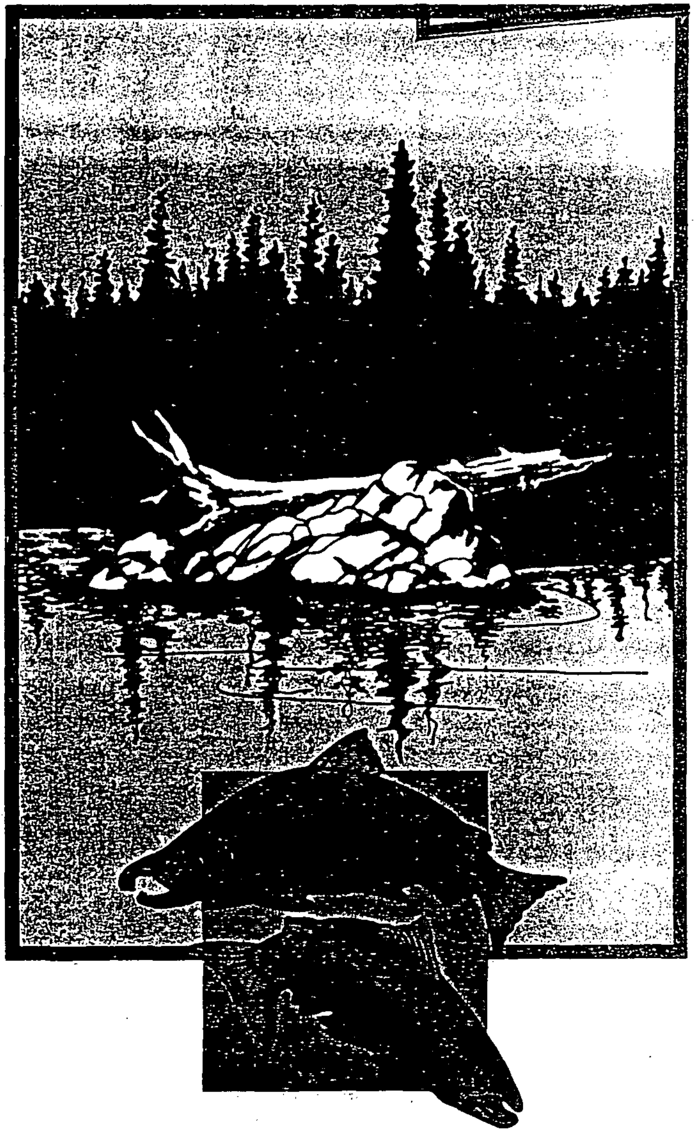
IMPACTS OF FORESTRY PRACTICES ON A COASTAL STREAM ECOSYSTEM, CARNATION CREEK, BRITISH COLUMBIA

G. F. Hartman and J. C. Scrivener



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Impacts of Forestry Practices on a Coastal Stream Ecosystem, Carnation Creek, British Columbia

G. F. Hartman and J. C. Scrivener

Department of Fisheries and Oceans
Biological Sciences Branch
Pacific Biological Station
Nanaimo, British Columbia V9R 5K6

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Abstract

HARTMAN, G. F., AND J. C. SCRIVENER. 1990. Impacts of forestry practices on a coastal stream ecosystem, Carnation Creek, British Columbia. Can. Bull. Fish. Aquat. Sci. 223 : 148 p.

Results from the first 17 yr of a multi-disciplinary study about the effects of logging activities on a small stream ecosystem in the coastal rainforest of British Columbia have been reviewed. The main hydrological, fluvial-geomorphological, thermal, and production relationships are integrated in four schematic illustrations. The study has revealed that each activity conducted within an overall forest management plan may affect the physical components of an ecosystem differently. Whether these effects had positive or negative impacts on fish and other stream biota depends upon the specific activity conducted, the species present, and the life stage of each species of fish.

In Carnation Creek forest practices that increased stream insolation, water temperature and nutrient levels increased the numbers, growth period and size of coho salmon fry (*Oncorhynchus kisutch*), but reduced the marine survival of chum fry (*O. keta*). They also increased the growth period and growth rate of trout fry (*O. mykiss* and *O. clarki*), but growth decreased among the older age groups of both coho salmon and trout. The positive effects of these changes were simultaneous with the commencement of logging and burning of slash.

Stream-side logging activities also decreased the stability of the stream channel and it's large organic debris. These changes and changes in the composition of spawning gravel reduced fish survival and numbers. The negative effects required more time to manifest themselves than the positive effects. Influences of the negative and positive freshwater impacts continued into the marine life history stages of both chum and coho salmon.

Applications of results to land use planning are also discussed. Logging-related changes in a drainage can occur over decades of time. Although coastal streams in British Columbia are diverse, the common features that must be considered in fisheries–forestry planning are high rainfall, high hydrological energy, physical instability, low nutrient levels and cool temperatures. Long-term case history studies such as the one reported here reveal ecosystem processes permitting researchers to partition climatic variability from man induced impacts. Resource managers must be able to understand and apply such process information to other stream systems in the light of their own experience and site specific information.

Résumé

Hartman, G. F., and J. C. Scrivener. 1990. Impacts of forestry practices on a coastal stream ecosystem. Carnation Creek, British Columbia. Can. Bull. Fish. Aquat. Sci. 223 : 148 p.

Les auteurs ont étudié les résultats recueillis au cours des 17 premières années d'une étude multidisciplinaire sur les incidences de l'exploitation forestière sur l'écosystème d'un petit cours d'eau de la forêt ombrophile côtière de la Colombie-Britannique. Les principales relations hydrologiques, fluviales–géomorphologiques, thermiques et relatives à la production sont présentées sous forme de schémas. Les résultats de l'étude révèlent que chaque activité réalisée dans le cadre d'un *plan de gestion forestière global peut influer de façon différente sur les composantes physiques* d'un écosystème. La nature de l'activité, les espèces présentes et le stade du cycle vital de chaque espèce de poisson déterminent si l'incidence sur les poissons et la biste fluviale sera négative ou positive.

Dans le ruisseau Carnation, les méthodes d'exploitation forestière qui ont entraîné un accroissement de l'ensoleillement du cours d'eau, de la température de l'eau et des niveaux nutritifs du milieu ont eu pour résultats une augmentation du nombre d'alevins de saumon coho (*Oncorhynchus kitsutch*), de la période de croissance et de la taille. Elles ont par contre amené une baisse du taux de survie en mer des alevins de saumon kéta (*O. keta*). On a aussi noté une augmentation de la période et du taux de croissance des alevins de *O. mykiss* et de *O. clarki*, ainsi qu'une baisse du taux de croissance chez les groupes plus âgés de *O. mykiss*, *O. clarki* et *O. kisutch*. L'incidence positive coïncidait avec le début du bûcheronnage et du brûlage de déchets forestiers.

L'exploitation forestière des rives a aussi diminué la stabilité du chenal du ruisseau et des gros débris organiques. Ces altérations du milieu ainsi que des gravières ont réduit le nombre de poissons et leur taux de survie. L'incidence négative était plus longue à se manifester que l'incidence positive. Ces incidences sur l'habitat d'eau douce ont eu des répercussions sur les stades marins du cycle vital des saumons coho et kéta.

Les auteurs traitent aussi de l'application des résultats à la planification de l'utilisation des terrains. Les modifications apportées à un bassin versant par l'exploitation forestière peuvent s'étirer sur plusieurs décennies. Même si les cours d'eau côtiers de la Colombie-Britannique sont hétérogènes, ils partagent des caractéristiques dont on doit tenir compte dans la planification de l'exploitation forestière et halieutique soit une forte pluviosité, l'importante énergie hydrolique, l'instabilité physique, les faibles niveaux nutritifs et les températures fraîches. Les études de cas à long terme comme celle mentionnée dans le présent document mettent à jour les processus inhérents à un écosystème qui permettent aux chercheurs de séparer la variabilité climatique de l'intervention humaine. Les gestionnaires des ressources doivent comprendre et appliquer de telles données sur les processus à d'autres systèmes fluviaux à la lumière de leur expérience personnelle et de données particulières à un emplacement.

Preface

Fishing and forest harvesting are two of the major resource industries in British Columbia. In coastal areas they depend on overlapping parts of the land base which has made interaction and conflict between the industries a part of recent British Columbian history. Logging and silvicultural activities have the potential to damage salmonid producing habitats, while land use restraints that are designed to protect these habitats have the potential to affect the scope and profitability of the forest industry. Therefore an integration of recent research that improves our understanding of the ecological interaction of fisheries and forestry should prove useful.

In this Bulletin we have attempted to review, integrate and synthesize the results from the Carnation Creek Experimental Watershed Project. They have appeared in more than 150 articles in a variety of different publications (Bibliography). Published proceedings from three workshops dealt with a 10-yr review, applying results, and herbicide studies. A more comprehensive synthesis is needed after nearly two decades of research.

Discussion of ocean life history of Carnation Creek salmonids is included, although forestry impacts on their habitats are confined to the stream. Conditions in fresh water altered salmonid growth and behaviour and consequently affected survival in the ocean. Conditions in the ocean further modified survival rates before adults returned to Carnation Creek. It is essential to separate these influences in order to assess the impact of forest practices on the populations.

This Bulletin is written in nine chapters. The first four chapters (Introduction, Study Area, Study Design, Methods) follow the format typical of research articles. They contain abridged descriptions of the watershed, study design and methods in enough detail to indicate what the stream system was like and what was done. The reader can refer to specific articles that are listed in the Cited References and Carnation Creek References for more details on individual topics.

Results are presented in chapters five and six as time series data. Chapter five contains physical data such as temperatures, precipitation, stream discharge, stream channel morphology, streambed composition, and sediment transport. Results of short-term studies (e.g. soil disturbance) and studies still in progress are placed within the 17-yr time frame. Chapter six contains the following biological results : The production of terrestrial and aquatic plants, stream detritus and stream macroinvertebrates ; Numbers of adult coho salmon, chum salmon, cutthroat trout and steelhead trout that spawned in Carnation Creek ; Egg-to-fry survival for chum and coho salmon ; Numbers, timing and sizes of chum and coho salmon fry that moved downstream through the main counting fence ; Numbers and sizes of salmonids and sculpins during spring, summer and early autumn at eight reaches and a tributary of Carnation Creek ; Numbers and lengths of salmonid juveniles moving into and out of tributaries and swamps located on the Carnation Creek flood-plain ; and Numbers, sizes and age structures of salmonid smolts moving downstream into the estuary. Some explanations of changes are made here.

Physical and biological changes are integrated in a discussion of watershed processes in chapter seven. Forest harvesting and silvicultural impacts on hydrology, stream channel debris, thermal regimes, fish-food production and fish production are introduced at this point in the Bulletin. They are examined in relation to natural background variability.

Chapter eight contains discussions of the influence of time on impacts and the importance of watershed diversity. Impacts that were observed during other studies are reviewed here. This presentation tends to be more speculative, because little published research exists on the processes of change spanning 25 to 100 yr. Major differences between Carnation Creek and other ecosystems and the applicability of the results to other streams and process concepts are presented.

The last chapter outlines the common features of many streams the size of Carnation Creek. It indicates the basis for diversity, and discusses managing despite diversity. Use of the results to aid planning of forest harvesting is examined. We emphasize that forest harvesting is better managed through application of ecological knowledge than through the employment of a list of prohibitions.

G. F. HARTMAN AND J. C. SCRIVENER

Acknowledgments

During the first 17 yr of the Carnation Creek Experimental Watershed Project (1971–87), many persons have contributed to field and laboratory studies that were associated with the project. We gratefully acknowledge this effort. B. C. Andersen, T. G. Brown, R. M. Leahy and P. I. Neaves have had a continuous or nearly continuous role ; their contributions and dedication are particularly appreciated. D. W. Narver, P. E. K. Symons and V. A. Poulin have previously served as project coordinators and L. B. Holtby has been a major contributor to the analysis of data. We are very grateful to the following people for their positive attitude of support for the project : G. Ainscough and D. Handley of MacMillan Bloedel Ltd., F. Boyd and J. Payne of Fisheries and Oceans Canada, R. MacDonald of Forestry Canada, D. Narver of the B.C. Ministry of Environment and Parks, G. Tofte of Environment Canada, and W. Young of the B.C. Ministry of Forests and Lands. Drafts of this manuscript were reviewed by T. G. Brown, L. B. Holtby, E. D. Hetherington, C. D. Levings, P. E. K. Symons, and M. Waldichuk. Support for the herbicide studies was provided through the B.C. FRDA Agreement.

Chapter 1. Introduction

Purpose

The first phase (1971–87) of the multi-disciplinary Carnation Creek watershed project has been completed. It was designed to study the effects of forest harvest activities on vegetation, soil, water and fish. Results have been reported and discussed in 154 publications (see Cited References "*", and Carnation Creek References) including reviews of the effects of stream-side treatments on fish (Hartman et al. 1987), of streambed composition changes on fish (Scrivener and Brownlee 1989) and of climate, fishing and logging on stock recruitment relationships (Holtby and Scrivener 1989). However none of these manuscripts has integrated and synthesized all components of the project. This document was written to fill this void and to meet six objectives :

1. To review briefly the major results from published articles and manuscripts currently in press.
2. To publish results where small gaps existed in the data analysis.
3. To elucidate important drainage basin processes and to show effects that logging might have on such processes including the production of fish.
4. To examine changes in stream temperature, hydrological conditions, woody debris volume and gravel quality through time (16–17 yr) following logging ; and to speculate about future patterns of change in the Carnation Creek ecosystem.
5. To consider the application of results from this study to forest land use planning.
6. To discuss some of the implications of diversity among coastal streams of the temperate zone.

These objectives conform loosely to the order of chapters five through nine of this Bulletin.

Project Background

The coastal zone of British Columbia has a high potential for the production of both forest products and fish. In the Vancouver and Prince Rupert Forest Regions, 3.3 % of the entire land base is classed as "*good*" industrial forest land, 32.9 % is classed as "*medium*" (Anon. 1980 ; BCML et al. 1987). Essentially all of this land base lies within the valleys of the two coastal forest regions. The land and its use are of key importance to the forest industry of British Columbia.

Five species of Pacific salmon and two species of trout spawn within coastal streams. Four of the seven species (2 salmon, 2 trout) utilize the stream environment for 1–3 yr of their lives. Such young fish depend upon water that is stored in, and released from forest soils. They depend upon the trees which fall naturally into the stream channels and which shape the structure of such channels. They also utilize terrestrial insects as a food source. The life history of young trout and salmon is intricately related to conditions of the forest and the land. These fish are by-products of the terrestrial environment.

Major industrial use of forests in British Columbia began in the 1890s. Total timber production for British Columbia was 9.9 million m^3 in 1920. It has doubled, approximately, every 20 yr since 1920 (Anon. 1980). During the first decade after World War II essentially all of the forest land in British Columbia other than private land or park land came under some form of tenure for forest harvest.

The methods of forest harvest that were used in coastal British Columbia were developed to rapidly remove large trees, with high economic return, from steep and irregular terrain. During the first half of the century this was done with little planning to protect the habitat that produced fish. The mutual recognition, by forest and fish managers, that systems of fish protection and land use planning were needed led to the establishment of a referral system in 1956 (Toews and Brownlee 1981) and later to the establishment of the Coastal

Forest Planning Guidelines, Protection Clauses (P-1 clauses), and guidelines for the construction of forest haul roads (see Brownlee and Morrison 1983 for review).

Decisions made within the referral process and in the application of guidelines required knowledge of drainage basin processes, the effects of forest harvest activities on these processes, and ultimately their effects on fish populations. The research information that was used until late 1960 was based on studies in areas that were not geoclimatically similar to those in coastal British Columbia. This caused uncertainty and debate and led to the recognition of a need for local research. In response to this need a forestry–fisheries study was initiated during 1970 in the Carnation Creek watershed, on the west coast of Vancouver Island.

Carnation Creek Project

The project was planned as a multi-disciplinary study and was structured with a *Coordinating Committee* (a steering and funding group) and a *Working Committee* (field research group). Members of these two groups were drawn from federal and provincial agencies and from the forest industry.

The project was established with three broad objectives (Narver 1974).

1. To develop a better understanding of how undisturbed coastal rainforest-salmonid stream ecosystems work.
2. To explain and quantify the impacts of timber production activities on stream environments and their capacity to produce salmonid fishes.
3. To provide continuous input to the further development of integrated resource management guidelines.

The transfer of Carnation Creek results to resource managers has been the focal point of countless presentations. Many of these have been given on site, many others have been presented via lectures or major workshops (Hartman 1982 ; Chamberlin 1988 ; Reynolds 1989). In their development, the new fishery–forestry guidelines that are now being implemented throughout coastal British Columbia have drawn largely upon the understanding of watershed processes that was obtained at Carnation Creek (BCMFL et al. 1987).

An intensive long-term study of a single watershed was chosen as the project design rather than an extensive multi-watershed design. An intensive long-term study helped clarify ecosystem processes and it showed the effects of climate trends which could be separated from the impacts of forest harvesting. The chances of demonstrating statistical significance also improved with a long-term data base because so much variability occurs in natural ecosystems. A short-term extensive study of many watersheds would not be complicated by climate trends, but process oriented research would be difficult. Large budgets are needed for such extensive short-term studies, while lower annual budgets can support an intensive study. A long-term approach seemed most feasible since short-term funding was quite limited. The project contained prelogging, logging and postlogging periods.

Chapter 2. Study Area

Location, Geography, and Climate

3470 ac

Carnation Creek watershed, ~10 km^2 in area, is located on the southeastern side of Barkley Sound on the west coast of Vancouver Island, British Columbia, 49°N and 125°W (inset, Fig. 1). It is within the Coastal Western Hemlock Biogeoclimatic (CWHB) Zone which is typical of the west coast of North America from the Olympic Peninsula in Washington State to southeast Alaska and the Queen Charlotte Islands (Krajina 1969). High rainfall and climax forests (Fig. 2) dominated this zone before timber harvesting.

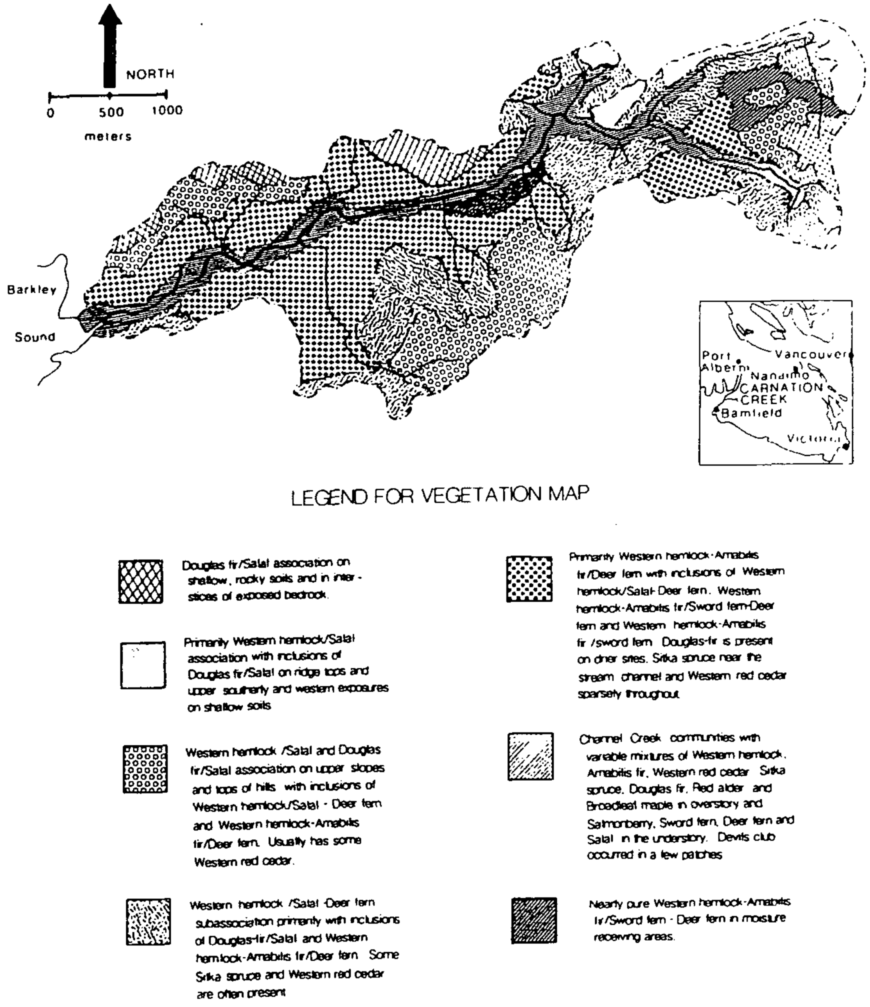

FIG. 1. Carnation Creek and vegetation associations on Vancouver Island, British Columbia. Seven main vegetation associations are indicated (see legend). Redrawn with permission from Oswald (1982).

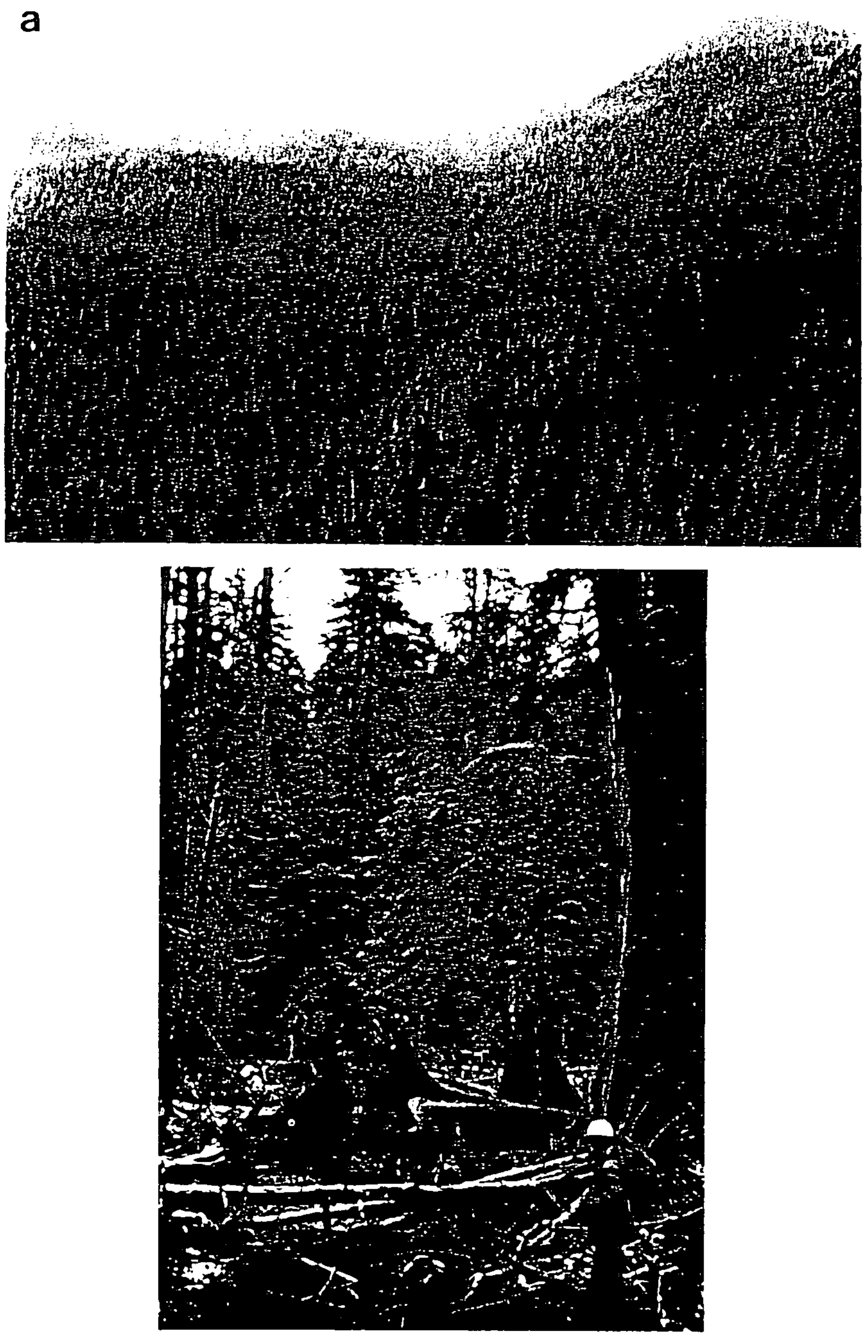

FIG. 2. (a) Old-growth forest in the Carnation Creek drainage before cutting ; (b) Carnation Creek in an opening in the old-growth forest.

The pre-harvest vegetation and soils in the drainage were described by Oswald (1982). The primary forest trees in Carnation Creek watershed were western hemlock (*Tsuga heterophylla*), western red cedar (*Thuja plicata*), amabilis fir (*Abies amabilis*), Douglas fir (*Pseudotsuga menziesii*), Sitka spruce (*Picea sitchensis*), and red alder (*Alnus rubra*). The predominant shrubs were salal (*Gaultheria shallon*), salmonberry (*Rubus spectabilis*), stink current (*Ribes bracteosum*), and four species of *Vaccinium*. The typical vegetation associations at Carnation Creek are shown in Fig. 1

Hydrological conditions in the watershed were described by Hetherington (1982). The inlet coastal areas of British Columbia are subject to frequent winter storms. Precipitation in the Carnation Creek drainage has ranged from 210 to over 500 cm annually with ~95 % falling as rain. Individual storms have produced up to 26 cm of precipitation in 48 h. Discharge at the stream mouth varied from 0.03 m^3·s^{-1} in summer to 64 m^3·s^{-1} in winter. Stream discharge regularly changed 200-fold during a 48 h period because of the intensity of storms and the speed of runoff. Greater than 90 % of annual precipitation leaves the watershed as runoff (Scrivener 1975).

The topography in the drainage basin is steep and irregular. The valley walls have gradients up to 80 % that are interrupted by bluffs and rock outcrops. The geology of the Carnation Creek basin was described by Eastwood (1975). Slope soils of 0.7 m mean depth overlie bedrock. They are composed of coarse colluvial material, gravelly loam and loamy sand with an organic surface layer (Oswald 1982). Soils have developed primarily from weathering of local rocks which are Jurassic volcanics of the Bonanza Group. They are coarse in texture, well drained, and except in the fluvial areas they are Orthic Ferro-humic podzols. Regosols occur on the rocky steep areas and the more active alluvial channels (Oswald 1982). Figure 3 illustrates the distribution of main soil types. The valley floor in the lower 3 km of stream consists of a 55 ha flood plain that is 50–200 m wide. Flood plain soils are composed of gravel, alluvial sands, lenses of sandy-clay and organics (Hetherington 1982).

Stream Features

Gradient can be used to divide Carnation Creek into four zones. The upper 2.4 km of the main creek, Zone 1, drains through a canyon area with a gradient of ~240 m·km^{-1} (Fig. 4). This is a typical first order stream or a "Class IV" in the British Columbia classification system (BCMFL et al. 1987). Below this the creek flows through a narrow, flat valley floor for 1 km with a gradient of ~25 m·km^{-1} (Zone 2 ; Fig. 4). This is followed by another 1 km section of canyon, Zone 3, with a 85 m·km^{-1} gradient. This reach contains many log-jams that are impassable to fish moving upstream. In the lower 3.1 km, Zone 4, the stream meanders along a flood plain at a 9 m·km^{-1} gradient (Fig. 4). Here, Carnation Creek is classified as a fourth order or "Class I" stream (BCMFL et al. 1987).

Substrate characteristics also differ in each of the four zones. The stream bottom in the upper canyon (Zone 1) is composed of bedrock and some large boulders. Log-jams of blown down trees with wedges of gravel stored upstream of the jams occur at irregular intervals. The stream channel in Zone 2 contains fallen trees interspersed between riffles and shallow pools with a gravel and cobble substrate. The lower canyon (Zone 3) appears similar to the upper canyon (Zone 1), but debris jams and gravel wedges are more numerous. Some of the debris and gravel torrented out of Zone 3 and into Zone 4 during 1984. The channel in Zone 4, (prior to logging), contained many large fallen trees and small debris jams (Fig. 2b) scattered along its length. These trees contributed to a diverse channel structure of riffles, deep pools and back-eddies with gravel bottoms (<10cm in diameter).

