or debris

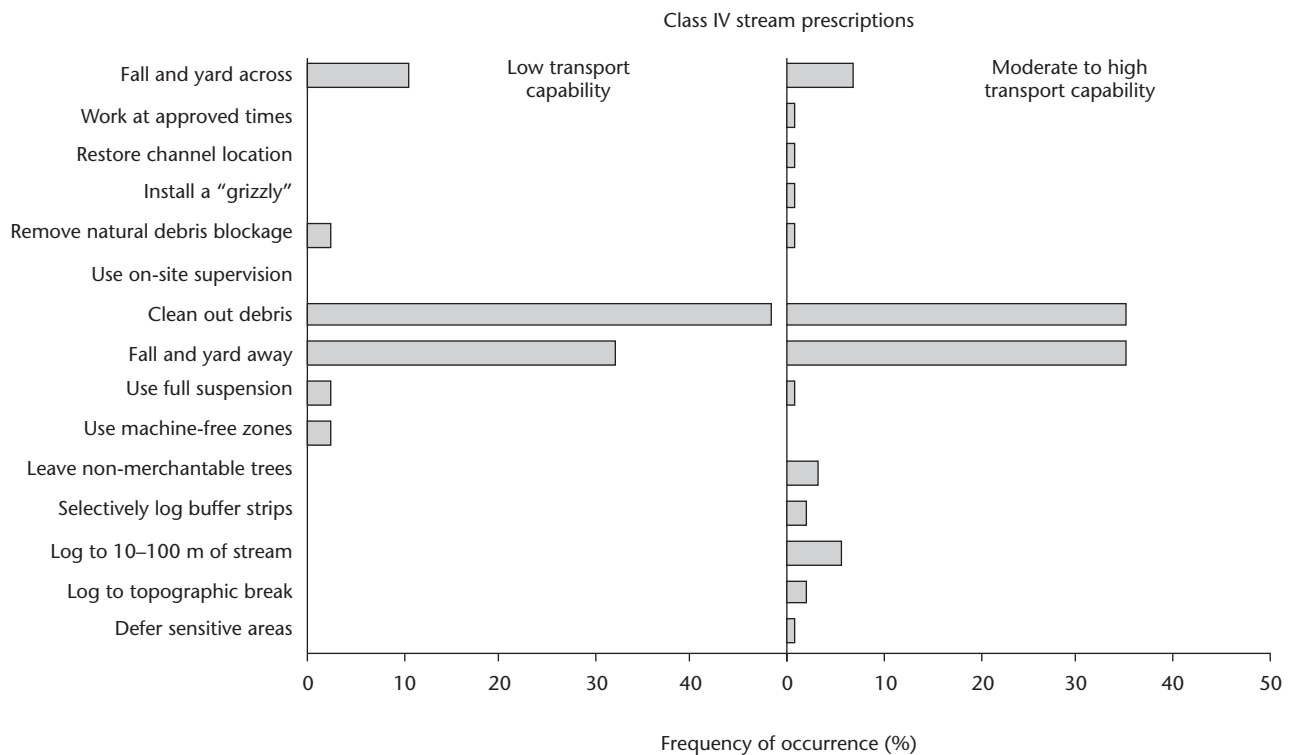


FIGURE 4 Frequency of occurrence of different site-specific prescriptions used on Class IV streams with low or low-moderate downstream transport capability and Class IV streams with moderate to high transport capability.

transport downstream) or that dealt with secondary as opposed to primary problems (e.g., constructing grizzlies in front of bridges or large culverts to catch debris, as opposed to keeping debris out of streams in the first place). Many of the most common but ineffective prescriptions were prescriptions to fall and yard away from streams, where falling and yarding away was clearly impossible given the road layout or the topography. Also effective were related instructions to clean out debris where the debris would be impossible to retrieve once falling started.

The list of prescriptions for a cutblock was frequently incomplete. Consequently, poor performance in one area sometimes nullified the effectiveness of site-specific prescriptions in other areas. Approvals, for example, were granted to fall and yard trees across two large Class IV streams in two districts. Though perhaps ill-advised in view of the flooding that scoured out the stream bed and stream banks of both streams, the impacts may have been reduced or eliminated had the large amounts of logging debris introduced been removed concurrently with logging

at a low flow period. In other areas, the benefits that would have resulted by following the guidelines or site-specific prescriptions (e.g., wide leave strips) were sometimes nullified because of the failure to prevent torrents or slides in upstream or upslope areas that affected the lower stream reaches.

Site-specific stream-side prescriptions were effective in reducing the amount of stream area affected by logging (Fig. 5). For all districts audited, the area affected when site-specific prescriptions were followed was 7 times less than the area affected when site-specific prescriptions were not followed. The area affected when just the CFFG were followed was 4 times less than when the guidelines were not followed. Together, the CFFG and site-specific prescriptions achieved an average 5-fold reduction in the amount of stream area affected by logging.

On streams without any specific instructions, the net amount of habitat damaged when the CFFG were not followed was 4 times greater than the area affected when the CFFG were followed. When specific prescriptions were not followed, 11 times

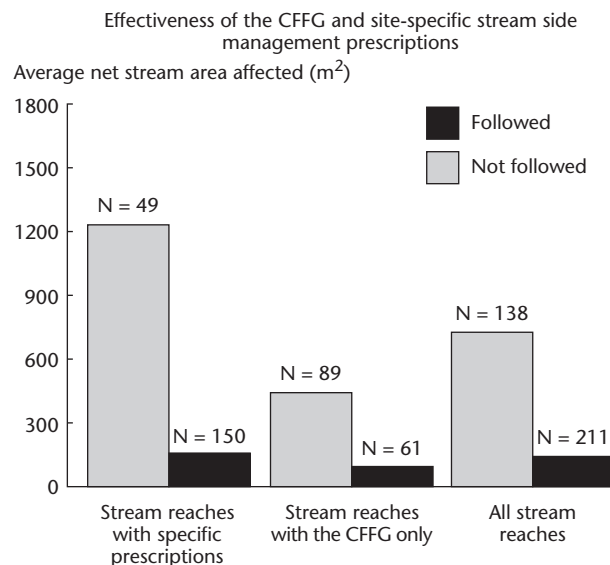


FIGURE 5 Average net stream area affected when the CFFG and site-specific prescriptions were or were not followed in coastal British Columbia.

more stream area was affected. In both cases, about 100 m² of stream was affected regardless of whether specific recommendations or the CFFG were followed. Part of this area indicates that not all impacts can be avoided. Part of the area is a result of natural disturbances. The relatively greater apparent effectiveness of site-specific recommendations compared to the CFFG alone is partly because the areas that typically get site-specific prescriptions are difficult or sensitive areas to log, and thus most likely to show impacts when the recommendations are not followed.

