Effects of Forest Harvesting on Spawning Gravel and Incubation Survival of Chum (*Oncorhynchus keta*) and Coho Salmon (*O. kisutch*) in Carnation Creek, British Columbia

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Following logging, pea gravel and sand (i.e. fines) in the stream bed of Carnation Creek, British Columbia increased 4.6 and 5.7%, respectively. The quantity of fines was greater in the bottom layer, while the frequency and magnitude of changes in composition were greater in the top layer of streambed cores. Changes in streambed fines depended on the timing and type of streamside logging and on the timing of large freshets. Accumulating fines appeared to originate from erosion of streambanks or from upstream storage areas and they were transported as bedload. Suspended sediment (11.4–44.5 $t \cdot km^{-2} \cdot yr^{-1}$) did not increase after road construction or logging. Deposition and scour rates of pea gravel and sand in the streambed were inversely related to particle size, and to their depth in the bed. Following logging, survival to emergence declined from 29.1 to 16.4% for coho salmon (*Oncorhynchus kisutch*) and from 22.2 to 11.5% for chum salmon (*O. keta*). Annual mean survival to emergence and size of fry of both species were positively related to two indices of substrate composition. Annual changes in substrate composition and peak flows explained 60 and 73% of the variability in survival to emergence for chum and coho salmon, respectively.

Après l'exploitation forestière, la quantité de gravier fin et de sable (c'est-à-dire de particules fines) sur le lit du ruisseau Coronation, Colombie britannique a augmenté respectivement de 4,6 et de 5,7 %. La quantité de particules fines était supérieure dans la couche du fond, tandis que la fréquence et l'amplitude des variations de composition étaient supérieures dans la couche du haut des carottes prélevées dans le lit. Les variations dans la nature des particules fines du lit dépendaient du moment de l'exploitation forestière le long du cours d'eau et du type, et non pas du moment où s'étaient produites d'importantes availaisons. Les particules fines semblaient provenir de l'érosion des rives ou de lieux d'accumulation en amont et ont été transportées sous forme de charge de fond. Les sédiments en suspension (11,4 à 44,5 $t \cdot km^{-2} \cdot an^{-1}$) n'ont pas augmenté après la construction des routes ou l'exploitation forestière. Les taux d'accumulation et d'érosion des graviers fins et des sables dans le lit du cours d'eau étaient inversement proportionnels à la taille des particules et à leur profondeur dans le lit. À la suite de l'exploitation forestière, la survie jusqu'au moment de l'émergence a diminué de 29,1 à 16,4 % pour le saumon coho (*Oncorhynchus kisutch*) et de 22,2 à 11,5 % pour le saumon keta (*O. keta*). La survie moyenne annuelle jusqu'à l'émergence et la taille des alevins étaient liées de façon positive à deux indices de la composition des matériaux du fond. Des variations annuelles de la composition des matériaux du fond et des débits de pointe ont expliqué, respectivement, 60 et 73 % de la variation de la survie jusqu'à l'émergence des saumons keta et coho.

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Much has been written about changes in fluvial processes and sediment production associated with timber harvesting (Anderson 1971; Gibbons and Salo 1973; Iwamoto et al. 1978). Some influences of fine particles on survival, emergence, and fitness of salmonid embryos and emerging fry are also known (Koski 1966, 1975; Hall and Lantz 1969; Phillips 1971). More recently the sources of fines, sedimentation processes, and the influence of sediment on fish production have been investigated (Beschta and Jackson 1979; Cederholm et al. 1981; Meehan and Swanston 1977). By understanding these fluvial processes and their influence on fish production, better forest management plans can be developed that protect aquatic habitat.

Sediment composition affects two critical properties of spawning gravel: permeability and porosity. Permeability affects delivery and removal rates of oxygen, carbon-dioxide, and other metabolites (Wickett 1958; McNeil and Ahnell 1964), which influence survival (Alderdice et al. 1958; Reiser and Bjornn 1979; Rombough 1983). Small pore size can restrict intergravel movement of alevins and create a barrier to emergence (Dill and Northcote 1970; Phillips 1971; Phillips et al. 1975).

The objectives of the Carnation Creek studies of spawning gravel are to assess the effects of current forest harvesting prac-

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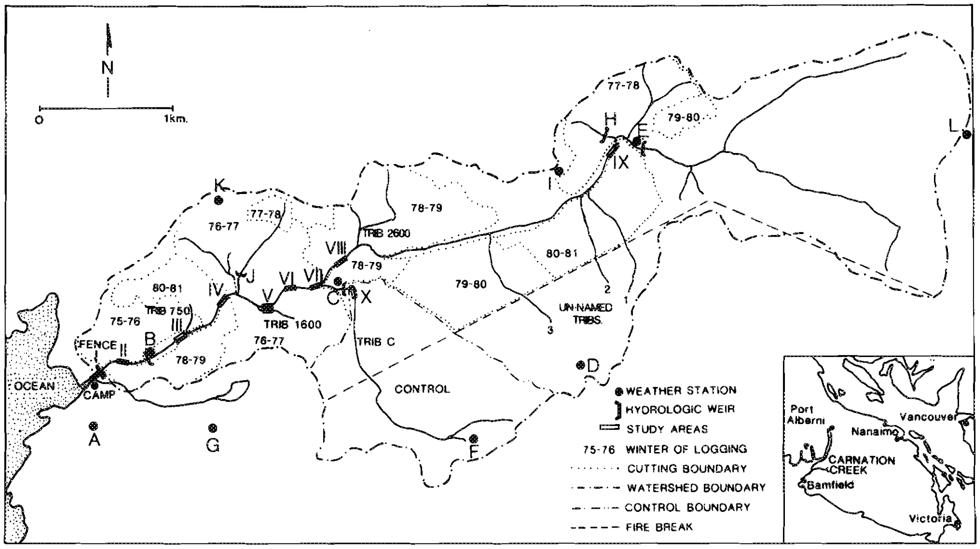

FIG. 1. Location of Carnation Creek (inset) and a detailed map of the watershed showing locations of stream study sections, fish counting fence, and boundaries of logging cutblocks.

tices on spawning gravel composition, intergravel dissolved oxygen levels, and permeability (Scrivener and Brownlee 1982), and the influence of these features on the survival and size of emerging fry. Long-term objectives are to understand influences on the abundance and production of these natural stocks of coho (*Oncorhynchus kisutch*) and chum salmon (*O. keta*). Variations in sediment yield, sources of sediments, and other fluvial processes were also investigated during a 14-yr study series (1973–86) and they provide some insight about the accumulation and scour rates of different particle sizes in a natural streambed. A more detailed study of the intertidal area of Carnation Creek where chum salmon spawn at higher densities has been reported elsewhere (Scrivener and Brownlee 1982; Scrivener 1988a).

Watershed and Study Description

Carnation Creek is a small stream that enters Barkley Sound on the west coast of Vancouver Island (Fig. 1). The stream drains an area of ~10 km^2 in the Coastal Hemlock Zone of British Columbia (Hartman et al. 1987). Annual precipitation is 250–480 cm. Stream flows are highly variable seasonally, ranging from 0.025 m^3·s^{-1} in summer to 33 m^3·s^{-1} in winter during most years. Peak flows of 37, 44, and 64 m^3·s^{-1} with return periods of 5, 12, and 30 yr, respectively have been observed during the study (Hetherington 1982, 1988). Air temperatures below 0°C were recorded for only a few d·yr^{-1} so freezing of incubating salmon eggs was of little concern.

Topographically the basin features rugged terrain of steep slopes to 700 m elevation and a narrow valley bottom through which the stream meanders. Slope soils are shallow, coarse textured, and highly organic (Oswald 1973). Bedrock is of volcanic origin, and the region was glaciated during the Pleistocene. Soils in the valley bottom are derived from recent alluvium and they are underlain by gravel deposits (as deep as 4 m), bedrock, and some sandy clay deposits.

Anadromous fish utilize the lower 3.2 km of the stream, encompassed by study sections I and VIII (Fig. 1). Most chum salmon spawn intertidally (section I), while a few chum salmon (3–30% of the total run), all coho salmon and all steelhead trout (*Salmo gairdneri*) passed through the counting fence (Fig. 1) to spawn (sections II to VIII). Mean gradient is 0.9% in the lower 3.2 km of stream and the bed consists of gravel with very few cobbles (>100 mm diameter; Scrivener 1975). Numerous fallen trees and buried logs occur in the channel both singly and in clusters providing fish habitat (i.e. LOD). Extensive gravel bars indicate considerable gravel movement. From 3.2 to 4.1 km, the stream is confined to a narrow bedrock canyon with an average gradient of 8.4%. The channel contains numerous logjams with gravel accumulations behind them. The next segment of stream, 4.1 km to E-weir (study section IX, Fig. 1) contains resident cutthroat trout (*S. clarki clarki*), and flows over a gravel substrate with some cobbles (100–200 mm).

The Carnation Creek Watershed project was initiated in 1971 as a 16-yr study. It consisted of prelogging (1971–75), logging (1976–spring 1981), and postlogging (1982–86) periods. It has now been extended until 1991. The logging plan contained three basic treatments.

(1) Leave-strip treatment — Area 1 (sections II–IV) was logged as three openings during 1976 (23 ha), 1978–79 (19.4 ha), and 1980–81 (16 ha). This left the lower 1300 m of Carnation Creek with a narrow strip of deciduous vegetation and ~200 merchantable trees along its banks. (Fig. 1).

(2) Intense streamside treatment — Area 2 included the next 900 m of stream (sections V and VI). It was logged in 1976–77 as two clearcuts (61, 34.4 ha). Streamside alders were girdled and injected with Tordon 22K herbicide. All merchantable trees were felled away from the channel, or if leaning over it, they were felled across and then yarded away from the stream to roadside landings. Streambanks and large debris in the channel were broken, scared and destabilized (Toews and Moore 1982).

(3) Careful streamside treatment — Area 3 (section VIII) was logged as two clearcuts (63, 13 ha) during 1978–79. Minor vegetation such as salmonberry was left; only six merchantable trees that could not be jacked or cabled were felled across the channel and removed. Streamside alder was felled and during scarification the logging debris was piled for burning. Gravel samples from this treatment area included cores from study section VII, because it was on the border of areas 2 and 3 (Fig. 1).