There are two types of tributaries in the Carnation Creek drainage, valley-wall tributaries and valley-floor (or wall-base) tributaries, as defined by Peterson and Reid (1984). The

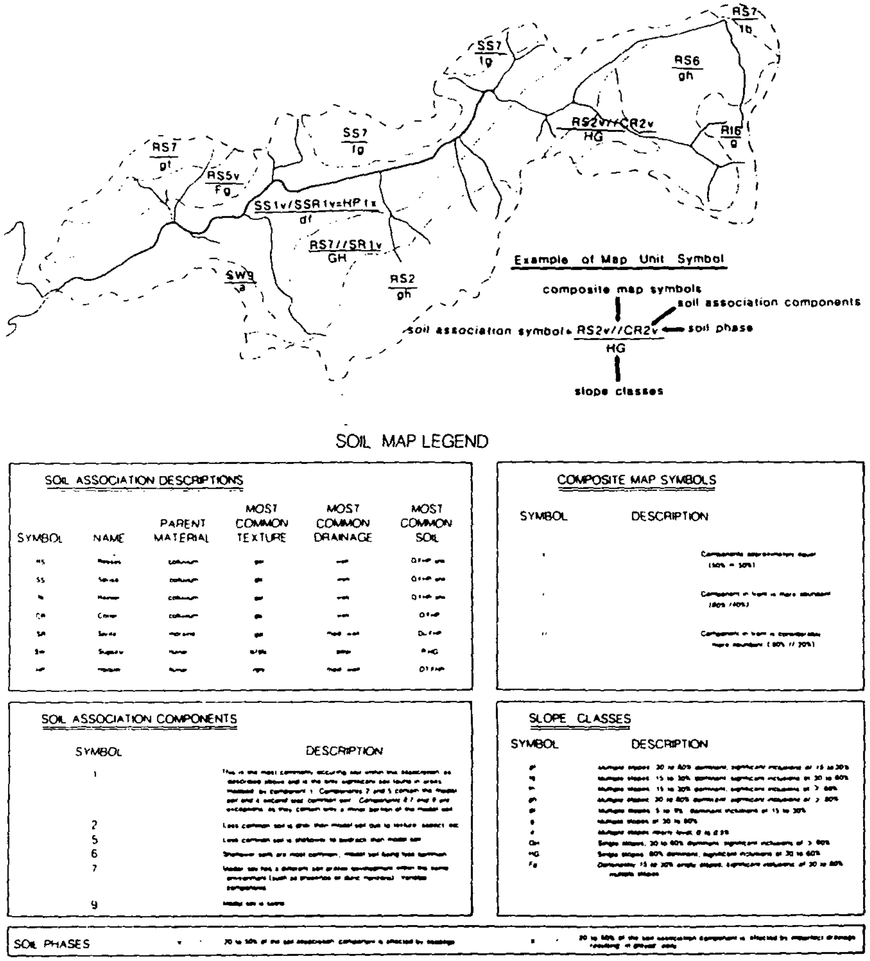

FIG. 3. Soil types in the Carnation Creek basin. Soil association components and slope classes are indicated by the legend. Redrawn with permission from Oswald (1982).

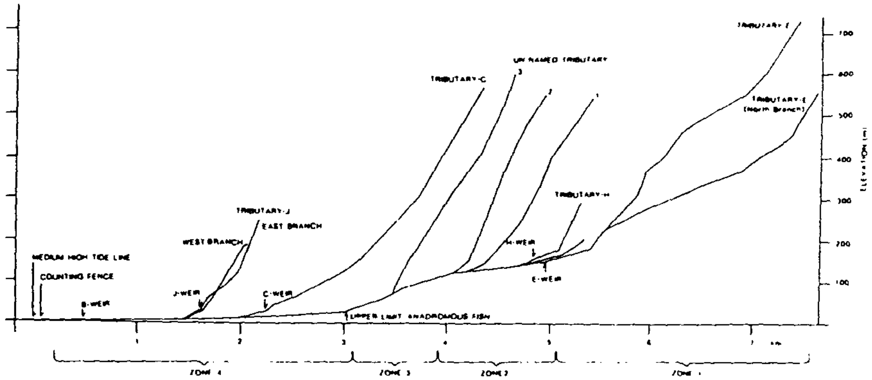

FIG. 4. Gradient of Carnation Creek and main tributaries. See text for descriptions of the stream in the four zones indicated.

valley-wall tributaries, which include Tributary-C, -J and -H, and three unnamed tributaries (Fig. 4), have average gradients ranging from 165 to 490 m•km^{-1}. These tributaries descend directly into Carnation Creek or descend onto and across a short distance of flood plain before joining the creek. The valley-floor tributaries, which include Tributary-750, -1600 and most of Tributary -2600, have gradients less than 10 m•km^{-1}. They flow parallel to the main channel before joining it.

Both kinds of tributaries have different substrate types. The valley-wall tributaries are characterized by bed rock and boulder bottoms. They contain fallen trees and associated stored gravel. The valley-floor tributaries are intermittent streams that flow among fallen and rooted trees and are characterized in their upper reaches by a bottom of organic muck and rooted emergent vegetation. In the lower reaches they have scoured sand–gravel bottoms (Brown 1985). On the flood plain there are several ephemeral swamps that are fed by stream channels that become connected to the main-stem of the creek during storms (~11 m^3•s^{-1} ; Brown 1985).

The main creek and tributaries were originally heavily shaded by tree canopy and understory vegetation that consisted of red alder, western red cedar and sitka spruce. Percentage canopy closure along the lower 3 km of Carnation Creek ranged from 15 to 100 %. Closure was over 50 % at 60 of 212 measured sites (Oswald 1982). The shaded sections of the stream had maximum light intensities of only one sixth of those found in the areas with no trees (deLeeuw 1982).

Fish Species and Numbers

The principal species of fish and range in numbers of spawning salmonids in the stream were : chum salmon (*Oncorhynchus keta*) 275–4170, coho salmon (*O. kisutch*) 74–426, and steelhead trout (*O. mykiss*[1]) 2–12. Sea-run cutthroat trout (*O. clarki*[2]) numbered fewer than 5 pairs each year. Sockeye salmon (*O. nerka*) and pink salmon (*O. gorbuscha*) spawners entered the stream in some years (1980, 1985), but they usually spawned in the estuary. These irregular runs ranged from 2 to 100 fish, but they were considered strays from other populations. Resident cutthroat trout occurred in Zones 2 and 3 and some of the tributaries (e.g. Trib. C and H ; Fig. 4). There were two species of sculpin within the drainage, the prickley sculpin (*Cottus asper*) and the coast range sculpin (*C. aleuticus*).

Anadromous fish can ascend to 3.1 km upstream from the sea. Most chum salmon spawned in the estuary or lower 500 m of stream. The coho salmon, steelhead and sea-run cutthroat trout spawned throughout the accessible stream.

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[1] Formally *Salmo gairdneri*.
[2] Formally *S. clarki*.

Chapter 3. Study Design

Logging Plan

The Carnation Creek project was initially planned to last 15 yr, to contain three time periods, and to include various treatments of tributary watersheds. Time periods were to include a prelogging monitoring stage — 1970 to 1975, a logging stage — winter of 1975-76 to 1979-80, and a postlogging stage — spring of 1980 to spring 1985 (Narver 1974). Logging activities are planned for the October to April period at relatively snow free sites like Carnation Creek, consequently, a 1975 labour dispute restricted the number of hectares that could be logged that year. Therefore the logging stage was extended until 1980-81, with minimal logging during 1975-76, and the postlogging stage was delayed and extended a year. It lasted from spring 1981 to 1986. Consequently, the winter of 1976-77 is taken throughout this manuscript to be the start of (major) logging operations. Watersheds C and E (Fig. 5), served as internal unlogged controls until 1986. Tributary-H was logged in 1 yr but the remaining debris was not burned except along the N.W. boundary (< 10 % of the watershed), while Tributary-J was logged in 2 yr and broadcast burned (Fig. 6 and 7).

Four other streams were monitored as external control watersheds in Barkley Sound (Andersen 1983). They were indicators of any long-term trends of climate or of fish populations between 1970 and 1986. Stream biota were monitored annually in Useless Creek (unlogged), Ritherdon Creek (recent logging), South Pachena Creek (20-yr postlogging) and Frederick Creek (35-yr postlogging).

The postlogging stage in Carnation Creek ended in 1987 when logging was begun in Watershed E. Here the streams do not contain fish so a new objective was to assess stability of the steep slopes and stream channels (Fig. 4) and to determine impacts from any material that is transported downstream into fish habitat. Watershed C has been maintained as a control drainage.

Construction of the major timber hauling roads was begun in January 1975, but access to a cutblock was usually built one year prior to logging. Most roads were located well away from the main stream (Fig. 5). There was a bridge over the stream where a main

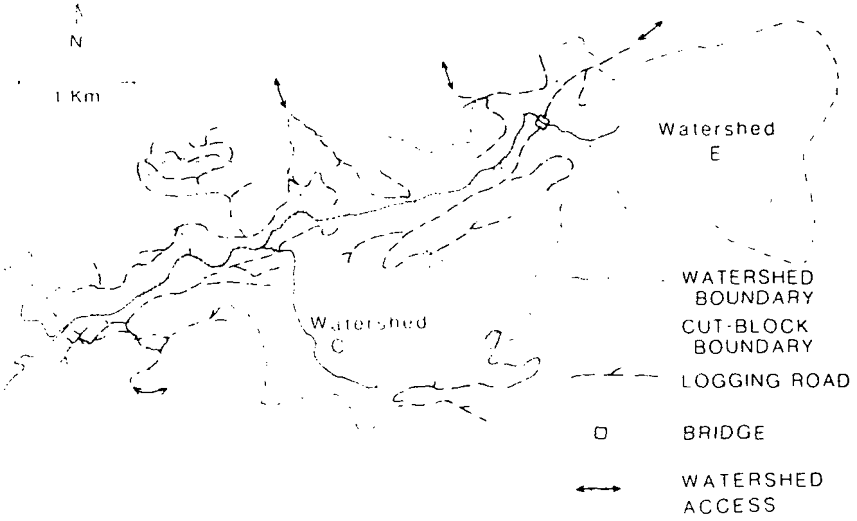

FIG. 5. A map of Carnation Creek watershed that locates cutblock boundaries and logging roads.

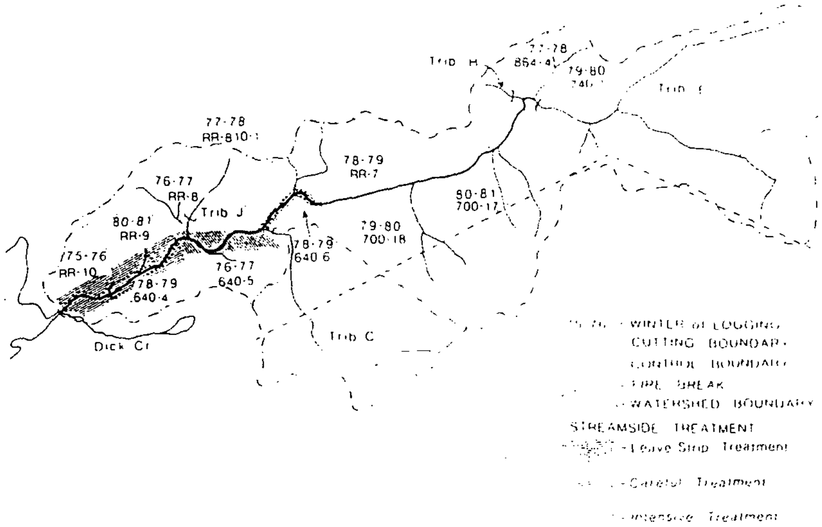

FIG. 6. Cutblock locations, years of cutting and locations of leave strip, careful, and intensive stream-side treatment areas. Details of treatments given in each cutblock are described in Table 1

FIG. 7. Burning logging slash in the Carnation Creek basin to enhance re-growth of coniferous trees (cutblock RR-8 ; Fig. 6).

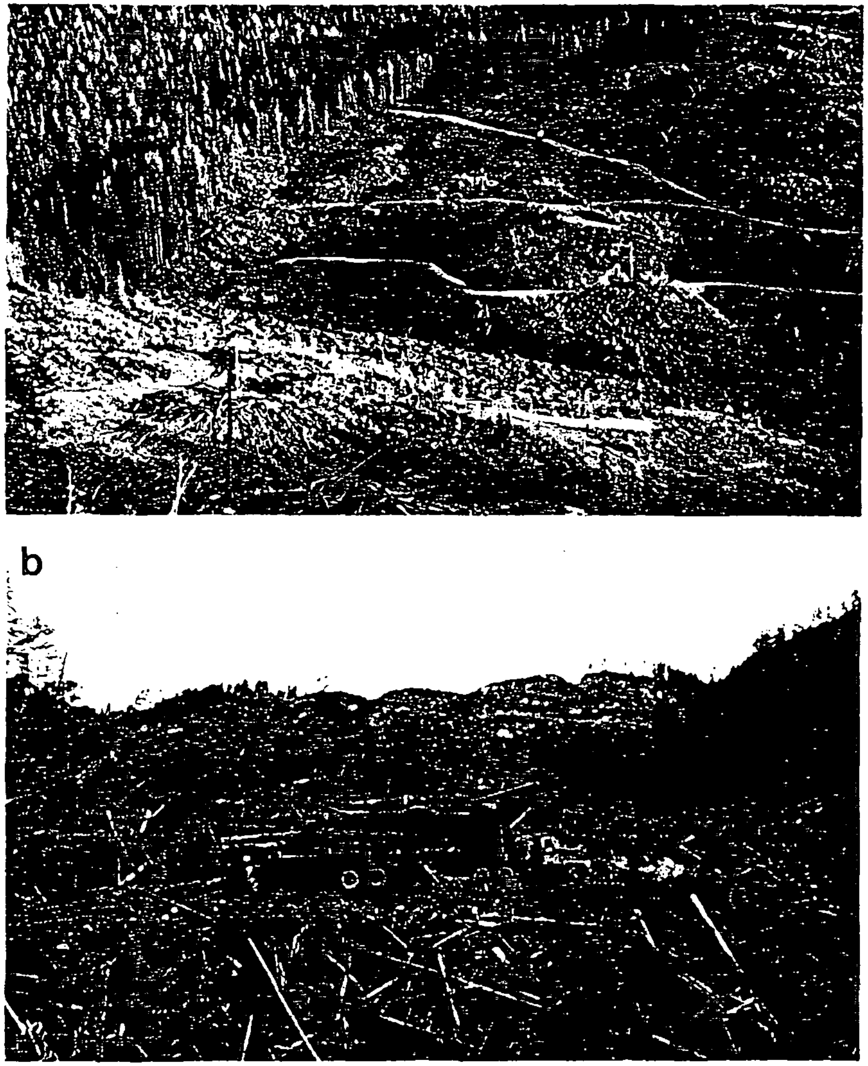

FIG. 8. (a) Cable logging in the Carnation Creek basin (cutblocks RR-8, 640-5 ; Fig. 6) ; (b) Logs being hauled by truck from a landing to a booming site in Barkley Sound.

road crossed the lower part of Tributary-E. Access to the watershed was by four low elevation dips in the topography. The lowest site was 500 m from the estuary. The topography also permitted full bench construction over the length of most roads that consisted of blasted rock that was covered with hard coarse gravel (Dryburgh 1982). Rock drilling equipment, Porclain shovels and D-8 cats were used during construction. The greatest length of road was built during the 1975–76 winter.

In 6 yr of logging 41 % of the drainage basin was harvested as 13 cutblocks. Cutblock locations and timing are indicated in Fig. 6. Each cutblock was clear cut and the logs were brought to the roads using cable yarders with metal spars (Fig. 8a) and grapples. Skidders with low pressure tires were used on a few valley-bottom sites. The logs were then hauled by truck to marine sorting areas nearby (Fig. 8b).

Stream-side Treatments

The project design contained three basic treatments along that part of the stream length which was available to salmon. The different stream-side treatments are located on Fig. 6, while the logging techniques are listed by cutblock in Table 1. Impacts were assessed by comparing changes in the stream study sections that had been located in each treatment (Fig. 9).

Leave strip treatment — a strip varying from 1 to 70 m in width was left uncut along the stream margin from the estuary to 1300 m upstream (Fig. 6). This area included study sections II, III and IV (Fig. 9). Another 1200 m of leave strip is located in a canyon area in the upstream portion of cutblocks RR-7 and 700-18 (Fig. 6). Trees that leaned towards the stream were left or they were felled away from the channel by using jacks or cables. Presently this is the normal treatment along British Columbia streams that contain salmon (BCMFL et al. 1987).

Intensive treatment — the second area included the next 900 m of stream and study sections V and VI (Fig. 6 and 9). Study section VII was on the upstream edge of the treatment because yarding deflections dictated a minor change to cutblock boundaries. Logging occurred simultaneously on both sides of the stream. Some trees were felled across the stream and yarded from it. Rotten windfalls in or across the channel were broken by falling and yarding, but a few merchantable windfalls within the stream channel were harvested. In 1976, this treatment was no longer permitted along stream reaches that contained salmon, but it had been the typical practice in coastal logging areas before 1972 (Brownlee and Morrison 1983). Stream-side alders were hacked with a machete and the cut filled with a herbicide (Tordon 22K) one year before logging. Logging debris was burned in both cutblocks (Fig. 7).

Careful treatment — the third area included the next 900 m of stream and study section VIII (Fig. 6 and 9). Minor vegetation such as salmonberry was left along the stream and

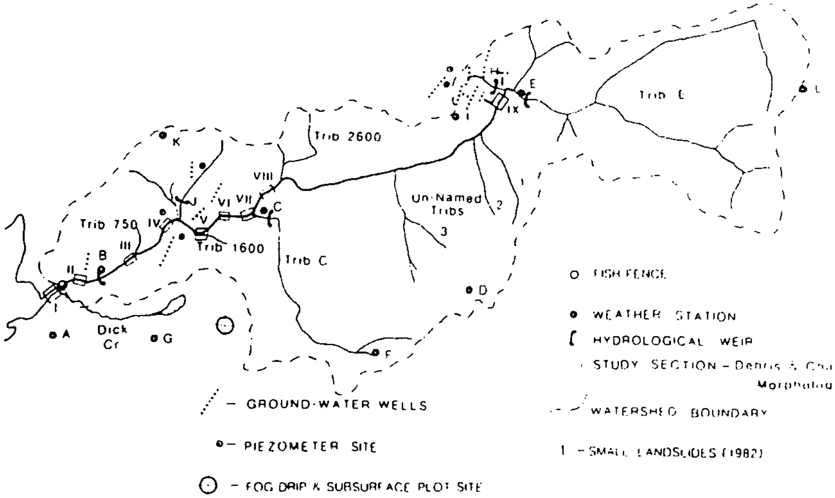

FIG. 9. Locations of hydro-meteorological monitoring facilities, and debris and channel morphology study sections I to IX within the Carnation Creek drainage.

TABLE 1. Summary of logging and postlogging treatments (table adapted from Dryburgh 1982) with notes added about treatments of tributaries. Locations are shown in Fig. 6

Area name	Logging[a]	Stream-side treatment	Slash treatment	Reforestation[b]
RR-10	1975 to 1976 (23.5 ha)	– Leave strip left along creek with major and minor vegetation intact (wider zone left along canyon). – No alder seed tree treatment.	– Broadcast burn with helicopter drip torch, fall 1976. – Patchy burn accomplished on slopes ; light intensity. – No burning accomplished on alluvial flats.	– Spring 1977-alluvial flats only (S, C). – Spring 1978-(S, C, H, F). – Spring 1979-(H). – Herbicide treatment September 1984
640-4	1978 to 1979 (19.4 ha)	– Leave strip along creek with major and minor vegetation intact (wider zone left along canyon portions). Jacks and cables used on leaners. – No alder seed tree treatment.	– Alluvial flats adjacent to creek scarified, spring 1979, by D-6 cat with brush blade. – Broadcast burn of slopes and of scarification piles, fall 1979, by helicopter drip torch and manually. – Patchy and light intensity burn achieved.	– Fall 1979-alluvial flats (S). – Spring 1980-alluvial flats and lower slopes (S, C, H). – Spring 1981-(H, C). – Herbicide treatment September 1984
RR-9	1980 to 1981 (16.2 ha)	– Leave strip left along creek with major and minor vegetation intact. Jacks used. – No alder seed tree treatment.	– Broadcast burn, manual lightup, fall 1981. – Complete burn coverage ; light intensity. – Patchy burn on alluvial flats.	– Spring 1982-complete setting (F, C, S).
640-6	1978 to 1979 (14.2 ha)	– Merchantable trees removed from creekside ; most of minor vegetation left. – Large alder seed trees broke during storm ; number of smaller alders felled, 1979.	– Alluvial flats adjacent to creek scarified, spring 1979, by D-6 cat with brush blade. – Broadcast burn of slopes and scarification piles done, fall 1979, manually.	– Fall 1979-alluvial flats (S). – Spring 1980-alluvial flats (S). – Spring 1982-(H). – Portions of upper slope are fully stocked with natural regeneration.
RR-7	1978 to 1979 (63.5 ha)	– Merchantable trees removed from creekside ; some minor vegetation left. – Leaning trees along creek pulled back with lines from yarder or felled with jacks. – Many alder seed trees blew down in storm ; other alders felled : 1979.	– Broadcast burn, manual lightup, fall 1979. – Complete burn accomplished on slopes; moderate + intensity. – Patchy burn accomplished on alluvial flats.	– Spring 1980-complete setting (F, C, S).

TABLE 1. (*Continued.*)

Area name	Logging[a]	Stream-side treatment	Slash treatment	Reforestation[b]
700-18	1979 to 1980 (51.1 ha)	– "Normal" treatment-"P1" clause in effect. – Wide leave strip left along creek in the canyon, but no leave strip on unnamed tributary. Jacks used on trees along alluvial flood plain.	– No burning on slopes ; large roadside landings burned fall 1982.	– Spring 1982-lower slopes only (H). – Upper slopes partially stocked with natural regeneration ; remainder planted spring 1983 (H).
700-17	1980 to 1981 (53.9 ha)	– "Normal" treatment-"P-1" clause in effect. – Heavy leaners and non-merchantable trees left along streambank. – Alder seed trees "hacked & squirted" with Tordon 22K in 1978 ; smaller alder trees felled in 1981 on flats. – No leave strip on unnamed tributaries.	– No burning to date ; large roadside landings planned for burning, fall 1982. – Flats adjacent to creek scarified, fall 1981, by D-6 cat with brush blade.	– Spring 1982-flats and lower slopes only (C, H). – Upper slopes planted spring 1983 (H).
640-5	1976 to 1977 (35.6 ha)	– No leave strip left along creek. – Trees felled and yarded from creek. – Alder seed trees "hacked & squirted" with Tordon 22K in 1975.	– Broadcast burn with helicopter drip torch ; fall 1977 ; unsuccessful. – Attempts to reburn in fall 1977 and 1979 gave only patchy accumulation burns on upper slopes.	– Spring 1978-alluvial only (S, C). – Spring 1979-(S). – Spring 1980-(C, H). – Spring 1981-(C). – Herbicide treatment September 1984. – Western hemlock reseeded naturally on upper slope.
RR-8	1976 to 1977 (61.1 ha)	– No leave strip left along creek. – Trees felled and yarded from creek. – Alder seed trees "hacked & squirted" with Tordon 22K in 1975. – No leave strip on Tributary-J.	– Broadcast burn with helicopter drip torch, fall 1977. – Good burn achieved on majority of upper slope ; light to moderate intensity. – No burning accomplished on alluvial flats and portions of lower slope. – Small portion reburned in slash-burn escape, fall 1979.	– Spring 1978-alluvial flats, lower slopes only (S, C, H, F, Bg). – Spring 1979-(F). – Spring 1980-(F). – Herbicide treatment of valley bottom, September 1984.

TABLE 1. (*Concluded.*)

Area name	Logging[a]	Stream-side treatment	Slash treatment	Reforestation[b]
864-4	1977 to 1978 (48.2 ha)	- "Normal" treatment-"P-1" clause in effect. - No leave in strip on Tributary-H - Leave strip left along creek due to topography.	- Broadcast burn, manual lightup, spring 1979 ; area NE of "H" creek - Light intensity broadcast burn achieved. - Landing and roadside accumulation burn, fall fall 1979 ; area SW of "H" creek only.	- Spring 1979-flats only (C, Ba). - Spring 1980-(F, C). - Spring 1981-(F, H, C, Ba).
RR-810-1	1977 to 1978 (7.3 ha)	- Not applicable.	- Broadcast burn, manual lightup, fall 1978. - Complete burn coverage ; moderate + intensity. - Eastern portion reburned in slash-burn escape, fall 1979.	- Spring 1979-(F). - Spring 1980-(F).
740-1	1979 to 1980 (8.5 ha)	- Not applicable.	- No slash treatment.	- Spring 1982-(Ba). - Portions of setting are fully stocked with natural regeneration.
RR-6	1980 to 1981 (1.5 ha)	- Not applicable.	- Broadcast burn, fall 1982 with larger opening outside watershed.	- Planted spring 1983.

[a] Total hectares includes road right-of-way.

[b] Planted species abbreviations : F = Douglas fir (*Pseudotsuga menziesii*) ; C = Western red ceder (*Thuja plicata*) ; H = Western hemlock (*Tsuga heterophylla*) . S = Sitka Spruce (*Picea sitchensis*) : Ba = Amabilis fir (*Abies amabilis*) ; Bg = Grand fir (*Abies grandis*).

only six trees which could not be jacked or cabled away from the stream were felled across the channel and removed. Stream-side alder was felled ; and in cutblock 640-6, logging debris was piled for burning when a D-6 cat with scarifier tine was used to prepare the site for planting. Cutblock RR-7 was burned (Table 1). This treatment is also no longer permitted along reaches that contain Pacific salmon, but it is permitted beside streams which contain other salmonids (BCMFL et al. 1987). Some streams that have been treated in this manner have later been found to contain salmon (Brown et al. 1987 and 1989).

Having the intensive treatment upstream of the leave strip treatment complicated interpretation of results, but their location was dictated by the topography. An intensive treatment near the estuary could only have been 500 m long, because the stream flowed through a short and shallow canyon in the middle of the leave strip treatment (B weir, Fig. 9). Steep banks and poor yarding deflection prevented logging to the stream bank in this area. Processes of downstream transport from the intensive treatment could be assessed with this design.

Silvicultural Treatments

After logging the cutblocks received different treatments depending upon their site characteristics and silviculture needs. Some cutblocks were burned (Fig. 7), some were scarified, and some that faced north were given no treatment (Table 1). Treated and untreated sites on the lower slopes and valley bottom were planted, while some untreated cutblocks were allowed to restock naturally with hemlock and red cedar. The planted cutblocks received various mixtures of Sitka spruce, western red cedar, Douglas fir, and amabilis fir seedlings depending on site characteristics such as elevation, orientation to the sun, and the presence of sea fog.[3]

Late in the project the study design was expanded to include evaluation of the effects of a herbicide on both the vegetation and the stream. Carnation Creek watershed was aerially treated with RoundUp[4] (glyphosate) during September 6–15, 1984. This herbicide is used to control deciduous vegetation which grows rapidly and prevents sunlight from reaching the planted and naturally-regenerated crop trees. A treatment of 2.0 kg•ha^{-1} was applied with a Bell-47 helicopter that was equipped with a MICROFOIL BOOM[5] to minimize aerial drift into fish bearing waters. A total of 41.7 ha, in four cutblocks was treated (Table 1). Tributary-1600 was deliberately oversprayed, while Tributary-2600 was used as a control (Fig. 9). The policy of maintaining a pesticide free zone along the main channel was maintained. Details of the methods, and results of these studies were presented in Proceedings of the Carnation Creek Herbicide Workshop (Reynolds 1989).

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[3] Sitka spruce is only planted in areas with sea fog. Here, temperatures are insufficient for the Spruce weevil (*Pissodes strobi* ; McMullen 1976).

[4] Registered trademark of Monsanto Co. Inc., St. Louis, MO, USA.

[5] Registered trademark of Union Carbide Inc., Ambler, PA, USA.

Chapter 4. Methods

Meteorological Records

Weather conditions were recorded at 10 locations which were either in the watershed or at its perimeter (Fig. 9). The instrumentation and the time of station installation varied (Table 2). Station A was the principal weather station for the project where air temperature, humidity, cloud cover, weather conditions, 24-h accumulated precipitation, wind mileage and evaporation were observed each morning at 0800 h. Atmospheric Environment Service equipped, inspected and published data for this site (Anon. 1971 to 1987). A streamside station at B-weir was also monitored daily at 0800 h. Instruments at Stations C, D, E, F, G, H and L were read and serviced weekly unless road or weather conditions prevented travel. On the first day of each month, all instruments were read, checked and, as required, calibrated. Weighing precipitation gauges were used at most sites, (Table 2) instead of tipping bucket guages because snow, even in small amounts, plugged the mechanism of a tipping bucket. Ethylene glycol and mineral oil were used in rain gauges to prevent freezing or evaporation. Information on weather recording and analysis was given in Narver (1974), Scrivener (1975, 1982), Hartman et al. (1982), and Holtby (1988).

