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

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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-

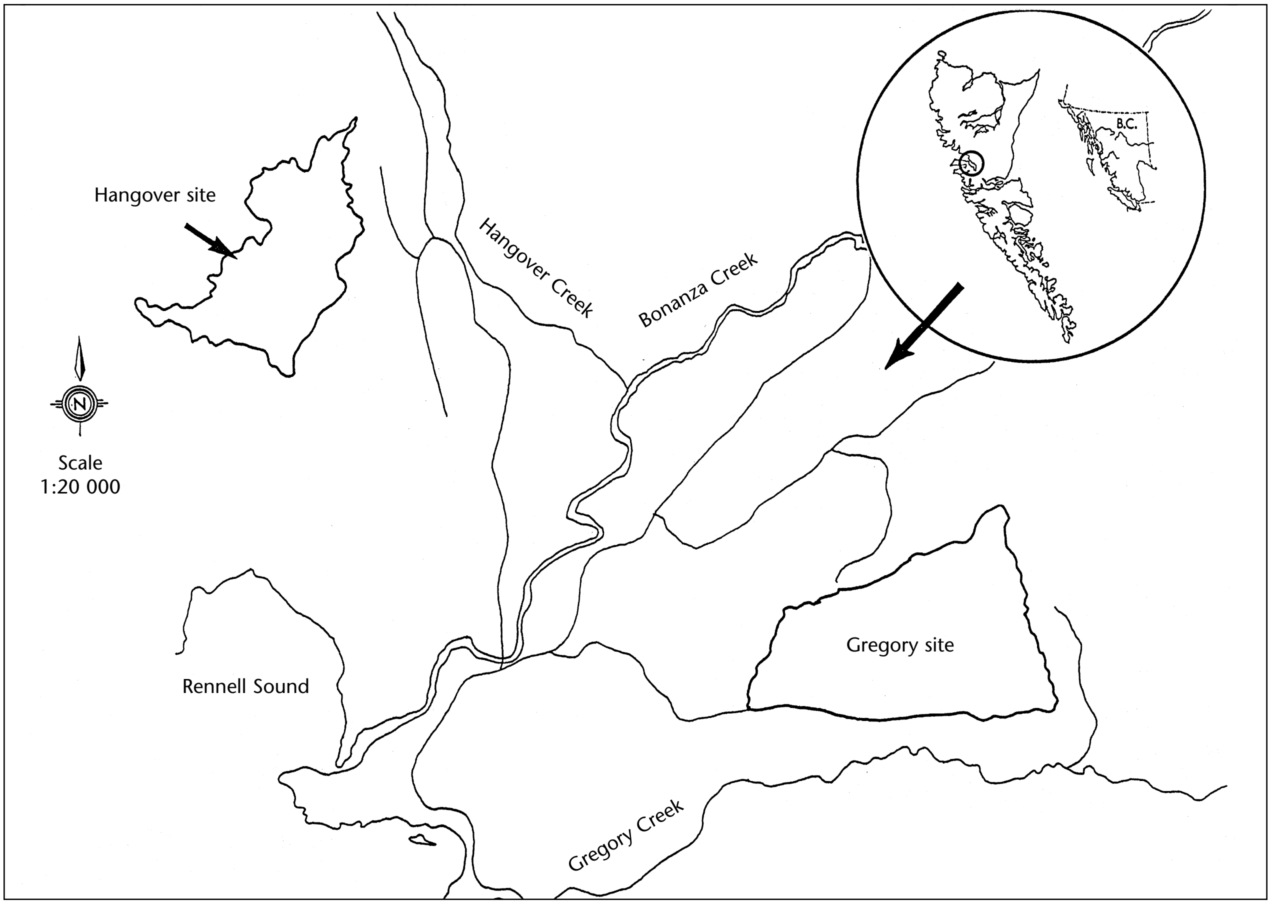

FIGURE 1 *Location of study area in Rennell Sound on the west coast of Graham Island, Queen Charlotte Islands.*

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 m^3/ha on Hangover Creek and 629 m^3/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

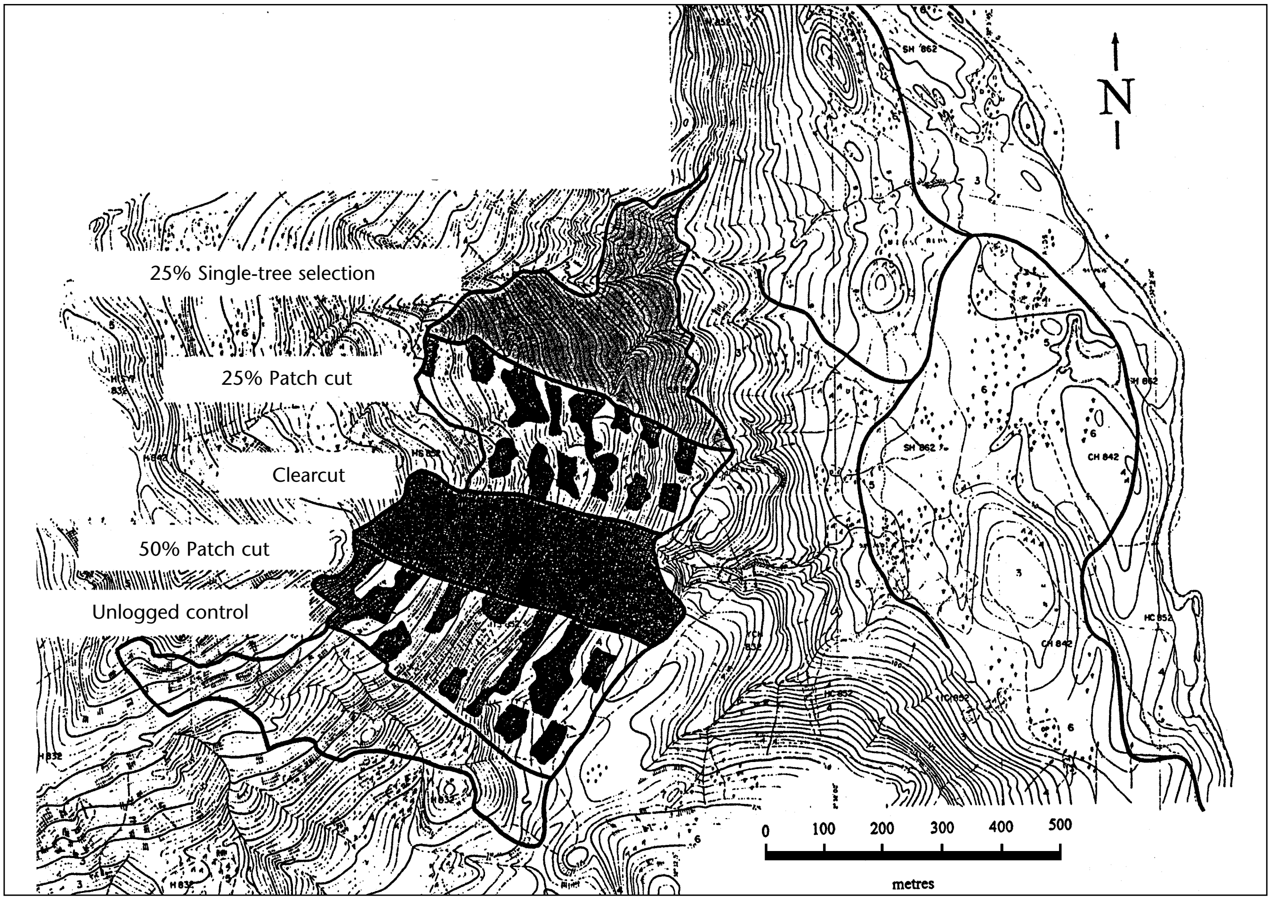

FIGURE 2 *Rennell Sound helicopter-logging trials: Hangover Creek.*

(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 hooktender, 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 × 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 m^3, 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 m^3 per cycle on Hangover Creek, and 26.2 turns, 117.2 logs, and 166.6 m^3 per cycle on Gregory Creek. ("Turn" refers to the sequence of activities required to transport logs from 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.