Study section IX was included as a fourth area, because the streambed contained coarser material and the timing of treatments was different than among the sections used by anadromous fish. The area adjacent to section IX was not logged until 1980–81 (Fig. 1). Clearcuts were completed on small tributaries upstream of section IX in 1977–78, but little change in the main stream was apparent.

About 41% of the watershed had been logged upon completion of the last clearcut in April 1981. Here, high-lead systems such as steel spars and grapple yarders were used to log between November and April. A more detailed description of the logging plans and study sections is available elsewhere (Dryburgh 1982; Scrivener and Brownlee 1982; Toews and Moore 1982).

Materials and Methods

Collection and Processing of Physical Data

Since 1973, samples of the streambed have been obtained from study sections II to IX during low flows of summer as part of an annual physical survey. During 1971, permanent survey hubs were established at 3-m intervals in each study section (Toews and Moore 1982). Forty-five hubs that were located at potential spawning sites were chosen for sampling (4–10·section^{-1}). Another 25 sites (hubs) were chosen for sampling during 1976 when access became easier (≥8·section^{-1}). Gravel samples were obtained from the cross sections of these hubs each year.

A modification of Ryan's (1970) freeze-core technique was used to sample the streambed. A 5-cm diameter steel probe attached to a sampling "pot" was driven 30 cm into the bed. Acetone and dry ice were added to the pot and the super-cooled acetone froze a gravel core 20–30 cm in diameter around the probe in ~25 min. The frozen cores, weighing 8–22 kg, were split into top (1–15 cm) and bottom (15–30 cm) layers, and bagged separately for particle size analysis. The diameter of the cores was larger than the largest rocks thereby reducing the bias of the weight of these rocks in the samples (Shirazi et al. 1981).

Each layer was oven dried at 105°C, and the largest and smallest diameter of the largest rock measured. The sample was then split one to four times depending upon its weight, and particles too large to pass through the sample splitter (25 mm) weighed. Split samples were weighed and one of them was passed through five nested sieves (9.55, 2.38, 1.19, 0.297, and 0.074 mm). The separated portions were weighed and the data stored in computer files. An indicator of the largest rock size in each layer (<150, <100, or <50 mm) was also stored in the files. During a few early years, weights retained by the sample splitter were not recorded separately. This analysis separated the sample into gravel; pea gravel; coarse, medium, and fine sand; and silt-clay components as classified by the U.S. Department of Agriculture (Scrivener and Brownlee 1982).

During 1982, dissolved oxygen (DO) was measured in the summer prior to gravel sampling at the original 45 sites sampled that year. A stainless steel syringe was used to slowly extract 700 mL of inter-gravel water from a depth of 20 cm. Surface stream water was also sampled at a number of locations in each study section. A Hach Kit was used to measure DO of the sample to the nearest 0.1 mg·L^{-1}. In order to reduce variability among DO concentrations that was caused by diel fluctuations of water temperature or of stream flow during the 4-d sampling period, concentrations were expressed as a percentage of mean surface DO.

Five measures of peak flow representing different periods of egg incubation were used as indicators of annual variation of potential streambed scour. They were obtained from the hydrological weir at station B where water levels have been recorded continuously since April 13, 1971 (Fig. 1). Water Survey of Canada methods and software were used to digitize the charts and to compute flows (Ozga 1974). Stage–discharge curves were checked and updated at least five times each year with measurements from a control cross section near the weir. These measures of peak flow were: (1) October 20 to January 15, and (2) October 20 to January 31, because adult chum salmon entered Carnation Creek and spawned between October 20 and November 5 (Andersen 1983, 1984, 1985), (3) November 16 to January 15, and (4) November 16 to February 15, because adult coho entered the stream in November, at an unripened stage and began spawning about 2-wk later (Holtby et al. 1984), and (5) annual peak flow (October–March) as an indicator of annual variation in scour potential. Flows from February to the time of fry emergence (April) were excluded from most of the measures of peak flow because other studies have indicated that the behaviour of salmon larvae at this time might make them less susceptible to scour (Bams 1969; Dill 1969).

Measurements of suspended sediment transport were also obtained at B-weir with a battery powered pumping sampler. Samples were pumped from a fixed point ~10 cm above the bed at intervals that were regulated by stream flow. During a number of freshets each year, these point samples were related to total stream transport by a series of depth integrated samples from various distances across the width of the channel. Size analyses of suspended particles were obtained for samples from some of these storms. Sediment hydrographs were obtained in this manner from 1973 to 1986 (ANON, 1973–85). Total suspended sediment that was transported and total volume of stream flow were then calculated for each water-year (October 1–September 30).

Collection and Processing of Biological Data

Annual egg-to-fry survival was estimated from calculated egg deposition and enumeration of emergent fry. Potential egg deposition was calculated from the number and fork length (FL) of all adult females at the counting fence, and fecundity relationships for chum (Egg No. = 69.6·(FL in cm) − 2361.1, n = 32, r = 0.73, p<0.001; Hartman 1981) and coho salmon ($\log_{10}$Egg No. = 2.786·Log_{10} (FL) − 1.730, r = 0.82, n = 45, p<0.001). The numbers of emerging chum salmon fry were obtained from counts at the downstream migrant traps of the fence (Fig. 1). Coho fry enumeration was based on a May population estimate in the stream after emergence and fence counts prior to the May census (Scrivener and Andersen 1984). All migrant fry were counted at the fence except during freshets when only a portion of the flow could be sampled. Egg-to-fry survival of chum salmon was not obtained for 1983–1984, because no unspawned females passed through the fence that year.

Mean FL of emerging coho and chum salmon were assumed to be the same as fry emigrating through the counting fence. During prelogging years (1973–76), fry first appeared at the fence in April, but they began appearing in March after 1976 (Scrivener and Andersen 1984). Measurements were obtained every 7–10 d thereafter from at least 50 fry of each species. Mean FL and fry counts of each sampling date were used to calculate a weighted annual mean during the first 50 or 60 d of movement. Chum fry emigration usually ended in ~50 d, and fry sizes were similar to those caught in intertidal emergence traps (Scrivener 1988a). The size of coho fry at the fence did not increase until after the first 60 d of movement (Andersen 1983, 1984, 1985, 1987), so growth had not affected the lengths significantly. A sampling period of 60 d was also judged representative, because coho salmon spawned over a long period (20–60 d; Holtby et al. 1984), and because coho fry have been shown to emerge from most individual redds during an extensive period (48–60 d; Tagart 1984).

The size of emerging fry is influenced by the egg size for both coho (Beacham et al. 1985) and chum salmon (Koski 1975; Beacham and Murray 1985). If environmental impacts on fry size are being studied, egg size should be kept constant or corrections for its variability should be made (Koski 1975). Egg size and fecundity are both functions of adult female length (Allen 1958; Koski 1975), so mean egg size each year could be predicted from mean length of spawning females. Mean size of chum salmon eggs was calculated for those fish that went through the counting fence each year by using the fecundity relationship mentioned earlier and the relationship between female length and egg weight (Egg weight in mg = 5.587 · (FL in cm) − 52.31, $r = 0.65$, $n = 31$, $p < 0.001$). Predicted mean size of fry was then calculated for each year (Fry FL = 18.30 + 0.0633 · Egg weight, $r = 0.63$, $n = 99$, $p < 0.001$; data from Beacham et al. 1985). Annual variability in fry size that was attributable to annual variability in egg size was obtained by subtracting fry length predicted from egg size each year from fry length predicted for 1973 (year of median female size). These values (−0.8 to +1.1 mm) were added to the mean size of fry of their year. Carnation Creek coho salmon that were obtained for fecundity estimates were not mature enough for estimating egg weights, so data from the literature and the fecundity relationship were used to predict annual mean diameter of coho eggs (Egg diameter in mm = 5.423 + 0.0294 · (FL in cm), $r = 0.63$, $n = 61$, $p < 0.001$; data from Allen 1958). Volume was calculated as a prolate spheroid (Groot and Alderdice 1985) by

$$\mathrm{mL} = 4/3\ \pi \cdot (\mathrm{diameter}/2.0)^2 \cdot (\mathrm{diameter}_2/2.0),$$

and weight was calculated by

$$\mathrm{mg} = \mathrm{mL} \cdot 1.062,$$

(D. Alderdice, Pacific Biological Station, Nanaimo, B.C., pers. comm.). Predicted size of fry was then calculated for each year (Mean FL = 26.83 + 0.0338·Egg weight, $r = 0.72$, $n = 107$, $p < 0.001$; data from Beacham et al. 1985), and differences in size of coho salmon fry due to annual variability in egg size (−0.4 to 0.4 mm) was used to correct mean size of fry as done with chum salmon.

Data Analysis

Initial analysis was suited to a three-way ANOVA, because the gravel sampling program was designed to compare: (1) layers within the cores (top and bottom), (2) different streamside treatments (areas 1 to 4), and (3) changes through time (pre-, during and postlogging). The data were grouped into the four streamside treatment areas; and into six time periods; 1973–76 (prelogging), 1977–78 (post-intense treatment to November 1978 freshet), 1979–80 (post-November freshet to completion of logging), 1981–82 (postlogging period influenced by many large freshets), 1983–84 (postlogging period with only one major freshet), and 1985–86 (a period of benign flows). Data of August 1976 were included with prelogging years because only study section II could have been affected by the small 1976 clearcut in which a variable width of timber was left along the stream (Fig. 1). The November 1978 storm was used to divide the logging period because this was the first large freshet after logging commenced. Major changes in channel morphology were noted within the intense treatment area during this freshet (Toews and Moore 1982). When tests were significant, the data was separated into subgroups and the differences were explored further.

Mean particle size (Dg, Platts et al. 1979) was calculated for each layer of each core by

$$Dg = d_1^{w_1} \cdot d_2^{w_2} \ldots \cdot d_n^{w_n},$$

where d = geometric mean diameter between two adjacent sieve sizes, w = proportion of the sample retained by the smaller sieve. The geometric mean between 9.55 mm and the average diameter of the largest rock was the largest diameter (d) used. It was raised to the power of the proportion of sample greater than 9.55 mm (w).