Most meteorological conditions were recorded on charts that had to be converted to digital data for analysis. A Techtronics computer and digitizing table of ±0.2 mm accuracy was used for this task. The data base was then transferred to a VAX mainframe computer for editing, analysing, and archiving.

Stream Temperatures

Stream temperature was recorded continuously after installation of B-, C-, E-, H-, and J-weirs and Station-1600 (Table 3). Records of shorter duration were obtained at 2300 m and Tributary-2600 in Carnation Creek and at control watersheds, Ritherdon and Fredrick Creeks. Temperature charts were changed either weekly or monthly and at the same time charts were referenced, and the instruments calibrated with a hand thermometer and a quartz watch. Continuous recording instruments for stream temperatures and stream levels were housed in heated sheds at B-, C-, E-, H-, and J-weirs, to maintain chart and instrument quality. Data on charts from these instruments were also digitized with the Techtronics system.

Stream Discharge and Groundwater Levels

Stream water level was recorded at five locations on the watershed (Fig. 9). Installation times and instrumentation varied among the sites (Table 3). Continuous records of water level were obtained with Stevens A-35 and A-72 recorders at a broad-crested stream control structure, B-weir (Fig. 10a), at a V-notch control structure, E-weir, and at V-notch weirs C, H (Fig. 10b) and J. From the time of installation only a few short gaps have occurred in the continuous data record. Stage-discharge curves that were frequently checked and updated were used to convert water levels to stream flows. Water Survey of Canada equipped, inspected, and published data for B- and E-weir (Anon. 1973 to 1988). For further details on stream discharge studies see Hetherington (1982) for methods and results, and Scrivener (1975, 1982) for methods of extracting and analysing data.

Groundwater levels were recorded on the slopes and flood plains. Transects of wells were monitored weekly on the slopes of Tributary-J and Tributary-H watersheds during the autumn, winter, and spring (Fig. 9). These wells were dry in the summer. Other transects of wells in the valley bottom between Tributary-J and Tributary-1600 were monitored weekly during the summer. During 1982 and 1983, groundwater levels were

Table 2. Meteorological stations, time (yr–mo) of installation and instruments used in Carnation Creek watershed.

	Station										
	A	B[a]	C[a]	D	E[a]	F	G	H	I	K	L
Stevenson screen	'71-04	'71-05	'72-05	'71-09	'71-09						
Max/min air thermometer	'71-04	'71-05	'72-05	'71-09	'71-09	—	—	—	—	—	—
Lambrecht hygro-thermograph	'71-04	—	'72-05	'71-09	'71-09	—	—	—	—	—	—
M.S.C. tipping bucket rain gauge	'75-09[b]	—	—	—	—	—	—	—	—	—	—
Belfort weighing rain gauge	—	—	'76-02	—	'75-11	'78-10	—	'76-02	—	—	'82-11
Bulk rain gauge (Sacramento)	—	—	'71-05	'71-05	'71-09	'71-09	'72-09	—	'72-09	'75-10	'81-03
Standard measuring rain gauge (graduated cylinder)	'71-04[b]	'71-05	—	—	—	—	—	—	—	—	—
Ground-level wind totalizer	'71-05	—	—	—	—	—	—	—	—	—	—
Lambrecht mechanical wind velocity and direction recorder	'72-10	—	—	—	—	—	—	—	—	—	—
Class "A" evaporation pan	'71-05	—	—	—	—	—	—	—	—	—	—
Belfort-pyro-heliograph	'71-05	—	—	—	—	—	—	—	—	—	—
Barometer (continuous recording)	'71-02	—	—	—	—	—	—	—	—	—	—

[a] These stations correspond with stream stations at B-, C-, and E-weirs

[b] Located at the camp-site about 200 m from station A.

Table 3. Stream station, time (yr–mo) of installation, and instruments used in the Carnation Creek drainage. Initiation of water sampling for chemical analyses is also shown.

	Stream Station								
	B-weir	C-weir	E-weir	H-weir	J-weir	2250-m	1600-m	Trib. 1600	Trib. 2600
Stevens (water level recorder)	'71-04	'72-05[b]	'71-10	'72-08	'75-08[c]	—	—	—	—
Lambrecht (stream temp.) thermograph	'71-05[a]	'72-06	'71-10	'72-09	'75-08	'77-04	'75-09	'75-09	'82-09
Pumping water sample (suspended sediment)	'72-10	—	—	—	—	—	—	—	—
Water chemistry samples	'71-09	'72-09	'71-10	'72-09	'74-10	—	—	'75-09	'83-09

[a] Kahl thermograph used first 11 months

[b] Read at staff gauge December 1971 to May 1972

[c] Water level recorded at a control site October 1974 to November 1975

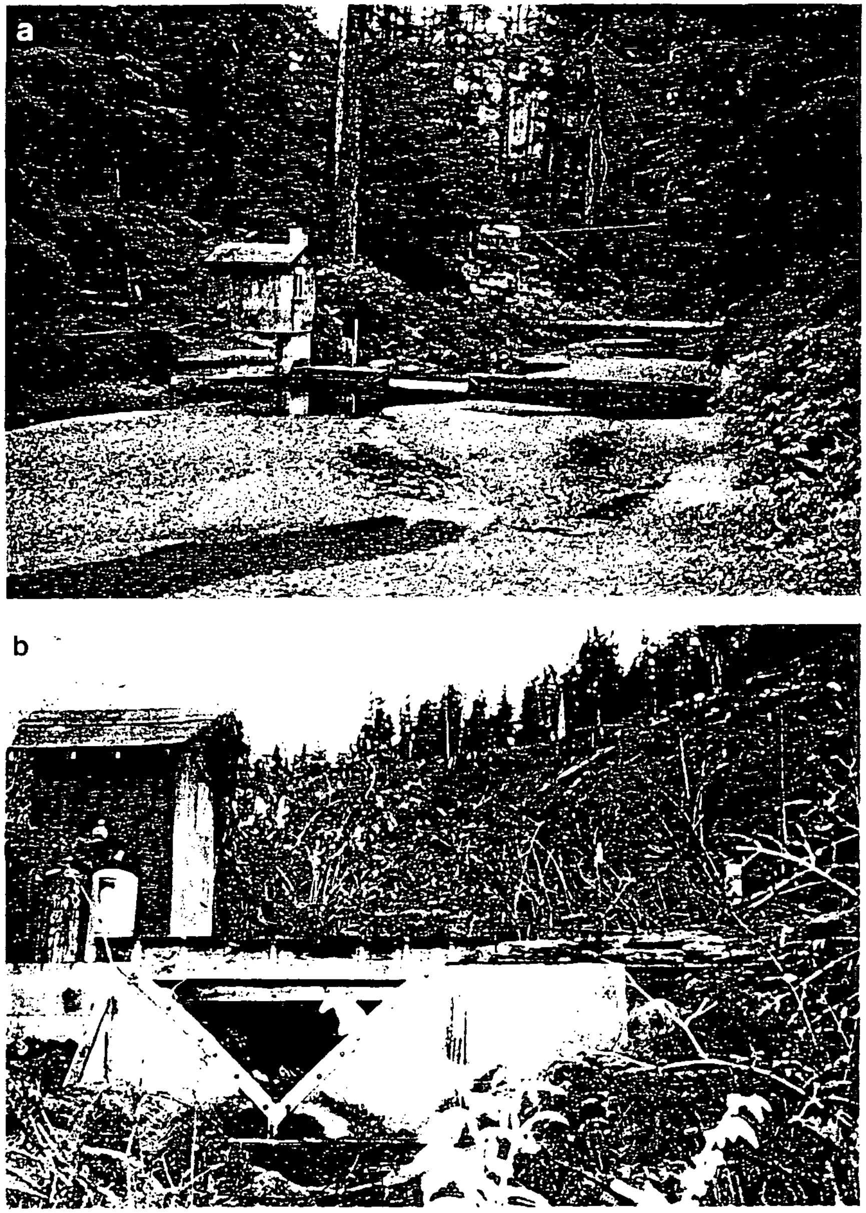

FIG. 10. (a) Broad-crested control structure (B-weir) used for assessment of discharge rate and total water yield from Carnation Creek. The foot bridge and cable way are visible in the background ; (b) A V-notch hydrological weir on Tributary H.

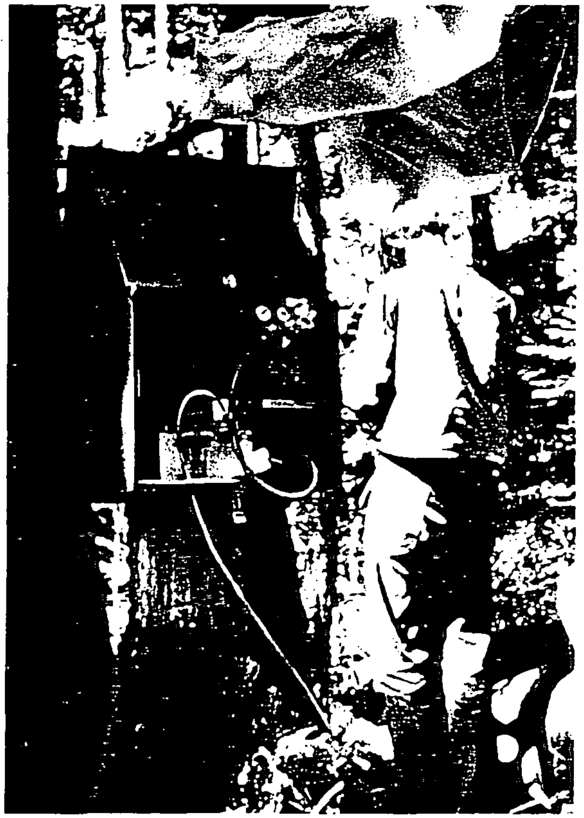

FIG. 11. Checking a continuous recording piezometer within the Carnation Creek basin.

also recorded each month at sites that were in the tributaries and swamps (Brown 1987). The wells were constructed with 25 mm I.D. PVC pipe and capped with a tin can. Transparent tubing (5 mm PVC) and styrofoam float served as a crest gauge. Continuous recording piezometers (Fig. 11) were in operation for various time periods from November 1975 at locations shown in Fig. 9.

Water Chemistry

Chemical analyses of water were obtained for samples from seven sites listed in Table 3. Samples were collected twice a month from the stream at B-weir and from rain water at Weather Station A. Stream water was obtained monthly at weir or fence sites on the tributaries (Fig. 9). Sets of samples were also taken before, during and after many storms. Alkalinity, pH and conductivity were measured in the field. The water samples were frozen in polyethylene bottles and shipped to a water quality laboratory for analyses of 16 different ions. Water sampled for phosphate analysis was collected in acid washed glass bottles and held under refrigeration until analysed. The methods of sampling were given in more detail in Scrivener (1982) and analysis techniques were described in Scrivener (1975). The water chemistry studies were terminated in September 1986.

Woody Debris and Channel Morphological Surveys

Logs in the stream channel (large organic debris, LOD) were marked, mapped, and quantified (volume) during annual surveys in study sections I to IX of Carnation Creek (Fig. 9). During 1971, permanent survey hubs were established, at 3-m intervals, in each of the 50–75 m sections. Standard survey methods were used to locate pieces of LOD with reference to these hubs along the survey section. The end diameters and lengths of each piece of debris greater than 3 m in length were measured for volume determinations. Annual stability of LOD was measured as the percentage of pieces that did not move from the study section. An index of LOD complexity was developed by ranking seven factors on a scale of 1 to 10 and then calculating the average rank. These factors were LOD surface area, LOD volume, surface to volume ratio, LOD stability (number of years), stream depth, LOD to stream position, and water velocity (Harris 1986).

Concurrent with the debris mapping, cross sections at the 3-m intervals and mid-channel profiles of the stream were surveyed with rod and theodolite. A contour map of each study section was then drawn from these data. These surveys were carried out annually from 1971 to the present. Further details of survey methods and of results are given in Toews and Moore (1982), Harris (1986, 1988), and Powell (1988).

FIG. 12. Titration to determine dissolved oxygen content of intergravel water samples drawn at locations from which gravel samples were to be taken.

Spawning Gravel Quality

An intensive gravel sampling program was carried out three times a year in Study Section I where most of the chum salmon spawned (Fig. 9). Frozen cores of the streambed were collected at 45 stations on 8 transects from 1973 until 1989. Each core was split for particle size analysis of top, middle, and bottom layers. Samples were taken during September, December, and March, in order to assess conditions during pre-spawning, *post-spawning, and pre-emergence periods (Scrivener and Brownlee 1982). Prior to gravel* sampling, sub-surface dissolved oxygen (D.O.) and permeability were measured. D.O. was determined to the nearest 0.1 $mg \cdot L^{-1}$ using a Hach modified Winkler technique (Fig. 12). Gravel permeability was also measured at each site with a Mark IV standpipe. The standpipe was described by Terhune (1958) and further details of the methodology were given in Scrivener and Brownlee (1982).

A less intensive program has been a component of the annual physical survey in study sections II to IX since 1973 (Fig. 9). Forty-five sites were chosen that were both locations of potential salmon spawning and of survey hub transects. Another 25 transects were chosen for sampling during 1976 ($>8 \cdot$study section^{-1}). Frozen cores were obtained from the cross sections of these hubs each summer and they were split into top and bottom layers (Fig. 13a). Methods and results were discussed in Scrivener and Brownlee (1989).

Streambed samples were collected with a freeze-core technique and their size composition determined by a dry-sieving technique. A double-wall steel pipe attached to a pot was driven 30 cm into the streambed. Acetone and dry ice were added to the pot (Fig. 13b) where the super-cooled acetone froze a gravel-core 20–30 cm in diameter around the pipe. Cores were then split into layers and bagged for particle size analysis (Fig. 13a). In the laboratory, samples were dried, diameters of the largest rocks measured, and samples partitioned with a 25 mm sieve. The smaller size fraction was then passed through five nested sieves (9.55, 2.38, 1.19, 0.297, and 0.074 mm ; Fig. 13c). This separated the samples into gravel, pea gravel, coarse sand, medium sand, fine sand, and silt-clay components (Scrivener and Brownlee 1982).

Sediment and Bedload Transport

Suspended sediment was measured at B-weir (Fig. 9) with an automated battery powered sampler. Its intake was 10 cm above the streambed, near the right stream bank of the stilling pool above B-weir (Fig. 10a). The sampler consisted of three programmable timers, and a network of solenoid switches and sample storage bottles (Fig. 14). Sampling frequency was $3 \cdot wk^{-1}$ at base flows in the stream, and 1 or $2 \cdot h^{-1}$ during storms.

Sediment was also sampled manually during as many winter storms as possible depending on staff availability and road access. Five vertical stations were marked on a foot bridge above B-weir (Fig. 10a), from which a DH48 sampler was used to collect depth-integrated samples. Up to 10 sets of five samples were collected during both ascending and descending water levels of a storm.

Sediment samples were analyzed in the laboratory of Inland Waters Directorate, New Westminster, British Columbia. Suspended sediment loads were calculated by integrating information from manually collected samples from the cross section, with data from pump samples from the automated point sampler. Sediment hydrographs were obtained when the annual relationships between sediment loads and stream flow were established. See Stichling (1973) for methods of establishing sediment hydrographs. Water Survey of Canada collected and published the data. (Anon. 1973 to 1985). The suspended sediment program was begun in October 1972 and terminated in April 1986.

Sediment concentrations were obtained in tributaries during the initial period of road construction (1975). Two automated portable samplers were used to collect samples during storms. These samples were analyzed in the field by measuring water volumes and

FIG. 13. Streambed sampling and its particle size composition. (a) Frozen core sectioned and put into sample bag ; (b) Core sampler : circulating acetone that is cooled by dry ice in the insert funnel freezes the streambed cores : (c) Sieves used for subsequent sorting of dried gravel samples.

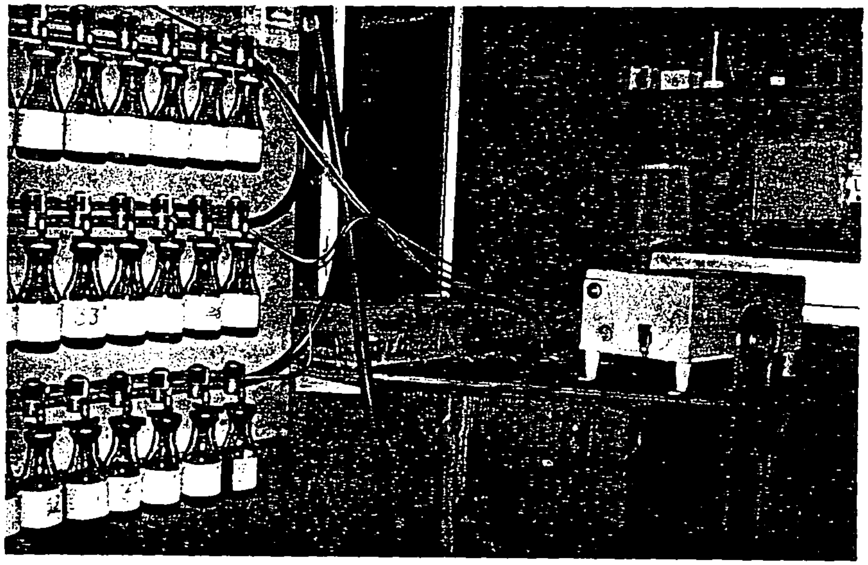

FIG. 14. Pump timer and sample bottles for suspended sediment monitoring at B-weir.

weighing their filterable sediment. Single samples were considered representative of sediment concentration in tributaries, because the tributaries were small and turbulent.

Bedload (gravel and sand) moving along the streambed, was sampled at B-weir (Fig. 9) from October 1973 to March 1986. Initially Arnhem, basket, or V.U.V. Hungarian samplers were used to collect bedload from either the cable crossing or the foot bridge (Fig. 10a). Sampling from the cable-way proved very difficult because of high velocities in the stream, so after November 1974, samples were collected only from the foot bridge. Here, a basket sampler and a quarter sized Arnhem sampler with a range of screen sizes were used. During many storms, two or three samples per storm were taken at each of the five stations where suspended sediment was obtained manually. A particle size analysis was obtained by dry-screening the samples through standard sieves. Methods of calculating transport rates of bedload were presented by Tassone (1988).

Volumes of material that were deposited above hydrologic weirs and the fish counting fence during freshets were also measured. At low flows, gravel was removed from the pools above B-weir, E-weir and the fence following most storms with peak flows greater than 30 $m^3 \cdot s^{-1}$. This provided a minimum measure of bedload movement. The material was excavated with a backhoe and then was placed along the scoured bank immediately downstream of the weir or fence. Excavated volumes were calculated from counts of bucket loads and from pre-and post-excavation surveys in the stream channel.

Ground Disturbance and Revegetation after Logging

Information on surface characteristics was obtained along transects (Fig. 15) in logged and unlogged cutblocks. Transects (9 of 10) were oriented a few degrees from perpendicular to land contours (Smith and Wass 1982). At each 3-m mark on the transect a point was established and information such as presence or type of disturbance, and presence or type of debris was recorded. Cutblocks were surveyed before and after logging and after burning. More details on the scheduling of surveys and on methods used were given in Smith and Wass (1982).

Two hundred and sixty plots were established in 10 cutblocks to evaluate revegetation of shrubs and herbs and growth of planted and non-planted trees. Transects of plots were laid out in the spring of 1978, 1979 and 1980 following logging and burning. The plots were established at 30–50 m intervals along each transect depending on the size of the cutblock and on the number of conditions within the cutblock. Each plot was marked with a permanent metal pin which had been located as to elevation and distance from the stream study sections. Further information on plot size and sub-sampling within the plots is available in King and Oswald (1982).

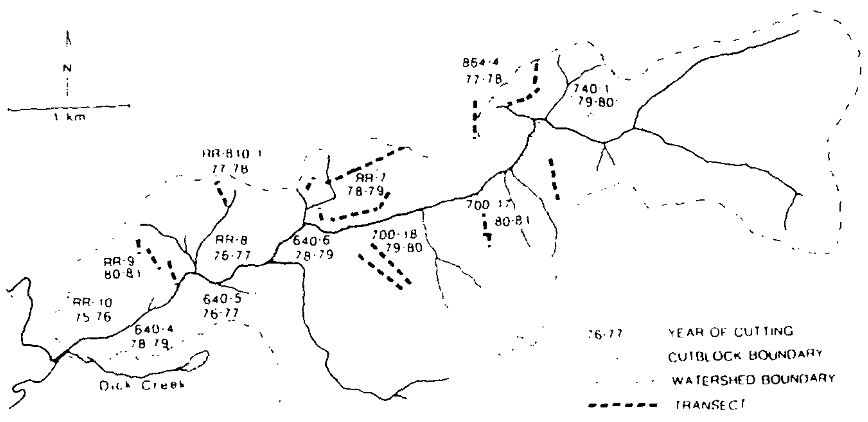

FIG. 15. Carnation Creek drainage basin and locations of groundsurface survey transects within the cutblocks. Modified with permission from Smith and Wass (1982).

Vegetation within each cutblock was assessed in May or June in the first spring after logging and burning. Repeat assessments were completed, or planned, 1, 2, 3, 5, 10 and 15 yr after the first spring survey. In each assessment the species, percent cover for all species and the height of woody plants was recorded. A 35 mm photograph was taken at each plot during each assessment. More information can be obtained from King and Oswald (1982) concerning methodology and progress.

Periphyton Biomass and Species Composition

Accumulation rates, biomass and species composition of periphyton were determined for the stream (Shortreed and Stockner 1982). Sampling stations were located within or adjacent to study sections II, III, IV, V, VI, VIII and IX between 1974 and 1979. Between April 1984 and April 1986, periphyton was also sampled in the mainstream and Tributary-1600 and -2600 (Fig. 9). The later program was a component of the herbicide study (Holtby and Baillie 1989).

Sampling was done as follows. A 400 cm^2 plexiglass plate, that had been roughened by fine sandpaper was bolted to concrete that was buried in the streambed. At ~1-mo intervals accumulated growth on the plate was removed with a razor blade and it was partitioned with a plankton splitter into parts for chlorophyll *a* measurement, ash-free weight determination, and species identification. Methodology details were described by Stockner and Shortreed (1976) and Holtby and Baillie (1989).

Macroinvertebrate Studies

Carnation Creek was sampled for benthic inveretebrates each month from May to September and every 2 mo from October to April from 1971 to 1986. The fauna consisted mainly of aquatic insects. Multiple samples in riffle habitat were obtained in or near study sections III (station 630), IV (stn. 1480), VI (stn. 2000), VIII (stn. 2350) and IX (stn. 4600). The station number indicated distance from the estuary of the stream (Culp and Davies 1983). Samples were also obtained during annual surveys of Useless, Ritherdon, South Pachena and Fredrick Creeks. A 0.144 m^2 sampler was set into the streambed and stones within it scrubbed and removed (Fig. 16). The remaining sediments were repeatedly turned over by hand to a depth of 15 cm so that the current swept all organisms into the cone of the net. Later, the preserved samples were split into equal parts with a plankton splitter (Fig. 17), a known portion sorted, and the organisms identified and counted.

Macroinvertebrates on the surface of the substrate were also sampled in Tributary-750, -1600, and -2600 as part of the 1984–86 herbicide study (Scrivener and Carruthers 1989). A 10 × 10 cm epibenthic sled was pulled a known distance over the bottom. Samples were collected monthly whenever possible and stratified by substrate type. Periodically these tributaries were dry during the summer months.

In total, 19 fish-feeding studies were completed in single riffle-pool sequences immediately above study section II (400 m) and below study section V (1600 m). These studies were either 6 h (including evening twilight) or 36 h long (two evening twilights). Macroinvertebrates which were being transported downstream were sampled in four drift nets. Macroinvertebrates which were landing on the water were sampled in six floating oil traps. Fish in the pool (10–15 coho fry, trout and sculpins) were collected every six hrs with a pole seine. Later, the contents of samples and fish stomachs were sorted, identified, and counted. Feeding studies were completed during May, June, July, August and September both before (1973–75) and after (1979 and 1982) these areas were logged, but a large part of this database has received only preliminary analysis.

FIG. 16. Sampling macroinvertebrates in a riffle at Carnation Creek.

FIG. 17. Preparing a sample of macroinvertebrates for sorting and identification.

Fish Population Studies

Fish counting fences

The main fence was constructed to count either adult fish going upstream (Fig. 18 and 19) or fry and smolts going downstream (Fig. 20a,b). The fans and flow dividers of the downstream trap could screen all of the water when flows in the stream were less than $6\ m^3 \cdot s^{-1}$. At higher flows part of the discharge would be allowed to flow over three lowered fan traps, while the two remaining traps sampled fry and smolts from an estimated fraction of the total discharge. All adults moving upstream during the autumn were caught, but only a portion of spawning trout were caught during the spring. These fish were marked and recovered as they returned to the ocean. For further information on the operation and structure of this fence see Lill and Sookachoff (1974), Narver and Andersen (1974), Andersen (1983), Hartman et al. (1982), and Scrivener and Andersen (1984).

Juvenile fish entering or leaving Tributary-750, -1600 and -2600 were also monitored. Trap locations on these tributaries are shown in Fig. 18. The fences were constructed of wood frame panels covered with 3.1 mm mesh galvanized hardware cloth (Fig. 21). Fish were captured in traps framed with metal rod and covered with 4 mm nylon mesh. Periods of trap operation are listed in Table 4. Methods and details of fence operations were discussed in Bustard and Narver (1975), Tschaplinski and Hartman (1983), Brown (1985), Hartman and Brown (1987).

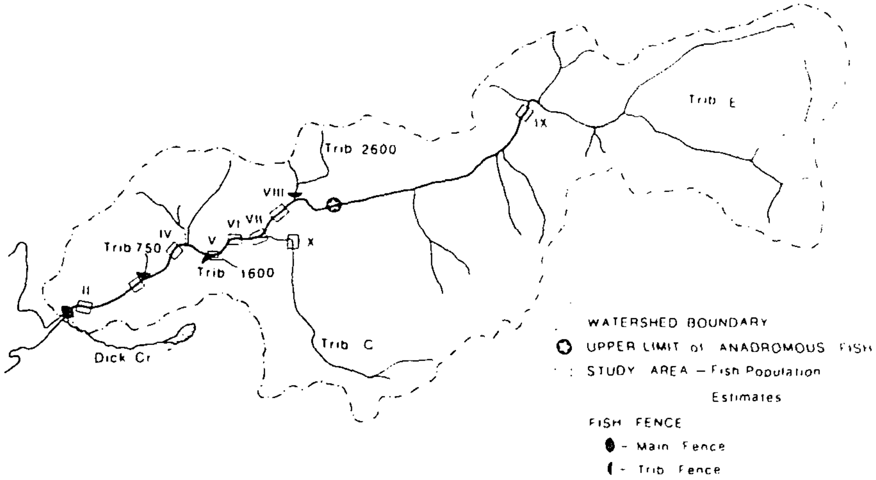

FIG. 18. Locations of fish counting fences, fish population study sections, and the upper limit of movement of anadromous fish

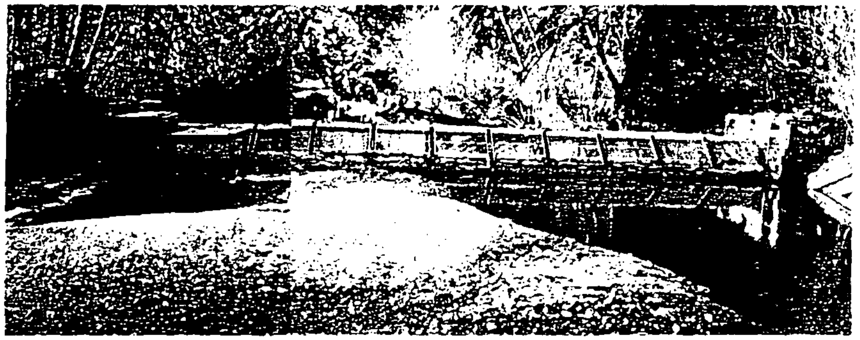

FIG. 19. Main fish counting fence with aluminum panels in place for sampling adult fish ascending the stream.