Overall Effectiveness of the Guidelines Net area affected, altered, or damaged in streams with fisheries concerns was strongly correlated with declines in overall compliance with the CFFG (Fig. 6). The relationship was close to a logarithmic relationship. For every 10% decline in compliance there was a 4-fold increase in net stream affected. For every 20% decline in compliance there was a 16-fold increase in net stream area affected.

Average compliance for all blocks audited in coastal British Columbia was 70%. The predicted net stream area affected at this level of compliance, based on the regression of net stream area affected (log₁₀) and compliance (Fig. 6), is equal to only 70 m². This underestimates the real risk of impacts

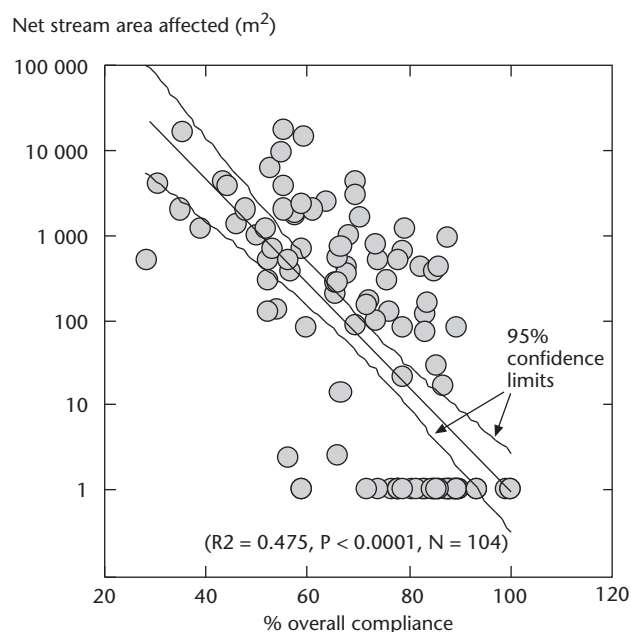


FIGURE 6 The relationship between overall compliance and net stream area (log₁₀ m²) affected in streams with fisheries concerns. The latter includes all Class I–III streams, plus Class IV streams with the potential to affect fish-bearing waters downstream.

at this level of compliance, because the data were still skewed after the log transformation. A more accurate estimate of the amount of stream area likely to be affected at 70% compliance is probably closer to 700–800 m², based on a true, locally weighted curve (Fig. 7). The latter also shows the sharp increase in the potential magnitude of stream impacts below 70% compliance. The overall, arithmetic average net stream area affected was 1210 m² (1 SD = 2970, N = 104, range 0–17 875 m²).

For all blocks in all districts combined, blocks with an overall compliance greater than 89% produced no conspicuous changes to fish-bearing streams, or non-fish-bearing streams that were sufficiently large or steep enough to transport sediment and woody debris into fish-bearing waters downstream. This level of compliance was achieved in 14 blocks, or 11% of the sample (Fig. 8). Thirty-two blocks (25% of the sample) had overall compliance below 58%, at which point there were always impacts. Between these two limits, some blocks had impacts and others did not. Average compliance in blocks without any major or moderate impacts was

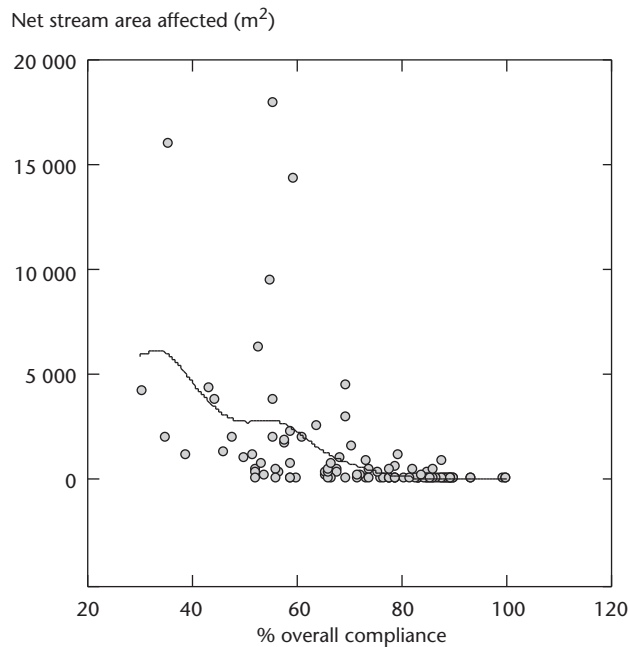


FIGURE 7 The relationship between overall block compliance with the CFFG and net stream area affected in streams with fisheries concerns. The line is a distance-weighted, least squares smooth that produces a true, locally weighted curve.

81.9% (N = 58), which was significantly greater ($P < 0.0001$) than compliance in blocks with impacts (59.9%, N = 67). The lowest overall compliance recorded for a single block was 28.4%; the highest was 100%.

Factors Affecting Compliance (Slope, Company, Year, Block Size) Hillslope accounted for a significant portion of the variation in overall compliance between blocks in coastal British Columbia—the steeper the slopes, the poorer the compliance (Fig. 9). For all blocks audited, there was approximately a 3% decline in compliance for every 10% increase in slope. When eight possible outliers were deleted from the data, compliance declined approximately 5% for every 10% increase in hillslope. The specific relationships for the two relationships are as follows:

All blocks:

$$\% \text{ Compliance} = 80.690 - 0.3152 \text{ hillslope } (\%)$$

($R^2 = 0.141$, $P < 0.0001$, N = 126)

All blocks minus eight possible outliers:

$$\% \text{ Compliance} = 85.474 - 0.507 \text{ hillslope } (\%)$$

($R^2 = 0.355$, $P < 0.0001$, N = 118)

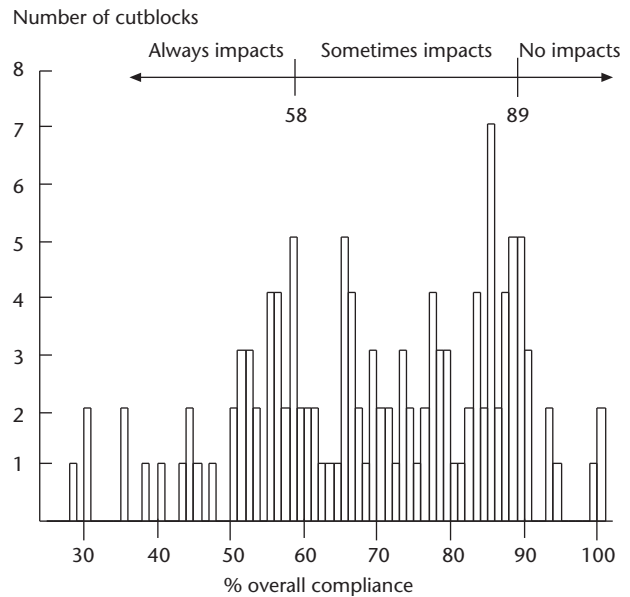


FIGURE 8 A histogram of overall block compliance with the CFFG for cutblocks logged in coastal British Columbia.