A fredle index (Fi, Lotspeich and Everest 1981) was calculated using:

$$Fi = Dg/So,$$

where $So = \sqrt{d_{75}/d_{25}}$ = the sorting coefficient, d_{75}, d_{25} = particle size diameter at which 75 and 25% of the sample was finer, respectively. Fi is a single measure of the mean particle size in a sample and the associated standard deviation of the distribution of particle sizes around the mean.

Because cumulative distributions of particle sizes in the freeze-cores were lognormal, equations were used to predict the mesh size through which 75 and 25% of a sample would pass (Scrivener 1989). The least squares graphical method of Shirazi et al. (1981) was used to generate equations of the form:

$$\mathrm{Percent} = b + a \cdot \log_{10} SIZE.$$

Where percent = inverse probability transformation of percentage of substrate smaller than a given mesh size, b = intercept of the regression line, a = slope, $SIZE$ = mesh size in millimetres.

Physical and biological data were compared through time with a correlation analysis. Annual survival to emergence for chum and coho salmon, mean lengths of emerging fry, means lengths of adult female spawners, adjusted fry lengths (fry length plus the measure of annual variability induced by egg size), peak flows during incubation, and mean Dg and Fi of the cores were related in a correlation matrix.

Four measures of mean Dg and Fi were used for each year: the mean for all samples, which included both layers from all four areas, and mean for the top layer only, mean for the bottom layer only, and mean for combined layers of areas 1 and 2. Data from areas 1 and 2 were used because their boundaries included all chum salmon that spawned above tidal influence and most coho salmon, and because they included the segments of stream that were within or downstream of the intense streamside treatment.

Results

Changes in Percent Fines

A comparison of the composition of spawning gravel within layers, streamside treatment areas, and time periods with a

TABLE 1. F statistics from ANOVA comparing percentage of streambed cores that were smaller than 9.55, 2.38, 1.19, 0.297, and 0.074 mm. Sample sizes and probabilities are also shown (NS = not significant, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$).

Analysis	Number of samples	<9.55 mm	<2.38 mm	<1.19 mm	<0.297 mm	<0.074 mm
Three-way ANOVA	1542					
Depth[a]		30.2***	53.0***	57.0***	36.3***	24.7***
Time[b]		23.2***	17.8***	13.4***	5.3***	1.0 NS
Area[c]		18.5***	13.3***	11.7***	2.3 NS	2.3 NS
Time/depth interaction		2.4*	1.1 NS	0.6 NS	0.6 NS	0.7 NS
Time/area		1.7 NS	1.6 NS	1.6 NS	1.1 NS	1.4 NS
Area/depth		0.9 NS	0.5 NS	0.8 NS	1.1 NS	1.0 NS
Two-way ANOVA (Top layer)	771					
Time		13.2***	10.5***	7.6***	4.8***	2.2 NS
Area		13.1***	9.4***	9.0***	5.6***	4.3**
Interaction		1.8*	1.6 NS	1.6 NS	2.4*	2.1*
Two-way ANOVA (Bottom layer)	771					
Time		12.3***	8.4***	6.8***	2.6*	0.7 NS
Area		6.2***	4.5**	3.6*	1.0 NS	1.5 NS
Interaction		0.5 NS	0.5 NS	0.8 NS	0.8 NS	1.2 NS

[a] Depth: (1) Top layer, (2) Bottom layer.

[b] Time periods: (1) August 1973 to August 1976, (2) September 1976 to October 1978, (3) November 1978 to December 1980, (4) January 1981 to February 1983, (5) March 1983 to August 1984, (6) October 1984 to August 1986.

[c] Areas: (1) sections II, III, and IV, (2) sections V and VI, (3) sections VII and VIII, (4) section IX.

TABLE 2. Mean percentages of 771 streambed cores that were smaller than 9.55, 2.38, 1.19, 0.297 and 0.074 mm.

Sieve size (mm)	Gravel layers (Mean % passing) Top	Bottom	Mean increase with depth
9.55	32.2	35.9	3.7
2.38	12.9	15.8	2.9
1.19	6.9	8.9	2.0
0.297	1.0	1.6	0.6
0.074	0.2	0.4	0.2

three-way ANOVA indicated that there were significant differences for most particle sizes (Table 1). Only silts and clays (particles <0.074 mm) were not significantly different through time and only fine sand, silt, and clay (<0.297 and <0.074 mm) were not significantly different among areas. The greatest differences in composition were between layers in the streambed. Fines were much greater in the bottom layer of the substrate (Table 2). The changes were general throughout the data, because interaction among ANOVA cells are rare. Only interaction between depth and time was significant for particles that were smaller than 9.55 mm (Table 1).

A two-way ANOVA using data from each layer separately showed significant differences through time and among areas for all particle sizes except those smaller than 0.074 mm (Table 1). Silt and clay components (<0.074 mm) were only significantly different in the top layer of the areas. Interaction between time and area in the top layer was probably caused by differences in logging times. This was not apparent in the bottom layer of the same freeze-cores.

The nature of the differences between layers and among areas were probably caused by impacts from logging and freshets and by spatial variability. In areas 1 and 2, pea gravel and sands (particles <9.55, <2.38, <1.19, <0.297 mm) increased significantly over time in the top and bottom layers (Table 3), but their patterns were different (Fig. 2). In the top layer, the composition of these particles increased after logging or the November 1978 freshet, declined during 1981–82 (the period influenced by many large freshets) and increased again during 1983–84 and 1985–86. In the bottom layer, they increased in a stepwise manner after logging and the November 1978 freshet, but the increase was not significant until 1981–82 or 1983–84 (Table 3). Despite the similarity of patterns, the cores from area 2 contained fewer fines in both the top and bottom layers (Fig. 2). Silt and clay components (<0.074 mm) in the streambed did not change through time (Table 3). The slightly different pattern of change in area 3 appeared to be caused by the timing of streamside logging which was not begun until after the November 1978 freshet. Unlike areas 1 and 2, area 3 had no changes in the composition of the streambed until 1981–82 (Fig. 2). In the top layer, the composition of fines in all categories declined during 1981–82 (Fig. 2), but the decline was statistically significant only for pea gravel (<9.55 mm), and coarse sand (<2.38 mm), silt and clay (<0.074 mm) components. Pea gravel and coarse sand increased again in 1983–84, while fine sand, silt, and clay components did not (<0.297 and <0.074 mm, Table 3). In the bottom layer, changes through time were significant only for particles smaller than 9.55 mm. Like areas 1 and 2, no reduction in fines occurred during 1981–82, and a tendency towards increasing fines was apparent by 1983–84 (Fig. 2). Logging adjacent to area 4 produced a pattern of change that differed from the other areas. Streambed composition changed more frequently in the top layer as in the other areas, but pea gravel and sands (<9.55 mm to >0.074 mm) decreased during 1977–78 instead of 1980–81 (Table 3; Fig. 2). They had increased again by 1983–84. A freshet on February 12, 1977 (peak flow 35 $m^3 \cdot s^{-1}$) may have been responsible for this loss of fines. Its influence on areas 1 and 2 could have been masked by the intense streamside logging treatment of early 1977. The streamside of area 4 was logged during the spring of 1981 (Fig. 1), and this was the only area where fines did not decline during 1981–82. As in the other areas, pea gravel and sand composition of the bottom layer did

TABLE 3. F statistics from 1-way ANOVA comparing through time percentages of streambed cores that were smaller than 9.55, 2.38, 1.19, 0.297, and 0.074 mm. Results of paired Student-Neuman-Keul tests are shown below significant F values (NS = not significant, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$). Corresponding means are shown in Fig. 2.

Analysis	Number of samples	<9.55 mm	<2.38 mm	<1.19 mm	<0.297 mm	<0.074 mm
One-way ANOVA (Top layer)						
Area 1 Time periods	274	11.9***	10.2***	9.2***	4.7***	0.8 NS
Pair tests		6>(3 5)>(1 2 4)	6>(3 5)>(1 2 4)	(3 5 6)>(1 2 4)	(5 6)>(1 4)	
Area 2 Time periods	207	3.1*	2.9*	3.6**	3.5**	1.3 NS
		(3>4)	(3>4)	(3 2)>4		
Pair tests		(3 5 6)>(1 2 4)	(5 6)>(1 2)	(5 6)>(1 4)	(5 6)>(2 3)>4	
Area 3 Time periods	179	2.8*	2.7*	0.9 NS	1.9 NS	3.0*
		6>2>4(5>4)	1>4			
Pair tests			5>(2 4)			(1 3)>(4 5 6)
Area 4 Time periods	111	3.0*	2.4*	2.5*	2.6*	1.3 NS
		(1 5)>2	6>2		1>2	
Pair tests		6>(1 2 3 4)	(1 5)>(2 4)	(1 5)>(2 4)	5>(2 3 4)	
One-way ANOVA (Bottom layer)						
Area 1 Time periods	274	7.2***	5.5***	4.4***	2.3*	1.0 NS
Pair tests		(5 6)>4>(2 1)	(5 6)>(4 3)>2	(5 6)>(4 2 1)	(5 6)>1	
Area 2 Time periods	207	3.3**	3.6**	5.2***	2.4*	1.5 NS
Pair tests		(5 6)>(1 2)	(5 6)>(1 2 3)	6>5>(1 3)	(5 6)>(2 3 1 4)	
Area 3 Time periods	179	3.5**	1.6 NS	0.9 NS	1.0 NS	0.8 NS
Pair tests		(5 6)>(1 2)				
Area 4 Time periods	111	2.3*	1.4 NS	1.0 NS	1.8 NS	0.8 NS
Pair tests		(4 5 6)>2				

not decline, but they tended to accumulate after logging had occurred (Table 3; Fig. 2).