Adult enumeration and distribution

Adult salmonids that entered Carnation Creek to spawn were counted, and sex, size and age determined. The sex was determined, fork length (FL) measured, and scales taken for aging whenever adult coho salmon, cutthroat trout or steelhead trout were captured at the main fence (Fig. 18). Numbers of spawning trout were calculated as total catch moving upstream and downstream minus the marked fish moving downstream. The sex and FL were also determined for chum salmon that were captured at the main fence, but most chum salmon spawned below the fence. These fish were counted twice a week and after each freshet during the autumn migration period. The numbers of recently

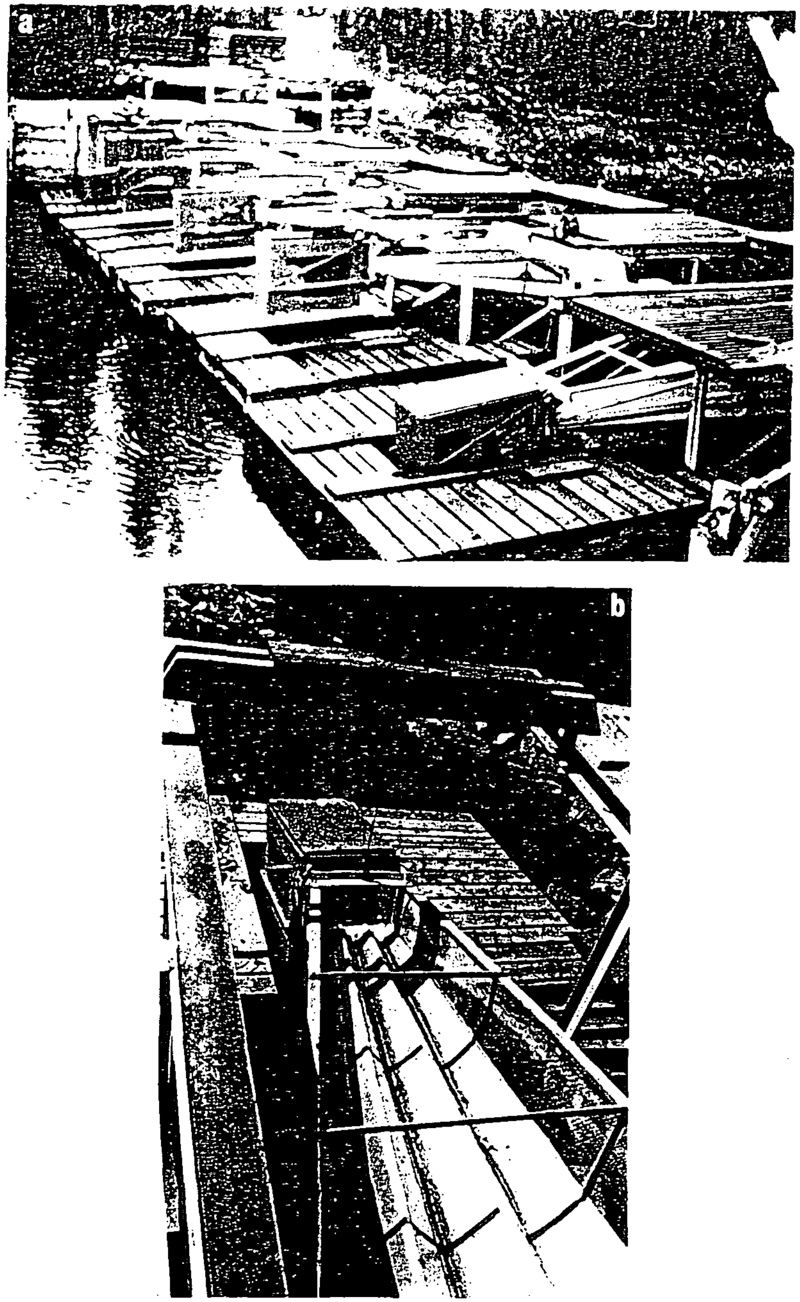

FIG. 20. (a) Five fan traps at the main fish counting fence. Two traps, one in the foreground and one at the opposite end of the fence, are operating. (b) Fan trap used to screen stream water and retain fish that were moving downstream in the spring and summer.

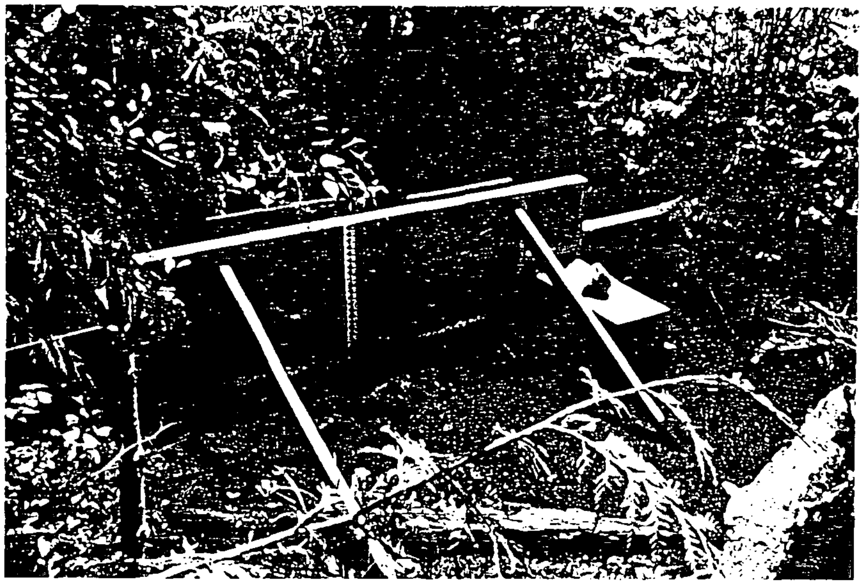

FIG. 21. Fish counting fence used to trap upstream and downstream migrants on Tributary 1600.

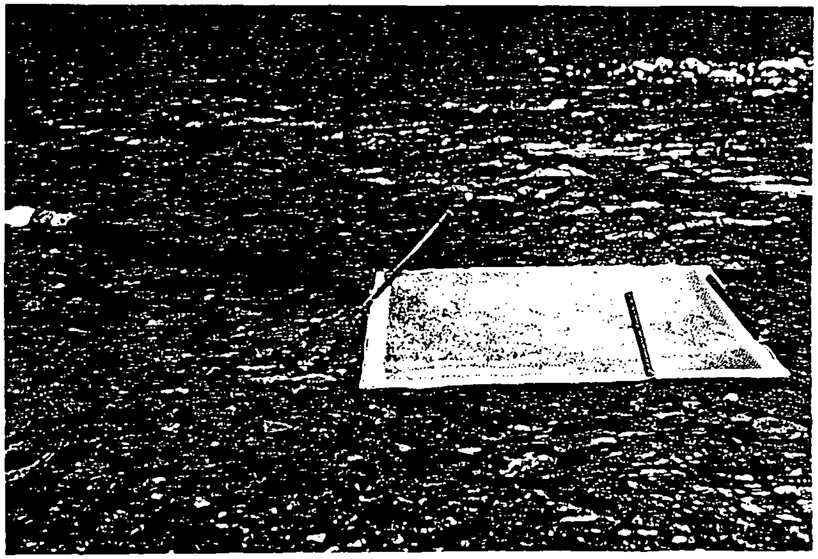

FIG. 22. Traps used to capture chum salmon fry that were emerging from the gravel in the estuary at Carnation Creek.

TABLE 4. Periods of operation of fish counting fences on main creek and three tributaries.

	Period of operation for					
	Adult entry			Smolt and fry exodus		
	Y - M - D		Y - M - D	Y - M - D		Y - M - D
Temporary counting fence	'71-09-15	to	'71-12-20	'71-03-10	to	'71-10-04
Main counting fence	'72-09-01	to	'73-03-10	'72-04-10	to	'72-09-01
	'73-09-28	to	'74-03-12	'73-03-11	to	'73-09-28
	'74-09-04	to	'75-03-20	'74-03-12	to	'74-09-04
	'75-09-05	to	'76-03-29	'75-03-20	to	'75-09-05
	'76-09-01	to	'77-03-20	'76-03-30	to	'76-08-25
	'77-09-06	to	'78-03-14	'77-03-20	to	'77-09-06
	'78-08-24	to	'79-03-19	'78-03-14	to	'78-08-23
	'79-09-13	to	'80-03-18	'79-03-21	to	'79-09-13
	'80-08-28	to	'81-03-05	'80-03-19	to	'80-08-27
	'81-08-12	to	'82-03-07	'81-03-05	to	'81-08-12
	'82-08-26	to	'83-02-24	'82-03-07	to	'82-08-26
	'83-08-11	to	'84-03-05	'83-02-25	to	'83-08-11
	'84-08-23	to	'85-02-27	'84-03-05	to	'84-08-23
	'85-08-29	to	'86-03-05	'85-02-27	to	'85-08-29
	'86-08-15	to	'87-03-01	'86-03-05	to	'86-08-15
	'87-08-10	to	'88-03-01	'87-03-02	to	'87-08-08
	Coho, age 0+, 1+ and 2+ and trout 0+ to 3+					
Tributary — 750 fence				'72-09	to	'79-02
				'79-09	to	'79-12
				'80-09	to	'84-10
				'85-04	to	'85-06
				'85-09	to	'86-06
Tributary — 1600 fence				'72-08	to	'74-06
				'80-01	to	'80-02
				'80-09	to	'83-12
				'84-04	to	'85-06
				'85-09	to	'86-06
Tributary — 2600 fence				'82-09	to	'85-06
				'85-09	to	'86-06

arrived chums (few skin abrasions) and the numbers of chums which had been in the creek for some time (discolored fish with many abrasions) were recorded. Otoliths and length (hypural length) data were taken from ~100 carcasses of male and female chum salmon. These data were used to determine sex ratios and to relate length to age. Any pink and sockeye salmon which had entered the stream were counted at the same time that the chum spawners were enumerated.

Incubation and emergence studies

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 FL of all adult females at the main fence and fecundity relationships. For chum these were Egg No. = 69.6•(FL in cm) − 2361.1 ($r = 0.73$, $n = 34$, $P < 0.001$) and coho salmon they were Log_{10} Egg No. = 2.786•Log_{10} (FL) − 1.730 ($r = 0.82$, $n = 45$, $P < 0.001$). These length-fecundity relationships were obtained originally from 30 Carnation Creek chum salmon (1980) and from 38 Robertson Creek coho salmon (1977) that were augmented in subsequent years by Carnation Creek fish. The number of emerging chum salmon fry were counted in the downstream traps (Fig. 20a,b). 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).

FIG. 23. Pipe and driving rod used to place capsules, containing chum salmon eggs, in the gravel for survival and emergence studies.

The timing of emergence and the size of emerging chum fry, were determined by trapping fry as they left the gravel (Fig. 22). In March each year 20–30 emergence traps were placed over spawning areas in close proximity to the sites in Study Section I from which gravel was sampled (Fig. 9). The traps were sampled daily and emerged fry were counted, measured (FL), weighed and released.

During the October to May period between 1982 and 1986, egg-to-fry survival and emergence success for chum salmon were indexed with planted egg capsules and intragravel fry releasers. They were put into the gravel through a pipe and driving core that involved minimal disturbance of the streambed (Fig. 23). For further information on this method see Scrivener (1988a).

Smolt and fry enumeration

Fish were captured in the downstream traps from March to July each year. All smolts passing through the main counting fence were anesthetized and measured (FL). Weights and scale samples were obtained weekly from 20 smolts of each species. Any cold-brand or fin-clip marks that were observed were recorded. Every 7–10 d fry captured at the fence were measured. All fry were measured if the nightly catch was less than 50, otherwise the catch was sub-sampled (Hartman et al. 1982 ; Scrivener and Andersen 1984).

When possible all fish entering and leaving the tributaries were also anesthetized and measured. After 1982, fish passing through the fences were either marked by cold branding (method described by Everest and Edmundson 1967) or scrutinized for marks. Brands were used for studies of growth rates and production within the tributary systems (Brown 1985 ; Brown and Hartman 1988).

Fish density in Barkley Sound streams

Population estimates were obtained for stream fish in Carnation Creek and four other Barkley Sound streams. Eight study sections were sampled in Carnation Creek (Fig. 18)

TABLE 5. Dates of fish sampling for population estimates in Carnation Creek and tributaries. The month is listed first, the day second

Year	Study Section								
	II	III	IV	V	VI	VIII	IX	1600	2100(C)
1970	08-06	08-06	—	—	08-07	08-08	—		
	09-14	09-15	—	—	09-16	09-16	—		
1971	06-16	06-16	06-17	—	06-17	06-18	—		
	08-03	08-03	08-04	—	08-04	08-04	—		
	09-15	09-15	09-15	—	09-16	09-16	—		
1972	05-24	05-24	05-24	—	05-25	05-25	—		
	06-19	06-20	06-20	—	06-20	06-20	—		
	07-31	08-01	08-01	—	08-02	08-02	08-04	08-03	08-03
	09-11	09-12	09-12		09-12	09-13	09-14	09-13	09-13
1973	05-17	05-18	05-17	—	05-17	05-17			
	06-25	06-28	06-27	—	06-26	06-26	06-28		06-26
	08-07	08-08	08-09	—	08-09	08-09	08-31		—
	09-10	09-13	09-12	09-11	09-11	09-11	—	09-11	09-11
1974	05-21	05-22	05-22	06-01	05-29	05-29	06-19	06-20	06-20
	07-25	07-25	07-24	07-24	07-23	07-23			
	09-16	09-17	09-17	09-19	09-18	09-18	09-20	09-19	09-18
	10-15	—	10-15	10-15	—	10-15		10-18	
1975	05-22	05-20	05-21	05-21	05-22	05-21	06-18	06-17	06-17
	07-21	07-24	07-23	07-23	07-22	07-22			
	09-18	09-16	09-16	09-17	09-17	09-18	09-20	09-17	09-18
1976	05-20	05-19	05-19	05-19	05-18	05-18	06-22	06-23	06-23
	07-15	07-15	07-14	07-14	07-13	07-13			
	09-20	09-21	09-21	09-22	09-23	09-23	09-24	09-22	09-22
1977	05-19	05-18	05-18	05-17	05-17	05-16	06-10		06-08
	07-21	07-21	07-20	07-20	07-19	07-19		07-20	
	09-29	09-29	09-28	09-26	09-27	09-27	09-28		09-27
1978	06-08	06-08	06-07	06-05	06-07	06-05	06-06		06-06
	07-25	07-25	07-26	07-26	07-27	07-27			
	10-05	10-05	09-26	09-26	09-26	09-20	09-19	09-20	10-06
1979	06-04	06-13	06-13	06-11	06-12	06-12	06-14		06-11
	07-24	07-24	07-25	07-25	07-26	07-26		07-26	
	09-20	09-20	09-19	09-19	09-18	09-18	10-10	09-19	09-17
1980	—	—	—			—			
	07-22	07-22	07-24	07-24	07-23	07-23	07-23	07-31	—
	09-16	09-16	09-17	09-17	09-18	09-18	09-24	09-17	09-15
1981	05-22	05-22	05-20	05-20	05-21	05-21	05-14	05-20	05-13
	07-28	07-27	07-29	07-29	07-30	07-28		07-29	
	10-14	09-15	09-16	09-16	09-17	09-17	09-15	09-16	09-14
1982	05-28	05-25	05-26	05-26	05-27	05-27	05-29	05-26	05-28
	07-26	07-27	07-27	07-28	07-28	07-28			
	09-22	09-20	09-22	09-23	09-23	09-23	09-21	09-22	09-21
1983	05-27	05-24	05-25	05-25	05-26	05-26	05-31		06-01
	07-28	07-26	07-26	07-27	07-27	07-27			
	09-22	09-19	09-20	09-20	09-21	09-21	09-15		09-21
	(09-12 to 14)[a]								
1984	05-30	05-30	05-29	05-29	05-29	05-28	05-31		06-01
	07-26	07-25	07-25	07-25	07-24	07-24			
	09-26	09-26	09-25	09-25	09-25	09-24	09-27		09-24
1985	05-27	05-28	05-29	05-29	05-29	05-28	05-30		05-30
	07-25	07-22	07-23	07-23	07-24	07-24			
	09-19	09-18	09-18	09-17	09-17	09-18	09-20		09-19
1986	06-05	06-04	06-04	06-04	06-03	06-03	06-05		06-03
	09-15	09-16	09-16	09-17	09-17	09-17	09-18		09-16

[a] Population estimate done for total stream length from 125 m to 2375 m from high tide line

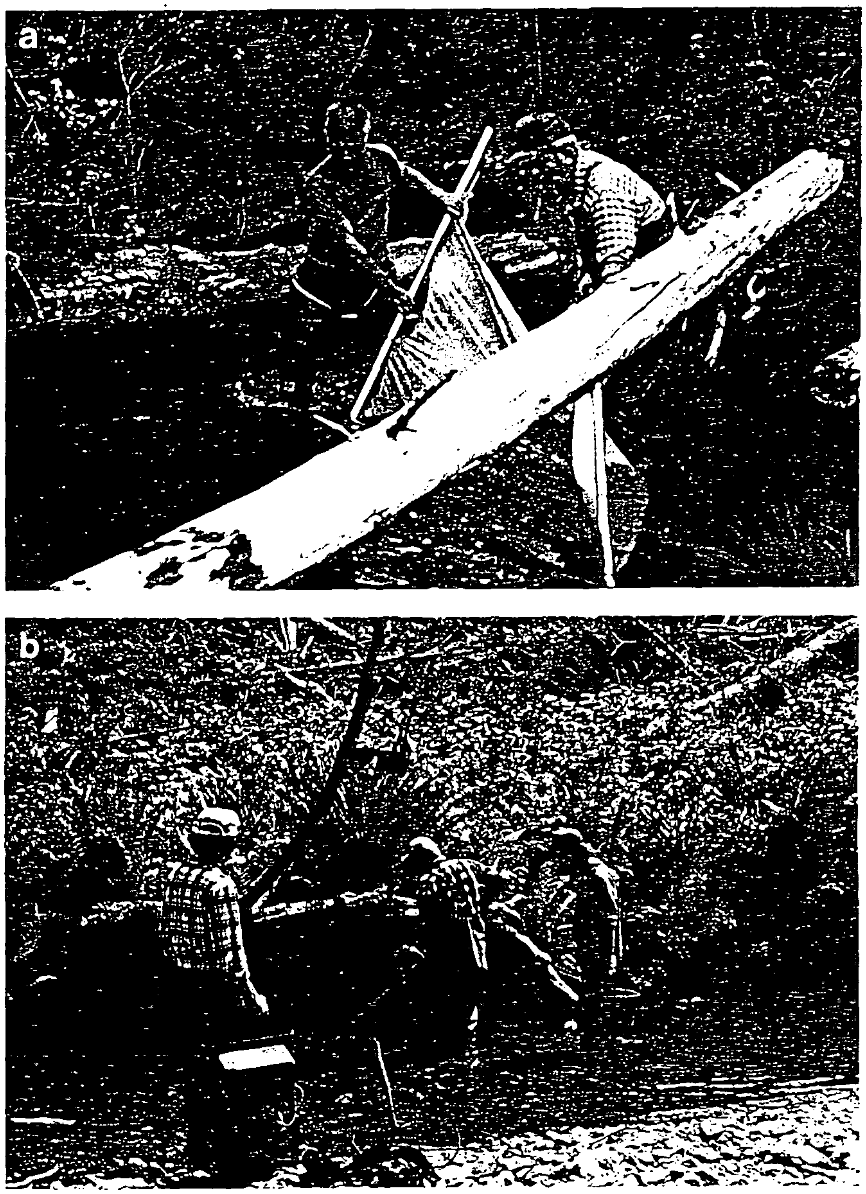

FIG. 24. Sampling fish for population estimates with (a) pole seine and (b) electro-fish shocker

TABLE 6. Dates (mo–d) of fish sampling for population estimates in Ritherdon, Useless, Fredrick, South Pachena and North Pachena creeks. These streams are adjacent or near Carnation Creek.

Year	Stream Rith.	 Useless	 Fredrick	 S. Pac.	 N. Pac.
1971	09–09	—	09–13	09–13	09–13
1972	08–04	08–23	08–22	08–23	—
1973	08–30	08–30	08–31	08–29	
1974	08–29	08–27	08–28	08–28	
1975	09–20	08–25	09–19	09–19	
1976	08–26	08–25	08–24	08–24	
1977	08–31	08–29	08–30	08–30	
1978	08–30	08–30	10–06	09–19	
1979	08–13	08–16	08–14	08–15	
1980	08–21	08–19	—	08–20	
1981	08–28	08–26	—	08–27	
1982	08–24	08–25	—	08–26	
1983	08–25	08–24	—	08–24	
1984	08–29	08–29	—	08–28	
1985	08–28	08–27	—	08–26	

two or three times a year (Table 5), while the other streams were sampled annually (Table 6). The removal method was used to estimate population size (Seber and Le Cren 1967). Study section access was blocked with stop nets and the section was fished, first with a pole seine (Fig. 24a) and second with a Smith-Root electro-fisher (Fig. 24b). These fish were combined, set aside, and the method was repeated. Fish were anesthetized, measured (FL), weighed, and counted by species. Scale samples were obtained for subsequent separation of age classes by length. The wetted area of riffle and pool was also measured during each survey. Total population size within the lower 3.1 km of Carnation Creek was extrapolated from population information of the measured study sections. Further information on methods, sizes of study sections, and classification of habitat within the sections is available in Narver and Andersen (1974), Andersen (1978, 1981, 1983, 1984, 1985, 1987) and Scrivener and Andersen (1984).

Population estimates in off-channel habitat

The size of winter populations (February) of coho salmon and cutthroat trout have been determined in six off-channel sites since 1982 (Trib.-750, -1200, -1500, -1550, -1600 and -2600 ; Fig. 18) by mark–recapture techniques. Minnow traps baited with sardines were used in the swamps to capture juvenile salmonids (Brown 1985). Fish in each swamp were uniquely marked with a cold brand that could be observed later at the main counting fence. Survival, growth and the contribution of off-channel habitat to overall smolt production were determined (Brown and Hartman 1988).

Salmonid populations and their distribution have also been studied in the estuary of Carnation Creek. Population numbers were estimated throughout the spring and summer of 1979 and 1980 (Tschaplinski 1988). Population numbers were also obtained during September 1981, 1983, 1987 and 1988. Methods of catching fish and estimating population numbers were the same as those used for the stream (Fig. 24a,b).

The contribution of estuary habitat to the next generation of coho salmon was measured by mark-and-release studies. Three hundred and 380 juvenile coho salmon were marked during the autumn of 1981 and 1983, respectively. A coded wire tag (CWT) was inserted into the cartilage of the snout of each fish and the adipose fin was clipped. See Ebel (1974) for method of CWT application. Tagged adults were recovered in the commercial fishery and at the main fence.

Chapter 5. Physical Conditions

Meteorological Records from Station A

General climate trends were monitored at Station A. This site was logged in 1968 prior to the start of the study. Brush and trees were cleared annually from the site, but the surrounding trees had reached a height of 12 m after two decades. These trees probably had only a minor influence on meteorological records because the cleared area was always larger than the height of the trees as prescribed for all climatological stations in Canada (Anon. 1977).

Monthly means of total radiant energy per day increased each spring and decreased each autumn, but they were similar during the prelogging and postlogging periods. An annual plot of radiant energy at Station A produced a bell-shaped curve with summer values (June, July, August) eight times higher than winter values (November, December, January ; Fig. 25). The wide confidence limits around the monthly means indicated the variability in cloud cover between years. Solar radiation tended to be lower after 1976 for February, April, July, and September, but it was not significantly lower during any month (Fig. 25). January 1977 was chosen to separate prelogging and postlogging periods because the first two large clearcuts, totaling 100 ha, were opened along the stream at this time (Fig. 6).

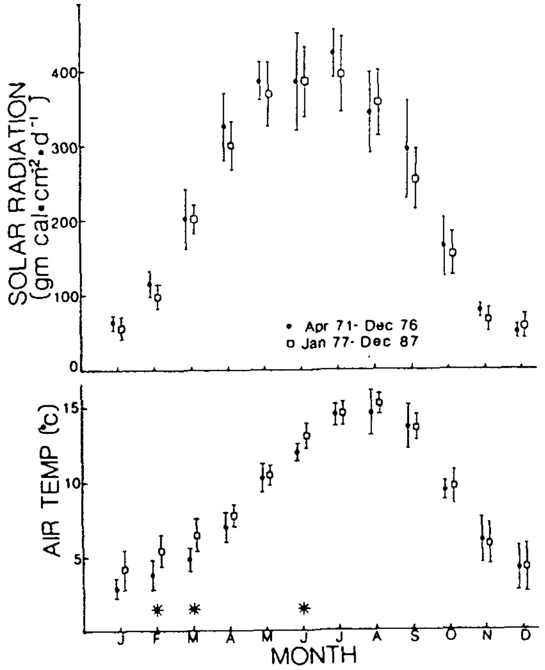

FIG. 25. Monthly means of daily radiant energy (g cal•cm^{-2}•d^{-1}) and air temperature (°C) at weather station A, Carnation Creek are shown for the time periods before (1971–76) and after (1977–87) the intensive logging treatment. Vertical lines indicated 95 % confidence limits around the mean, while an asterisk indicated a significant difference between means.

Mean monthly air temperatures at Station A produced an annual pattern that was slightly different than for solar radiation, and where temperatures were greater for some months after logging was begun. Air temperature at Station A increased more slowly from January to April and decreased more slowly from September to November each year than did solar radiation (Fig. 25). The annual pattern of monthly means was a skewed bell-shaped curve where July and August temperatures were four times those of January, February and December. Confidence limits as large as 2°C indicated that inter-annual variability was nearly as large for air temperatures as it was for solar radiation (Fig. 25). February, March and June air temperatures were significantly greater during the postlogging period. This trend towards warmer spring temperatures was not apparent during the remainder of the year.

The annual pattern of precipitation was more variable and was the inverse of those of solar radiation and air temperature. Total monthly precipitation was approximately five times greater from November to March than from June to August producing a bowl-shaped annual pattern (Fig. 26). A typical minimum was ~7 cm•mo^{-1} for July or August. Totals rose to more than 40 cm•mo^{-1} for November, December, January or February. Confidence limits around the monthly means were 25–60 % of the means even during months with 40 cm of precipitation.

Only September precipitation was significantly greater after 1976, but some winter and spring months tended to be different (Fig. 26). February and April also tended to be wetter, while December and January tended to be drier during the postlogging period. Precipitation was similar for the other seven months during the prelogging and postlogging periods.

Unusually wet and dry periods occurred both before and after logging was begun in the watershed. The wettest winters occurred during 1973–74 and 1982–83 when 265 cm and 256 cm of rainfall, respectively, were recorded between November 1 and March 31. The benign winters of 1976–77 and 1984–85 produced only 143 cm and 119 cm of rainfall, respectively. Dry summers occurred during both 1973 (13.3 cm) and 1987 (6.9 cm).

Meteorological records from Station A indicated that some changes had occurred during early spring and during September. Frontal systems with warm moist air have been more frequent during February and early April since 1976. Higher air temperatures were accompanied by slightly greater precipitation and lower solar radiation during this period. The greater frequency of small September storms during the postlogging period has produced more precipitation and cloud cover. These results concur with the hypothesis of a regional warming trend since 1976 (Holtby 1988).

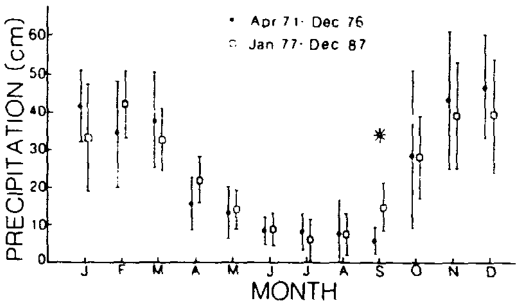

FIG. 26. Means of monthly precipitation totals (cm) at Station A, Carnation Creek for the periods before and after the intensive logging treatment. Vertical lines showed 95 % confidence limits around the means. An asterisk on the monthly axis indicated a significant difference between means.

Stream Temperature

Annual temperature patterns were observed at all sites where stream temperatures were recorded and the variability between years was smaller than for air temperature. Mean monthly temperatures at B-weir and in four major tributaries were about three times higher during July and August (10.5–14.5°C) than during January and February (2.5–5°C : Fig. 27). The shape of the annual curve for stream temperature (Fig. 27) was similar to but was less extreme than that of the air temperature (Fig. 25). Confidence limits around mean temperatures in the stream and all tributaries (< 1°C) were also half those for mean air temperatures at Station A (~ 2°C).