One of the blocks considered an outlier was a relatively low gradient block that had considerable erosion on the roads as a result of some stream diversions onto the road, a poorly located borrow area, and some poorly located backspare trails. A number of low gradient, small- to medium-size fish streams were also left blocked with logging debris. The remaining seven blocks were relatively steep blocks which, in retrospect, may not have represented a good test of the CFFG. The blocks either lacked roads (one was helicopter-logged) or the only road present was a short section of an active main haul road. All seven blocks also lacked any streams that would pose a problem (i.e., the blocks had either no streams or only a small Class IV stream with little or no potential to move large quantities of debris or coarse sediment downstream). The blocks were selected mainly because of their location beside a large major stream with high fishery values or high downstream concerns. Each block had a prescription for a buffer strip along the streams, though in one case the prescription also permitted the merchantable timber within the buffer strip to be harvested. Because it would have been very difficult for any of the above seven blocks to be substantially out of compliance, possibly they should have been excluded from the sample.

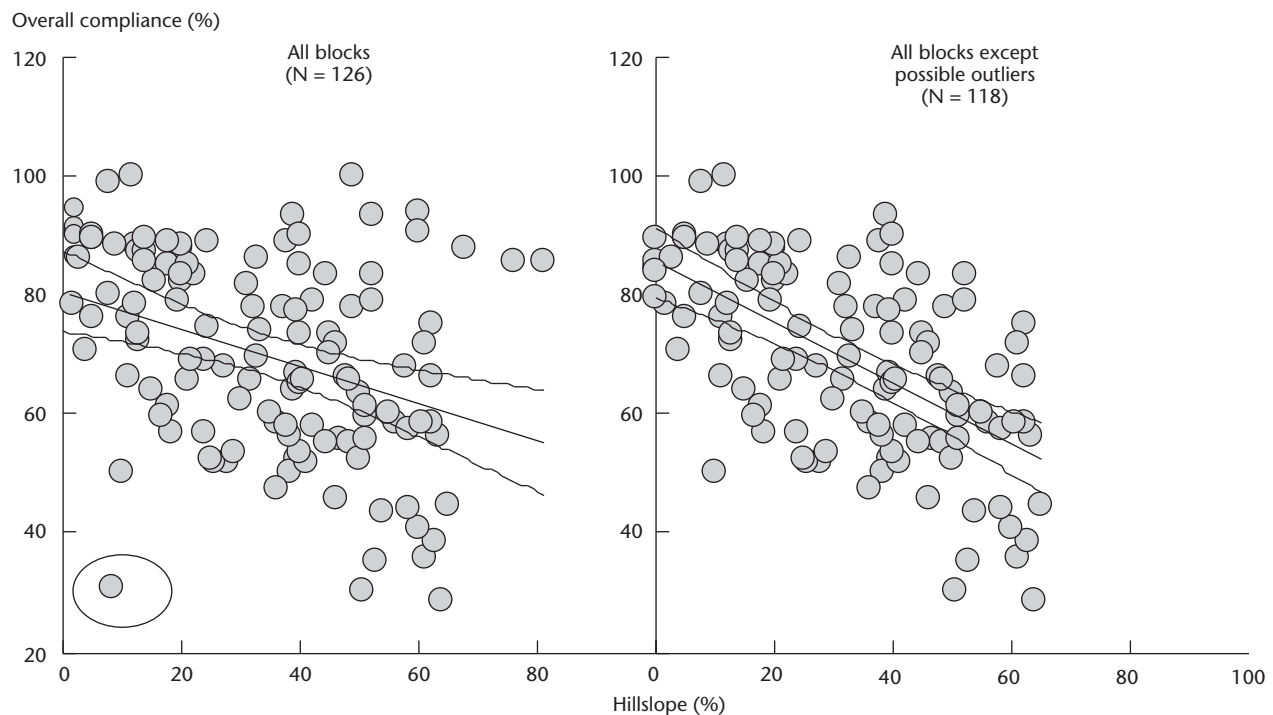


FIGURE 9 The relationship between overall compliance with the CFFG and hillslope in coastal British Columbia. Encircled blocks are possible outliers. The straight lines are the regressions of overall compliance in each cutblock on hillslope; the curved lines are the 95% confidence limits about the regressions.

Specific components of compliance that were most affected by hillslope included falling and yarding away from streams (especially steep Class IV streams), clean-up, and the maintenance of natural drainage patterns. The steeper the slopes, the less likely timber would (or could) be felled and yarded away from streams, and the less likely the debris introduced into the stream would (or could) be cleaned out. Erosion of road surfaces and encroachment on streams at stream crossings were other factors affected by slope.

Specific aspects of compliance that were not related to slope included the proper identification of streams by class, selection of proper strategies for harvesting alongside streams, road deactivation, encroachment on streams, road failures, sidecasting into streams, and construction and maintenance of culverts and waterbars. Problems with skid trails and backspur trails across streams, borrow pits on water courses, excessive or improper clean-up, and over-harvesting in Streamside Management Zones were also unrelated to slope.

Slope was not the only factor affecting compliance, and not every district showed a significant correlation between compliance and hillslope. Differences among the companies that logged the blocks were also significant. When comparisons were made among districts or companies, adjusting for slope reduced the magnitude of the differences, but only occasionally was the order or significance of the differences in company or district performance affected.

There was no relationship between compliance and block size. Large blocks were just as likely to have high or low compliance as small blocks (Fig. 10). Compliance was also unrelated to the year harvesting started. There was no compelling evidence that compliance with the CFFG improved or declined from 1988 to 1992 (Fig. 11).