Since 1976, percent composition of pea gravel in the streambed increased 4.6% for areas 1 and 2 combined, while total sands (0.074–2.38 mm) increased 5.7%. Although the net increase among fines tended to be similar for the top and bottom layers (Table 4, column 3; top>bottom in area 1, bottom>top in area 2), the annual rates of change and their proportion of the percentage composition during 1973–76 were very different between layers and among particle sizes. In both areas, the annual rates of change were 1.3–1.9 times greater in the top layer for pea gravel, coarse sand, and medium sand (Table 4, column 4). Rates as a proportion of percentage composition were 1.4–3.5 times greater in the top layer than in the bottom layer (Table 4, column 5). Net increases among pea gravel and sands were similar for both layers because in the bottom layer, deposition of fines was more frequent (Fig. 2), but at a much lower rate. The net increase and rate of scouring or filling annually (Table 4, column 5) increased as the particle size decreased for both areas and layers with the exception of silt-clay. Scour and deposition rates of pea gravel and sands were inversely related to particle size and to the depth of the particles (Table 5, greater slope and intercept for the top layer). Silt and clay probably changed so rapidly that rates that were calculated from annual samples underestimated scour and deposition rates. More frequent sampling might produce better estimates for silt-clay. These rates are probably accurate estimates for pea gravel and sands because they were correlated with particle size in a semilog manner (Table 5), and because freshets were not great enough to move significant quantities of the larger particle sizes every year.

Mean Particle Size (*Dg*) of Gravel Cores

The pattern of change for mean *Dg* of each layer was similar to that found for percent fines. In areas 1 and 2, *Dg* changed little and inconsistently for both layers immediately after the intense logging treatment in the spring of 1977 (Fig. 3). After the November 1978 freshet, mean *Dg* declined during 1979–80, increased during 1981–82 and declined again during 1983–84 in the top layer of the cores (Fig. 3). In the bottom layer, it progressively declined for each time period after the November 1978 freshet. The decline was not significant until 1981–82 in area 1 ($t = -2.62, p < 0.01$) and until 1983–84 in area 2 (1979–80 versus 1983–84, $t = -2.21, p = 0.028$). Logging in area 3 was not begun until the spring of 1979, and changes were not apparent until 1981–82. In the top layer, mean *Dg* increased in 1981–82 and declined in 1983–84 (Fig. 3). In the bottom layer, it progressively declined during 1981–82 and 1983–84. The change between 1977–78 and 1983–84 was significant ($t = -2.37, p = 0.02$). In area 4, mean *Dg* increased in 1977–78 prior to logging, but tended to decline thereafter (Fig. 3). The decline was significant by 1979–80 and 1981–82, in the top ($t = -1.8, p < 0.07$) and bottom ($t = -2.1, p = 0.04$) layer, respectively.

Yields of Suspended Sediment

Few of the fine sediments that were deposited in streambed gravels between 1977 and 1986 were transported in suspension. Suspended sediment from the November 1978 freshet contained 36% fine sand (0.06–0.98 mm), 55% silt (0.002–0.06 mm) and 9% clay (<0.002 mm). At station B, yields of suspended sediment ranged from 11.4 to 44.5 $t \cdot km^{-2}$, but they did not increase during the periods of road construction and logging (Fig. 4). Similarly, mean sediment concentrations did not change for more than 1 yr with these activities. Maximum yield and maximum mean concentration occurred during a prelogging water-year (1973–74), while minimums occurred during a postlogging water-year (1984–85; Fig. 4). The year of major road construction (1975–76) produced the second largest yield (33 $t \cdot km^{-2}$) at the fourth largest mean concentration, but the second smallest yield at the fourth smallest mean concentration occurred during the year following the intensive log-

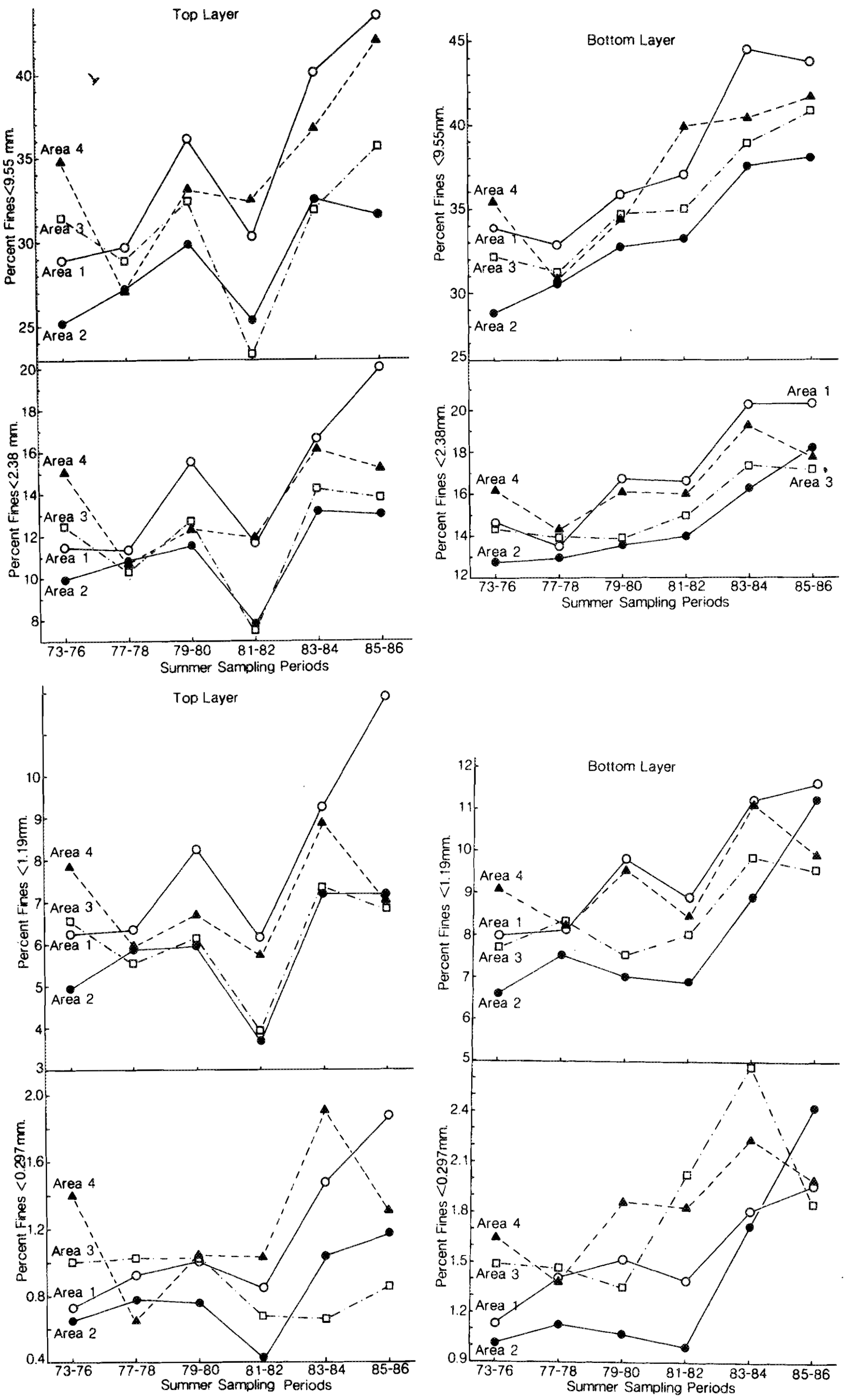

FIG. 2. Mean percentage of sample weight which passed 9.55, 2.38, 1.19, and 0.297-mm sieves. The plots include data from top and bottom layers of freeze-cores from area 1 (study sections II, III, and IV), area 2 (sections V and VI), area 3 (sections VII, and VIII), and area 4 (section IX) at Carnation Creek, British Columbia.

TABLE 4. Mean percentage composition is listed for pea gravel (2.38–9.55 mm), coarse sand (1.19–2.38 mm), medium sand (0.30–1.19 mm), fine sand (0.074–0.30 mm), and silt-clay (<0.074 mm) in streambed cores from Carnation Creek during 1973–76 (prelogging) and during 1985–86. The net increase of these fines between the two time periods (column 3 = (2–1/1)·(100%)); the annual rate of change in composition between 1973 and 1986 (sum of absolute annual changes divided by No. of years); and the proportion of annual rate of change to composition during 1973–76 are also shown.

			Column			
		1	2	3	4	5
		Composition 1973–76 (%)	Composition 1985–86 (%)	Net increase (%)	Annual rate of change 1973–1986 percent·yr^{-1}	Ratio column 4/ column 1
Area 1 Top layer	Pea gravel	17.4	23.4	+34	±2.55	0.15
	Coarse sand	5.28	7.95	+50	±1.21	0.23
	Medium sand	5.50	10.0	+81	±1.41	0.26
	Fine sand	0.57	1.57	+175	±0.29	0.51
	Silt-Clay	0.16	0.22	+34	±0.04	0.25
Bottom layer	Pea gravel	19.3	23.8	+24	±1.65	0.08
	Coarse sand	6.50	8.60	+33	±0.91	0.14
	Medium sand	6.88	9.83	+43	±1.07	0.16
	Fine sand	0.86	1.72	+100	±0.27	0.31
	Silt-Clay	0.28	0.31	+11	±0.02	0.07
Area 2 Top layer	Pea gravel	15.1	18.9	+25	±1.98	0.13
	Coarse sand	4.96	5.85	+18	±1.15	0.23
	Medium sand	4.28	6.11	+43	±1.36	0.32
	Fine sand	0.48	0.93	+93	±0.26	0.54
	Silt-Clay	0.17	0.29	+70	±0.05	0.30
Bottom layer	Pea gravel	16.2	19.6	+21	±1.51	0.09
	Coarse sand	6.03	7.36	+22	±0.63	0.10
	Medium sand	5.64	8.66	+53	±0.92	0.16
	Fine sand	0.78	1.76	+125	±0.26	0.33
	Silt-Clay	0.28	0.65	+132	±0.06	0.21

TABLE 5. Summary of relationships between particle size (pea gravel and sand) and the proportion of composition scouring or filling annually (from Table 4). Geometric mean diameter of pea gravel, coarse sand, medium sand, and fine sand were 4.76, 1.68, 0.57, and 0.15 mm, respectively.