Watershed orientation, elevation, and water source probably caused differences for prelogging temperatures in the five tributaries. Stream temperatures were lower, during winter, in Tributary-C and -E which faced north and drained from higher elevations than they were in the south-facing Tributary-H and -J (Fig. 27). During the summer months,

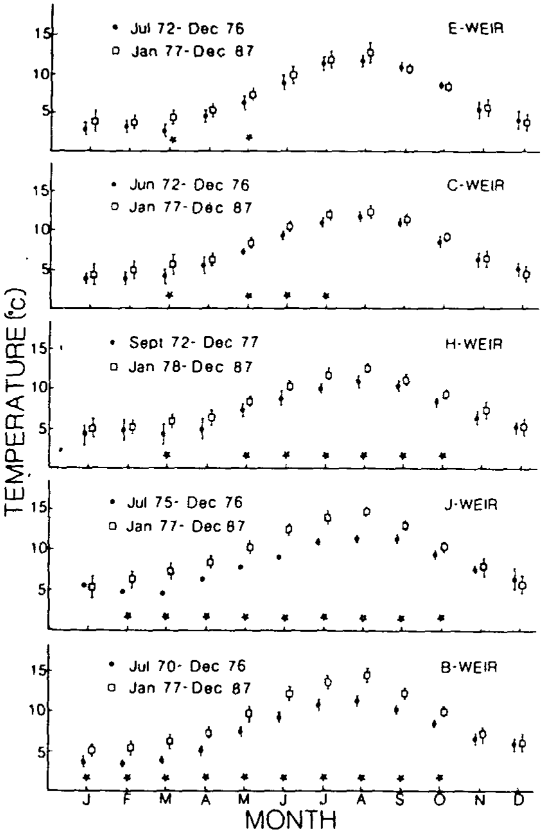

FIG. 27. Mean monthly stream temperatures (°C) are shown for Carnation Creek and its tributaries. The data were separated into two periods by the timing of the first major logging within the watershed or along the tributary. Vertical lines on the monthly axis indicated 95 % confidence limits, while asterisks indicated statistical significance.

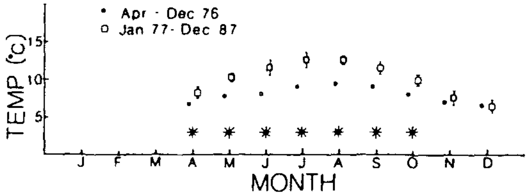

FIG. 28. Monthly means of stream temperature (°C) in Tributary 1600 before the stream-side was logged (April to December 1976) and after logging (January 1977 to December 1987). Vertical lines and asterisks on the monthly axis showed 95 % confidence limits and statistical significance of means respectively.

temperatures were similar in these four tributaries. Mean monthly temperatures of Tributary-1600 were lower from May to October and higher during November, December, and April than at any other site (Fig. 28). Sources of ground water were extensive for Tributary-1600 and they probably ameliorated the high temperatures during summer and the low temperatures during winter (Fig. 29). This stream type has been classified as a wall-base channel (Brown 1987 ; Peterson and Reid 1984). Tributary-1600 had a north-facing and low-elevation watershed that could also temper annual variability. Stream temperatures at B-weir were similar to those observed in four of the tributaries during the prelogging period (Fig. 27).

Stream temperatures at B-weir were affected when stream margins were opened both along the main channel and along some of the tributaries. Average temperatures were elevated by 0.8°C in January and by 3.2°C in August after logging (Fig. 27). Only during November and December were they not significantly higher after 1976. These increases of water temperature were correlated with the increasing proportion of stream-side logged (Holtby 1988).

After 1976 mean monthly temperatures in the unlogged control tributaries (C, E) were elevated during a few months of the year. They were significantly higher for 4 mo in Tributary-C and for 2 mo in Tributary-E (Fig. 27). Again, this probably reflected the spring warming trend that has been observed since 1976 (Holtby 1988). Clearcuts adjacent to the bottom end of Tributary-C may have contributed to the higher June and July temperatures at C-weir (Fig. 6).

Stream temperatures also increased in the tributaries that were logged. Actual dates of logging in each tributary were used to partition the data. Mean monthly stream temperatures were significantly greater during spring, summer, and autumn in both Tributary-H and Tributary-J after logging (Fig. 27). The increase was larger in Tributary-J than in Tributary-H. Burned areas probably influenced the temperature difference, because all logging debris was burned in Watershed-J, but only the margin of Watershed-H was burned. In Tributary-1600, mean temperatures were significantly higher in seven of nine months ; and during May and June they were elevated above those in all parts of the drainage other than Tributary-J (Fig. 28). Deciduous vegetation along Tributary-1600 had been suppressed in 1984 by a herbicide (Reynolds 1989). Therefore more sunlight probably reached this stream when the sun was near its zenith (June).

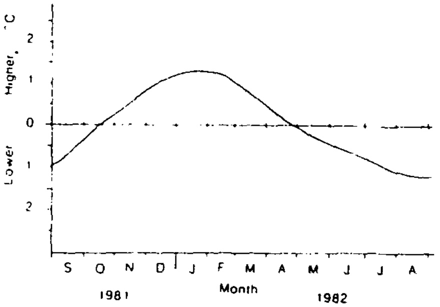

FIG. 29. Pattern of differences observed between mean intergravel temperatures and stream temperatures (recorded at the same time) in the main stem of Carnation Creek during 1981 and 1982 (redrawn from Hartman and Leahy 1983).

Ranges in diel temperature also increased in Carnation Creek and it's tributaries following logging. Diel temperature ranges from 1972 to 1976 averaged 1.4°C at B-weir, while they averaged 3.5°C from 1977 to 1980 (Hartman et al. 1982). During the summer months, they increased 2 and 4°C in Tributary-H and -J, respectively, following clear-cutting (Holtby and Newcombe 1982). Both daily maxima and minima increased along with the temperature range. Maximum daily temperatures increased 5°C during August (Holtby 1988).

Water temperatures within the stream and the streambed differed at Carnation Creek (Hartman and Leahy 1983). Intra-gravel water temperatures averaged 1.5°C warmer than those of the stream during the coldest period of winter, and 1°C cooler than the stream during the warmest part of the summer (Fig. 29). Intra-gravel water temperatures were highly variable from site to site. This variability was probably caused by site specific differences in the relative contributions of downwelling stream water and upwelling ground water.

Stream Discharge

A bowl-shaped annual pattern was shown for both stream discharge and precipitation. Mean monthly flows decreased to ~ 15 % of winter flows between March and May (Fig. 30). They increased again to winter levels during October and November. Confidence limits around the mean monthly flows were often 60 % of the means as observed for total monthly precipitation (Fig. 26). B-weir flows ranged from ~ 0.03 m^3·s^{-1} in August to ~ 64 m^3·s^{-1} in winter. The magnitude of the range was similar at all five weirs, but the absolute flows were relative to the area of watershed drained (Watershed-B = 930 ha, Tributary-C = 154 ha, -E = 270 ha, -H = 12 ha, -J = 25 ha).

Mean monthly flows showed little change after logging was begun. Only April flows at H- and J-weirs and September flows at B- and E-weirs were significantly greater during the postlogging period (Fig. 30). Greater flows in September were also observed at H-weir during a few years immediately after logging (Hetherington 1982). The differences were mainly due to greater precipitation during these postlogging months (Fig. 26). Wetter soils in the clearcut watersheds, a result of reduced evapo-transpiration losses, probably contributed to the greater flows during September because less precipitation was needed during the first storms of autumn to saturate these soils (Hetherington 1982). A tendency for reduced stream flows during December and January was observed at all weirs, but they were not statistically significant (Fig. 30). Precipitation also tended to be lower during these months (Fig. 26). During the other eight months, mean flows were similar for the prelogging and postlogging periods. Any logging influences on mean discharge were confined to the first few postlogging years (Hetherington 1988).

Storm runoff

Groundwater levels on the slopes and flows in the stream responded very rapidly to rainfall as illustrated in Fig. 31. During the wet winters, rapid runoff was caused by transmission of water from the surface through shallow, porous soils to the bedrock layer and then downslope through coarse material at that interface and through macrochannels

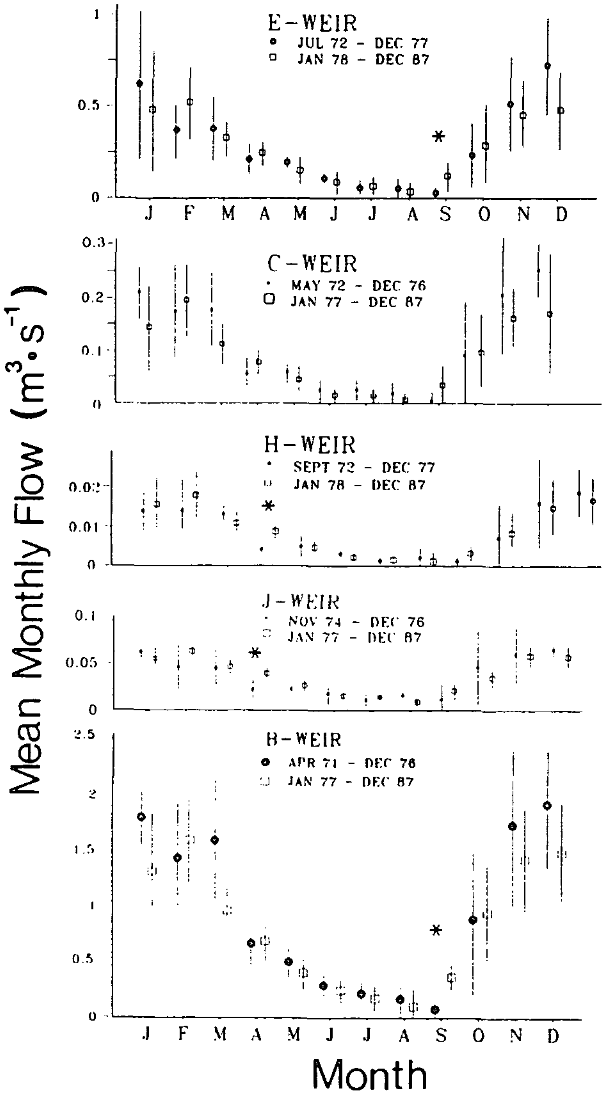

FIG. 30. Means of monthly flow (m³•s⁻¹) through the weirs are shown for Carnation Creek and its tributaries. The data were separated into two periods by the timing of the first major logging within the watershed or along the tributary. Vertical lines, above and below means, and asterisks on the monthly axis indicated 95 % confidence limits and statistical significances of monthly means, respectively.

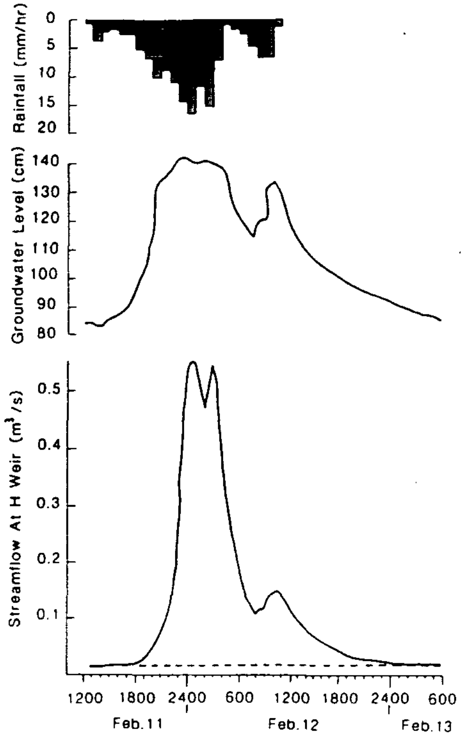

FIG. 31. Rainfall, ground-water level, and streamflow are shown for the basin of Tributary-H during a prelogging storm. The dashed line separated the H-weir hydrograph into storm flow ("quickflow") and base flow (redrawn from Hetherington 1982).

left by decayed roots (Hetherington 1982). Groundwater levels on the slopes of Watershed-H began rising immediately after the rain began, while flows at H-weir responded within 2 h. Groundwater levels also declined before stream levels after the rain ceased. About 90 % of the precipitation that entered H watershed during the storm had passed H-weir as storm flow within a 30-h period (Fig. 31).

Logging roads and clearcutting of H watershed affected runoff during storms. Peak levels of ground water declined at a site below a recently constructed logging road (Fig. 32), when the road diverted water away from the site (Hetherington 1982). Water that was diverted to another site flowed over the soil causing surface erosion. It triggered a small landslide where it eventually entered the soil and increased groundwater levels. Groundwater levels also increased at other sites after forest harvesting (Fig. 32 and 33). Peak flows at H-weir increased ~20 % after both road construction and clearcutting. These increases continued for 2 or 3 yr in the clearcut watersheds, but they were not observed at B-weir, upstream from which only 41 % of the watershed was logged (Hetherington 1988).

A trend towards more extreme, but less frequent storms has occurred during the last two decades. Peak flows were greater during the postlogging period (Mann–Whitney *U*-test, $P = 0.021$), but the frequency of storms that were large enough to cause erosion were greater during the prelogging period (*U*-test on rank, $P = 0.009$; Table 7). Storms

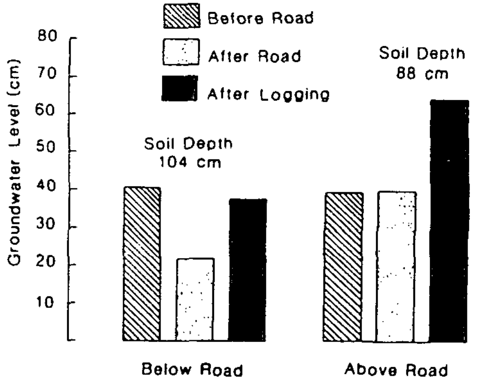

FIG. 32. Comparisons of peak ground-water levels above and below a road in the drainage basin of Tributary-H. Storms with similar hydrograph patterns were compared for the period before road construction, after construction and after logging. Redrawn with permission from Hetherington (1982).

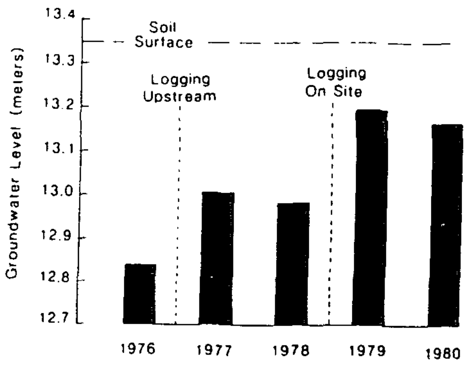

FIG. 33. Ground-water levels observed at one site on the flood plain during comparable parts of a flow regime when discharge at B-weir was 0.09 $m^3 \cdot s^{-1}$. Redrawn with permission from Hetherington (1982).

were very frequent during 1973–74 (2.25 times the mean) and 1975–76 (twice the mean), but the size of the annual peak flows were less than the mean for all years. Peak flows during 1983–84 and 1981–82 caused major changes in the watershed (Hetherington 1988), but the frequency of large storms was below average during these years (Table 7). During the period of logging, the first major storm did not occur until November 1978. With the exception of the 1981–82 storm, these differences were probably caused by the intensity and duration of precipitation and not by forest harvesting. The 1981–82 storm was a rain-on-snow event (Hetherington 1988) when peak flows are known to be increased by clearcut logging (Harr 1986).

TABLE 7. Peak flows, number of large storms, and ranking of water-years observed at B-weir. A water-year began October 1 and ended the following September 30. Peak flow was estimated from a staff gauge during 1970–71.

Water-year	Peak flow $m^3 \cdot s^{-1}$	Storm rank	Number of storms $>15\ m^3 \cdot s^{-1}$	Number of storms $>12\ m^3 \cdot s^{-1}$	Ranking
					prelogging
1970-71	~15	17	—	—	—
1971-72	31.5	8	6	7	3
1972-73	30.3	11	4	5	8
1973-74	19.8	16	10	12	1
1974-75	22.3	15	4	5	6
1975-76	31.4	9	9	10	2
					logging
1976-77	33.8	7	4	5	7
1977-78	24.6	13	3	3	12
1978-79	44.2	4	4	4	9
1979-80	23.4	14	2	4	14
1980-81	43.1	5	5	7	5
					postlogging
1981-82	50.0	2	3	5	10
1982-83	36.2	6	6	6	4
1983-84	64.9	1	3	5	11
1984-85	28.0	12	3	3	13
1985-86	49.0	3	2	3	15
1986-87	31.1	10	2	2	16
Means	34.0		4.4	5.4	

Water yield

Water yield increased for the postlogging water-years in both clearcut watersheds. Postlogging water yields (water per unit area per year) were compared with prelogging regression lines that had been established between watersheds about to be logged and their unlogged controls (Hetherington 1982). Watershed-H averaged 34.9 $cm \cdot yr^{-1}$ more water in relation to Watershed-C (Fig. 34a ; Wilcoxon's sign test $P < 0.01$) and 20.5 $cm \cdot yr^{-1}$ more water in relation to Watershed-E (Fig. 34b ; Wilcoxon's test $P < 0.01$) from 1977–78 to 1986–87. This represented a 16 % and 9 % increase, respectively. Water yields might be returning to prelogging levels again, because the average increase was only 18.5 $cm \cdot yr^{-1}$ in relation to both control watersheds during the last 3 yr. Watershed-J yielded 37.9 $cm \cdot yr^{-1}$ more water (+24 %) from 1976–77 to 1986–87 and 27.2 $cm \cdot yr^{-1}$ more water from 1984–85 to 1986–87 in relation to Watershed-C (Fig. 35 ; Wilcoxon's test $P < 0.01$). Forest harvesting reduced transpiration and interception losses from the vegetation, leaving more water available for stream flow (Hetherington 1982). Bosch and Hewlett (1982) concluded in a major review that total annual yield had either increased following a reduction of forest cover or decreased following development of a forest during 93 of 94 paired watershed studies.

Differences in water yield were more difficult to detect in the main stream, because only 41 % of the watershed was logged. Water yield decreased by 14.8 $cm \cdot yr^{-1}$ in relation to Watershed-C (Fig. 34c) and by 24.5 $cm \cdot yr^{-1}$ in relation to Watershed-E (Fig. 34d) during the logging period (1976–77 to 1980–81). It increased by 23.5 $cm \cdot yr^{-1}$ (+9 %) in relation to Watershed-C (Wilcoxon's test $P < 0.05$) and by 1.0 $cm \cdot yr^{-1}$ in relation to Watershed-E (Wilcoxon's test $0.10 > P < 0.05$) after logging was completed (1981–82 to 1986–87). Apparently, reductions in forest cover of less than 20 % can not be detected by measuring stream flow (Bosch and Hewlett 1982), so no change in yield

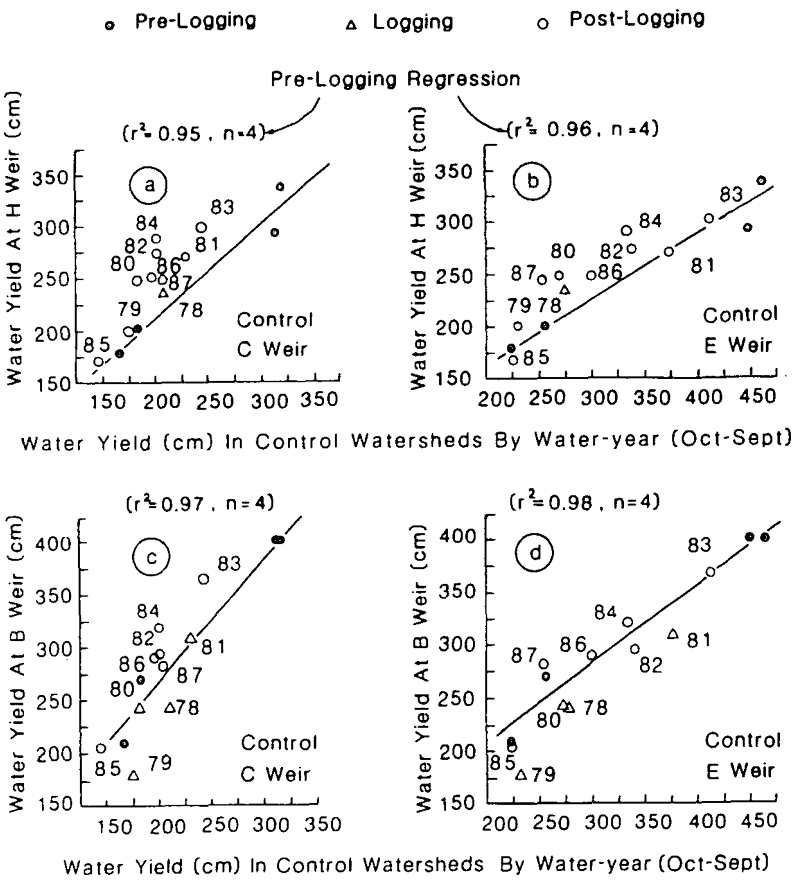

FIG. 34. Relationships are shown between annual water yields in logged or partly logged drainages (above H-weir and B-weir) and water yields from control drainages above E- and C- weirs. Updated with permission from Hetherington (1982).

should have been expected at B-weir until at least 1979–80 when 27 % of the watershed had been logged.

Groundwater levels on the floodplain were elevated ~30 cm following clearcutting (Fig. 33). The increase was due to tree removal and not diversion of water, because no roads were constructed nearby. Hetherington (1982) estimated that ground water in the valley bottom supplied 30–40 % of the stream flow during low discharge periods. Relative to controls, the number of days of low flow decreased at both H-weir and B-weir after logging.

In summary, road construction and clearcut logging affected the hydrological regime by modifying runoff patterns, by increasing groundwater levels, peak flows and water yields, and by decreasing the number of days of low flow in the stream. Changes were measured in localized areas on the slopes and in clearcut tributary watersheds, but they were less easily detected in the main stream. These inconsistencies were explained by differences in the amount and rate of clearcutting and vegetation regrowth, and by the size and characteristics of these watersheds. Tributary-H and -J were >95 % clearcut in 1 or 2 yr, but only 71 % of the total watershed is to be logged in 15 yr (by 1991). Evapotranspiration and interception losses from a new forest on the old clearcuts were occurring before clearcutting was completed in the larger watershed. The many localized diversions of water also tend to cancel each other out as larger watershed areas are considered. Little change to peak flows should be expected in Carnation Creek, because stream flow was so responsive to precipitation intensity. Water storage in the thin and wet soils was so limited that stormflow discharge was 90 % of storm rainfall (Hetherington 1988).

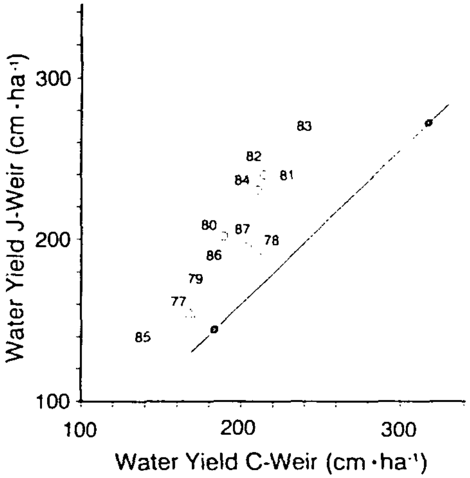

FIG. 35. Annual water yields from 13 water-years are compared for Watershed-C (154 ha) and Watershed-J (25 ha). Prelogging (dots), logging (triangles) and postlogging (circles) years are shown for Watershed-J, while the mature forest was maintained in Watershed-C.

Ion Concentration in the Stream

Scrivener (1982, 1988c) described three different annual patterns of ion concentration relative to stream discharge. The patterns were governed by ion source and type, by hydrological flux, by logging conditions, and by silvicultural prescriptions in a drainage basin. Stream water in Carnation Creek was weakly acidic (pH 6.0 – 7.1) with conductivities from 60–70 μmhos·cm^{-2} in summer to 18–30 μmhos·cm^{-2} in winter.

Conductivity was typical of the first annual pattern that was observed for ions such as calcium, silica, bicarbonate, sodium, and magnesium. These ions originated from weathering of rock and soils and from chemical or biological processes in ground water. Total ion concentration was inversely related to the amount of precipitation in the 60-d period prior to measurement (Fig. 36). This correlation was derived from deviations between the conductivity versus discharge relationships for individual storms and the relationship for the whole water-year in which the storms occurred (Scrivener 1975, 1982). Ion concentrations were reduced by 75 % during freshets, but total ion export was much higher then because discharge had increased ~30 times. These relationships occurred because a stream responds to rainfall by extending the channel network into draws, road ditches and shallow soil areas, thus intercepting water further upslope during storms (Scrivener 1975). Residence time of water in the soil and its ability to leach ions are reduced. Source areas shrink and residence time increases between storms.

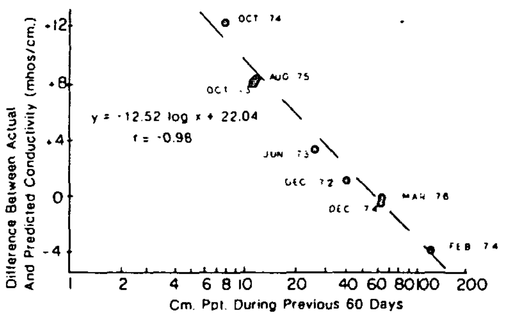

FIG. 36. The relationship observed between prelogging stream conductivity and previous hydrological flux in the Carnation Creek drainage (from Scrivener 1982).

The second annual pattern was typified by chloride, sulphate, and nitrate which came from outside of the watershed (in rain, dry fallout, nitrogen fixing bacteria). Concentrations were also related to discharge, but they were much greater during the first autumn storms and smaller during later winter storms (Scrivener 1988c). Apparently, these ions were flushed out at much higher concentrations after periods of low flow when they had been accumulating on the forest canopy or in the soil.

The third pattern was typified by the phosphate ion. Concentrations of phosphate in the stream were usually just above the minimum detectable limits and neither a seasonal pattern nor a relationship with discharge was observed. This ion is rapidly bound in the watershed. This conclusion was drawn because phosphate concentrations in rainfall were twice those in the stream, while precipitation washing the forest canopy contained four times the phosphate in the stream (Scrivener 1975).

The total ion concentration increased in Carnation Creek and its tributaries during the early period of logging and slash burning (Fig. 37). Conductivity increased at J-weir after clearcutting, but only when discharges were large. The increase persisted for only 2 yr after slash burning. Increased conductivities were also observed at H-weir after logging, but they persisted for 3–4 yr. This longer period of increased conductivity probably occurred because the watershed was burned only along one of its margins (Scrivener 1988c). A smaller increase in conductivity was observed at B-weir upstream of which 41 % of the watershed was clearcut (Fig. 37). These changes began and ended with the logging period (1976–77 to 1980–81). Conductivity increased at E-weir, a control watershed, but only during 1976–77 and 1977–78. These were dry years with few storms (Table 7). The logged watersheds showed the accumulative impacts of logging and drought because the changes at B-weir and J-weir were greater than at E-weir during 1976–77 and 1977–78 (Fig. 37).

Nitrate concentrations were increased by logging and slash burning, but little effect was observed on phosphate values. Unlike conductivity, nitrate-N concentrations increased over the full range of stream flow (Scrivener 1988c). They had increased 2-fold at B-weir (41 % clearcut) and 7-fold in Tributary-1600 (100 % clearcut and burned ; Scrivener 1989). Elevated nitrate-N values persisted for 2 yr at low flows and for at least 3 yr at high flows after which they declined below prelogging levels. Phosphate-P concentrations were unchanged at B-weir from 1971 to 1982 (Fig. 38), although increases were obtained for a few months following slash burning in Tributary-1600. They declined below prelogging levels after forest harvesting had ceased at Carnation Creek (Fig. 38). Stream nitrate and phosphate concentrations declined during postlogging water-years because more nutrients were probably absorbed by stream algae (Shortreed and Stockner 1982) and by the regenerating forest (Bormann and Likens 1980).

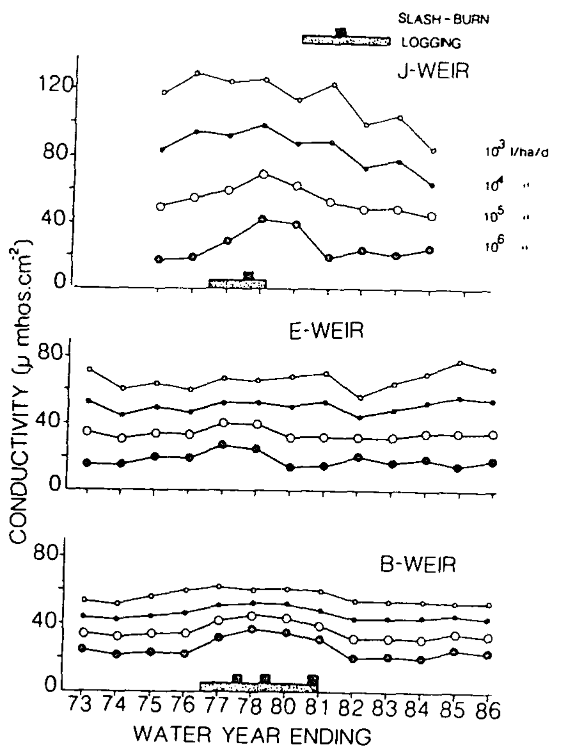

FIG. 37. Ion concentrations are shown for the period 1971–73 and for annual periods 1973–74 to 1985–86 at J-, E-, and B-weirs at discharges of 10^3, 10^4, 10^5, and 10^6 L•ha^{-1}•d^{-1}. The period of logging and slash burning are indicated on the time axis.