Conclusions

The results presented in this paper demonstrate how compliance with a set of guidelines can be quantified and therefore more easily analyzed and assessed

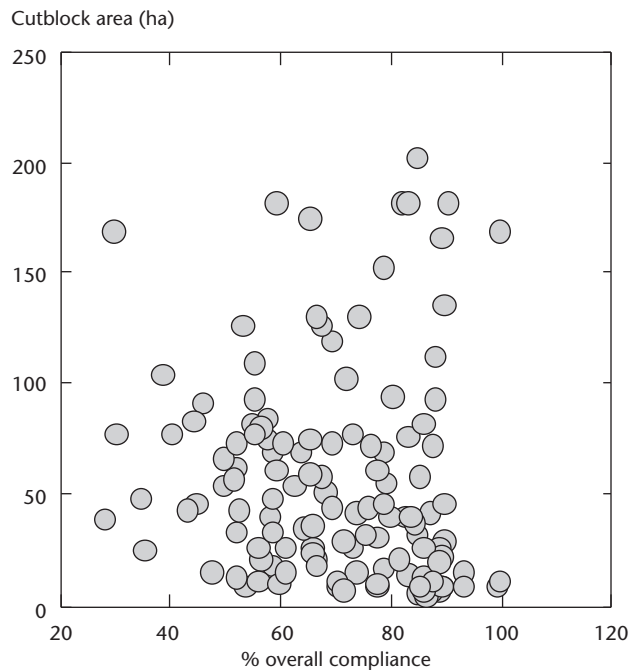


FIGURE 10 *The relationship between cutblock area (ha) and overall compliance with the CFFG.*

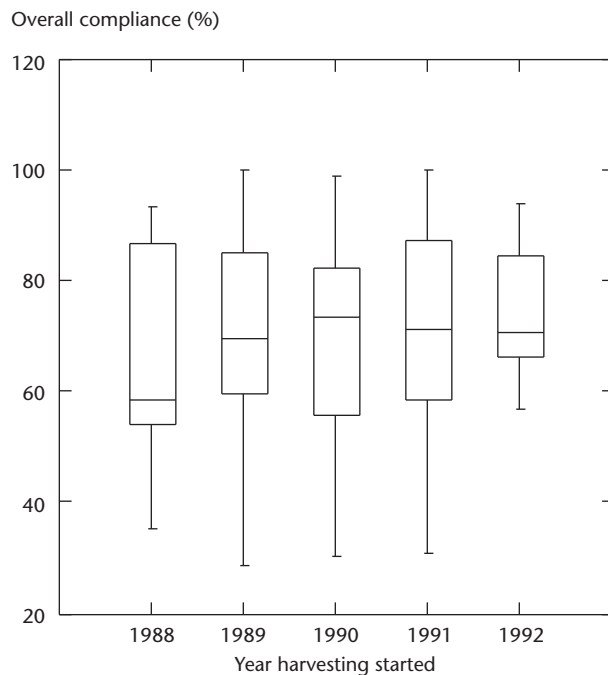


FIGURE 11 *Overall compliance with the CFFG by year harvesting was started in cutblocks. The centre horizontal line in each box marks the median, while the box encloses half the values above and below the median. The vertical lines mark the range of values.*

as to their effectiveness. It also demonstrates that improved compliance is equated with a reduction in stream area affected. This allows for a decision on what different levels of compliance mean in terms of stream disturbances, and thus what acceptable levels of compliance are.

It is not known if the CFFG themselves would provide an adequate level of protection for streams. Though no pre-1988 blocks were assessed, the absence of any change in compliance from 1988 to 1992 suggests that logging practices did not change with the introduction of the guidelines. This is supported by the fact that actual specific references to the guidelines were found in less than 10% of the blocks audited. Other references to earlier standards were just as common. Site-specific prescriptions are an effective alternative to general guidelines, but they need to be applied to all streams with fisheries concerns, not just high profile salmon and trout streams.

Of the streams inspected in the audits, almost half with fish or of direct concern to fish-bearing streams were affected by logging. Streams most likely to be affected were those that lacked specific prescriptions for some sort of buffer strip or appropriate harvest techniques. Non-fish-bearing streams with a reasonable potential of affecting fish resources downstream were particularly prone to problems. This indicates that upstream or upslope risks are not always recognized or evaluated in a consistent fashion. Simple, reproducible methods to accomplish such assessments are needed.

Roads are regularly assumed to be the main source of the problems. This may well be true in terms of overall site degradation or the loss of plantable sites, but it was clearly harvest operations that caused most of the stream damages observed. Torrent or torrent-like events damaged the most habitat, but inappropriate, if not illegal, activities (such as machinery in streams and trespasses over streams) caused or contributed substantially to some of the greatest individual problems.

Properly followed, the CFFG appeared to be effective in reducing many of the impacts associated with clearcut logging on streams. In some cases, more frequent on-site inspections before, during, and after harvesting are probably also needed to ensure better compliance. In other cases, better compliance likely requires some greater emphasis or modification of the guidelines. Chief among these is

the need to respect the integrity of streamside management zones and natural drainage patterns throughout the harvesting process, from road construction and harvesting to road deactivation or abandonment. The impacts that sometimes resulted from even small transgressions of this type were often out of proportion to their original significance. Finally, there is a need for a better appreciation in the field of the sediment and debris transport capabilities of all stream systems, and better decisions on how such streams should be logged. This is particularly true of steep country where compliance with the guidelines and reducing impacts on streams are apparently doubly difficult.

The combination of wide leave strips and clear, comprehensive site-specific prescriptions was easily the most effective means of protecting streams from all the varied impacts of logging. Agencies should be free to customize these "leave areas" or "buffer strips" to satisfy local conditions or unique problems, but strict defaults should be instituted if agencies are unable to comment on logging proposals or conduct the necessary field work. Evidence in this and earlier audits indicates that, in the absence of site-specific recommendations or strictly defined limits, compliance with the guidelines is very poor. The more room left for interpretation, the more likely minimum standards will be selected.

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The Spatial Variation and Routine Sampling of Spawning Gravels in Small Coastal Streams

STEPHEN RICE

The size distribution (texture) of the sediments that make up the bed of a stream channel are an important component of fish habitat. Efficient and accurate characterization of bed material in the steep, forested watersheds typical of British Columbia's coastal mountains requires a clear understanding of the nature and causes of textural variations. The accompanying poster describes the background, methods, and results of a study of bed material texture in two creeks on the Queen Charlotte Islands. On the basis of this study, sampling guidelines for habitat assessment and monitoring purposes are presented. The key recommendations, and some additional discussion of sampling techniques, are presented on this handout.

Recommendation 1: There is no simple relation between the full size distribution of subsurface material and the sizes visible on the surface. The former is largely responsible for redd-gravel permeability; the latter may limit the ability of some species to construct redds. Both populations should be sampled independently.

Notes on Subsurface Sampling

Obtaining dependable information about subsurface sediments is difficult yet crucial in helping us understand habitat issues. The subsurface sampling scheme used in this study proved to be both representative and realistic, and some additional discussion is therefore warranted.

A sediment sample must contain sufficient material for each size class to be represented in its true population proportion. A useful criterion for sampling at isolated sites is that any individual clast should not exceed 0.5% of the total sample weight. Wet samples of 80–90 kg can be collected and sieved with portable equipment in a few hours, and will yield representative samples of all sizes up to approximately 64 mm. A common truncation point

is necessary for any of the spawning quality criteria to be comparable between sites, and truncation is inherent in both freeze-core and McNeil sampling. The 64-mm limit employed in this study provides reliable information about those sizes that are of most interest in the context of subsurface permeability. Coarser material can be characterized by surface sampling.