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	–

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 × yarding distance (m))
= 0.47 min. @ 751 m
Travel loaded time (min.) = 0.44528 + (0.000355 × yarding distance (m))
= 0.70 min. @ 731 m

Gregory Creek:
Travel empty time (min.) = 0.22542 + (0.000270 × yarding distance (m))
= 0.33 min. @ 370 m
Travel loaded time (min.) = 0.38849 + (0.000317 × yarding distance (m))
= 0.49 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*

	Hangover Creek		**Gregory Creek**	
Treatment unit	**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 Gross turn weight (kg)	Hangover Creek Change (%)	Gregory Creek Gross turn weight (kg)	Gregory Creek Change (%)
Clearcut				
gross weight (kg)	6712	–	6575	–
net volume (m^3)	6.79		6.39	
50% Patch cut				
gross weight (kg)	6819	+1.6	6643	+1.0
net volume (m^3)	6.91		6.46	
25% Patch cut				
gross weight (kg)	6841	+1.9	6687	+1.7
net volume (m^3)	6.93		6.50	
25% Single-tree selection				
gross weight (kg)	6677	-0.5	6553	-0.3
net volume (m^3)	6.76		6.36	
15% Single-tree selection				
gross weight (kg)	n/a	n/a	6088	-7.4
net volume (m^3)	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 cm^2. Large scars, which for the purposes of this paper were defined as scars greater than 900 cm^2, 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*

	Hangover Creek		Gregory Creek	
Treatment unit	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.) (no.)	Tress with scars of any size (no.)	Tress with scars of any size (%)	Trees with scars >900 cm² (no.)	Trees with scars >900 cm² (%)
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					
	Undisturbed (%)	Preharvest exposed mineral soil (%)	Disturbance resulting from logging (%)	Slash (%)	Other (%)	Total (%)
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 m^3 per shift in clearcuts; 100 m^3 per shift in patch-cuts; and 85 m^3 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/m^3), intermediate for the patch cuts ($51.99–$53.71/m^3), and highest for the single-tree selection cuts ($56.84–$60.62/m^3). For the 50%

TABLE 9 *Combined falling and yarding costs per cubic metre for the Gregory Creek study site (excludes loading and hauling phases)*

	Treatment unit				
Cost centre	Clearcut ($/m³)	50% patch cut ($/m³)	25% patch cut 25% Patch cut ($/m³)	25% single-tree selection ($/m³)	15% single-tree selection ($/m³)
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 cm^2) 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, Higgens, 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 (Cummans 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

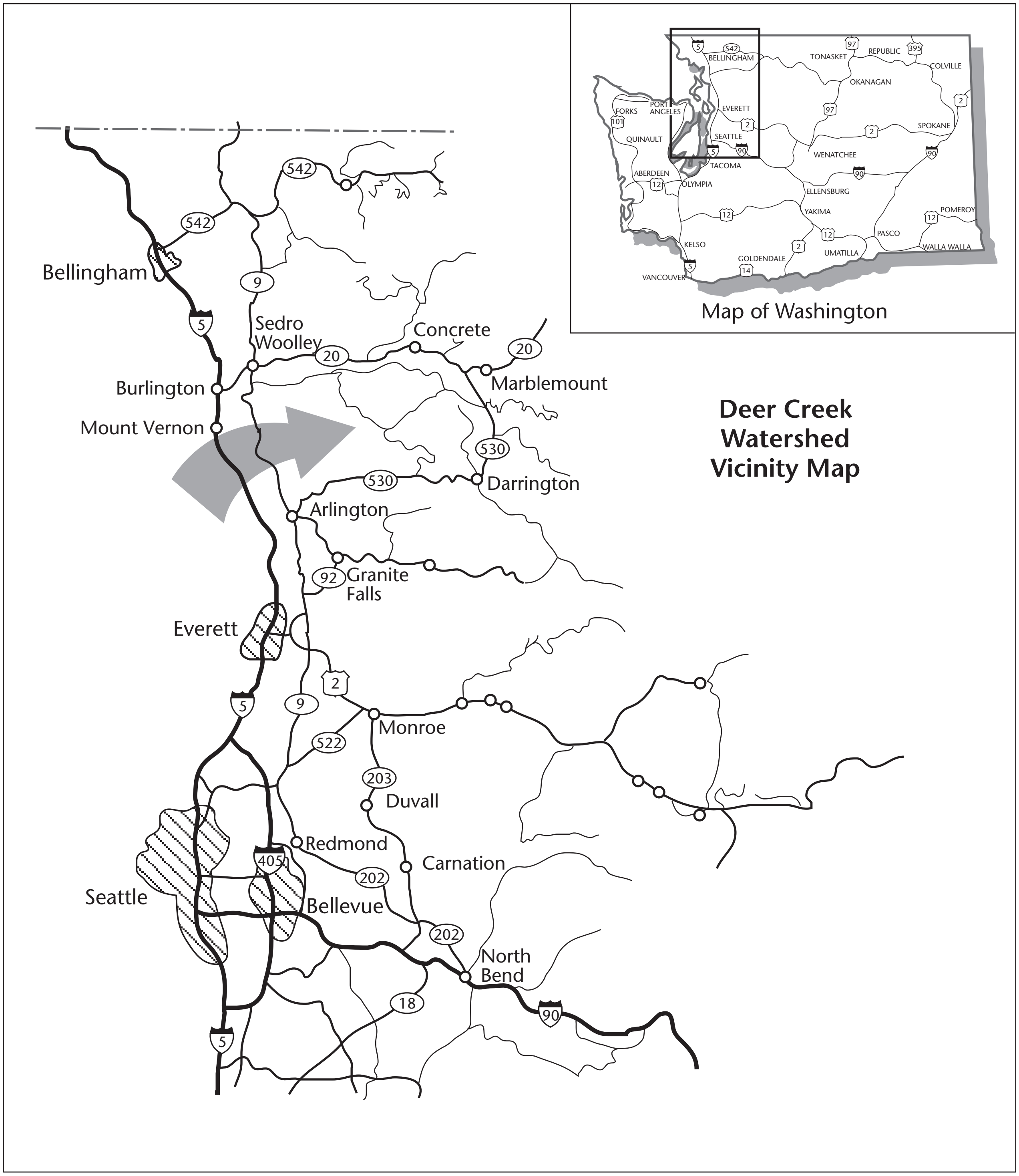

FIGURE 1 *Location of Deer Creek Watershed, North Cascades Mountain Range, Western Washington.*

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 (Tulalips 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 if 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 Higgens 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 Higgens 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 m^3 (85 000 ft^3) 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

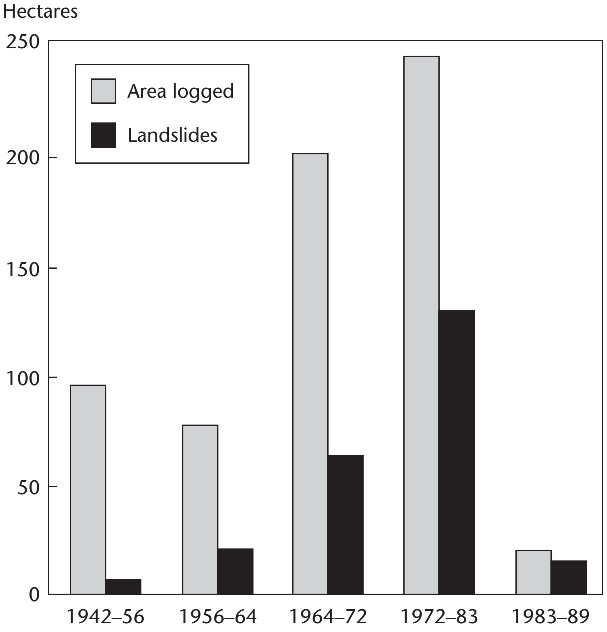

FIGURE 2 *Relationship between the number of landslides and the area of Deer Creek logged within a 48-year period (from Eide 1990).*

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 a 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 a 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 Higgens 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 streambanks 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 outsloping 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 where 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 a 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 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/ torm-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 landowners. 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/m^2 and the density in 1992 was 0.071 fish/m^2. 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 km^2 in size which contain fish populations or have habitat that could potentially support fish populations. Watersheds are subdivided into subbasins 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	UBC, Forestry and Civil Engineering
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.