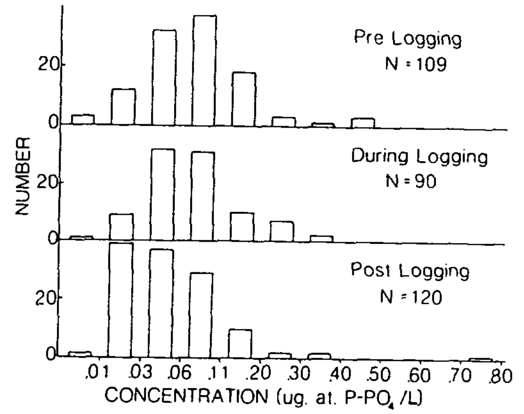

FIG. 38. Frequency distributions of phosphate-P concentrations (e.g., μg at.PO$_4$-P•L^{-1}) in stream water from B-weir during 1971–84.

Ion concentrations increased at B-weir and in Tributary-1600 after 4 % and 50 %, respectively, of their watersheds were treated with the herbicide RoundUp (glyphosate). Inverse relationships between the concentration of most ions and discharge persisted, but the concentration increases were limited to ~25 % of those observed after logging and slash burning (Scrivener 1989). Concentrations of nitrate-N increased only during large discharges. Phosphate-P concentration doubled for 1–2 yr at both B-weir and Tributary-1600 after the herbicide treatment. This phosphate was probably leached from the phosphate rich deciduous vegetation that was killed by the herbicide. Duvigneaud and Denaeyer-de-Smet (1970) have shown that logging debris, mainly from coniferous vegetation, contained less phosphate and that much of it would have been lost to the atmosphere during burning. Thus phosphate concentrations increased after herbicide use, but they were unchanged after logging and burning.

Woody Debris And Channel Morphology

Volume, stability and distribution of large organic debris (LOD), channel morphology and streambed composition changed through interrelated processes following logging in Carnation Creek. The condition and characteristics of the debris controlled the channel form and bed stability. Location of many pieces of LOD and of the wetted portion of the channel during low flow remained unchanged from 1971 to 1985 in study sections II, III and IV (Powell 1988 ; Fig. 39, 40). Some stream-side trees remained in this leave strip treatment. The location of both LOD and the channel changed between 1976 and 1985 in study sections V and VI (intensive stream-side treatment ; Fig. 41) and in section VIII (careful stream-side treatment ; Fig. 42) where logging occurred to the stream bank. LOD was either swept out of these sections (Fig. 41), or concentrated in large piles (Fig. 42). These debris piles that accumulated after logging were not stable and one pile in study section VIII moved ~15 m during a storm. In the lower third of study section VIII, the right bank receded 8 m, while the left bank receded 2 m during a 6-yr period (1980–85). Many of the changes of LOD distribution and bank location occurred in sections V and VI during the November 7, 1978 storm (Toews and Moore 1982) and in section VIII during the January 4, 1984 storm (Hartman et al. 1987). Pool depths decreased, gravel accumulated or was scoured, and channel width increased coincident with the changes in debris distribution in these study sections.

Large debris changes

The fate of LOD was different in the three stream-side treatments. The number of pieces of LOD increased after logging, while volume and stability decreased in the intensive and careful treatment study sections (sections V to VIII ; Table 8). Average piece size and thus stability had declined. Individual pieces of LOD were moved into and out of the sections that were bordered by a leave strip (sections II, III and IV), but number of pieces, total volume, and stability was not changed significantly after logging (Table 8). In study section IV, 61.1 % of the pieces present in 1973 were still in the same location in 1980, 2 yr after logging (Toews and Moore 1982).

Small debris changes

Debris pieces that were less than 3 m in length were not consistently located and measured during the prelogging period so changes could only be estimated from early photographs and surveys obtained after 1978 (Toews and Moore 1982). The intensive stream-side treatment (trees felled and removed from the stream) introduced considerable small debris to study section V, VI and VII. It was reduced by more than 50 % and the remaining pieces were accumulated into dense piles by the November 1978 freshet.

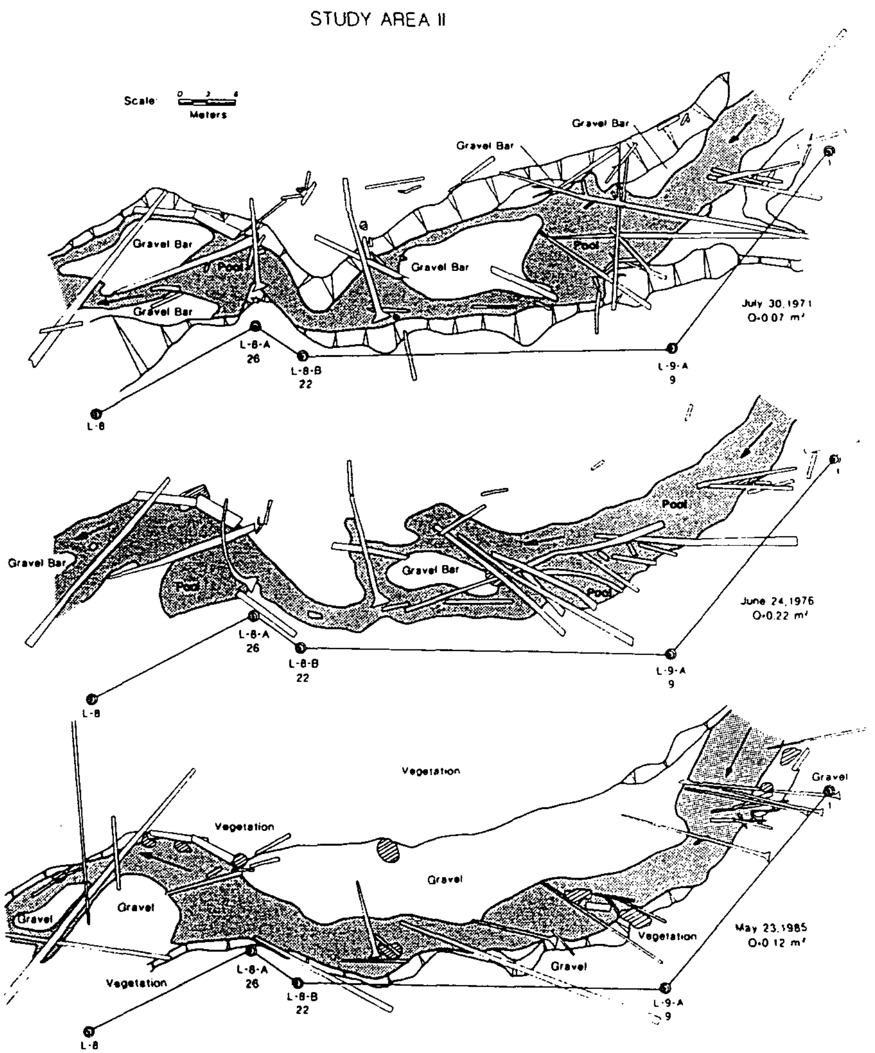

FIG. 39. Distribution of woody debris and location of the stream channel mapped during low flow conditions in Study Section II, (leave strip treatment) Carnation Creek, during surveys in 1971, 1976, and 1985. The dates of surveys and stream discharge at the time of the survey are indicated.

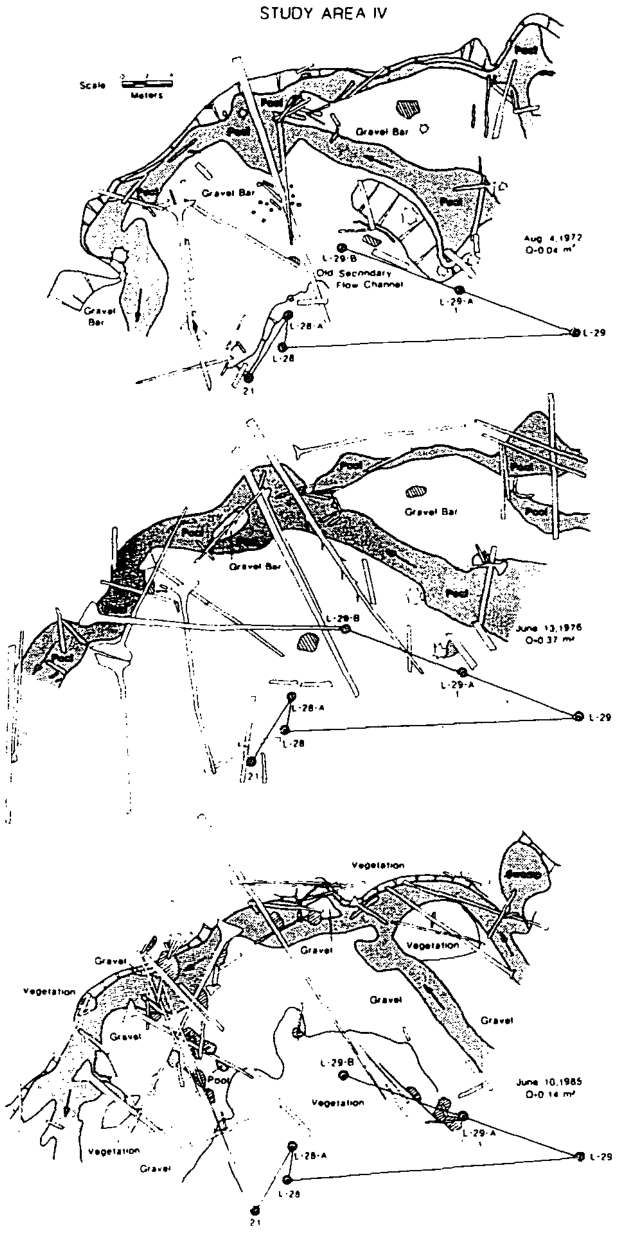

FIG. 40. Distribution of woody debris and location of the stream channel are shown for low flow conditions in Study Section IV (immediately downstream of the intensive treatment) in Carnation Creek during surveys in 1972, 1976, and 1985. The dates of surveys and stream discharge, at the time of survey, are indicated.

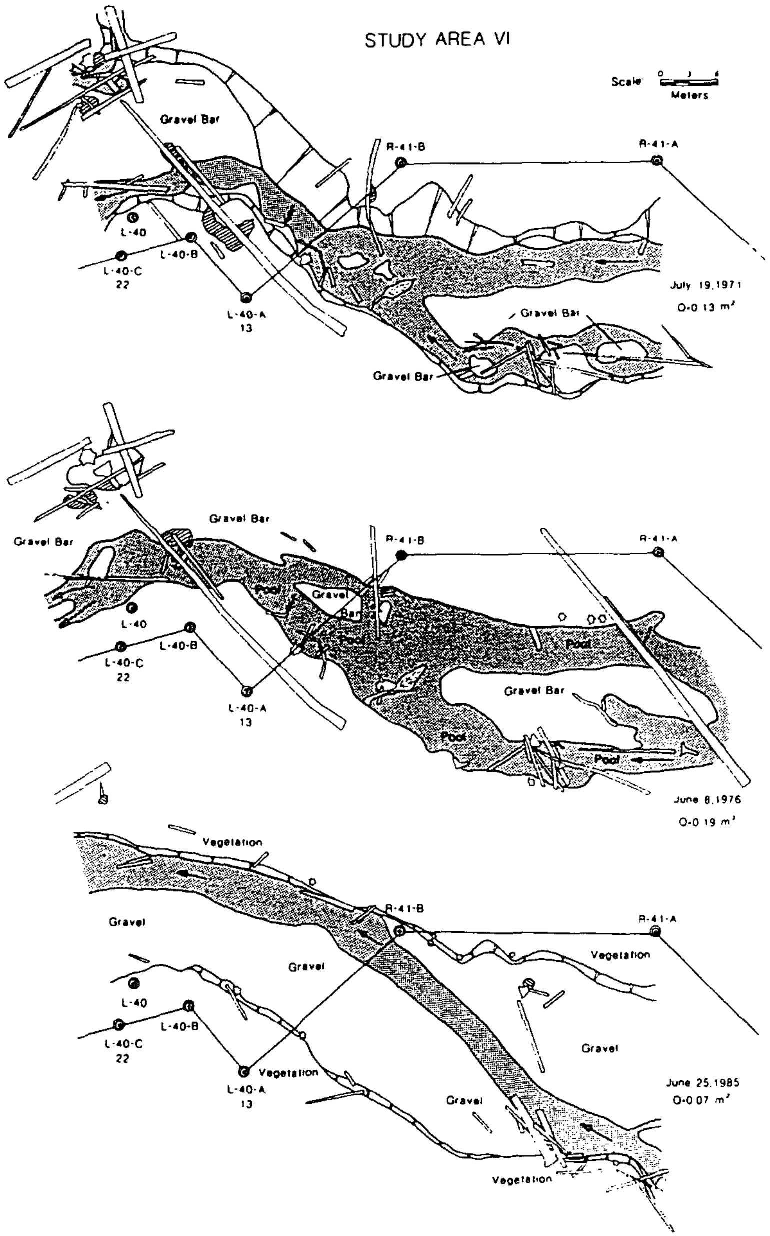

FIG. 41. Distribution of woody debris and location of the stream channel are shown for low flow conditions in Study Section VI (intensive treatment) in Carnation Creek during surveys in 1971, 1976, and 1985. The dates of surveys and stream discharge, at the time of survey, are indicated.

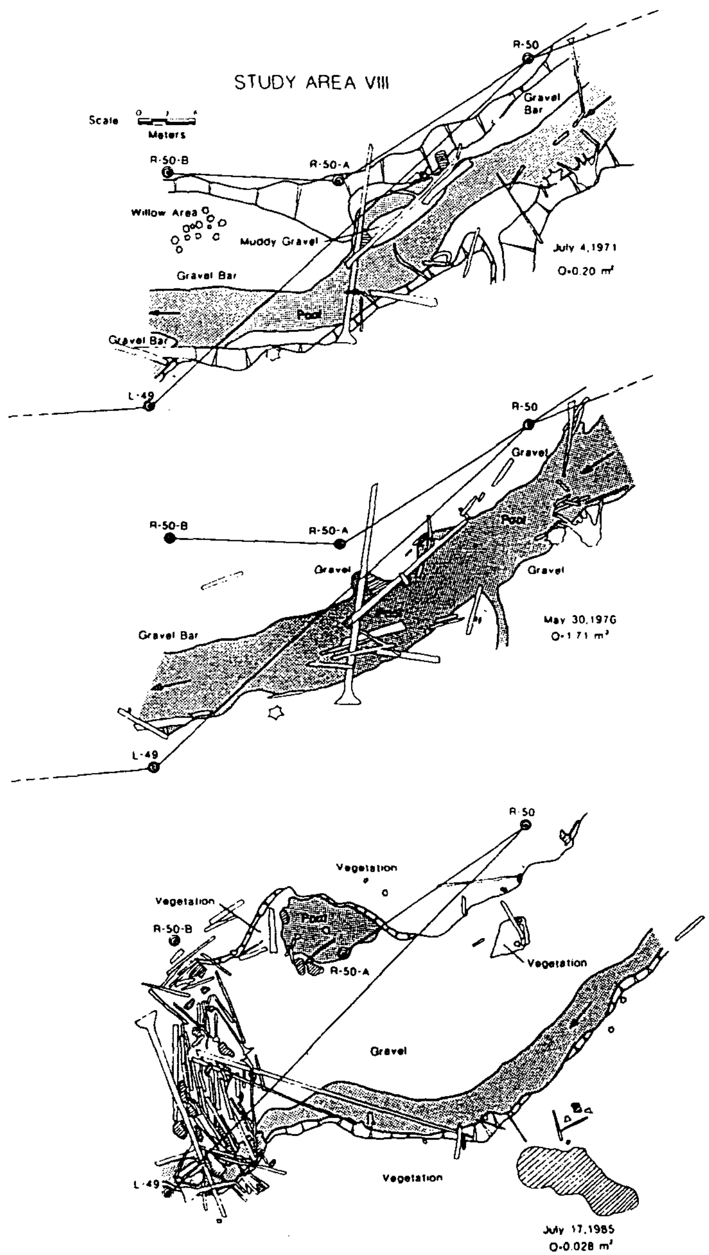

FIG. 42. Distribution of woody debris and location of the stream mapped during low flow conditions in Study Section VIII (careful treatment) in Carnation Creek during surveys in 1971, 1976, and 1985. The dates of surveys and stream discharge, at the time of survey, are indicated.

TABLE 8. Means of the number of pieces, volumes, and stability indices in each study section before and after logging. These values were calculated from the annual total number of pieces and volume of debris in a study section. The annual stability index of a study section was the percentage of debris pieces that could be relocated and mapped during the following annual survey.

	Section	Before logging	After logging	Treatment
Number of pieces	II	34.0	36.5	1. Leave strip
	III	27.3	27.0	1. Leave strip
	IV	32.0	30.0	1. Leave strip
	VIII	19.8	23.0	2. Careful
	V	14.2	29.0[a]	3. Intensive
	VI	25.0	27.5	3. Intensive
	VII	25.3	36.2	3. Intensive
Volume (m^3•30 m^{-1} of stream)	II	29.6	29.5	1. Leave strip
	III	34.2	50.4	1. Leave strip
	IV	37.4	36.4	1. Leave strip
	VIII	14.3	14.7	2. Careful
	V	25.4	23.2	3. Intensive
	VI	26.0	20.0[a]	3. Intensive
	VII	78.2	19.5[a]	3. Intensive
Mean Stability Indices %	II	54.7	63.3	1. Leave strip
	III	53.0	61.7	1. Leave strip
	IV	84.4	61.2	1. Leave strip
	VIII	82.3	39.0[a]	2. Careful
	V	80.2	35.7[a]	3. Intensive
	VI	93.1	43.9[a]	3. Intensive
	VII	98.9	56.2[a]	3. Intensive

[a] Significantly different than prior to logging (t-test, $P < 0.05$)

Volumes in these piles were reduced to 10 % by 1981 (Toews and Moore 1982). Much smaller volumes of small debris were introduced into the careful treatment section (VIII). Freshets removed this debris within a few years. Accumulations of small debris were rare in leave strip sections and first appeared during the postlogging period. The distribution of small debris influenced fish densities (see Chapter 7 Fluvial, geological and debris changes in the stream), LOD stability and channel erosion (Powell 1988).

Channel morphology

Annual changes in channel form and location occurred in Carnation Creek, but they were accelerated by stream-side cutting in both the intensive treatment (study sections V, VI and VII) and careful treatment stream side (section VIII ; Fig. 43). Accelerated erosion of the streambed in these treatment areas increased scour and deposition rates downstream in the leave strip (sections II and IV). These rates were greatest in all study sections after logging and the November 1978 freshet (1979–85 ; Fig. 43). The increase in scour and deposition rates was greatest in the careful treatment sections and smallest in the leave strip sections (Fig. 43). The careful treatment section was 300 m below the stream reach that was subjected to a debris torrent in January 1984. Most of the scour or deposition in the careful treatment occurred after this event. The loss of fines and gravel due to erosion of the streambed left only cobble and freshly exposed glacial till

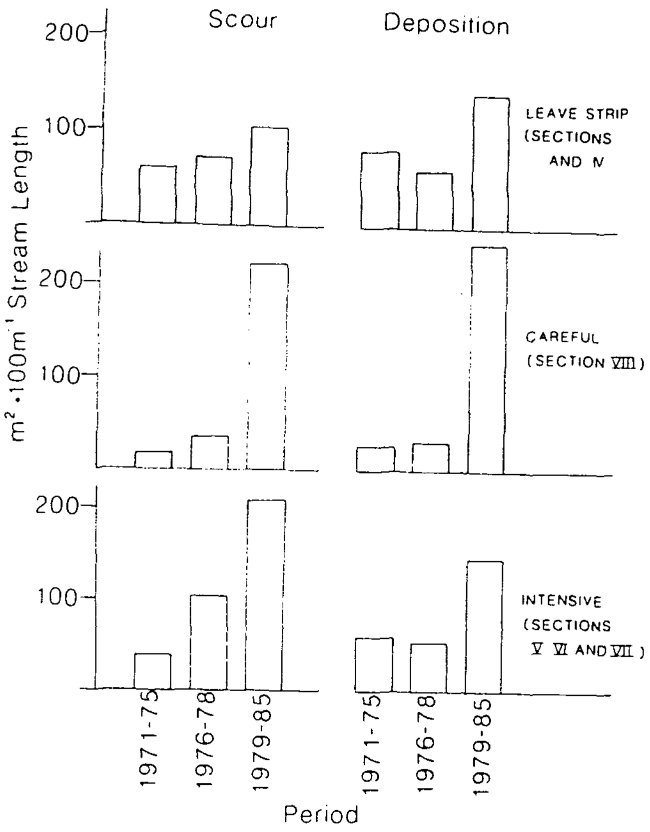

FIG. 43. Areas of streambed scour and deposition in leave strip, careful and intensive treatment study sections during the prelogging period (1971-75), the period prior to the November 1978 storm (1976-78) and the remainder of the logging and postlogging periods (1979-85).

in a few reaches (Fig. 44a), while gravel bars (as high as the stream banks) were deposited in two other reaches (Fig. 44b) within the intensive and careful stream-side treatments.

Annual changes in width of the stream channel corresponded in magnitude and timing to the increases in streambed scour and deposition (Fig. 45). Very few changes occurred in any study section during the prelogging period (1971–76). After logging was begun, channel width increased significantly only in the study sections where the stream banks had been logged. The increases began in intensive treatment sections (V, VI, VII) after logging and accelerated after the November 1978 freshet (1979–85 ; Fig. 45). The channel began widening later in the careful treatment section (VIII) especially after the January 1984 freshet.

In summary, LOD was reduced to ~30 % of prelogging in those sections of stream that were logged to the stream bank. Rates of scour, deposition, bank erosion and change in channel topography also increased. Streambed scour and deposition effects were transmitted downstream. As a consequence of these changes, LOD accumulations became larger and fewer in number, and long straight glides developed in the stream (Fig. 41). Aggrading reaches of stream that were dry during late summer also developed (Fig. 44b), despite an increase in water yield (Fig. 34).

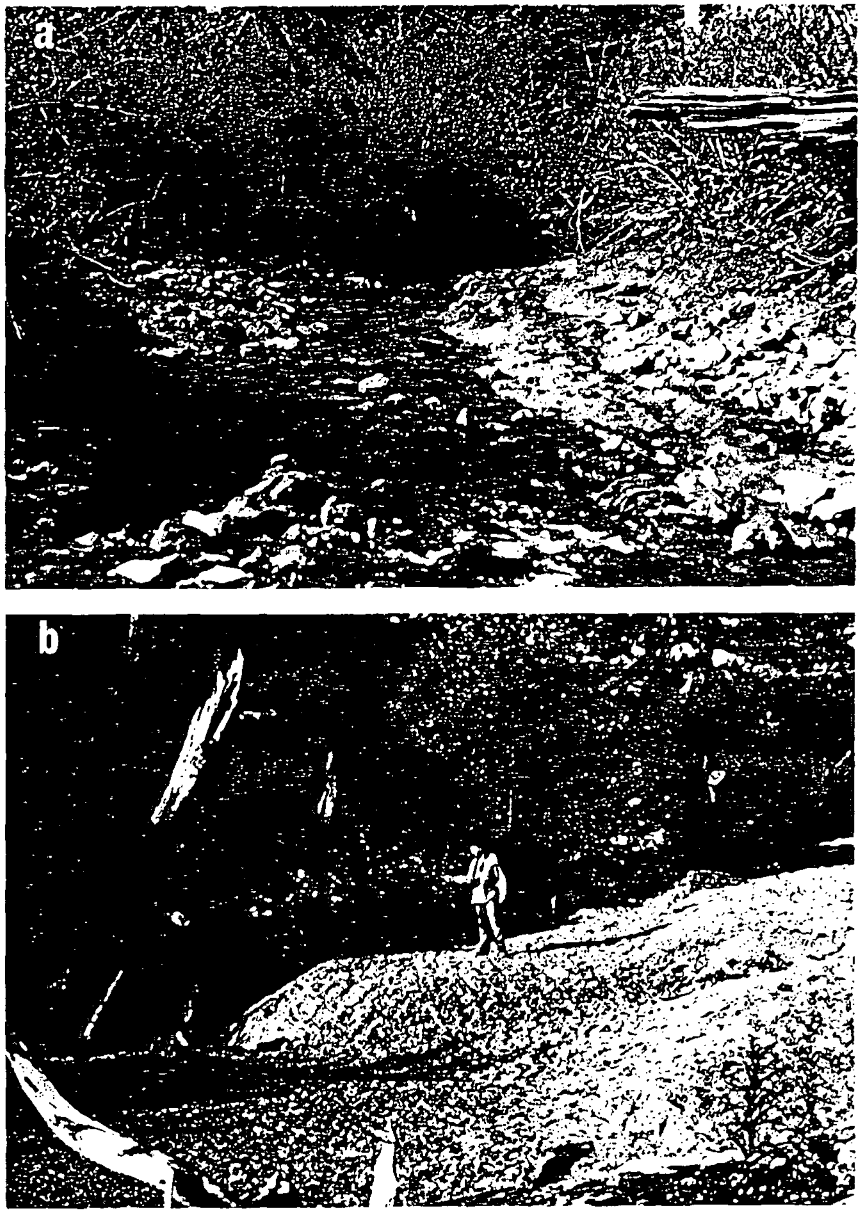

FIG. 44. (a) Scoured stream bottom, cobbles and freshly exposed clay in an area of active erosion (above Study Section VIII) ; (b) Deposition of gravel in the careful treatment section. Much of this material was laid down after a single large freshet and debris torrent in January 1984

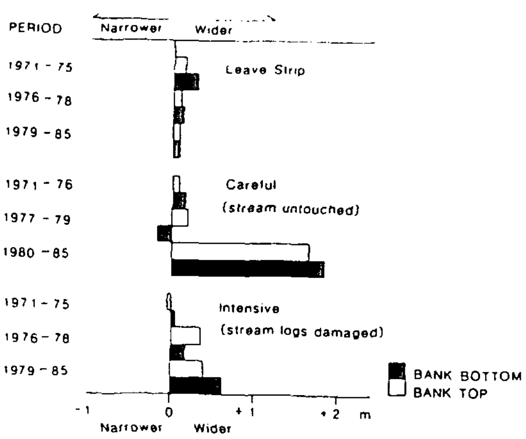

FIG. 45. Mean annual changes observed for stream width at the top (open) and bottom (solid) of the stream bank in study sections II to VIII at Carnation Creek. Time was partitioned into prelogging (1971–76), early logging (1976–79), and the remainder of the study (1980–85).

Spawning Gravel Composition

Composition of Carnation Creek spawning gravel changed after logging, both in the study sections above the fish counting fence and in the chum spawning area below the fence. The changes were most prevalent in the careful and intensive treatment areas, however fine sediments from these treatments were transported downstream into the area with a leave strip (Scrivener and Brownlee 1982). Much of the sediment that was added to the stream came from eroding stream banks (Scrivener 1988d).

Particle size analysis of streambed freeze-cores from the study sections have produced nine observations (Scrivener and Brownlee 1982, 1989) :

1. Particles less than 9.55 mm in diameter tended to increase with streambed depth throughout the study (1973–86 ; Fig. 46).
2. Most particles in this size range were transported and deposited along the bottom as bedload during storms.
3. Rates of scour and deposition of fine sand (0.074–0.30 mm in diameter), medium sand (0.30–1.19 mm), coarse sand (1.19–2.38 mm), and pea gravel (2.38–9.55 mm) were inversely related to their size and depth in the streambed.
4. A seasonal pattern of accumulation during summer and of erosion during winter was observed for silt and clay particles (<0.074 mm).
5. The concentration of dissolved oxygen in interstitial water was positively correlated with the mean particle size of the streambed.
6. After logging, sand (0.30–2.38 mm) increased by 4.6 % and pea gravel (2.38–9.55 mm) increased by 5.7 % of a freeze-cores total weight (Fig. 46).
7. The top layer of the streambed was more dynamic than the bottom layer, therefore sand and pea gravel began increasing first in the top layer after logging.
8. Net increases among pea gravel and sands were similar for both layers of the streambed because in the bottom layer, deposition of fines occurred continually, but at a much lower rate (Fig. 46).
9. Mean particle size of the streambed and peak discharge at B-weir each year were negatively correlated during this period when fine sediments were accumulating in the streambed.