The McNeil sampler enabled recovery of sediment in the active channel to a depth of 25 cm with minimal loss of fines. Shovelling material invariably results in loss of fines, while freeze-core techniques are biased toward coarse particles that adhere to the periphery. Up to six “pulls” were made across the pool-riffle break and pooled to provide the full sample. This approach also overcame any cross-channel heterogeneity. After sieving to 16 mm in the field a split of 5–10 kg was bagged for laboratory analysis.

Notes on Surface Sampling

Wolman surface samples of 100 stones, generally regarded as sufficient for the reasonable characterization of median size, were used in this study. Recent work at the University of British Columbia's Geography Department shows that samples of 300–400 stones significantly improve the precision of all grain-size parameter estimates, while additional increases in precision are achieved only at the expense of much greater sampling effort. Samples of this size should be collected wherever possible, and can be obtained in an hour or less if templates are used.

Notes on Photographic Sampling

The photographic technique used in this study provided limited information at a large number of sites. It is a valuable adjunct to regular surface

sampling, but not a general alternative. Regular samples are needed to construct a calibration curve, and this limits its value to work where a large number of samples are needed. Photographic methods that involve direct measurement from stereo pairs are probably more reliable, although problems of hiding and clast orientation must be considered.

Recommendation 2: The variance of surface and subsurface parameters indicates that 30 surface samples and 13 subsurface samples are needed to characterize bed material texture with 20% precision in small, steep, forested streams. Improved precision is achieved at the expense of greater sampling effort. Approximately 120 samples are needed to characterize surface D_{50} with 10% precision.

Recommendation 3: The lack of any spatial trends means that pool-riffle break sample sites can be arbitrarily positioned at accessible points along the

stream. However, major jams can affect sediment texture for many channel widths upstream and downstream, and it would be unwise to collect all of the necessary samples in such reaches.

Two outstanding issues could be the focus of future work:

- Within the constraints discussed above, the 64-mm truncation for subsurface sampling adopted here is somewhat arbitrary. A more informed judgement would be based on the resolution of an issue that has received little attention: over what range of sizes do gravel quality indices usefully relate to spawning, emergence, and rearing success?
- Within the coastal region it is possible that lithology and land use have an effect on the variability of bed material, with implications for sampling requirements.

Debris Avalanches-flows on British Columbia's North Coast

JIM W. SCHWAB

Study Description

Heavy rainfall is the dominant environmental factor contributing to rapid debris avalanches-flows on British Columbia's North Coast. The legacy of events triggering slope failures is carved onto hillsides as linear strips of vegetation.

The location of large failures is readily identified on air photographs. In selected study areas, slope failures were identified on air photographs and mapped. The identification of failures was repeated for each available photo coverage to determine the year of photography when the failure first appeared. The oldest photography available on the Queen Charlottes was from 1936 to 1937 and near Prince Rupert in 1947.

A field sampling program was undertaken in the Rennell Sound, Pivot Mountain (northwest Graham Island), and Prince Rupert area. Failures that were greater than 1 ha in size or large enough to extend into the valley bottom were sampled in the field to determine the possible date of the event. Tree sampling was done on slide deposits in the depositional zone or on levees within torrent channels. Generally, 10–15 core samples were obtained for each slide. Scarred trees located along the edge of a slide, and trees showing vigorous or suppressed growth, were also cored or a cross-section disk taken. A search for storm and landslide events recorded in newspapers, journals, technical reports, ship logs, diaries, and company documents was also undertaken. The ages of trees sampled on landslides were then compared

and linked to known events. A vegetation description of field-sampled landslides made it possible to group landslides viewed from a helicopter in a way that showed various canopy structure characteristics linked to specific events.

Preliminary Results

Preliminary study results have revealed notable ages for large landslides that have occurred over the past 150 years. Most of the landslide volume transported occurred during major events. The Riley and Gregory Creek watersheds, in the years 1875, 1891, 1917, 1935, and 1978 transported, respectively, 1.6%, 2.9%, 13.3%, 2.1%, 9.6% of the volume (Fig. 1). In comparison, Beresford Creek watershed experienced major events in 1875, 1891, 1917, and 1935, respectively transporting 16.5%, 10.8%, 36.2%, and 9.5% of the landslide volume (Fig. 2). Interestingly, Beresford Creek area did not experience landslides during the 1978 storm. Four major storms since 1875 moved 73% of the volume transported by landslides in the Beresford Creek watershed. Data collected for Graham Island and the Prince Rupert area indicate that six storms over the last 150 years transported 76% of the landslide material: 9.5%, 14%, 30.9%, 6.5%, 6.4%, and 9.1%, respectively, for the years 1875, 1891, 1917, 1935, 1957, and 1978. This historical documentation of landslide ages suggests that forest management activity on the North Coast has yet to experience the "Big Storm" similar to the 1917 event.