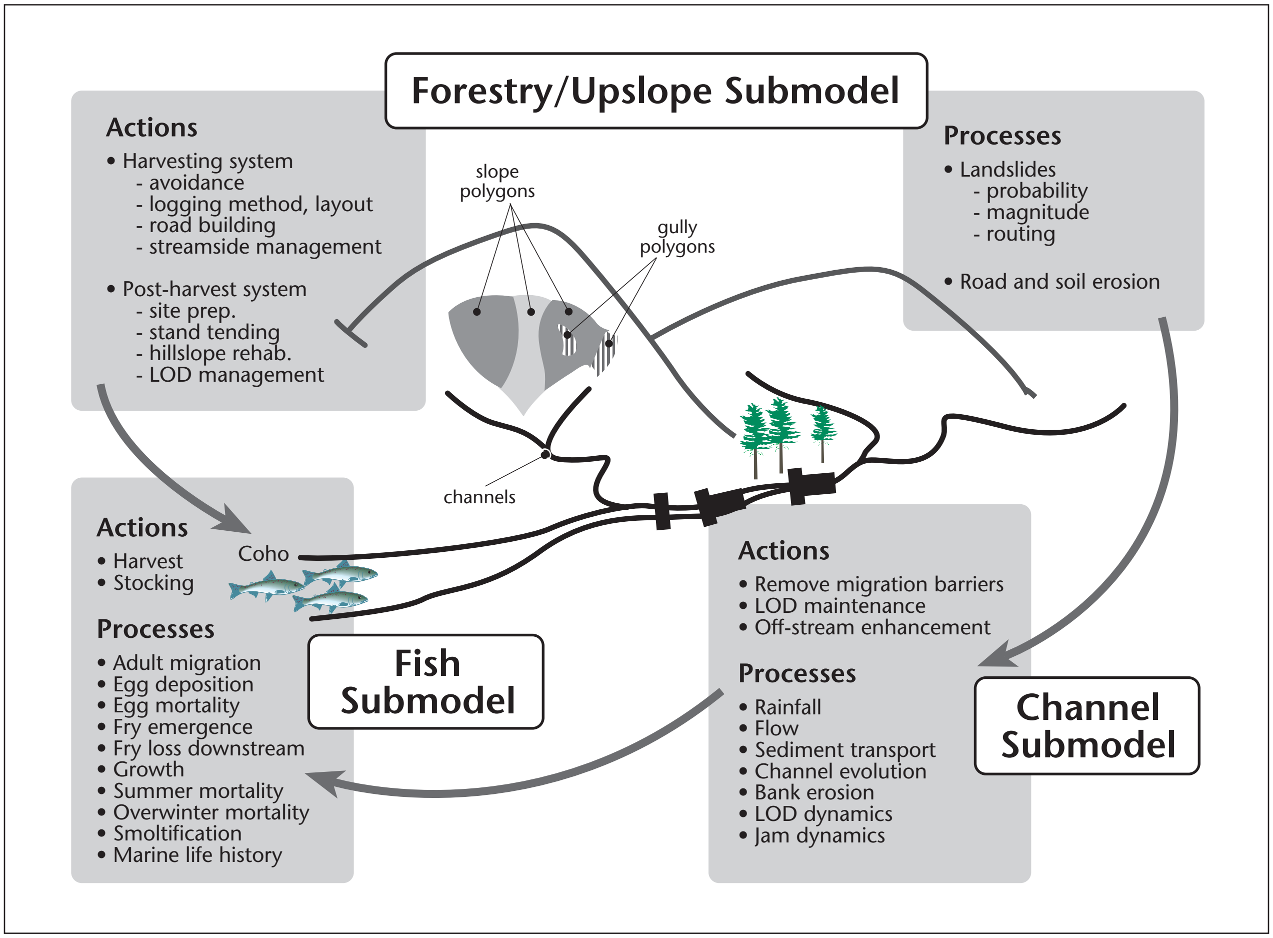

FIGURE 1 *Management actions and processes included in the design of the Fish/Forestry Interaction Program Simulation Model (FFIPS).*

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.

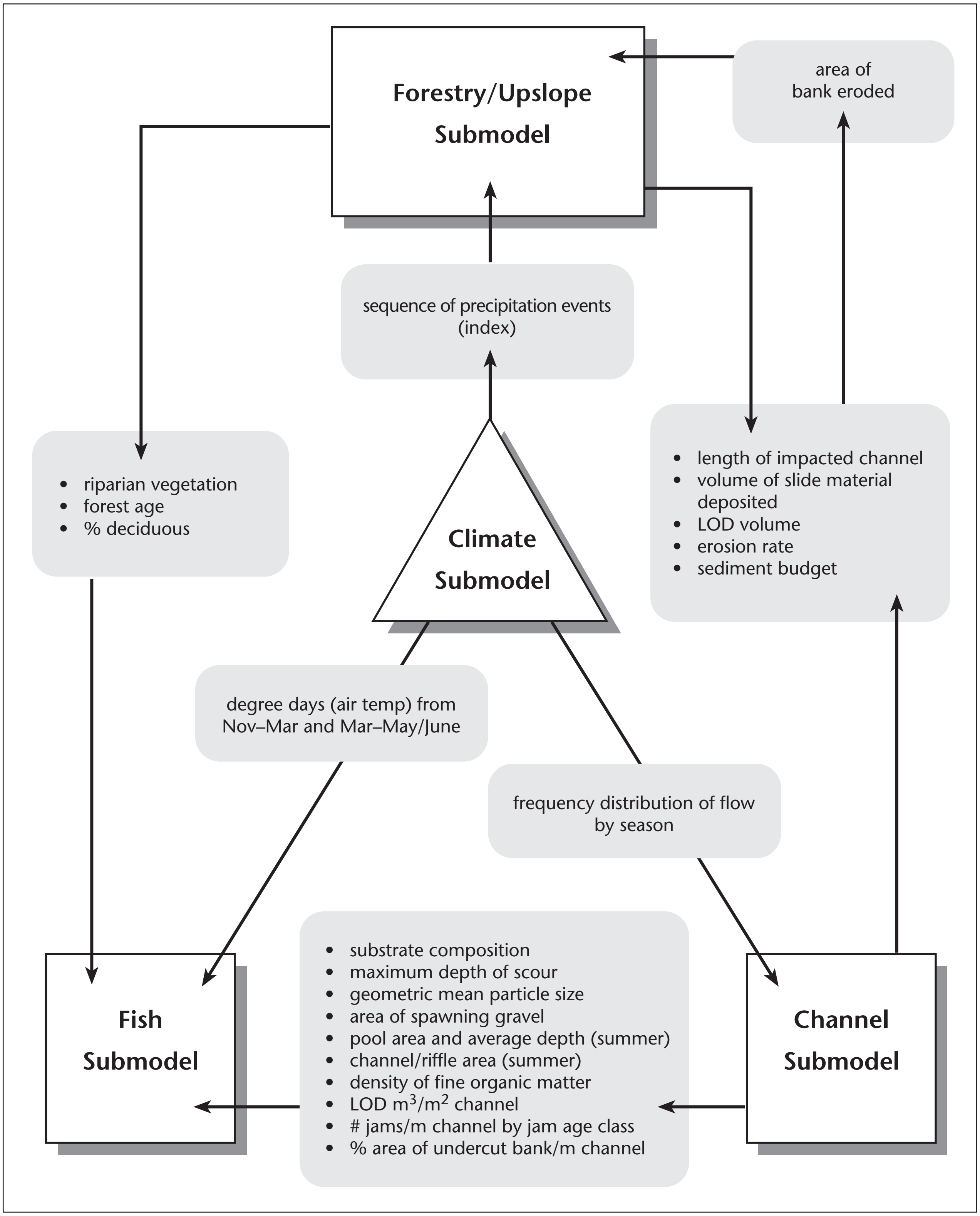

FIGURE 2 *Schematic representation of the linkages between the three submodels conceptualized at the December 1991 model design workshop.*

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).