	Equation	r	n	Significance
Area 1				
Top layer	Prop. = $-0.228\cdot\text{Log}_{10}$(diameter in millimetres)$+0.278$	−0.95	4	$p = 0.05$
Bottom layer	Prop. = $-0.145\cdot\text{Log}_{10}$(diameter in millimetres)$+0.167$	−0.96	4	$p < 0.05$
Area 2				
Top layer	Prop. = $-0.268\cdot\text{Log}_{10}$(diameter in millimetres)$+0.294$	−0.98	4	$p = 0.01$
Bottom layer	Prop. = $-0.161\cdot\text{Log}_{10}$(diameter in millimetres)$+0.163$	−0.93	4	$p < 0.07$

ging. Most of the particles that accumulated in the streambed were probably too large to be transported in suspension and therefore they must have been moving along the surface of the bed.

Incubation Survival of Chum and Coho Salmon

Estimates of salmon egg-to-fry survival above the counting fence declined during the study. During 1972 to 1978, survival ranged from 16.3 to 25.0% for chum salmon and from 22.5 to 37.0% for coho salmon (Fig. 5). After the November 1978 freshet, survival declined from 29.1 to 16.4% for coho salmon and from 22.2 to 11.5% for chum salmon. These changes were significant (Mann–Whitney 2 tailed U-test; chum, $p = 0.01$; coho, $p = 0.02$). An exception to the pattern occurred during 1981, when survival for chum salmon increased (Fig. 5) and when fines declined in the top layer of the streambed (Fig. 2 and 3). The intense logging treatment of area 2 in 1976–77 (some trees felled across the stream) may have directly reduced the survival of coho salmon that year, while chum salmon were not affected because they spawned below area 2 (Fig. 5). During 1985, survival of coho increased when the smallest adult returns were obtained the previous autumn (Andersen 1985), and when winter peak flows were the smallest of those observed since the November 1978 freshet. It declined again in 1986 when adult returns were also small (Andersen 1987).

Relationship Between Gravel Composition and Dissolved Oxygen

Dissolved oxygen (DO) in the streambed was positively correlated with Dg (Fig. 6) and Fi ($r = 0.40$, $p<0.01$) in the top layer, and in the total core (both $r = 0.37$, $p = 0.013$) at the 45 sites sampled in 1982. It was not correlated with either Dg

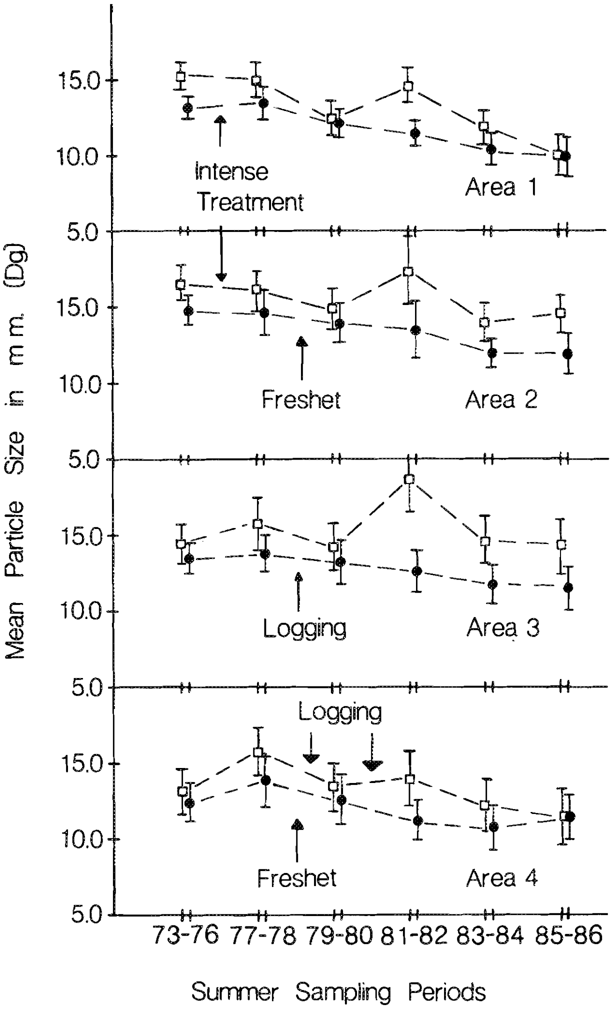

FIG. 3. Mean *Dg* (with 95% confidence limits) for top (squares) and bottom (dots) layers of streambed cores from Carnation Creek. Area 1 (downstream of the intense treatment), area 2 (intense streamside treatment), area 3 (anadromous fish habitat above this treatment), and area 4 (resident cutthroat trout habitat) include study sections II, III, and IV, sections V and VI, sections VII and VIII and section IX, respectively. Time of logging and freshets is indicated.

(r = 0.15) or *Fi* (r = 0.13) in the bottom layer of the same cores. The correlations were of little value as predictive tools, because neither index of gravel quality could account for more than 20% of the variability in DO (Fig. 6). DO varied between 18 and 96% of surface concentrations when *Dg* was 10–12 mm, but it was always 60% or greater when *Dg* was more than 18 mm. Inter-gravel DO concentrations ranged from 1.3 to 8.9 $mg \cdot L^{-1}$, while they ranged from 7.5 to 9.5 $mg \cdot L^{-1}$ at the surface. Concentrations were less than or equal to 2.5 $mg \cdot L^{-1}$ at six of the 45 sites that were sampled, but these values were obtained prior to spawning during low summer flows.

Relationships Among Physical and Biological Variables

Survival to emergence of chum salmon, and fry FL and adult female FL of coho salmon decreased during the study (negative *r*, Table 6). *Dg* and *Fi* of the bottom layer and of the total core from areas 1 and 2 also declined over time. Some annual peak flows (November 16–February 15; Winter peak) have increased during the study (Table 6).

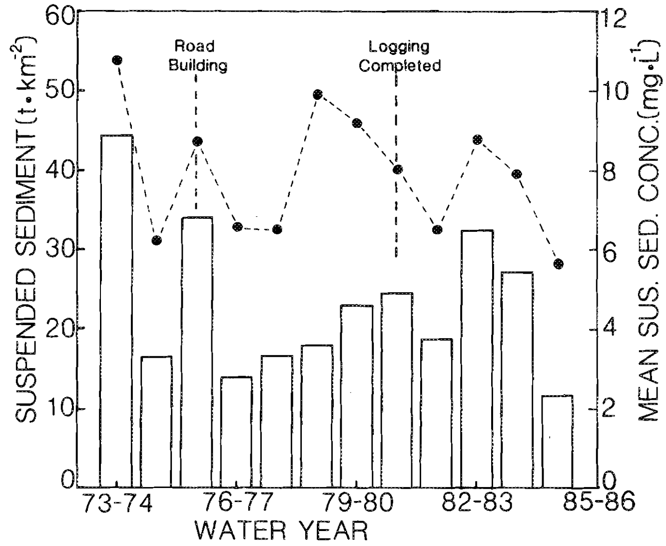

FIG. 4. Suspended sediment yield (bars) and its mean concentration (●- -●) by water-year (October to September) observed at station B in Carnation Creek watershed.

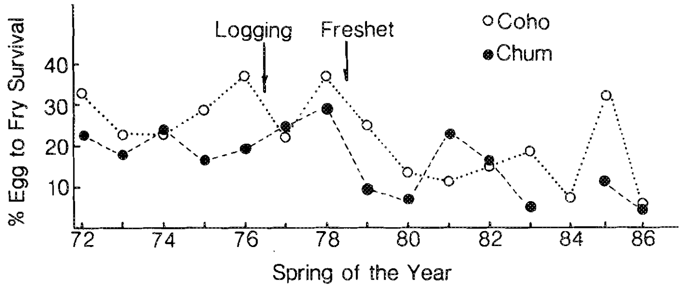

FIG. 5. Annual survival from potential egg deposition to fry emergence for coho and chum salmon located above the fish counting fence at Carnation Creek. Times of intense streamside logging during 1976–77 and the November 1978 freshet are indicated. No chum salmon females passed through the counting fence in autumn 1983.

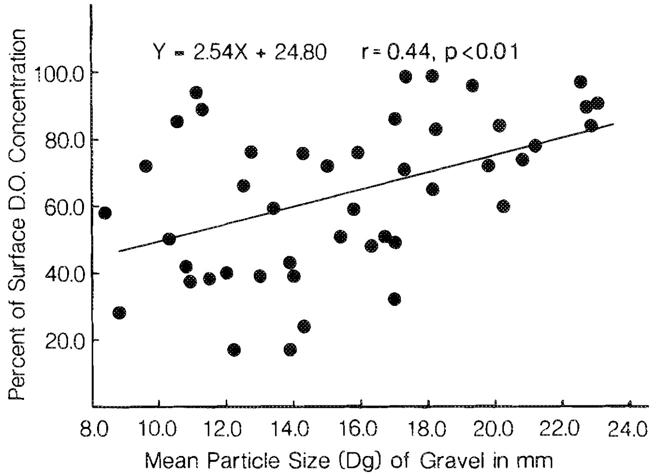

FIG. 6. Relationship between intergravel dissolved oxygen, expressed as percent of surface concentration, and mean particle size (millimetres) in the top layer of the streambed. The data were obtained from 45 Carnation Creek sites in study sections II to IX during August 1982.

Survival to emergence of chum salmon was positively correlated with *Dg* and *Fi* of the top layer of the streambed and of the two layers combined (Table 6). It was not correlated with

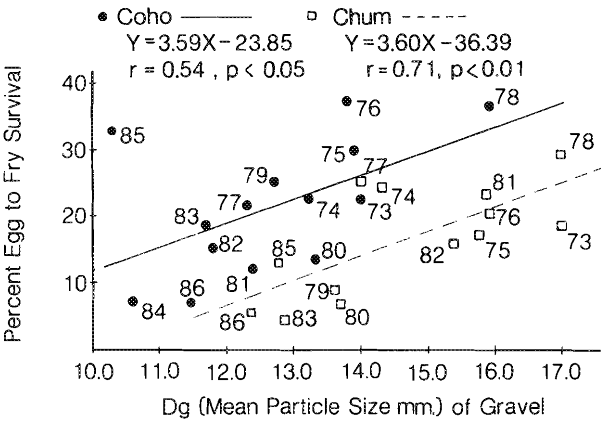

FIG. 7. Relationship between annual survival to emergence of coho salmon and mean particle size (*Dg*) in the bottom layer of freeze core samples taken from study sections II, III, IV, V, and VI; and between chum salmon survival to emergence above the counting fence and in the top layer of the same gravel cores.