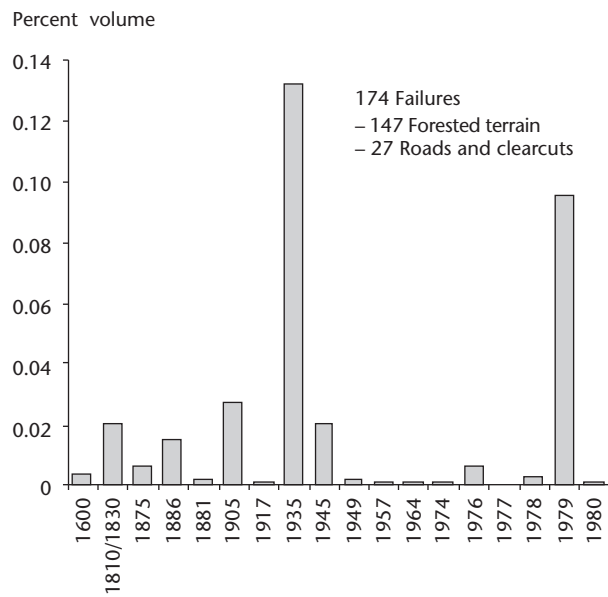


FIGURE 1 *Riley and Gregory Creeks, percent landslide volume by year.*

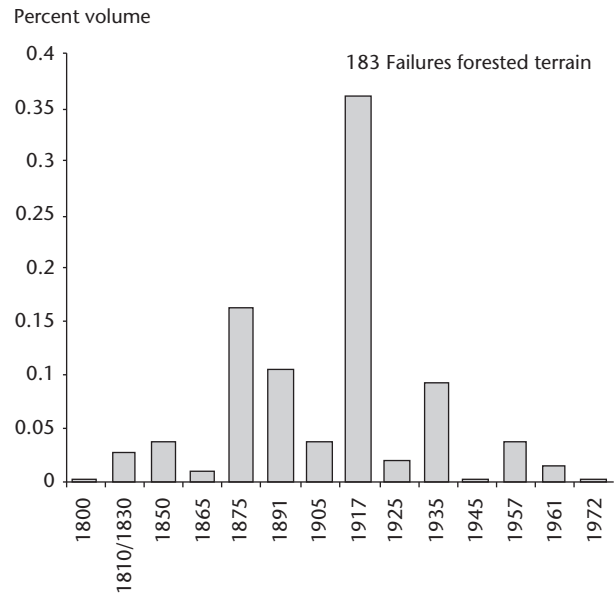


FIGURE 2 *Beresford Creek, percent landslide volume by year.*

Landslide Runout Behaviour in the Queen Charlotte Islands

R.J. FANNIN, M.P. WISE, AND T.P. ROLLERSON

Field observations of 449 debris flows on the Skidegate Plateau of the Queen Charlotte Islands are summarized. Movement of debris is classified according to seven characteristic types and an analysis of the data, using morphological criteria, is made with reference to event yield and deposition. The classification is based on event location (open slope or channelized), gradient of the path of movement, and whether two or more event paths join together. The data are used in an analysis of event initiation on open slopes, transportation and deposition of debris, and debris yield rates along the

path of movement. A key distinction is made between events on open slopes and those which initiate or travel within a gully.

With regard to runout behaviour, the total travel distance and volume of deposited material are found to vary with event type. Deposition of channelized events is found to be influenced by the ratio of channel width to channel gradient. Five classes of depositional area are proposed, based on the field observations. The use of the data for development of a simple model to predict debris flow travel distance is illustrated.

Landslide Reforestation and Erosion Control in the Queen Charlotte Islands

WILLIAM J. BEESE

Project Objectives

The objective of this project was to evaluate methods for early establishment of conifers on debris slides. Specifically, it sought to:

- compare conifer plantation success when combined with hydroseeding and shrub planting;
- test row versus grid shrub planting designs;
- test the suitability of several native shrubs and hardwood trees for slide planting; and
- measure erosion and vegetation cover.

The study area is a 2 ha debris slide near Sue Lake, about 20 km north of Queen Charlotte City on Graham Island in the Queen Charlotte Islands. The slide occurred in 1974 as a road-induced failure resulting from an overloaded fillslope. Since the initial failure, the size of the slide area had increased and only small islands of vegetation had become established before seeding and planting in March 1984.

Findings

Sitka spruce (*Picea sitchensis*) survival was over 80% after 10 years. Growth was extremely variable, ranging from less than 1 m on shallow, upper slopes to 3–6 m on lower slopes. Deer browse was heavy in the first season, but insignificant thereafter. However, early browse affected subsequent growth. There was no evidence that grass and legume cover adversely affected growth. The best seedling growth occurred where grass and legume cover was greatest. Annual growth rates have declined in the past 5 years, most likely a result of poor nutrition.

Native shrubs and hardwood trees tested were: Sitka alder (*Alnus crispa* ssp. *sinuata*), salmonberry (*Rubus spectabilis*), thimbleberry (*Rubus parviflorus*), hardhack (*Spiraea douglasii*), black twinberry (*Lonicera involucrata*), and willow (*Salix* spp.). Sitka alder had the best survival of the species tested. Continual browsing kept most of the alder under

20 cm tall. The best individuals were 60 cm tall after 10 years. Salmonberry also showed promise for slide plantings. Other species had very poor survival in this trial, although stock shipment and handling was probably a major factor. Sitka spruce had superior root biomass and aboveground growth to any of the shrubs and small hardwoods. Heavy browsing from deer prevented valid comparisons of the grid and row planting designs.

Grass cover peaked after three growing seasons at 60%, but declined by about 10% by year 10. Clover and birdsfoot trefoil cover reached about 20% after two seasons, but declined to 5–10% by year 10. Colonization of native forbs and shrubs reached 5–10% cover after 10 years. Moss cover increased substantially over time, reaching over 50% cover on one site.

The “erosion bridge” technique proved useful for monitoring surface level changes over time. After 5 years, the ungrassed portion of the slide showed an average loss of 3 cm of soil, or about 80 Mg/ha per year. This represents an average of upper slopes that lost 11 cm of soil, and middle to lower slopes that gained up to 2 cm of soil. On adjacent grassed areas, there was a net gain of 1 cm in the surface level after 5 years. Changes in surface level were extremely variable.

Recommendations

- Exposed mineral soil on landslides and roadsides should be seeded immediately to reduce soil loss.
- Conifers should be planted on landslides after grass-legume seeding where there is sufficient depth of productive soil.
- Sitka alder and salmonberry can be used to revegetate landslides where browse pressure is not severe. Red alder may be a better alternative to Sitka alder because of rapid growth rates.
- Refertilization may be required to maintain tree growth and vegetation cover on landslides.

River Otter Predation on Juvenile Salmonids in Winter: Preliminary Report of River Otter Scat Collection and Diet Analysis

J.M.E. BALKE, P.J. TSCHAPLINSKI, S.J. CROCKFORD, AND G. SUTHER

Several creeks in the Queen Charlotte Islands, British Columbia have been identified as sites where the rates of river otter (*Lutra canadensis*) predation on overwintering juvenile coho salmon (*Oncorhynchus kisutch*) and rainbow trout (*O. mykiss*) might be high. A study was undertaken in six watersheds on Graham and Moresby islands to determine the presence or absence of river otters, to assess the feasibility of collecting analyzable river otter scats in winter, and to identify river otter prey species from scat analysis.

Over 500 river otter scats were collected from seven creeks during surveys in November 1992 and February 1993. The November sampling period corresponded with the end of salmon spawning runs and bones of adult salmonids were found in scats from all creeks and shorelines. In February, when spawning salmon were unavailable, the scats

contained bones from salmonids as well as 19 other freshwater and marine fish species/genera. River otters using these creeks were also foraging in the ocean. Juvenile salmonid bones were found in the scats from four creeks in November and from all creeks or adjacent shorelines in February. Fresh samples of at least 97 scats, collected in February from four river systems, contained 347 salmonid otoliths. Ninety-three percent of these otoliths were between 1.5 and 2.5 mm long.

This study confirmed that river otters use these river systems in the Queen Charlottes during winter and that, despite the adverse weather conditions, river otter scats can be readily collected and the prey species determined. To further quantify the impact of river otter predation on overwintering salmonids, a more detailed study of river otter populations in these watersheds would be required.