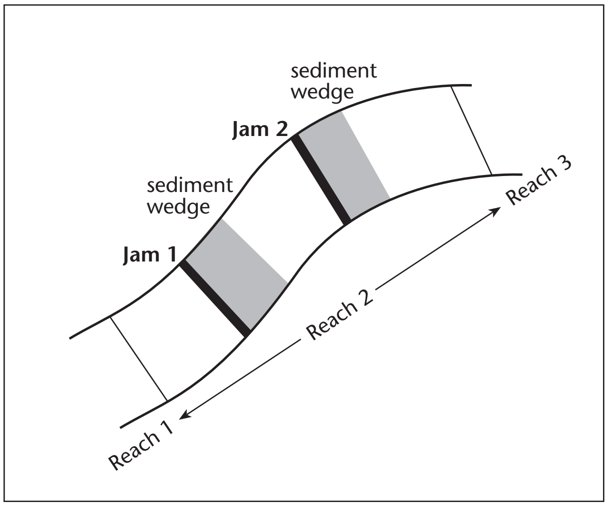

FIGURE 3 *General spatial structure of the channel submodel.*

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).

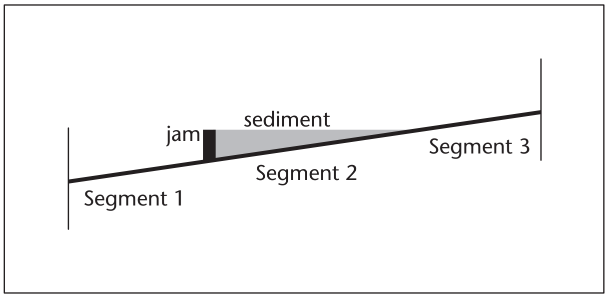

FIGURE 4 *Separation of a reach into three reach segments as a result of the presence of a jam.*

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 m^3; 0.1<medium, <1 m^3; large, >1 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 m^3 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 an 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 highlight 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.

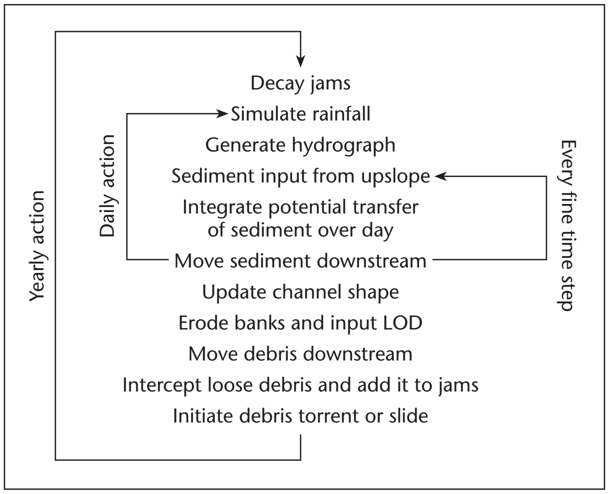

FIGURE 5 *Order and frequency of events performed by the channel submodel.*

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

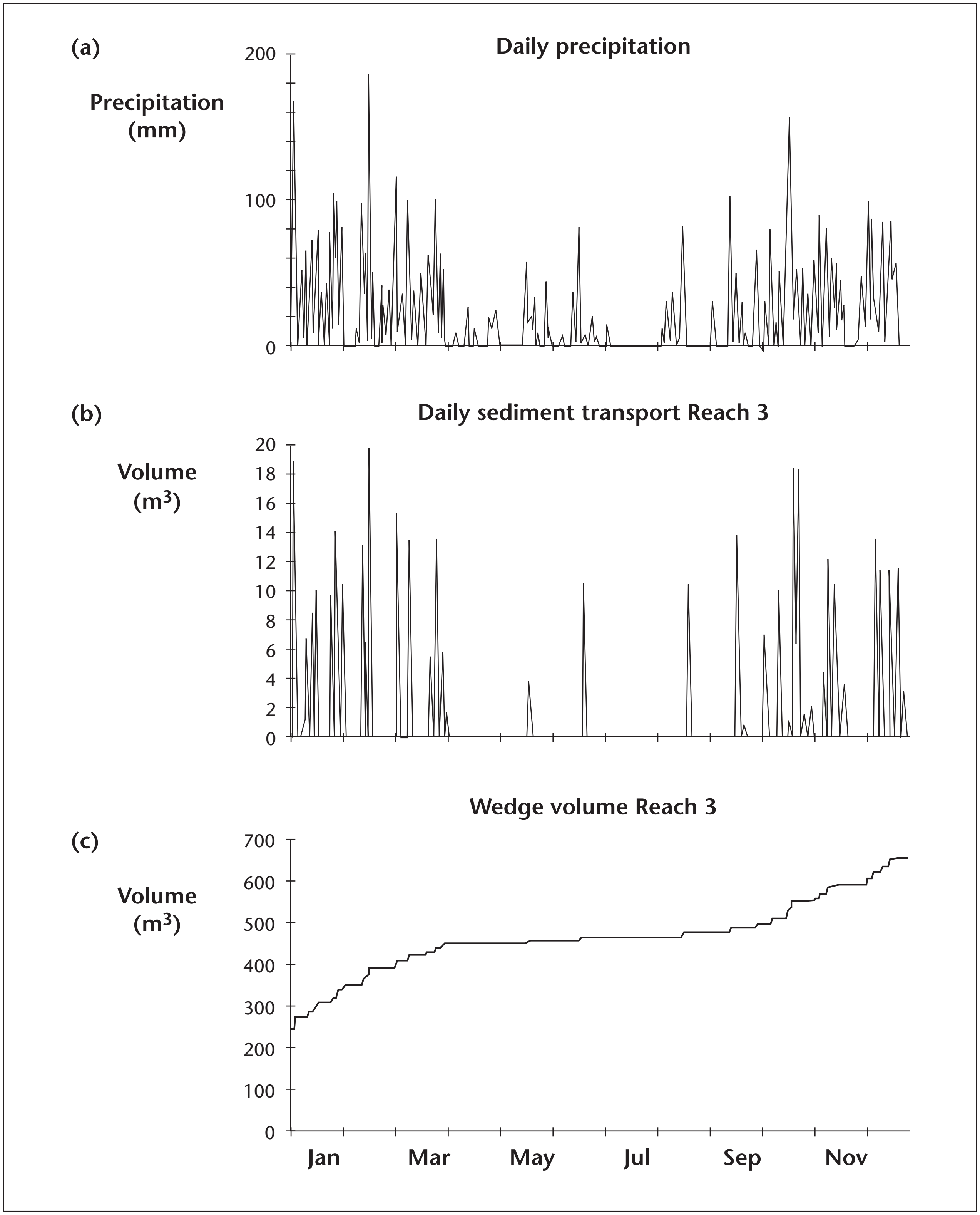

FIGURE 6 *Comparison of (a) daily precipitation, (b) daily sediment transport, and (c) wedge volume in a single reach for 1 year.*

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 m^3, 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 is 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.

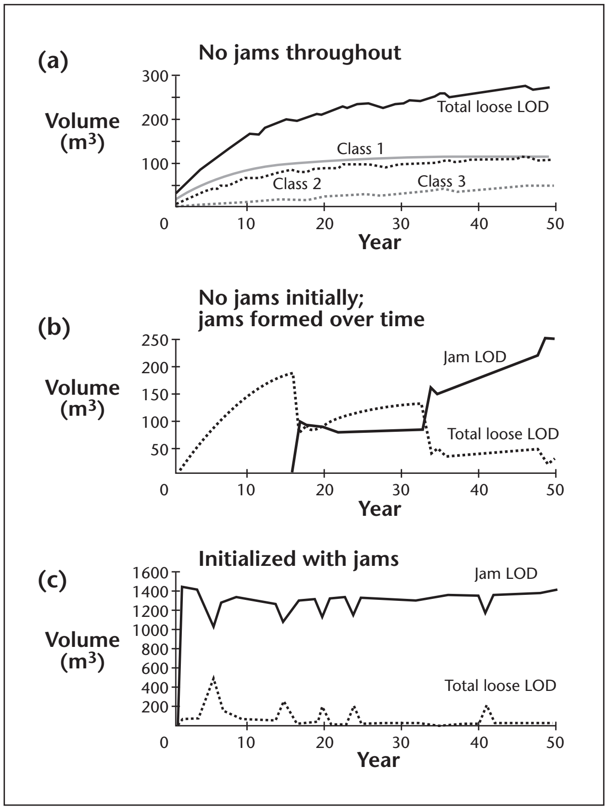

FIGURE 7 *Large organic debris (LOD) behaviour in Reach 3 of Government Creek, Queen Charlotte Islands, under three scenarios of jam formation: (a) no jams, (b) no jams initially, but jams form over time, and (c) jams initialized as in Government Creek. Class 1 = small LOD (<0.1 m^3), class 2 = medium LOD (0.1–1 m^3), and class 3 = large LOD (>1 m^3).*