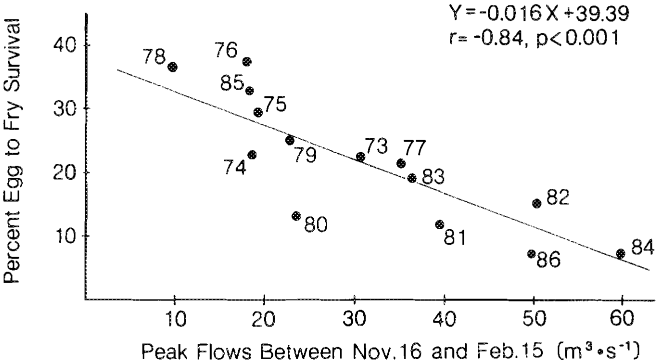

FIG. 8. Relationship between annual egg-to-fry survival of coho salmon and peak flow (B-weir) during November 16 to February 15 at Carnation Creek.

annual variations of gravel composition in the bottom layer nor with any of the peak flows. Changes of *Dg* in the top layer of the streambed explained 50% of the variability in egg-to-fry survival between 1973 and 1986 (Fig. 7). Peak survivals occurred during 1978 and 1981 (Fig. 5), when a cleaning of pea gravel and sand from the top layer was apparent (Fig. 3), but they were poor during 1979, 1980, and 1983 when intrusions of pea gravel and sand occurred. Deviations from the correlation were large and positive during 1974 and 1977, after winters of small and infrequent freshets prior to hatching (Fig. 7). A relationship between residuals and peak flows between October 20 and January 15 was not significant ($r = -0.32, p = 0.29$), but peak flows explained 10% of the variation of these residuals.

Survival to emergence of coho salmon was positively correlated with fry lengths, and *Dg* and *Fi* of the lower layer of the gravel cores, but it was not correlated with gravel composition in the top layer (Table 6; Fig. 7). Changes of *Dg* in the bottom layer of the streambed explained 28% of the variability in egg-to-fry survival of coho salmon. A large positive deviation from this relationship occurred during 1985 (Fig. 7), a year of very benign flows (Fig. 8). Residuals from the relationship between *Dg* and survival were correlated with peak flows between November 16 and February 15 ($r = -0.60, p = 0.02$) and they explained 36% of the variation in residuals. Egg-to-fry survival was negatively correlated with peak flows between

TABLE 6. Correlation matrix comparing chum and coho salmon annual egg-to-fry survivals; annual mean length of emerging fry, of adult females the previous autumn at the counting fence and of emerging fry corrected for egg size; annual mean particle sizes (*Dg*) and (*Fi*) of streambed gravel; and annual peek flows from Carnation Creek during 1973 to 1986 (* = $p < 0.05$, ** = $p < 0.01$).

		Incubation survival		Coho fry length	Coho female length	Corrected fry length	Chum fry length	Chum female length	Corrected fry length	Flow 1	Flow 2	Flow 3	Flow 4	Flow 5
	Year	Chum	Coho											
Year	1.0													
Chum egg survival	−0.56*	1.0												
Coho egg survival	−0.49	0.41	1.0											
Coho fry length	−0.81**	—	0.56*	1.0										
Coho female adult length	−0.70**	—	0.36	0.72**	1.0									
Coho fry length corrected for egg size	−0.77**	—	0.55*	—	0.52	1.0								
Chum fry length	−0.20	−0.04	—	—	—	—	1.0							
Chum female adult length	0.12	−0.15	—	—	—	—	0.63*	1.0						
Chum fry length corrected for egg size	−0.41	0.25	—	—	—	—	—	0.10	1.0					
Flow 1 Peak Nov. 16 to Jan. 15	0.14	0.14	−0.45	−0.32	−0.22	−0.30	0.09	−0.36	0.44	1.0				
Flow 2 Peak Nov. 16 to Feb. 15	0.56*	−0.30	−0.84**	−0.61*	−0.47	−0.59*	0.33	0.16	0.22	0.51	1.0			
Flow 3 Peak Oct. 20 to Jan. 31	0.24	0.01	−0.39	−0.37	−0.29	−0.35	0.54	0.28	0.45	0.54	0.59*	1.0		
Flow 4 Peak Oct. 20 to Jan. 15	0.06	0.02	−0.19	−0.32	−0.17	−0.31	0.18	−0.11	0.36	0.66*	0.26	0.76**	1.0	
Flow 5 Winter Peak Oct. to Mar.	0.61*	−0.32	−0.64*	−0.59*	−0.47	−0.67*	0.50	0.30	0.09	0.33	0.87**	0.75**	0.45	1.0
Dg all areas	−0.65*	0.68*	0.50	0.76**	0.63*	0.74**	0.27	−0.27	0.64*	−0.15	−0.51	−0.05	0.02	−0.46
Dg areas 1 and 2 top layer	−0.69**	0.71**	0.46	0.80**	0.69**	0.76**	0.30	−0.29	0.71**	−0.03	−0.38	−0.03	0.00	−0.40
Dg areas 1 and 2 bottom layer	−0.75**	0.51	0.54*	0.78**	0.60*	0.79**	0.25	−0.20	0.56*	−0.32	−0.65*	−0.27	−0.11	−0.61*
Dg areas 1 and 2 both layers	−0.76**	0.65*	0.51	0.83**	0.69**	0.81**	0.30	−0.26	0.68*	−0.19	−0.54*	−0.12	−0.06	−0.52
Fi all areas	−0.40	0.57*	0.46	0.58*	0.52	0.56*	0.18	−0.27	0.51	−0.19	−0.44	−0.04	−0.03	−0.34
Fi areas 1 and 2 top layer	−0.52	0.66*	0.46	0.70**	0.60*	0.66*	0.24	−0.30	0.66*	−0.12	−0.39	0.03	−0.04	−0.35
Fi areas 1 and 2 bottom layer	−0.60*	0.49	0.53*	0.67*	0.51	0.68**	0.20	−0.17	0.48	−0.34	−0.64*	0.20	0.07	−0.55*
Fi areas 1 and 2 both layers	−0.57*	0.60*	0.50	0.71**	0.60*	0.69**	0.23	−0.27	0.60*	−0.25	−0.51	−0.09	−0.08	−0.45

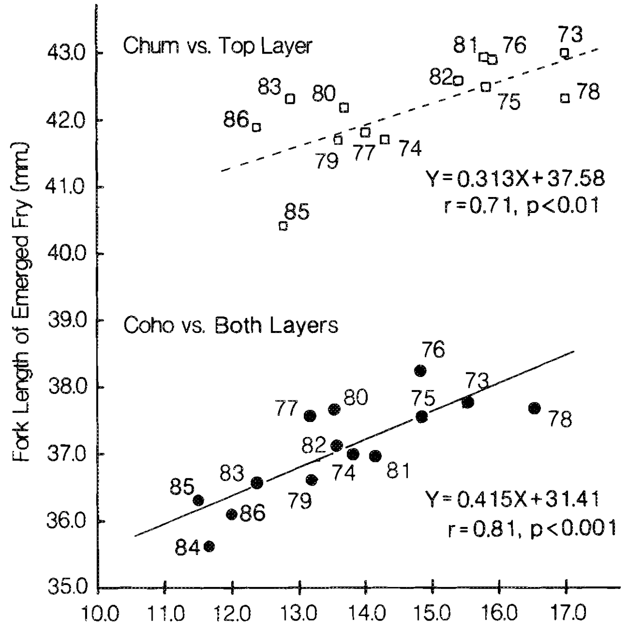

FIG. 9. Relationships between mean particle size (*Dg*) in streambed cores from study sections II, III, IV, V, and VI and the length of recently emerged salmon fry from the counting fence at Carnation Creek. Fry lengths are corrected for the influence of annual variation in size of the adult females which produced the fry.

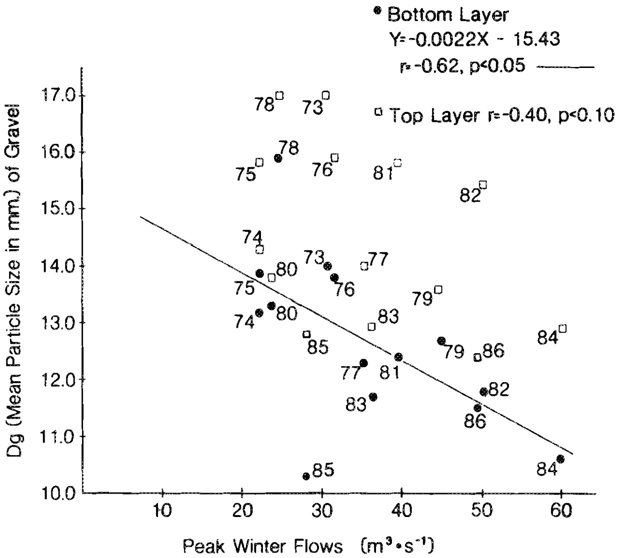

FIG. 10. Relationship between winter peak flow (the annual peak B-weir) and mean particle size (*Dg*) in the bottom and top layers of streambed cores from study sections II, III, IV, V, and VI at Carnation Creek, British Columbia.

November 16 and February 15 (Fig. 8). Peak flows and *Dg* of the lower layer of streambed cores explained 73% of the variability in incubation survival ($r = 0.86$, $r^2 = 0.73$, $p<0.001$) of coho salmon.