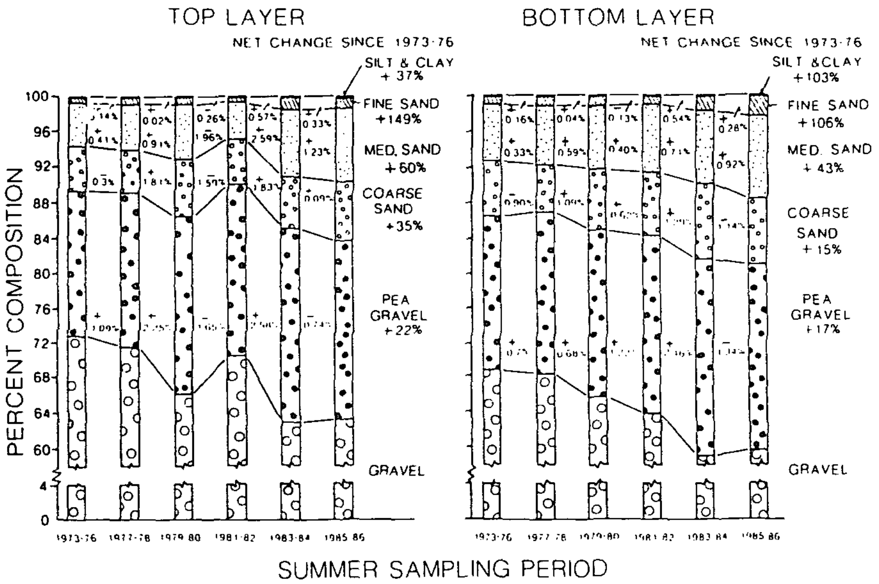

FIG. 46. Percentage composition, rate of change and net change, since 1973–76 gravel surveys, of pea gravel, coarse sand, medium sand, fine sand, and silt-clay in the top and bottom halves of streambed cores from Carnation Creek.

Changes in streambed composition were dependent upon the frequency and magnitude of peak flows, on proximity to the different stream-side treatments (sources of sediment), and on the timing of logging activities (Scrivener and Brownlee 1989). The size of particles transported in the stream, the distance they moved and the depth of scour and re-deposition increased with increasing stream discharge. Consequently, the deposition of pea gravel and sand began in the top layer, and pea gravel composition changed more in or immediately below the intensive stream-side treatment (study sections IV, V and VI), while sand composition changed more in the leave strip treatment downstream (sections I, II and III ; Scrivener 1988d). As Carnation Creek was exposed to larger freshets, more sediment was eroded from the stream banks and it penetrated deeper into the streambed. Pea gravel and sand were still accumulating in the deeper layers 10 yr after logging was begun. The cleaning and re-deposition of fine sediment suggested that sudden pulses of fine sediment entering Carnation Creek would have been deposited and then cleaned away within a few years if the logging activity had not produced such persistent sources of sediment (Scrivener and Brownlee 1989).

Suspended Sediment and Bedload Transport

Two modes of sediment transport have been described for streams. Suspended transport occurred when fine particles, usually less than 1 mm in diameter, were maintained in suspension by the turbulence of flowing water. Bedload transport occurred when coarser particles rolled, slid or saltated downstream in close proximity to the stream bottom during freshets.

Transport of suspended sediment varied at B-weir each water-year and logging appeared to have a minor impact on it. Total suspended sediment ranged from 11.3 to 42.4

t·km^{-2}·yr^{-1} between 1973 and 1986 (Fig. 47). Mean concentration of suspended sediment ranged from 5.7 to 10.4 mg·L^{-1}·yr^{-1}. Each year, most of the transport occurred between November and February when loads were greater than 0.1 t·km^{-2}·d^{-1} (Tassone 1988). The highest yield of suspended sediment at the highest mean concentration occurred during 1973–74 (Fig. 47), which was a prelogging year with many storms (Table 7). The second highest yield occurred during 1982–83, a postlogging year, while the third highest yield occurred during 1975–76, a wet year with extensive road construction (Table 1). The second highest sediment concentration was obtained during 1978–79, a logging year with few storms.

Suspended sediment yield was correlated with the number per year of peak flows greater than 12 m^3·s^{-1} (r = 0.83, n = 12, P = 0.001). They were also correlated for the three prelogging years for which data was available (Fig. 48). Actual yields were 6.7 t·km^{-1}·yr^{-1} greater during logging and postlogging water-years than yields predicted by the prelogging relationship (Wilcoxon's sign test $P < 0.01$). This represented a 22 % increase above prelogging years.

The movement of sediment in suspension has been the principle transport mechanism leading to reduced quality of spawning gravels after logging in other watershed studies. Yields of suspended sediment increased from 26–97 to 90–300 t·km^{-2}·yr^{-1} after road construction and forest harvesting in the Alsea watershed, Oregon (Beschta 1978). These fine sediments were smaller than 0.85 mm and they originated from the surface of logging roads in the Clearwater watershed, Washington (Cederholm et al. 1981). The increased yield of suspended sediment was much smaller at Carnation Creek and few particles smaller than 0.85 mm accumulated in the streambed after logging (fine sand, silt-clay; Fig. 46).

Bedload transport was one of the major channel forming mechanisms in Carnation Creek and it increased after logging was begun. Significant bedload transport (>1 kg·m^{-1}·min^{-1}) did not begin until the discharge reached 10 m^3·s^{-1} during a freshet (Tassone 1988). A conservative estimate of bedload transport was 251 t·yr^{-1} at B-weir during prelogging years (1973–76). It increased to at least 289 t·yr^{-1} during the logging years (1977–81), and to 270 t·yr^{-1} during the postlogging years (1982–85). After logging, the increase in area of streambed scour and deposition also indicated an increase of bedload transport within the intensive and careful stream-side treatments upstream (Fig. 43). The bedload consisted mainly of sand (0.3–2.38 mm in diameter), pea gravel (2.38–9.55 mm), and gravel (9.55–40 mm) size particles.

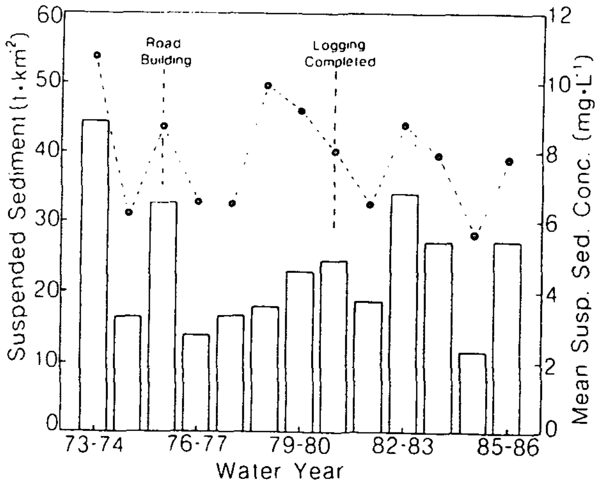

FIG. 47. Total suspended sediment transported (bars, t·km^{-2}) and mean annual concentration (•—•, mg·L^{-1}) measured at B-weir, Carnation Creek for each water year (Oct. 1 to Sept. 30).

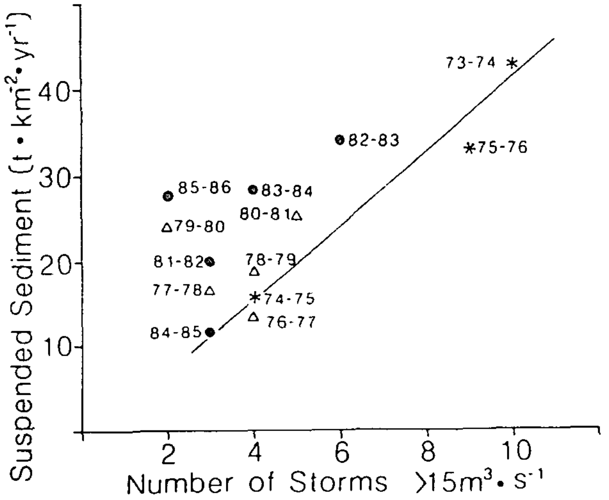

FIG. 48. The relationship observed between suspended sediment yield and discharge at B-weir during prelogging (asterisks), logging (triangles), and postlogging water-years (dots).

Soil Disturbance

Changes in ground-surface characteristics have affected soil stability, surface soil erosion, and site productivity. Other studies have related forestry operations to increased soil loss from forest sites and sediment production to streams (Carr 1985 ; Dyrness 1967 ; Fredricksen 1970 ; Megahan et al. 1978). Decayed root channels, macrochannels, normally pipe water rapidly through forested soils of the Pacific Northwest (Chamberlin 1972). Logging disturbance that exposes mineral soil can plug these macrochannels and cause a shift in the water flow pathway to the soil matrix during storms (deVries and Chow 1978). Water flow through the soil can thus be slowed causing slides and mass wasting (Megahan et al. 1978 ; Sauder et al. 1987). Surface erosion is also directly related to the area of mineral soil exposure to raindrops or flowing water (Lowdermilk 1930). Water surfaces in rills and gullies and erodes exposed mineral soil (Carr 1985).

At Carnation Creek, the percent surface area of soil disturbance was highest on cutblocks that were logged and burned and lowest on cutblocks that were unlogged (Fig. 49). Clearcutting reduced the vegetation cover from 100 to 24 % and increased the area of mineral soil exposure from 0 to 16 %. However, logging slash covered 50 % of the area following clearcutting (Smith and Wass 1982). Burning (Fig. 7) reduced vegetation cover to ~5 %, reduced slash cover to 15 %, and increased mineral soil exposure to 26 % (Fig. 49). Most of the mineral soil exposure resulted from gouges made by yarded logs, but 20 % of the soil exposure was caused by loss of the organic mat during burning. Exposure of mineral soil increased again during the first rainy season indicating that some

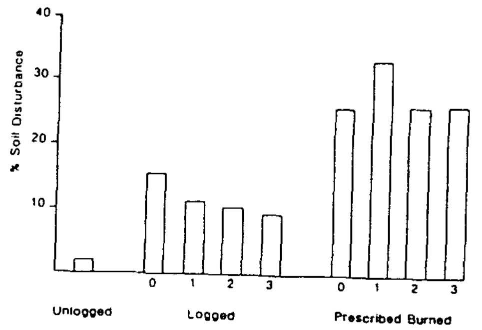

FIG. 49. Average percentage of soil disturbance observed on unlogged, logged, and logged and burned cutblocks. The number of years since logging is indicated beneath each bar on the horizontal axis. Redrawn with permission from Smith and Wass (1982).

erosion was occurring on the burned sites (Smith and Wass 1982 ; Smith et al. 1988). These changes were more pronounced on steeper slopes but less so near the valley bottom.

Results from the three postburning years indicated that surface erosion was short lived at sites that were burned (Smith and Wass 1982). Only 8 % of the area was classified as eroding and this appeared to persist for only 1 or 2 yr. The only material that probably reached the stream came from ephemeral channels. Erodable sediment was either added to old channels or present in new ones gouged during yarding. The rapid revegetation of disturbed sites (King and Oswald 1982), the small increase in suspended sediment yield (Fig. 48), and the lack of very fine sediments in streambed gravels (Fig. 46) also supported this conclusion.

Chapter 6. Biological Conditions

Forest Regeneration

The invasion rate and species of vegetation which colonize an area following logging and burning influence other watershed processes. They affect the erodability of the soil (Smith et al. 1988), the stability of slopes (Carr 1985), the sediment budget of the stream (Beschta 1978), the evapotranspiration rate, the water yield of streams (Bosch and Hewlett 1982), the insolation of the soil and streams (Holtby 1988), and the insect fauna of the stream side (fish food). Therefore knowledge of the successional stages of vegetation is necessary for understanding logging influences on the stream ecosystem.

Vegetation covered 80–90 % of the surface of Carnation Creek watershed as overlapping tree, shrub/herb, and forb/moss layers. Clearcutting virtually eliminated the tree layer and it reduced total cover to an average of 24 % (Smith et al. 1988). Vegetative cover was reduced to 5 % at sites that were burned.

Three years later, the three layers of vegetation had reappeared, and total cover was 27 % at logged and burned sites and 36 % at logged sites. Vegetative cover was also greater on the valley bottom than on the slopes (King and Oswald 1982). On the flood plain, trees consisted of planted conifers (1 m in height) and red alder (2 m), while shrubs consisted of salmonberry (0.6 m) and forbs consisted mainly of ferns. On the slopes, conifers and red alder trees were smaller and their distribution more clumped than in the valley bottom. The predominant shrub on the lower slope, salmonberry, was replaced by salal (*Gaultheria shallon*) on the upper slopes. Forbs predominated on the upper slopes. Ferns on the lower slopes were replaced by fireweed (*Epilobium* spp.) on the upper slope (King and Oswald 1982).

Five years after logging, the tree, shrub and forb layers became more distinct and the plant community became more complex. Planted conifers were 2 m tall at 5 yr and naturally seeded western hemlock was frequently recorded. Red alder had reached maximum frequency in the vegetation plots and it was 4 m in height (Smith et al. 1988). Shrubs such as salmonberry had also reached their maximum frequency (on 90 % of plots) and height (0.9 m). Average cover by salmonberry was 43 % on the valley bottom. Forbs such as sword fern (*Polystichum munitum*) also reached their maximum frequency (70 %), height (0.6 m), and cover (17 %) on the valley bottom (Smith et al. 1988). On the slopes, salal and huckleberry (*Vaccinium* spp.) had become more frequent and this shrub layer covered 25 % of the area. Forbs such as fireweed were being replaced by deer fern (*Blechnum spicant*), thistles, and grasses.

Ten years after logging, vegetation cover was again at prelogging levels (80–90 %) at sites that had received no silvicultural treatments. Conifers (3.5 m in height) and red alder (8 m) shaded the understory and smaller trees (Reynolds et al. 1989a). The coniferous trees were no longer successfully competing with red alder and salmonberry at some locations on the lower slopes and valley bottom.

The herbicide RoundUp® was used in some cutblocks to reduce competition for the conifer crop 7.5 yr after logging. Herbicide efficacy was species dependent, but salmonberry and red alder were effectively controlled for 3 yr by RoundUp with minimal damage to the conifers (Reynolds et al. 1989a). Within 3 yr, Sitka spruce on the treated sites had a 40 % advantage in diameter and a 63 % advantage in diameter-increment over trees on the untreated sites. Herbicide application had also influenced water temperatures, nutrients, and biota in a tributary stream (Reynolds et al. 1989b).

Stream Periphyton

The accumulation of attached algae in Carnation Creek was affected in varying ways by light, nutrient levels, freshets, logging, and silvicultural activities. It was low

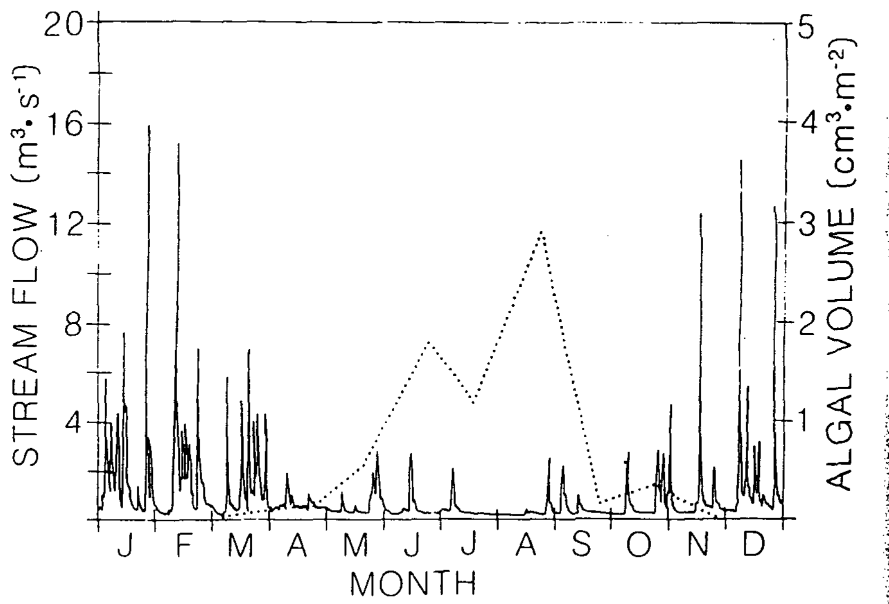

FIG. 50. Annual hydrograph observed at B-weir (solid line) and algal volume (dotted) in Study Section IV during 1976. Redrawn with permission from Shortreed and Stockner (1982).

(3.4 μg org·cm^{-2}·d^{-1}) relative to other streams that were reported in the literature and the algal community consisted mainly of diatoms (Stockner and Shortreed 1976). A seasonal pattern of accumulation during the summer period of stable stream flows was followed by losses during the winter period of frequent freshets (Fig. 50).

No relationship was obtained between mean incidence of light and chlorophyll *a* concentrations, rate of ash-free dry weight (AFDW) accumulation, or algal volume at sites where nutrient conditions were similar. However, there may be a critical threshold of light intensity, 50–60 g-cal·cm^{-2}·d^{-1}, below which algal production is limited (Stockner and Shortreed 1978). Light reaching the stream ranged from 24 to 47 % of the intensity at Station A (Fig. 25) during the prelogging period (Shortreed and Stockner 1982, 1983). While this variation of light intensity had only a small effect on the AFDW of algae produced among sites (Fig. 51), it did affect the percentage of diatoms in the algal community and potentially, the food supply of stream invertebrates. After logging, light at the same stream sites ranged from 40 to 97 % of mean intensity at Station A, but rates of AFDW accumulation increased at only a few sites (Fig. 51).

In Carnation Creek, changes of nutrient concentrations were more influential than changes of light intensity in altering periphyton production. Algal growth was increased nearly 3-fold in trough cultures that were both under the forest canopy and enriched with NaNO$_3$ and Na$_2$ HPO$_4$ (Stockner and Shortreed 1976). Phosphorus was shown to be the more limiting nutrient in another experiment (Stockner and Shortreed 1978). Production (chlorophyll *a* concentration, algal volume, and rate of AFDW accumulation) was much greater when either phosphorus or a combination of nitrogen and phosphorus enrichment was used than when either a nitrogen enrichment or a control condition was used (Fig. 52).

Stream flow limited the duration of periphyton accumulation, but it had little influence on production during the growing season. The final spring freshet and the first autumn freshet effectively delineated the summer growing season (Shortreed and Stockner 1983), although the occasional summer freshet reduced algal biomass (Fig. 50). Measurable accumulations of periphyton also occurred during any extended period of low stream flows during the winter (Oct. 1974, Nov. 1978, Mar. 1979 ; Fig. 51).

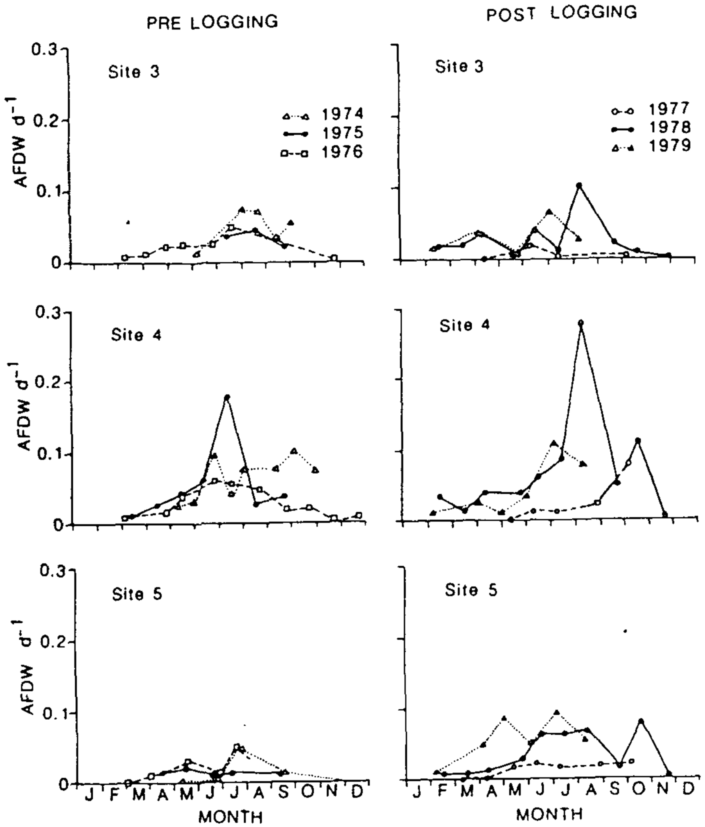

FIG. 51. Seasonal variation of periphyton ash free dry weights (AFDW) adjacent to study sections IV, V, and VI in Carnation Creek during prelogging (1974–76) and during logging (1977–79) periods of the study. Redrawn with permission from Shortreed and Stockner (1983).

Clearcut logging and burning had only a small impact on periphyton production in Carnation Creek (Shortreed and Stockner 1983). Although logging increased light intensity, stream temperature (Fig. 27), and nitrogen concentration (Scrivener 1988c), greater accumulations of algae were obtained only during 1978 at a few sites (Fig. 51). Some high phosphate concentrations were also measured in the stream during 1978, after the year of intense logging and burning (1977, Table 1), but throughout most of the logging and postlogging periods (1977–84), they were similar to or less than prelogging concentrations (Fig. 38). Sediment transport increased after logging (Fig. 48), but not during the summer period of algal accumulation (Tassone 1988). Moving sediments are known to be effective scouring agents (Gumtow 1955). Stability of the algal substrate also declined because more streambed area was experiencing scour and deposition (Fig. 43), and because mean particle size of the substrate was declining (Scrivener and Brownlee 1989). These factors would only influence algal accumulation during the occasional summer or winter freshet.

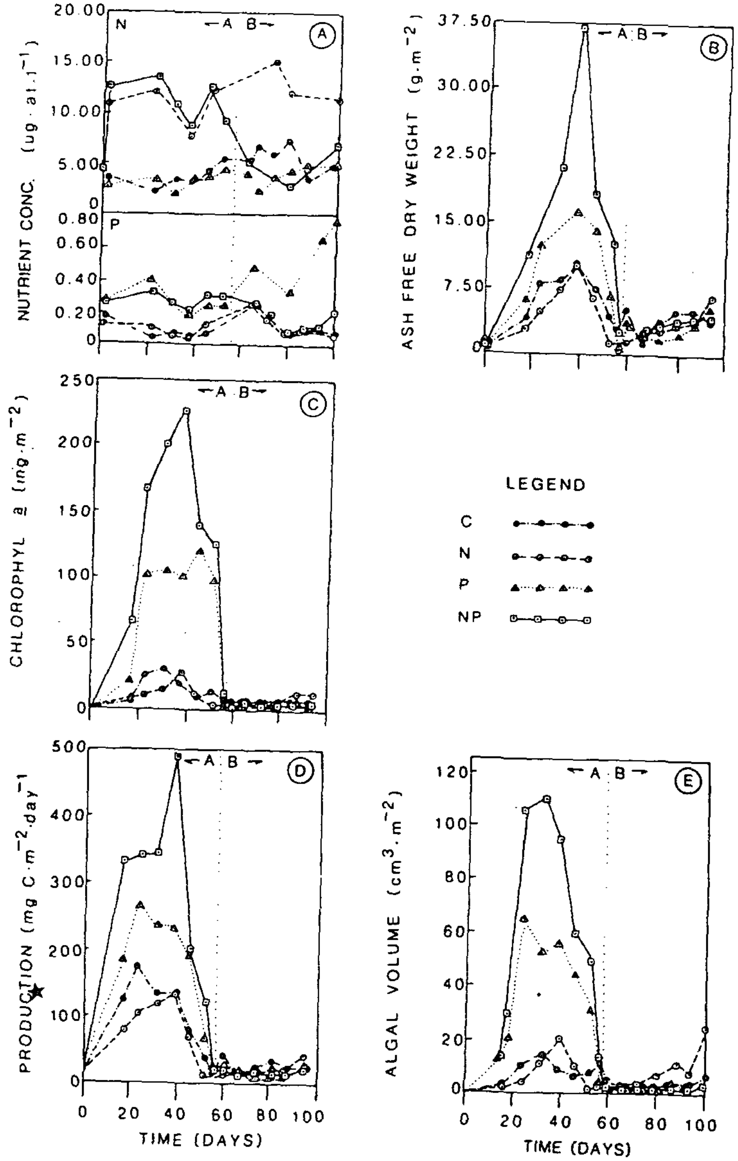

FIG. 52. Temporal variation during 0–56 d (←A) and 57–101 d (B→) of a 1976 nutrient enrichment experiment in Carnation Creek. Ⓐ nitrate and phosphate concentrations ; Ⓑ ash-free dry weight ; Ⓒ chlorophyl *a* ; Ⓓ net production ; and Ⓔ algal volume are shown for controls (C), nitrate additions (N), phosphate additions (P), and N + P additions (NP) from Stockner and Shortreed (1978).

The herbicide RoundUp influenced algal production in the vicinity of its application during September 1984. Algal biomass declined in the main stream and the treated tributary two weeks after the herbicide application (Holtby and Baillie 1989a). This was followed by an increase in both phosphate-P concentrations (Scrivener 1989) and periphyton production during 1985.

Leaf Litter

Current concepts of stream ecosystems recognize the importance of detrital inputs as the major energy source for small forested streams (Vannote et al. 1980). Utilization of detrital inputs, mostly leaf litter, is critically dependent upon mechanisms that enhance the capture and retention of litter (Cummins et al. 1980). The total input of litter to the streambed of Carnation Creek was 32.5 metric t·yr^{-1} during 1974–75 (prelogging, Neaves 1978). Over 80 % of this litter input was leaf material and it entered the stream between September 1 and November 30 (Fig. 53). Input of coniferous litter was more evenly

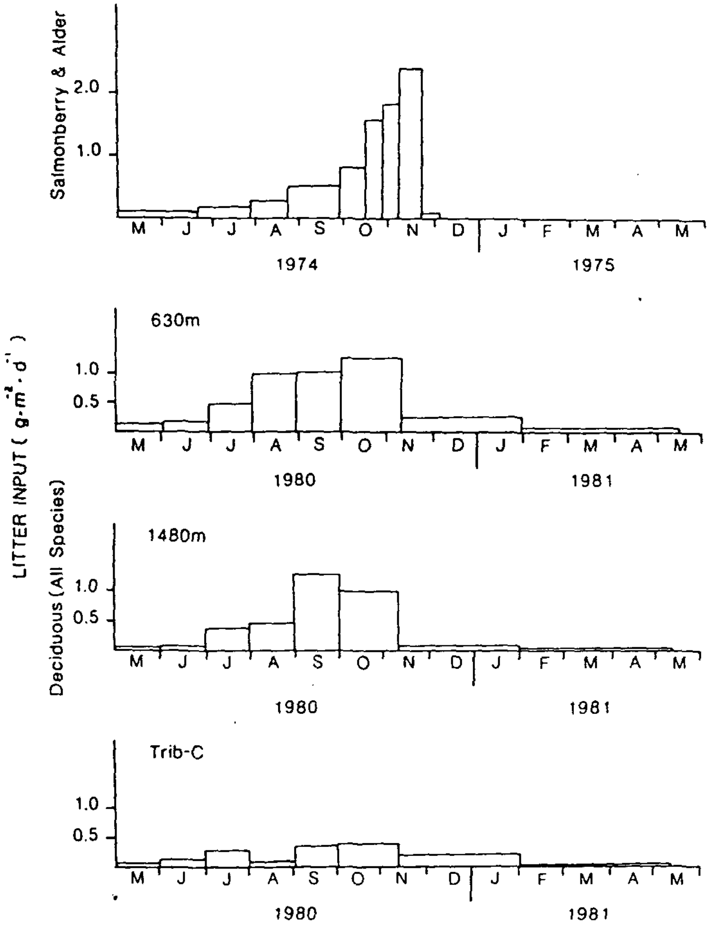

FIG. 53. Salmonberry and alder leaf-litter fall (g·m^{-2}·d^{-1}) for the whole stream during prelogging years, 1974–75, (Neaves 1978) and total deciduous litter fall after logging, 1980–81, in the leave strip (630 m) and intensive (1480 m) stream-side treatments, and in an unlogged tributary (Trib-C ; from Culp and Davis 1983).