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 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

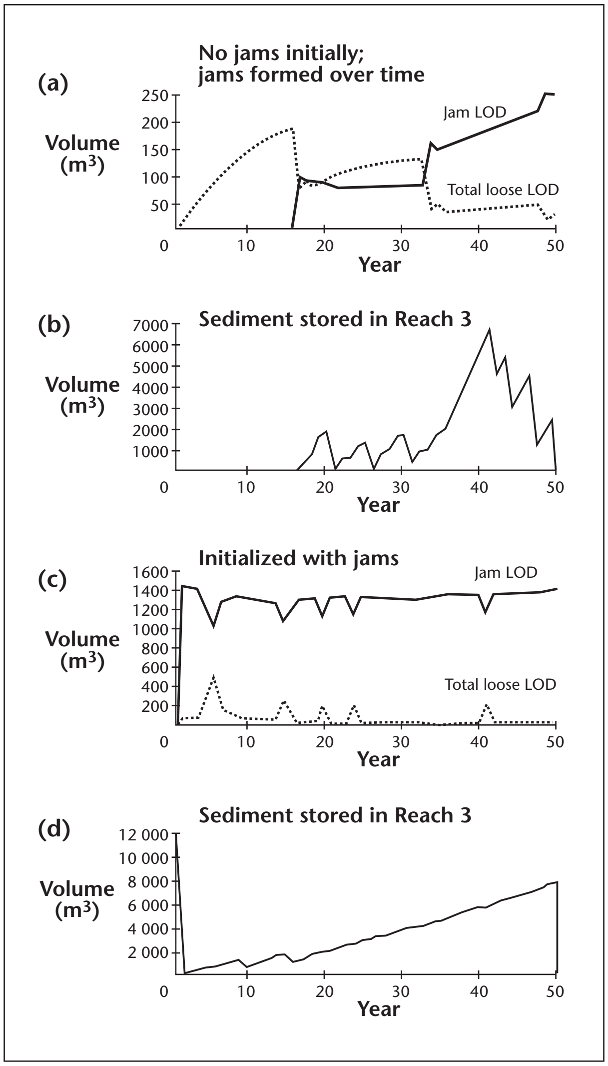

FIGURE 8 *Loose LOD, jam LOD, and sediment storage in a single reach for two scenarios of jam formation: no jams initially, but jams form over time (a, b), and jams initialized as in Government Creek, Queen Charlotte Islands (c, d).*

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

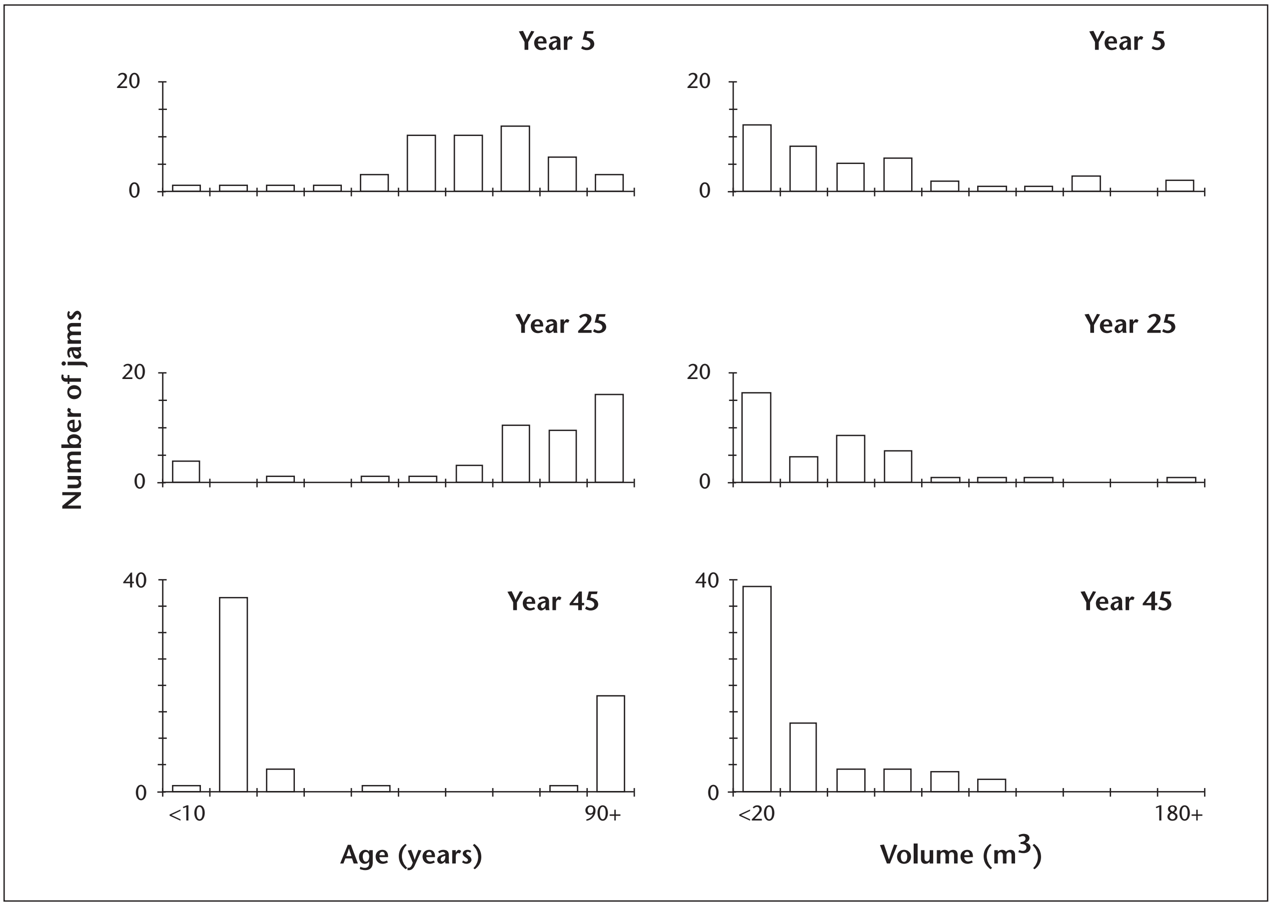

FIGURE 9 *Frequency distributions of jam age structure and jam LOD (m3) in a single reach after 5, 25, and 40 years. Jams initialized as in Government Creek, Queen Charlotte Islands.*

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 cutblocks 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.

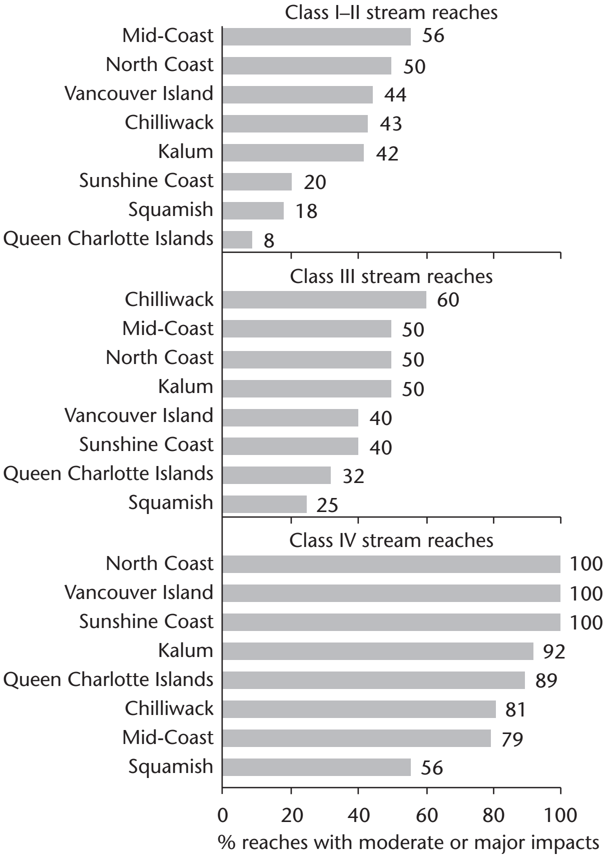

FIGURE 1 *Percent of streams with a moderate or major impact, by Forest District and stream class. Class IV streams refer only to Class I–III tributary streams with a moderate to high transport potential.*

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 m^2) than poor road practices (16 000 m^2).