Applications of Photography in Geomorphology: Size Scales and Appropriate Platforms

DARREN HAM AND DAN HOGAN

Objective

A general overview of several photographic techniques available for use in field investigations of small (1–10 m²) to large (>100 km²) geomorphic features is given. These techniques range from inexpensive manual methods (e.g., unipod or balloon photography) to comparatively expensive remote sensing methods such as standard aerial photography and satellite imagery. The photographs can be used for a wide variety of purposes, depending on the objectives of the project and the level of accuracy required. Some examples of their application in geomorphology are provided.

Photographic Techniques

Photographic documentation is common in most geomorphic studies and at spatial scales ranging from photos of streambed morphology and sedimentology at the large scale to satellite pictures of entire regions at the very small scale. Additionally, chronological sequences of photos are commonly used to document temporal changes. These examples are probably fairly well known to geoscientists. However, documentation at intermediate scales is often poor; features are generally too large to photograph using standard hand-held 35-mm cameras, and correspondingly too small to be evaluated from conventional aerial photography. Another problem is that, at the intermediate scale, features of interest are often partially or fully obscured from view by vegetation, particularly along stream channels. Three relatively unknown techniques of photographic documentation are further presented here to address these problems. Figure 1 illustrates the different techniques that are appropriate for the study of different geomorphic features.

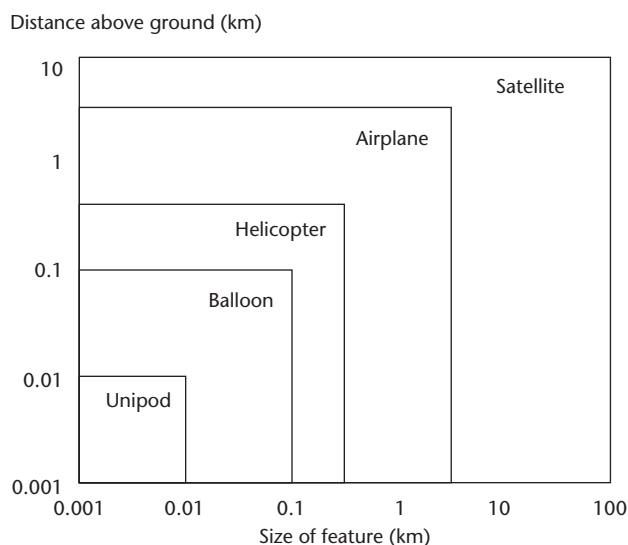


FIGURE 1 *Size scales and appropriate platforms for different photographic techniques.*

Unipod Photography

For smaller features, two main techniques can be used. The first of these is the unipod, a 10-m long rigid pole that supports a 35-mm camera held aloft. A telescoping antenna or janitorial “tuck” pole are appropriate. The camera is attached to the pole using a self-levelling gimbal, which allows adjustments to accommodate different cameras and winders. Winders enable the frames to be advanced without having to lower the pole. Two people are required to operate the system, which simply works by raising the pole, taking the necessary frames, and advancing the pole to a new position. Typical stream channel features that can be viewed include sediment texture, flow lines, areal sorting, and scour

holes. This allows the photos to be used in providing an assessment of channel hydraulics, morphology, and habitat conditions. The accuracy of measurements made using this system depends on both the pole being vertical and the presence of a scale device (such as a metre ruler) in the photo. A <10 cm horizontal error is reasonable.

Balloon Photography

Balloon photography uses a 35-mm (or other) camera attached to a tethered helium-filled balloon. The balloon may be of a variety of sizes and shapes, but must be able to support the camera and gimbal, which are connected to the balloon by strong line. Similarly, strong kevlar or monofilament fishing line can be used to tether the balloon to the ground. A remote camera controller is required to signal the shutter and film winder. To use the system, operators assemble all equipment and raise the balloon and camera platform to a desired height (using a marked line for elevation reference; a surveyor's hip chain with thread works best). The height is determined both by the size of the feature to be photographed and the lens used.

Once the photos have been taken, the operators simply walk to a new ground position where the distance moved is a function of the camera height and the desired overlap between frames. Balloon photography is useful on slightly larger systems. Although certain sediment texture characteristics are lost, the photos provide fairly detailed information on habitat, channel morphology, and stream hydraulics. Flow patterns, large organic debris and other channel obstructions, pool-riffle sequences, and bar morphology can be observed from the photos.

Both the unipod and balloon low-altitude techniques provide a level of morphologic detail that cannot be obtained from more conventional methods. Photos are generally of high resolution and are provided at low cost, making them ideal for long-term projects requiring repeat surveys. However, these techniques are unsuitable for photogrammetric mapping because of camera tilt and drift. They are more appropriate for projects where qualitative assessments are required. Planimetric measurement errors no greater than 10–20 cm would be reasonable using this method.

Helicopter Boom Photography

The helicopter boom system consists of two 70-mm Hasselblad cameras attached to the end of a 6.1 m long boom, which in turn is attached to the bottom of a Bell Jet Ranger helicopter. The system is particularly flexible as it can provide high resolution stereo photographs at scales from 1:200 to 1:1200 using the standard 100-mm lens. Smaller scale photos can be flown, but vertical exaggeration (stereo image quality) is greatly reduced. Typically, photos are taken by triggering both cameras simultaneously, so differences between image pairs are due to the physical separation of the cameras. However, the system can also be configured such that one or both cameras fire at different times. In effect, because this replicates the technique used to acquire conventional aerial photography, photo scale can be reduced without affecting stereo resolution. The images are generally very clear and detailed because of the high quality camera lens and can be used to create detailed maps. They can also be used to provide either a qualitative or quantitative assessment of riparian habitat and channel morphology features. If ground reference points are available, both vertical and horizontal measurements can be made to an accuracy of <15 cm (based on previous tests).

Airplane Photography

Conventional aerial photography is very familiar to most readers. All regions of British Columbia are covered by several years of photography at a variety of scales. The main limitation of this format is that any specific geographic region of interest may not be well represented. There may be only a few years of available photos, no recent (or very old) photography, and no large scales. Nonetheless, this format of photography is especially useful for terrain analysis, qualitative land assessment (e.g., studying the effects of harvesting on slope stability), and general mapping purposes. Small features, however, cannot be studied because of the limitations of image resolution. For larger rivers (>30 m width), conventional aerial photography can be used to provide such information as log jam and pool-riffle spacing, channel width, and changes in channel pattern.

Detailed maps have been made with the aid of an analytic stereoplotter, a device that mathematically relates two-dimensional coordinates on stereo photos to three-dimensional coordinates on the ground surface. Photos are “tied” to the ground using surveyed points or topographic maps as base reference. This allows the operator to collect distances, areas, angles, and slopes directly from the photographs (both conventional and helicopter photos). These data can be collected and stored on a PC, or imported into CAD/GIS systems for further analysis. The accuracy of the system is largely operator dependent, but typical results would be 0.5–2.0 m horizontal and 0.5–3.0 m vertical, depending on the scale and quality of the photos. Although the device is generally used as a mapping tool, the mapped data has been used to make quantitative assessments of channel morphology,

including areal and width changes and locations of aggradation and degradation. This technology is fairly expensive, however, and it is relatively time consuming to collect the data if many stereo models are involved.