As expected, mean length of emerging fry of both species was positively correlated with mean FL of the adult females that produced them (Table 6), indicating that female influence on egg size was affecting fry size. After correction for variation of egg size, fry lengths of coho and chum salmon were positively correlated with *Dg* and *Fi* (Table 6; Fig. 9). The best relationship was obtained with *Dg* in the top layer for chum salmon and with *Dg* of both layers combined for coho. Length of coho fry was negatively correlated with two of the peak flow indicators (Table 6). This may reflect the fact that, fry length, and adult length of coho salmon, and gravel quality all have declined over time, while peak flows increased (Table 6). The measures of substrate composition explained more of the variability in the length of emerging coho fry than can be explained by peak flows.

Two of five indicators of peak flow were negatively correlated with substrate composition in the lower and in the combined layers of the gravel cores, but none of them were related to composition of the top layer (Table 6; Fig. 10). Fines have accumulated in the bottom layer since 1981, when greater peak flows and channel instability have been recorded. The cleaning of pea gravel and sand from the top layer during 1981 and 1982 freshets is pronounced in the scatter plot of *Dg* against annual peak flow (Fig. 10).

Discussion

Sediment Sources at Carnation Creek

In watersheds with forest harvesting, three major sources of sediment to streams are from landslides or debris torrents (Everest et al. 1987; Poulin 1986), from surface scour on logging roads (Beschta 1978; Cederholm et al. 1981), and from upstream storage (gravel bars and wedges in the stream) or erosion of the stream banks (Anderson 1971; Hartman et al. 1987). Transport of these materials occurs periodically during storms.

Since logging was begun in 1976–77, five landslides and three debris torrents in steep valley wall tributaries have occurred in Carnation Creek watershed (Hartman et al. 1987). The areas involved were small, and significant quantities of sediment from probably just one of the torrents reached the main channel. Most of the material was deposited on roads, on lower valley slopes, or on the valley floor (Hartman et al. 1987). Therefore, these sediment sources were not major contributors to the marked changes observed in the composition of spawning gravel at this time.

Road surfaces can be a major source of sediment. In the Clearwater River watershed, sediments that were washed from roads equalled the volume produced by landslides. Particles smaller than 0.85 mm in diameter in the streambed were correlated with the area of roads in the basin (Cederholm et al. 1981). Frequent heavy traffic on the roads crushed surfacing materials making them more erodable.

At Carnation Creek, roads were not a major source of the sediment that accumulated in the gravels. Roads were constructed from blasted rock and they were surfaced with hard and coarse gravel, so fines were scoured from them only during a few storms and even subsequent heavy traffic generated little sediment (Ottens and Rudd 1977). We concluded that few fine sediments from the road reached the main channel because: (1) most roads were located well away from the stream; (2) most of the sediments affecting the composition of spawning gravel were medium sands or larger (>1 mm); (3) sediments washed from road surfaces are usually finer (Cederholm et al. 1981); and (4) a small increase in the yield of suspended sediment in the main channel occurred during only one of the six years with road construction (1975–76) or logging.

In Carnation Creek, much of the sediment that affects the quality of spawning gravels probably came from scoured stream banks or from washed channel sediments that had been protected or stored behind large organic debris (LOD) upstream. As a consequence of logging, major realignment and loss of LOD has occurred (Toews and Moore 1982), and this has greatly reduced channel and substrate stability (Everest et al. 1987). Because of the loss of living roots of streamside vegetation and because of LOD losses, greater streambank erosion has widened and straightened the channel (Toews and Moore 1982; Hartman et al. 1987), thus introducing much more material to the stream and permitting more rapid routing of sediments downstream. After logging, erosion of streambanks increased from 0.18 to 0.50 $m^3 \cdot m^{-1}$ of stream in the careful treatment area and from 0.47 to 1.25 $m^3 \cdot m^{-1}$ in the intense streamside treatment (Hartman et al. 1987). Only a slight increase occurred in the leave-strip treatment (0.37 versus 0.49 $m^3 \cdot m^{-1}$; Hartman et al. 1987). During a January 1984 freshet, loss of LOD and channel sediments in the canyon upstream of section VIII initiated a torrent which deposited materials in the careful treatment area (area 3). These sediments are being washed and redistributed downstream.

Cyclical Variations in Gravel Particle Size Distribution

Two modes of sediment transport have been described for streams: (1) suspended transport, in which fine particles are maintained in suspension by the turbulence of flowing water; and (2) bedload transport in which coarser particles (>1 mm in diameter) roll, slide, or saltate downstream in close proximity to the stream bottom. Suspended sediments increase in concentration and in particle size as stream flows increase (Maximum ≈1 mm in diameter; Everest et al. 1987). When water with its suspended load infiltrates the streambed, velocity and turbulence are reduced causing sediment to be deposited to the depth of surface water penetration. It can sift lower in the streambed if open pore spaces are available. Therefore, sediment from suspension tends to fill pore spaces in the gravel from the bottom up, leaving the upper layers relatively clean (Einstein 1968).

Suspended sediment has been the principle transport mechanism leading to reduced quality of spawning gravels in the Alsea watershed, Oregon (Beschta 1978; Adams and Beschta 1980), in the Clearwater River, Washington (Cederholm et al. 1981), and in Alaskan basins (Sheridan et al. 1984; Everest et al. 1987). The impacts occurred quite quickly and they were caused by particles smaller than 1 mm in diameter. These fines often originated from the surface of logging roads. Conversely, spawning gravels could be cleaned of these fines in as short a time as 1 yr (Adams and Beschta 1980). Annual yields of suspended sediment increased from 26–97 to 60–315 $t \cdot km^{-2}$ after road construction and forest harvesting in the Alsea watershed (Beschta 1978).

In Carnation Creek, suspended sediment did not increase after road construction or logging, and processes of suspended transport and deposition have had only a minor impact on spawning gravel. This probably occurred because soils are highly organic and contain little silt and clay (Oswald 1973), because roads were located well away from the channel, and because sediments in some tributaries were probably deposited in swampy areas when streams had to cross the valley floor to reach the main channel. Annual, postlogging transport of suspended sediment was 5 to 40% of that observed during the Alsea watershed study (Beschta 1978). The average composition was 65% silts and clays (<0.06 mm; Anon 1973–1985). These particle sizes changed so frequently in the streambed because of the many freshets that a seasonal pattern was observed during many years (Scrivener and Brownlee 1982). Spring and summer accumulations, followed by autumn and winter decreases, exceeded the net increase between 1976 and 1986 that was reported here. Changes in the composition of the streambed occurred first in the top layer which is not consistent with the processes of deposition of suspended sediments (Einstein 1968).

Given the predominance of larger materials accumulating in the gravels at Carnation Creek, sedimentation is principally by bedload transport processes. Flume studies have shown that as the various particles are moved downstream during freshets, they become trapped in the surface voids of the substrate (Beschta and Jackson 1979). The smaller the particle size the deeper they penetrate and these particles form a barrier to further intrusion (usually at ~10 cm during small freshets). The size of particles transported, the distance they move, and the depth of scour increase with increasing streamflows (Beschta and Jackson 1979). Sand particles become trapped a few centimetres below the depth to which scour occurs during a freshet. Therefore sedimentation occurs from the top down in the streambed and the composition of deeper layers is unchanged until a freshet occurs that is large enough to cause movement at considerable depths in the streambed.

Carnation Creek results showed this pattern of deposition and scour. When the volume of sands and pea gravel in the bedload was increased by watershed disturbance, changes in streambed composition became apparent first near the surface. As the stream was exposed to larger freshets with longer return periods, the depth at which sand seals were formed became greater. When the sources of sediment decline, as the basin stabilizes, and if the frequency of freshets is unchanged, cleaning of the substrate should occur in the same way, although the larger the fine particles and the deeper their penetration the slower the rate of cleaning.

Changes in gravel composition were dependent upon the frequency and magnitude of peak flows, on proximity to the different streamside treatments (sources of sediment), and on the timing of logging activities. Fines increased with gravel depth (Scrivener and Brownlee 1982), simply because cleaning at these depths was less frequent. The increase in sand and pea gravel was apparent first in the upper layers of the streambed, but eventually penetrated deeper. Sands and pea gravel were still accumulating in the deeper layers, 10 yr after logging commenced. If the new sediment sources were eliminated now (most unlikely given the instability noted; Hartman et al. 1987), the composition of the deeper layers of spawning gravel would not return to prelogging levels for another 10 yr, unless large freshets were to occur more frequently than observed over the last 16 yr (1971–1986). Upstream, fines would probably be cleaned from the top 15 cm within 3 yr should sediment sources (inchannel and streambank) be eliminated and no new sources occur, although this would also be unlikely given the instability of the channel.

Shape of streambed material can also have an appreciable effect on deposition and cleaning rates. At low flows, round gravels tended to accumulate more fine sediment than angular gravels, but this relationship is reversed as flow rates are increased (Meehan and Swanston 1977). Once fines have intruded into the streambed, cleaning is slower in angular gravels. At Carnation Creek, spawning gravels consist mainly of angular materials.

Gravel Composition and its Relationship with Other Physical and Biological Parameters

A weak correlation between gravel composition and intergravel DO was obtained from these data. Other investigators reported either a strong relationship (Koski 1975; Tagart 1984) or no relationship (Koski 1966; Scrivener and Brownlee 1982; Sowden and Power 1985). This is hardly surprising, because composition of the streambed is only one factor that effects interstitial DO. Oxygen supply to a site is a function of ambient DO and of delivery rate (Phillips 1971). Variation in ambient DO among sites was reduced for Carnation Creek data by expressing DO as a percent of surface concentration. Delivery rate (subsurface water velocity) is a function of streamflow, of hydraulic gradient, of streambed microtopography, and of flow direction over the site as well as composition of the bed (Phillips 1971; Reiser and Bjornn 1979; Sowden and Power 1985). A better correlation between gravel composition and DO may be obtained at a time when streamflow is not near summer minimums. Bed composition may have only a minor influence on interstitial DO for sites fed by upwelling groundwater instead of downwelling surface water (Sowden and Power 1985). The best relationship between DO and core composition was obtained for the top layer, because this layer effects the exchange between surface and interstitial water. All these factors should be considered if a predictive relationship is required between composition of the streambed and DO of its interstitial water.