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.

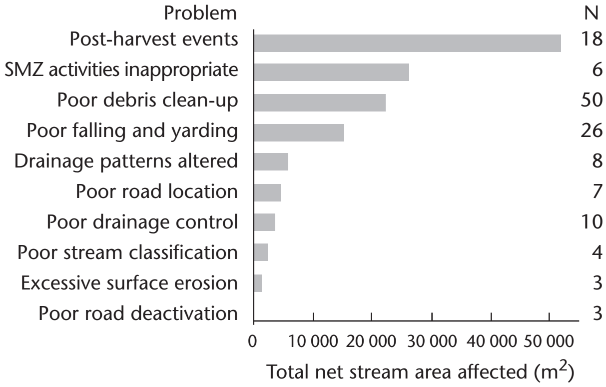

FIGURE 2 *Total net stream area (m²) affected by each of the 10 main problems observed in coastal Forest Districts of British Columbia. Numbers arranged vertically on the right are the number of times each problem was observed. SMZ – Streamside Management Zone.*

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. Road deactivation work accounted for the least area affected per incident (70 m²), 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

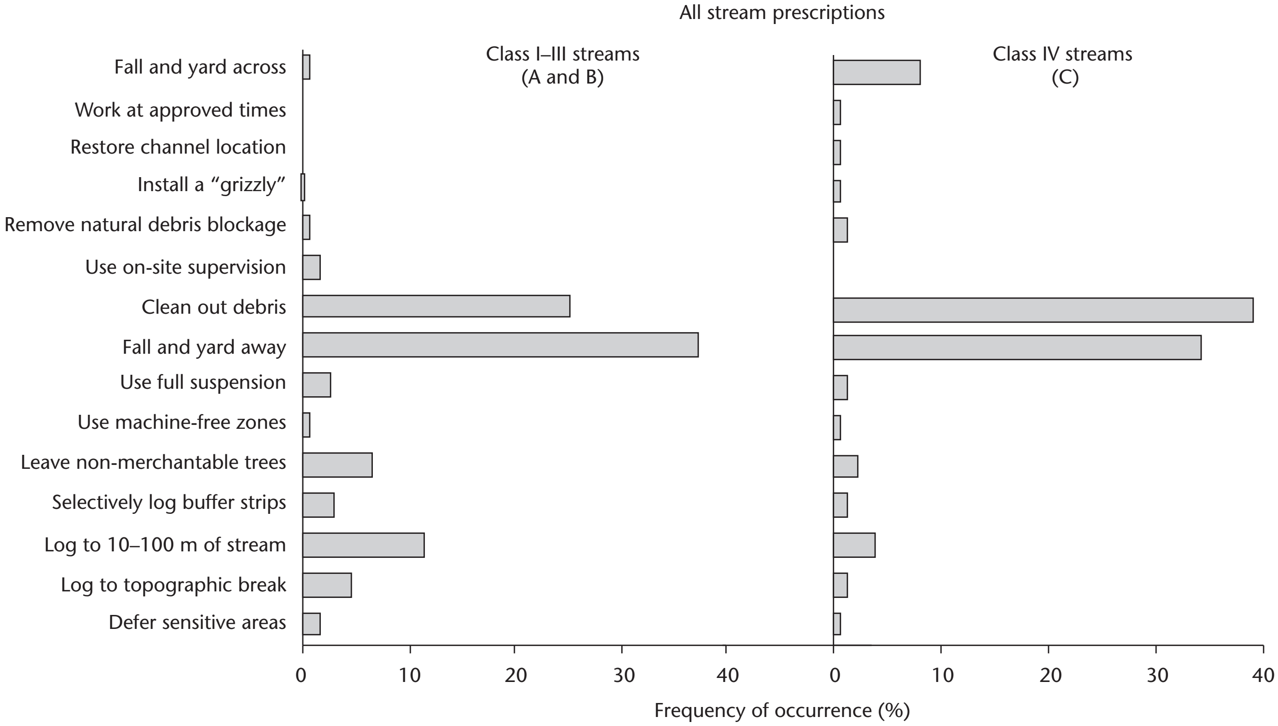

FIGURE 3 *Frequency of occurrence of different site-specific prescriptions used on Class I–III streams and Class IV streams.*

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

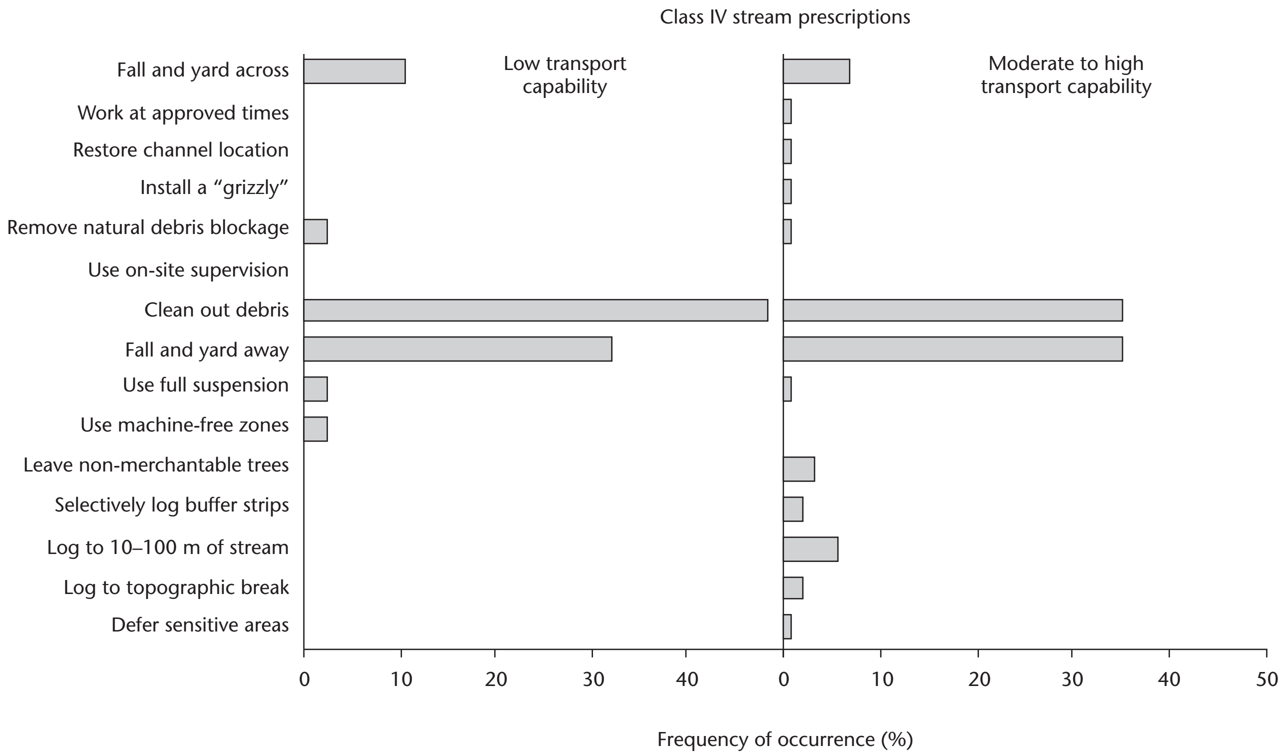

FIGURE 4 *Frequency of occurrence of different site-specific prescriptions used on Class IV streams with low or low-moderate downstream transport capability and Class IV streams with moderate to high transport capability.*