Summary

Individuals who are using (or plan to use) photography in their field work are urged to carefully consider two things: first, what purpose the photographs are being taken for; and second, what the most appropriate technique is to use. Considerable time and expense could be wasted if these simple points are not followed. Those interested in exploring the techniques listed in this write-up may obtain more information from the authors.

Terrain Attribute Study: Slope Failure Frequencies Following Logging in Coastal British Columbia

B. THOMSON

The identification of terrain that will be subject to slope failures following logging or road building is a high priority for forest management in coastal British Columbia. This information can be used at the planning level to ensure that annual allowable cuts (AAC) calculations reflect the land base truly available for harvest, and at the development stage to ensure that environmentally sensitive areas are not damaged.

There is a need for a more objective and quantitative approach for the prediction of post-logging slope stability. This approach requires the collection of data on the frequency of slope failures following logging, so that the reliability of the criteria used by mappers for slope stability assessments can be improved.

An empirical approach, applied to a representative sample of landscape units over a wide geographical area, has potential for quantifying the likelihood of landslide occurrence. The objectives of the study are two-fold:

1. to characterize steepland terrain types that are subject to slope failures following conventional clearcutting and road building, and those which are not; and
2. to develop a multi-factor terrain-based stability classification system that addresses the likelihood and frequency of slope failures occurring following conventional clearcutting and road building.

The study area involves a number of large contiguous land units within the western portion of the Insular Mountains of Vancouver Island, and the Cascade Mountains and southern Coast Mountains on the British Columbia mainland. The study is ongoing; data acquisition is completed for the Vancouver Island portion, and data acquisition for the Cascade and Coast mountains will begin this field season.

Methodology, including data collection and analysis, were presented. An example of results of analysis of a limited set of data was also presented.

Quantifying Basin Comparisons in the Queen Charlotte Islands

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Because of the subjectivity in previous methods of comparing drainage basins, there is a need to quantify such procedures. This study (Cheong 1992) attempted to formalize the analysis of similarity in an objective manner within the framework of a knowledge-based system. The 31 basin characteristics that were assessed can be categorized into four groups: landscape (e.g., geology); geometry (e.g., relief); topology (e.g., order); and history (e.g., mass wasting).

A comprehensive similarity comparison procedure was developed to incorporate different levels of information (ordinal, interval and ratio) and standardization of mensuration. The three stages of the procedure are:

1. for ordinal information – binary test
2. for interval information – $d_{ijk} = (w_i(x_{ij} - x_{ik})^2 / 0.25 * R)$
3. for ratio information – $d_{ijk} = (w_i(x_{ij} - x_{ik})^2 / \sigma)$
where d_{ijk} is the dissimilarity of variable i between basins j and k , w_i is the weighting, x is the characteristics, and R and s are the range and the standard deviation of i , respectively. These similarity testing procedures were combined and developed into a knowledge-based system (Cheong 1992).

The analysis was performed on 28 characteristics of 65 drainage basins from Rennell Sound and South Moresby Island. If only geometric and topologic parameters are used (interval and ratio data), basin similarity is not limited by proximity, and the most similar basin to a watershed in Rennell Sound may be on South Moresby. However, if certain landscape parameters are included in the analysis (such as geology or vegetation), this typically limits the scope of the analysis to a region in close proximity to the basin in question. The weighting of parameters in the analysis also affects the cluster structure and grouping of similar watersheds.

The common assumption that the most similar basins are the ones in closest proximity is not always correct. Further work is required in determining the level of similarity needed to obtain two characteristically similar basins. While current research in common basin morphometric groupings in British Columbia suggests that the similarity test can be limited to approximately six characteristics, research on determining relevant characteristics at a smaller scale for the Queen Charlotte Islands needs to be expanded.

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Riparian Area Response to the Development of a Lateral Sediment Wedge

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At the scale of a watershed, forest ecosystems operate as a landscape consisting of a mosaic of patches different in shape, type, and function (Forman and Godron 1986). Individual forest patches are both interconnected and interdependent, fundamentally linked by the transfer of water through the system. The riparian area amplifies the significance of these connections, as water, biomass, and sediment are concentrated from within a watershed and either temporally stored or transported directly out of the system. DeBano and Heede (1987) suggest that the soils, geomorphology, and hydrology of the riparian area evolves through a series of aggradation and degradation steps following the establishment of a channel structure such as a log jam. (In steep, forested watersheds on the Queen Charlotte Islands, log jams disrupt sediment transport by creating a local base level that initiates the deposition of a sediment wedge [see, for example, Hogan et. al., this volume].) Those plant species most tolerant of a specific range of flooding disturbance establish along a gradient of decreasing flood frequency and intensity above bankfull stage (see Hupp 1988). Consequently, riparian plant communities are expected to form bands that parallel the stream channel, each occupying a unique elevation above bankfull stage.

Field work was conducted in 1991 on a 3.75-ha riparian area in the Gregory Creek watershed, Rennell Sound. Thirty-eight discrete patches of riparian vegetation representing four seral stages were identified: pioneer seral (12 yr), young seral (71 yr), maturing seral (99 yr), and maturing edaphic climax (>250 yr). Ages were determined by coring the oldest living trees found in each seral stage and counting the growth rings. The elevation of each seral stage, relative to bankfull stage, was measured by a series of surveyed transects. Only the elevation of the pioneer seral vegetation was unique, and it was therefore concluded that repeated

episodes of flooding behind log jams did not represent the dominant process responsible for the distribution of riparian forest patches in Gregory Creek.

However, the ages of the pioneer, young, and maturing seral stages did correspond to episodes of mass wasting documented by Schwab (this volume) that occurred throughout the watershed in 1978, 1917, and 1891. Analysis of log jams in the study site suggested that during these episodes, an increase in discharge and sediment transport forced the channel around existing log jams, out of the channel, and into the riparian area. Patches of vegetation were destroyed as log jams shifted laterally across the valley bottom. Once flow subsided and the sediments stabilized, opportunistic, pioneering riparian vegetation colonized the fresh alluvium deposited in the sediment wedge.

Patterns of riparian vegetation are ultimately determined by the spatial and temporal adjustment of the stream channel. In Gregory Creek, the response of the stream channel to mass wasting has created a mosaic of forest patches different in age and successional status, independent (with the exception of the pioneer seral) of their position relative to bankfull stage.

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