Laboratory studies have shown that incubation survival is inversely related to gravel composition (Bjornn 1968; Phillips et al. 1975; Witzel and MacCrimmon 1981, 1983), but these results often could not be extrapolated directly to natural salmon redds (Tagart 1984; Sowden and Power 1985; Scrivener 1989). Variability of survival among redds depended on DO, on removal rates of carbon dioxide and other metabolites, on streambed scouring, and on behavioural responses of alevins as well as composition of the substrate (Koski 1966; Tagart 1984; Sowden and Power 1985). Salmonid eggs have incubated successfully in redds that contained mostly sand, but usually the fry could not escape from the substrate (Koski 1966; Tagart 1984). At Carnation Creek, this variability among redds was removed by using annual survival of the whole population and mean annual composition of the substrate. Incubating salmonid eggs require the greatest oxygen concentrations just before hatching (Alderdice et al. 1958), but alevins survive at lower DO because their gill membranes obtain oxygen more efficiently (McNeil 1966). If pore spaces in the substrate are large enough, alevins could disperse from the egg pockets (Koski 1966; Dill and Northcote 1970) and select more preferable sites (Dill 1969; Reiser and Bjornn 1979) thus reducing oxygen demand in the redd. However, fines in the substrate of some redds probably prevent this (Phillips and Koski 1969). Substrate composition influences survival indirectly during the egg incubation phase, but it has a direct effect later during any dispersal of alevins or the emergence of fry (Koski 1966; Dill 1969; Koski 1975). Emerging fry move to the surface of the bed through pore spaces in the gravel, but they can penetrate a thin layer of fine sand near the surface (Bams 1969). When these pore spaces are filled with fine sediments, fry become entombed in the bed and eventually starve to death (Phillips 1971). At Carnation Creek, entombment was probably the greatest source of mortality, because pore spaces in the substrate were filled mainly with coarse fines.

At Carnation Creek, differences of coho and chum salmon relationships between survival to emergence and composition of the streambed possibly reflected differences in redd depths between species. Coho salmon eggs were deposited at 18 to 28 cm in Oregon streams (Koski 1966). Female size was also related to nest depth among some populations of coho salmon, which indicated that most females at Carnation Creek (61 to 78 cm FL; Andersen 1983, 1984, 1985, 1987) deposited their eggs at a depth of 14.6 to 21.6 cm (depth in centimetres = 0.411·(FL cm) − 10.44; Van den Berghe and Gross 1984; Holtby and Healey 1986). This agrees with the observed relationship for coho survival and substrate composition of the bottom layer. Less information is available concerning the depth of redds of chum salmon. Eggs were deposited at 10–50 cm in Big Beef Creek, Washington and at a mean depth of 21.5 cm in Olsen Creek, Alaska (K V. Koski, National Marine Fisheries Service, Auke Bay, AK, pers. comm.). Egg deposition is probably shallower at Carnation Creek because these chum salmon produce exceptionally large eggs and because they have low energy reserves for spawning (spawn <48 h, die ~1 wk; Scrivener 1988b). Their eggs are usually found between 5 and 20 cm in December streambed cores from below the counting fence (Les Powell, Fisheries and Oceans Canada, Vancouver, B.C., pers. comm.). Many eggs are probably deposited below the top layer (>15 cm), but subsequent scour leave them at shallower depths during most of the period of incubation. Therefore incubation survival of chum salmon related better to composition of the top layer of streambed cores.

During other studies, deposition of fines in the streambed has caused size selective mortalities among large fry that were emerging from salmon redds (Koski 1966, 1975; Tagart 1984; Sowden and Power 1985). Differences of morphology such as cranial diameter among species have also been cited as the reason for survival differences in laboratory experiments using various incubation mixtures of gravel (Phillips et al. 1975; Reiser and Bjornn 1979; Witzel and MacCrimmon 1983). At Carnation Creek, increasing fines were correlated with declining sizes within the total population of emerging coho fry but the relationship was not apparent for chum salmon until the influence of egg and female size on size of progeny was removed statistically. Variability of female and egg sizes also masked size selective mortality among emerging fry of chum salmon at Big Beef Creek (Koski 1975). Selection against larger fry would alter the relative fitness of coho rearing in a stream or chum salmon emigrating to the ocean. Shortly after emergence, both species are subjected to intensive mortalities that are selective against the smaller sizes (Chapman 1966; Healey 1982). This has apparently reduced survival among returning adults of Carnation Creek chum salmon (Scrivener 1988b).

Emerging chum salmon fry were larger than those of coho salmon. This difference might also explain why the size and survival of chum salmon fry were better correlated with streambed composition in the top layer, while fry size and survival of coho salmon were better correlated with the composition of the bottom layer. Mean FL of chum salmon fry was 41.8 mm (Scrivener 1988b), while mean FL of emerging coho fry was 37.1 mm (Andersen 1983, 1984, 1985, 1987) during 1972 to 1986. The larger chum fry probably had greater difficulty penetrating the top layer of the substrate with its more variable fines than the smaller coho salmon fry.

Peak flows can influence survival of incubating eggs and alevins through changes in the stability of spawning gravels (McNeil 1966), or when they are linked with changes in composition of the bed as reported here (Fig. 10). Stability of the bed has declined at Carnation Creek as indicated by changes in channel morphology and in stability of LOD (Toews and Moore 1982; Hartman et al. 1987). These factors are reflected in the strong relationship between coho survival to emergence and peak flows. The weak relationship between peak flows and survival of chum salmon was obtained because chum redds were probably shallower than coho redds. Therefore, a threshold of maximum potential impact on chum salmon could be occurring more frequently and at much smaller peak flows (see Fig. 8). The fact that significant relationships were obtained between peak flows and streambed composition of the bottom, but not the top layer supported this hypothesis. Changes were so common for the top layer that more frequent sampling would be required to directly relate streamflow to either substrate composition in the top layer or incubation survival of chum salmon.

The positive relationships between composition of the streambed and peak flows should deteriorate and they could become inverse relationships as sources of new sediments decline and the cleaning of fines is begun. The positive relationship developed because large freshets scoured fines from the stream banks and distributed them in the bed. That was the habitat degradation stage being observed. During the rehabilitation stage, large freshets should be related to the scouring of fines from the streambed and their transport to the estuary. Data from 1985 to 1986 appeared to weaken the relationships between composition of the streambed and peak flows (see Fig. 10) indicating that Carnation Creek could be entering either a stage of equilibrium between deposition and scour or that after a decade the rehabilitation stage was about to begin.

Planning and Management Implications for Coastal Forest Harvesting Operations

The transfer of Carnation Creek results to resource managers has been the focus of countless presentations both on site and in various lectures, workshops (Hartman 1982; Chamberlin 1988), and conferences (Hartman et al. 1987; Holtby et al. 1984). In their development, the new fishery forestry guidelines that are now being implemented for forest harvesting throughout coastal British Columbia have drawn largely upon Carnation Creek results and our understanding of watershed processes (BCMFL et al. 1987).

It is very clear that gravel composition and stability are closely tied to the integrity of the riparian zone and to LOD in the stream (Hartman et al. 1987; Bisson et al. 1987). Forest management practices that had the greatest destabilizing influence in this area were streamside felling and yarding activities (Toews and Moore 1982). Specific impacts that must be considered include direct physical damage, exposure of the banks, and loss of living root networks due to these activities. In active fluvial floodplains, living roots have a major role of maintaining the stability of streamside zones (Sullivan et al. 1987). These observations have held true for many other streams including the Eve River, Nimpkish River, and Kim Creek in British Columbia (D. Morrison, B.C. Ministry of Environment, Nanaimo, pers. comm.). Damage to LOD by felling and yarding or the introduction of smaller pieces that lodge behind stable instream structures, that create dams, and that subsequently initiate undercutting or sidecutting must also be avoided. Smaller debris that is unstable can also be transported by the stream to more sensitive zones downstream. Streamside practices that directly impact on these riparian or instream features or indirectly by accelerating windthrow must be carefully planned in order to avoid these consequences. Consideration to the long-term source of LOD, particularly larger growing conifers (Bisson et al. 1987; Hartman et al. 1987; Poulin 1986) must also be given consideration now, if stream channel complexity and stability are to be maintained throughout the forest harvesting rotation. Forestry activities in riparian zones that are adjacent to salmonid habitat should be reduced and strips of timber left where stream waters have enough energy to cause considerable erosion or to transport large volumes of sediments and LOD. These leave strips should not be fixed in size, but tailored to each specific stream side and watershed geology.

In addition, opportunities for resource managers to offset or mitigate these impacts are becoming more apparent. Placement of armoring materials on destabilized banks, placement of LOD in channels to stabilize bedload (Hartman and Scrivener 1986), promotion of deciduous brush and tree species to stabilize stream banks (Sullivan et al. 1987), enhancement of off-channel habitat for rearing if instream areas are inhospitable during freshets (Cederholm and Reid 1987) are examples. Resource managers must give these opportunities more careful consideration. The new fishery forestry guidelines for coastal British Columbia reflect these results and permit exploration of these opportunities (BCMFL et al. 1987).

Resource managers must understand fluvial processes in a watershed in order to develop the best forest harvesting plan. Increased mortality among incubating salmon eggs was reported during the Clearwater (Cederholm et al. 1981; Tagart 1984) and Carnation Creek watershed studies. This was also implied for the Alsea watershed and Queen Charlotte Island studies, when the quality of spawning gravel declined (Moring 1975; Poulin 1986), but the size of offending particles in the streambed, their mode of transport and deposition, and their source areas varied among the studies. Therefore, the required management prescriptions to reduce incubation mortalities may have to be specific to given areas and to those problems identified.

The duration of impacts must also be considered by managers if the best resource options are to be chosen and long-term problems alleviated. For example, silt and clay size particles may produce impacts of shorter term that might be less harmful than longer term sedimentation of larger particles. The duration of impacts may be also influenced by their magnitude. If these impacts are of long duration, then the cumulative effect from some natural occurring regulators are more probable. Events that are natural and detrimental such as floods in the stream or El Nino currents in the ocean can act synergistically with these man-induced impacts to severely affect the resilience of a salmon stock (Cederholm et al. 1981; Holtby 1988; Scrivener 1988b).

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