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

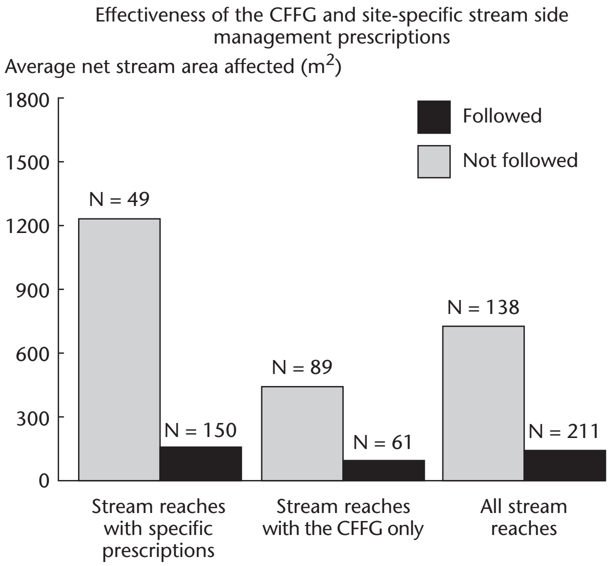

FIGURE 5 *Average net stream area affected when the CFFG and site-specific prescriptions were or were not followed in coastal British Columbia.*

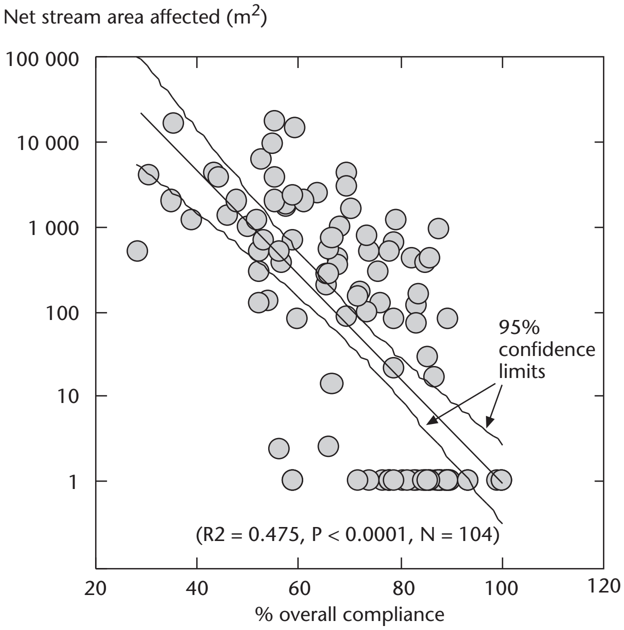

FIGURE 6 *The relationship between overall compliance and net stream area ($\log_{10}$ m^2) affected in streams with fisheries concerns. The latter includes all Class I–III streams, plus Class IV streams with the potential to affect fish-bearing waters downstream.*

more stream area was affected. In both cases, about 100 m^2 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 ($\log_{10}$) and compliance (Fig. 6), is equal to only 70 m^2. This underestimates the real risk of impacts 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 m^2, 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 m^2 (1 SD = 2970, N = 104, range 0–17 875 m^2).

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

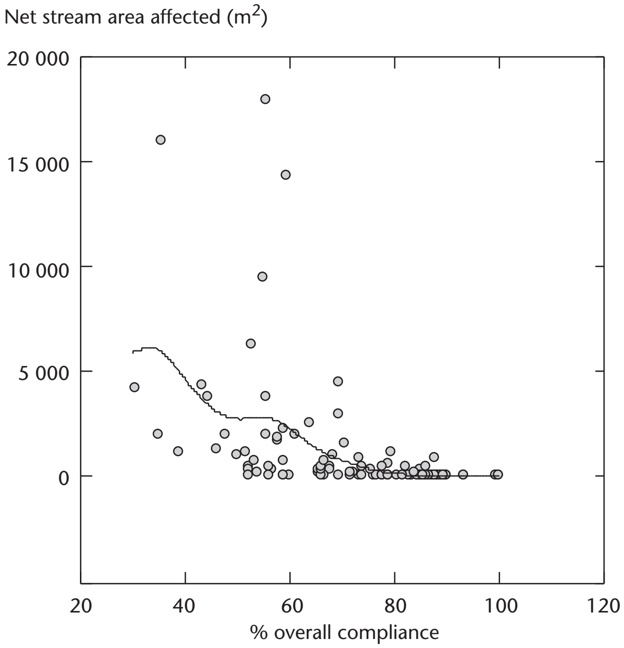

FIGURE 7 *The relationship between overall block compliance with the CFFG and net stream area affected in streams with fisheries concerns. The line is a distance-weighted, least squares smooth that produces a true, locally weighted curve.*

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:
% Compliance = 80.690 - 0.3152 hillslope (%)
($R^2 = 0.141$, $P < 0.0001$, N = 126)
All blocks minus eight possible outliers:
% Compliance = 85.474 - 0.507 hillslope (%)
($R^2 = 0.355$, $P < 0.0001$, N = 118)

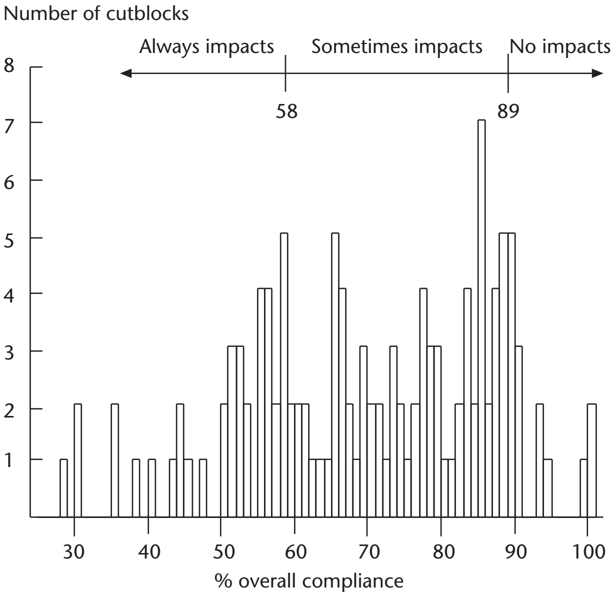

FIGURE 8 *A histogram of overall block compliance with the CFFG for cutblocks logged in coastal British Columbia.*

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 backspar 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.

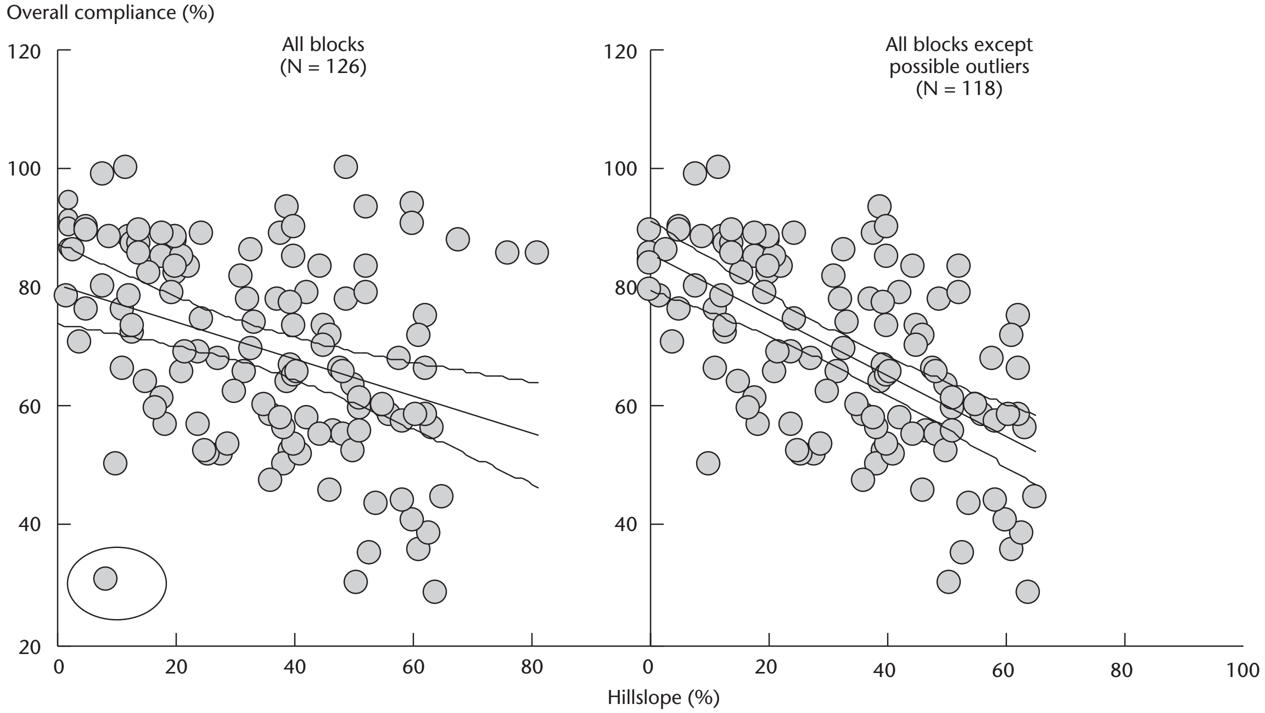

FIGURE 9 *The relationship between overall compliance with the CFFG and hillslope in coastal British Columbia. Encircled blocks are possible outliers. The straight lines are the regressions of overall compliance in each cutblock on hillslope; the curved lines are the 95% confidence limits about the regressions.*

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 backspar trails across streams, borrow pits on water courses, excessive or improper clean-up, and overharvesting 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

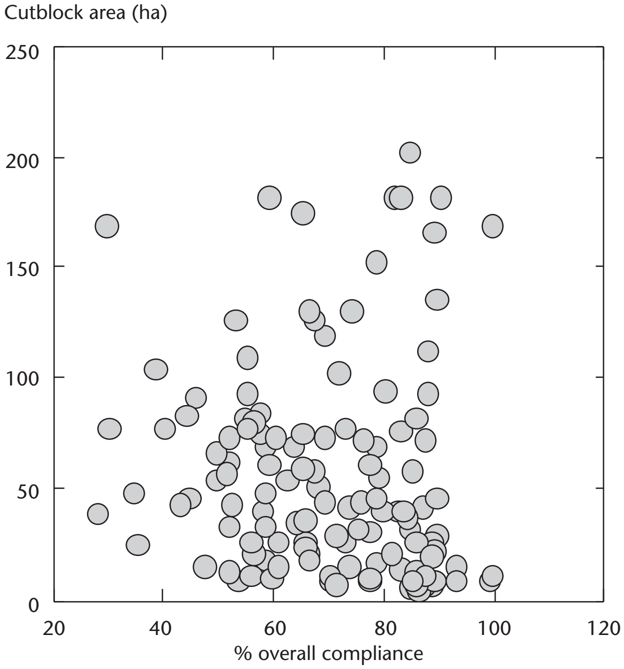

FIGURE 10 *The relationship between cutblock area (ha) and overall compliance with the CFFG.*

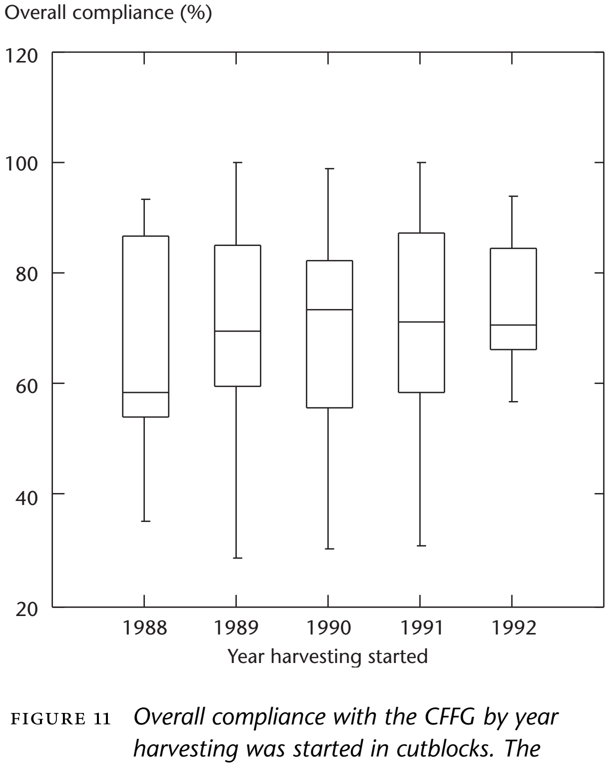

FIGURE 11 *Overall compliance with the CFFG by year harvesting was started in cutblocks. The centre horizontal line in each box marks the median, while the box encloses half the values above and below the median. The vertical lines mark the range of values.*

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.

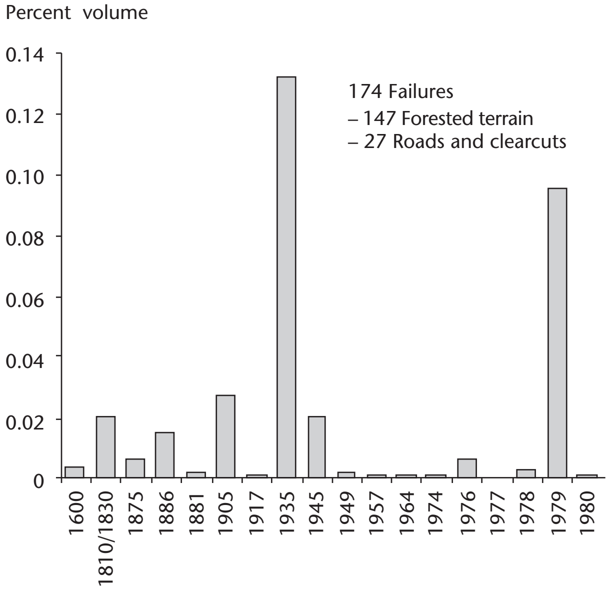

FIGURE 1 *Riley and Gregory Creeks, percent landslide volume by year.*

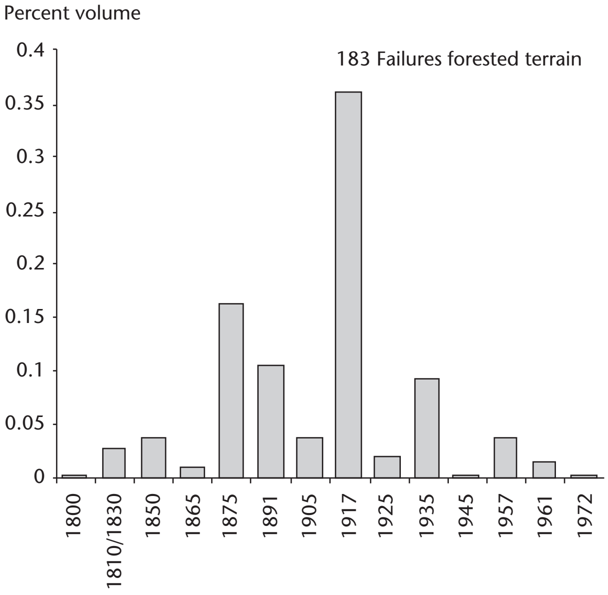

FIGURE 2 *Beresford Creek, percent landslide volume by year.*

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 slamonids, 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 m^2) to large (>100 km^2) 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.

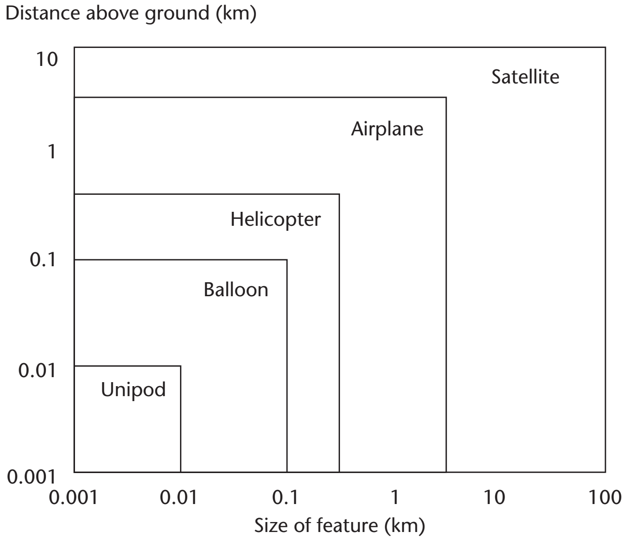

FIGURE 1 *Size scales and appropriate platforms for different photographic techniques.*

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 file 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

Anthony L. Cheong

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

Stephen A. Bird

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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