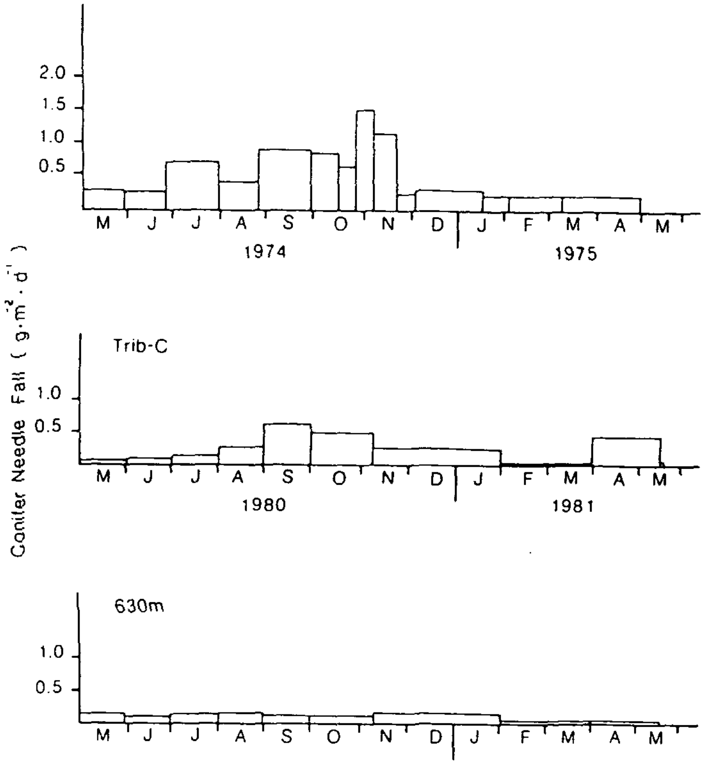

FIG. 54. Coniferous litter input ($g \cdot m^{-2} \cdot d^{-1}$) for the whole stream before logging (1974–75 ; Neaves 1978) and for the leave strip treatment (630 m) and an unlogged tributary (Trib-C) after logging (1980–81 ; Culp and Davies 1983).

distributed throughout the year (Fig. 54). At least 8.8 t (particles > 1 mm) of the total litter were flushed into the estuary during 1974–75. Most of it (89 %) was transported during November and December (Neaves 1978). The concentration of litter transported by the stream increased with discharge until the peak of leaf litter input in early November (Fig. 55). Thereafter, its concentration at winter mean flows declined from November to March.

Logging reduced litter input to Carnation Creek and it affected the streams ability to retain litter. Inputs of deciduous litter were reduced to 35 % in the leave strip and to 27 % in the intensive stream-side treatments after clearcut logging (1980–81, Fig. 53). Inputs of coniferous litter were reduced to 26 % in the leave strip (Fig. 54) and to 0 % in the intensive treatment (Culp and Davies 1983). Inputs of deciduous litter to an unlogged tributary (Trib-C, Fig. 53) were smaller than at prelogging sites along the main stream or postlogging sites within the leave strip, so deciduous litter from unlogged tributaries could not compensate for the reduced litter fall to the main channel. Although peak stream flows in the main channel did not appear to be affected by logging (Hetherington 1982), changes of streambed stability and composition have probably affected litter retention. More area has undergone scour and deposition (Fig. 43) and more fine sediments occupy the interstice of the streambed (Fig. 46) which should reduce incorporation of litter in the substrate.

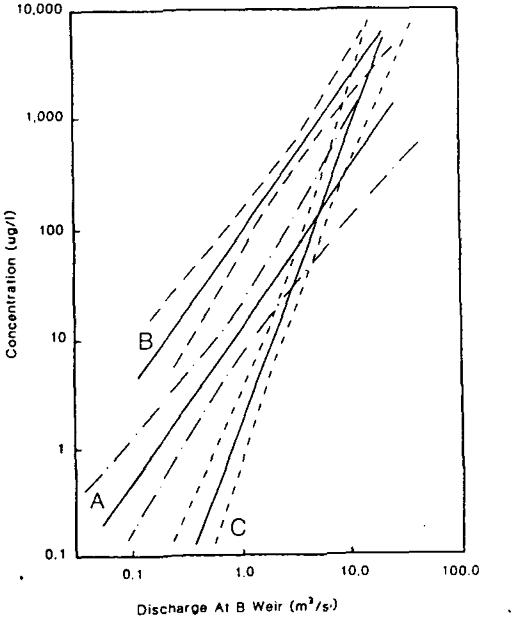

FIG. 55. Litter concentration ($\mu g \cdot L^{-1}$) versus stream discharge : A) April 1 to September 30, 1974 ; B) October 1 to November 21, 1974 ; and C) November 22, 1974 to March 31, 1975. Confidence limits of 95 % are indicated for each.

Inputs of deciduous litter also declined where the herbicide was applied. Inputs had increased from ~148 $g \cdot m^{-2} \cdot yr^{-1}$ in 1981 to ~300 $g \cdot m^{-2} \cdot yr^{-1}$ in 1984 prior to the use of RoundUp® (Holtby and Baillie 1989b). It declined to 18 $g \cdot m^{-2} \cdot yr^{-1}$ in 1985 for areas affected by the herbicide. Inputs of deciduous litter, although not measured, were presumed to have increased to 1984 levels by 1987, because the vegetation rapidly recolonized the area (Reynolds et al. 1989b).

Stream Macroinvertebrates

The macroinvertebrate community in Carnation Creek riffles was typical of forested streams. Macroinvertebrate densities were ~6000 · m^{-2} (200 µm net, Culp and Davies 1983) during prelogging years. These densities were similar to small northern California (Newbold et al. 1980) and Oregon streams (Hawkins and Sedell 1981). Chironomids were often the most common family. Mayflies such as *Cinygmula* sp., *Epeorus* sp., *Baetis tricaudatus*, and *Paraleptophlebia* sp. were 30 % of the fauna. *Cinygmula*, *Epeorus*, and *Baetis* consumed diatoms from rocks during the summer and leaf detritus during the winter (Scrivener unpubl. data) as observed in Oregon streams (Chapman and Demory 1963). Paraleptophlebia consumed only leaf detritus. About 20 % of the fauna consisted of stoneflies which were dominated by *Alloperla* sp. This stonefly was a predator in Oregon streams (Chapman and Demory 1963), but it consumed only diatoms during the first summer and leaf detritus during the first winter in Carnation Creek (Scrivener unpubl. data). Alloperla was a predator by age 1+. Carnation Creek macroinvertebrates were very opportunistic consumers.

TABLE 9. Relationships observed between the density of benthic fish-food organisms and stream flow at B-weir (60-d mean) before and after the herbicide "RoundUp" was used at Carnation Creek. Station 2350 m was upstream of the treated area, while station 630 m was below the confluence of the treated tributary with the main stream. Stream flow is the independent variable X, while density is dependent variable Y. Mean stream flow from 3 to 78 cfs were used to calculate the relationships (from Scrivener and Carruthers 1989).

Station and scenarios	Relationship	Corr. coef. r	Number sampling periods	Prob. P	Comparison of intercepts
2350 m					
1983–86	$Y = \log(X) \cdot -1803.4 + 4499.5$	−0.54	28	<0.01	
Pre-herb.	$Y = \log(X) \cdot -2104.8 + 5072.4$	−0.60	15	0.02	$F = 0.16$
Post-herb.		−0.45	13	0.12	$P = 0.85$
630 m					
1983–86	$Y = \log(X) \cdot -4259.1 + 9909.8$	−0.78	28	<0.001	
Pre-herb.	$Y = \log(X) \cdot -2963.3 + 7931.1$	−0.70	15	<0.01	$F = 2.65$
Post-herb.	$Y = \log(X) \cdot -5610.4 + 11208.5$	−0.86	13	<0.001	$P = 0.09$

A negative relationship between density of macroinvertebrates and stream flow was observed for Carnation Creek (Table 9). Higher densities occurred during lower summer and autumn flows because the organisms were forced into a smaller wetted area as stream flow declined. In addition, new recruits from hatching eggs became large enough to be retained by the sampler net. The organisms could diperse in a greater wetted area during higher water levels in winter. Many of them were scoured from the streambed and transported downstream during freshets (Culp and Davies 1983). Densities were reduced ~60 % after periods of frequent freshetting (Table 9).

Clearcut logging impacts on the macroinvertebrates were dependent on the stream-side treatment. The densities of seven taxa in summer ; and of five taxa during autumn, winter and spring were smaller at sites that were cut to the stream bank than at sites with a leave strip (Fig. 6 ; Culp and Davies 1983). The total density of 10 diagnostic species was lower in both the leave strip area and the areas logged to the bank than it was at the same sites during the prelogging period (1974–76). During the logging period (1977–80), densities of aquatic invertebrates were reduced 41 % in winter and 50 % in summer in the intensive and careful treatment areas. Densities were reduced ~23 % in both summer and winter within the leave strip treatment. Culp and Davies (1983) hypothesized that increased sediment transport, reduced channel stability, and reduced litter input were responsible for the reduced fauna.

Densities of macroinvertebrates were also influenced by the herbicide RoundUp®. Densities were 42 % lower for 1.5 years at the treated site following periods of high stream flows, but they remained unchanged during periods of low flow and at the untreated site (Table 9). Similar results were obtained when data were compared for the treated and untreated tributaries, but the macroinvertebrates entered inactive stages (eggs, pupae) as water levels declined in these intermittent channels (Scrivener and Carruthers 1989). The cumulative effects of increased water velocity, of sediments bouncing along the streambed (saltating downstream), and of a irritation response to the herbicide (2-d duration) were believed responsible for the reduced fauna (Reynolds et al. 1989b).

Enclosure experiments in Carnation Creek were used to test the influence of substrate composition, leaf detritus, and sediment transport and deposition on macroinvertebrate abundance. Substrate particle sizes ranging from homogeneous pebbles (16–32 mm in diameter) to heterogeneous mixtures of sandy pea gravel (1–9.5 mm), gravel (9.5–16 mm), pebbles and cobbles did not significantly affect the density or biomass of macroinvertebrates (16 of 19 taxa) when detritus was standardized among the substrate mixtures (Culp et al. 1983). Biomass and density were significantly smaller in substrates without detritus than in identical substrates with the standardized detritus, thus establishing the prime importance of detritus in macroinvertebrate distribution. However, substrate particle size influenced the substrates ability to retain leaf detritus (Culp and Davies 1983) and it was affected by logging (Fig. 46).

Deposited and transported sediments did influence macroinvertebrate abundance in two riffles of Carnation Creek. Sand particles (0.5 – 2 mm) were deposited on the lower half of two riffles with water velocities with 0.2 and 1.5 kg•m^{-2} tractive force. This raised the sand content of the substrates from 14 to 24 % (Culp et al. 1986). Increased drift and decreased densities were observed for the mayfly *Paraleptophlebia* sp., but not for other taxa in the low velocity riffle with stable deposited sand. The deposited sand saltated downstream in the higher velocity riffle causing catastrophic drift among many taxa of macroinvertebrates (Fig. 56). Drift rates increased within 3 h among four taxa (Culp et al. 1986). Biomass and density of macroinvertebrates were reduced by 50 % in 24 h. Similar reductions were observed for Carnation Creek after periods of frequent freshetting (Table 9). The transport and composition of sand and pea gravel have also increased by more than 10 % during logging and postlogging years (Fig. 43, 46, and 48).

Detritus quality and quantity affected microbial activity and macroinvertebrate abundance during another enclosure experiment, but macroinvertebrates were unaffected when predators (coho fry) were added. Macroinvertebrate taxa also responded differently to

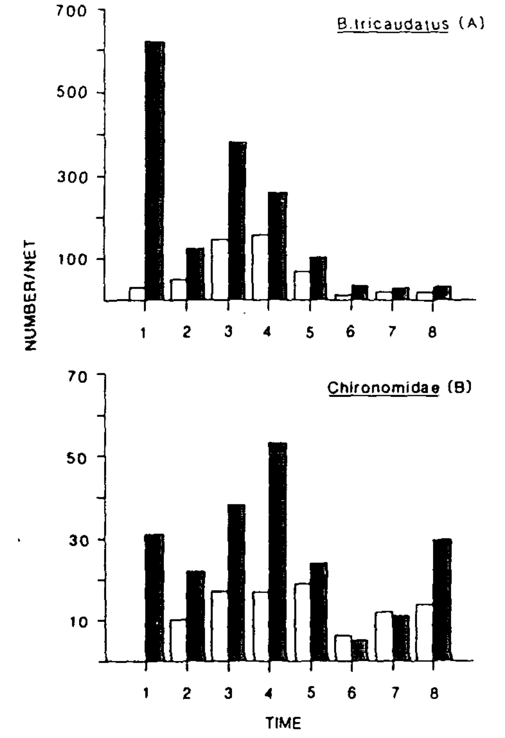

FIG. 56. Diurnal pattern (1500h Aug. 15 to 1500h Aug. 16, 1980) of drift every 3 h for (A) *Baetis tricaudatus* and (B) Chironomidae leaving the control (open bars) and sediment treated (black bars) riffles (Culp and Davies 1983).

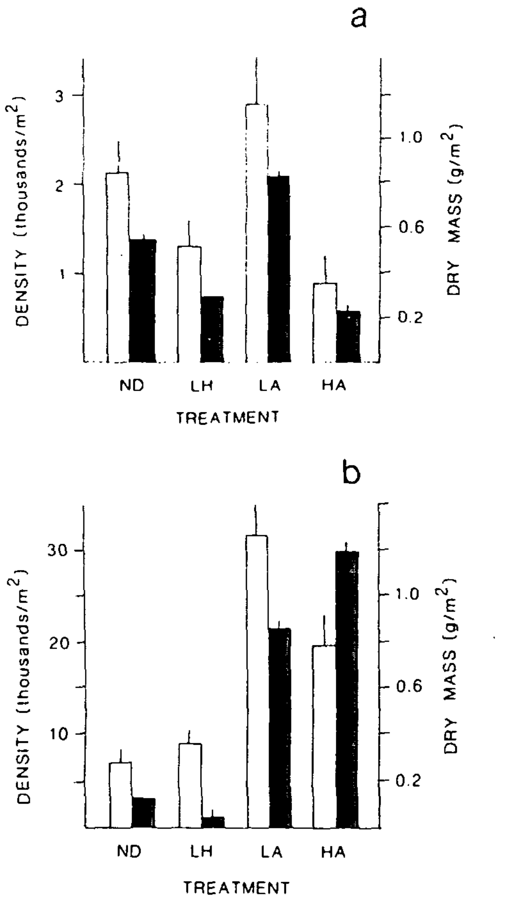

FIG. 57. (a) Ephemeroptera density (open bars) and biomass (black bars) in the ND (no detritus), LH (low hemlock detritus 62.5 g•m^{-2}), LA (low alder detritus 62.5 g•m^{-2}), and HA (high alder detritus 125 g•m^{-2}) treatments ; (b) Chironomid taxa which, relative to ND and LH treatments, exhibited higher densities (open bars) and biomass (black bars) in the LA and HA treatments. Redrawn with permission from Culp and Davies (1985).

the detritus composition in the substrate. Microbial activity, detritus processing, and macroinvertebrate density and biomass were highest in substrates with alder detritus (Fig. 57 ; Culp and Davies 1985). After logging, input of alder litter to Carnation Creek declined for at least 5 yr in all stream-side treatments (Fig. 53). Although the quality and quantity of detritus affected macroinvertebrate density and drift, the addition of coho salmon fry at 0, 1, 2, and 4 times the average density in the stream had no effect on drift rates, densities, or biomass of macroinvertebrates in the enclosures (Culp 1986). Mean weight gains of fry were similar for all densities. These results applied only to the low flow period in summer when densities of macroinvertebrate were at their annual maxima (Culp 1986).

Salmonid Populations

Spawning fish

Annually, 275 to 4168 adult chum salmon entered Carnation Creek to spawn from 1970 to 1987 (Fig. 58). During all years, 4-yr-old fish predominated (Table 10). The percentages of males and females within each age class were consistent during most years. More males than females usually returned (mean M/F ratio = 1.14). Each year, adult chum salmon entered Carnation Creek en masse during one or two freshets between October 20 and November 5 (Andersen 1983). They began spawning almost immediately and after 48 h, few unspawned females remained (Scrivener 1988b). Most adults spawned in the estuary below the counting fence, but 2–32 % (1971–87) of them were assisted to pass through the fence and they spawned upstream.

Between 74 and 426 adult coho salmon ascended Carnation Creek annually to spawn from 1971 to 1987 (Fig. 59). Their numbers declined from 1971 to 1977, but they remained between 150 and 250 fish. After 1977 the numbers rose sharply to 426 adults and then declined more rapidly to below prelogging numbers (Fig. 59). Precocious males, "jacks", that returned after only 6 mo in the ocean were ~30 % of returning numbers, except during 1978, when 69 % of the spawners returned as jacks. The majority of spawners returned after 18 mo in the ocean. Sex ratios were usually M/F = 2.0 because of the jacks. The annual variation in adult numbers was greater in the period after 1977 (74–426 fish) than it was before 1977 (157–251 fish). Coho salmon entered the creek during freshets and during some years ~50 % of the spawners moved into the stream during a single freshet (Holtby et al. 1984).

The numbers of adult cutthroat and steelhead trout handled annually at the fence were <10•yr^{-1} for each species. Trout numbers indicated in Fig. 60 are minimal for both

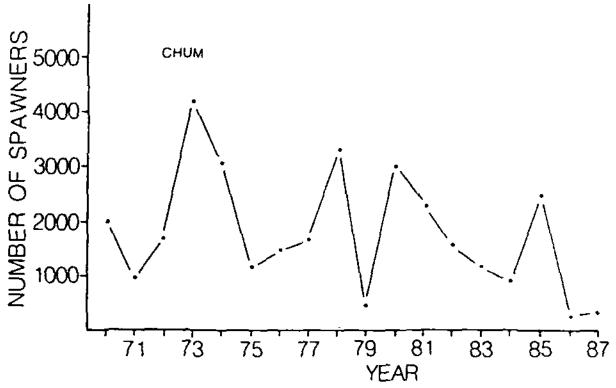

FIG. 58. Numbers of chum salmon spawners entering Carnation Creek from 1970 to 1987.

TABLE 10. Mean and standard deviation of percentages of escapement within each age class (III, IV, V) for male and female chum salmon from 1972 to 1987. The ages represent years from egg deposition.

Age class					
III		IV		V	
Female (F)	Male (M)	F	M	F	M
13.3 ± 7.4	13.7 ± 6.5	82.5 ± 5.9	80.1 ± 6.1	4.2 ± 2.4	6.2 ± 2.8

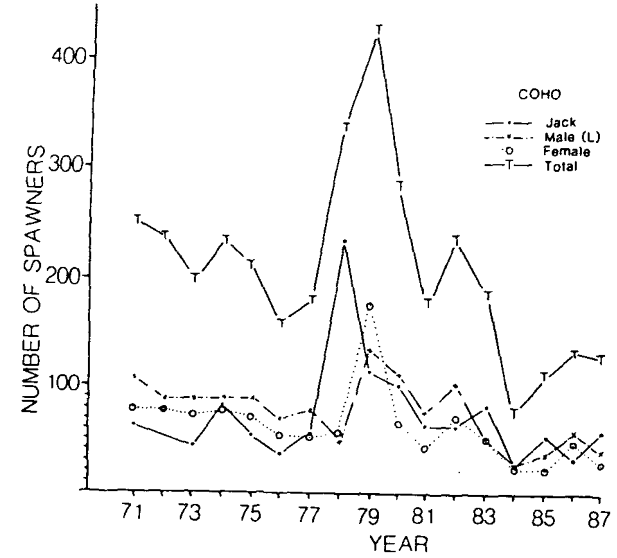

FIG. 59. Numbers of coho jacks, large males, and females ; and total numbers of coho salmon spawners entering Carnation Creek from 1971 to 1987.

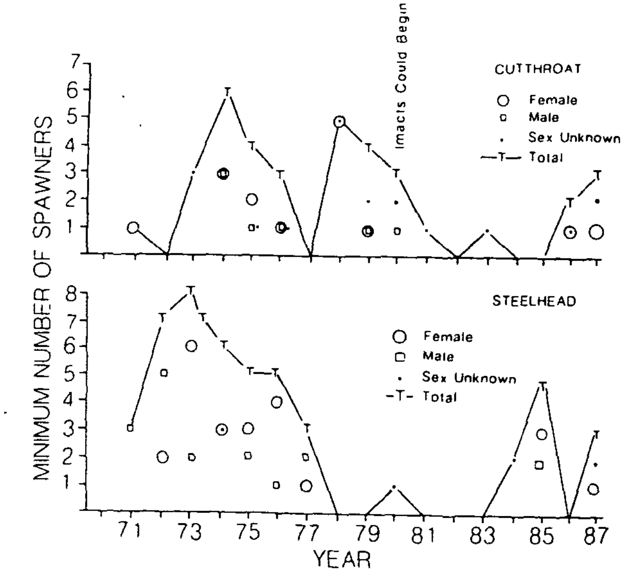

FIG. 60. Minimum numbers of cutthroat and steelhead trout which entered Carnation Creek to spawn, 1971 to 1987. Totals, which include males, females and fish of undetermined sex, are based on numbers of fish entering and leaving the stream. A fish caught leaving the stream, which was the same length and sex as one caught entering it, was counted only once.

species, because only a proportion of the water was screened during large freshets in the spring of the year. Adult steelhead declined from 1973 to 1978, but the data were not necessarily a reliable indicator of trends because some spawners avoided capture during both their upstream and downstream migrations. Cutthroat trout numbers also declined after 1978–79 (Fig. 60), but they began to decline at a later date than steelhead numbers.

Resident cutthroat trout were also present above the impassable log-jams in the main channel and in Tributary-C. About 5· 100 m^{-1} were large enough to spawn (i.e. over 140 mm) in an upstream reach. This estimate is based on data from one study section and it should not be extrapolated to the whole area above the log-jam barrier.

The distributions of adults were different for the four species of salmonids although a few individuals of each species could be found throughout the lower 3.1 km of stream (Fig. 61). Most chum salmon spawned where tides influenced the lowest 200 m of stream, but some of them (mean = 11.5 %) spawned above the fence in the next 600 m of stream. Coho spawned above the counting fence up to an impassable log-jam ~3.1 km from the stream mouth. Each year, prior to logging, a few pairs of coho ascended Tributary-1600 to spawn. Spawners have rarely been observed in this tributary after its watershed was logged. The distribution of steelhead trout was similar to that of coho salmon, but spawners were not observed and young trout fry were observed only rarely in the lower 600 m of stream (Andersen 1983). Anadromous cutthroat trout entered and spawned in Tributary-1600, -2600, and -J. Resident cutthroat trout were the only species of fish above the impassable log-jams (Fig. 61). The distributions of adult fish, for species other than chum salmon, are based on observations of redds, of spawning fish, and of recently emerged fry. They are qualitative rather than quantitative.

Egg to fry survival — chum and coho salmon

Survival to emergence in the stream declined for chum and coho salmon following logging in the watershed (Fig. 62). Mean egg-to-fry survivals during prelogging years (1972–76) were 20.3 % for chum salmon and 28.8 % for coho salmon. They rose to peak levels during 1978 and/or 1977 (Fig. 62). Thereafter, survivals were reduced for both species to half of their previous values (chum = 10.9 %, coho = 15.6 %). Relatively high survivals were obtained during the first 2 yr of logging, because freshets causing scour and deposition were rare (Table 7), and because few changes occurred in the channel during these years (Fig. 43, 45, and 46). The first major freshet during the logging period occurred on November 7, 1978 (Table 7), after which instability and poorer survival was observed in the main channel (Hartman et al. 1987).

Survival to emergence for chum salmon below the counting fence appeared to be similar to that above the fence except for a density effect (Scrivener 1988a ; Holtby and Scrivener 1989). Superimposition of redds and the use of marginal spawning habitat occurred in the estuary when the number of spawners exceeded 2000. Marginal habitats in the Carnation Creek estuary were sites with periods of high salinity concentrations. Changes in spawning gravel quality were similar above and below the counting fence (Scrivener and Brownlee 1982 ; Scrivener 1988d).

Mortality among chum salmon eggs is known to be a function of salinity concentration and of exposure time (Rockwell 1956 ; Groot 1989). They thrived at 6 ‰, but they all died at 12 ‰ constant salinity. Salinity concentration in the streambed below the Carnation Creek fence was a function of site elevation, of stream flow, and of tidal height (Scrivener 1988a). During freshets, salinity in the streambed never exceeded 1 ‰ even during the highest tides. During summer or winter low flow periods, saline water (>12 ‰) was not flushed from the streambed of pools, streambed depressions or lower estuary sites during low tides.

Chum salmon redds were concentrated in three areas of the estuary when spawner densities were <2400 (Fig. 63). These areas were frequently inundated with saline water

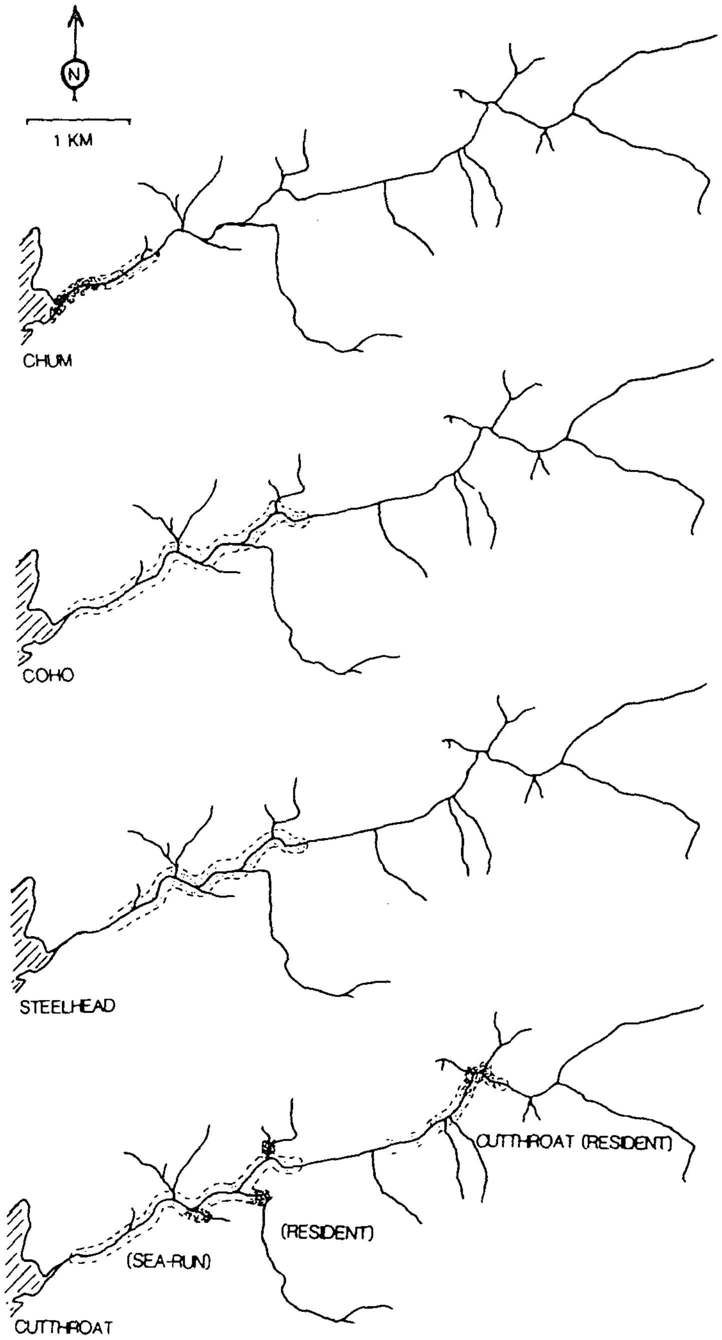

FIG. 61. Distributions observed for adult salmonids in Carnation Creek and tributaries. Heavier stippling indicates areas of higher spawner density.

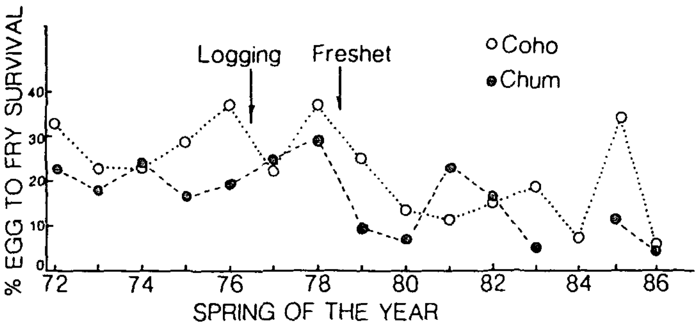

FIG. 62. Survival of chum and coho salmon in Carnation Creek from potential egg deposition (sum of fecundities for every female) to emerging fry.

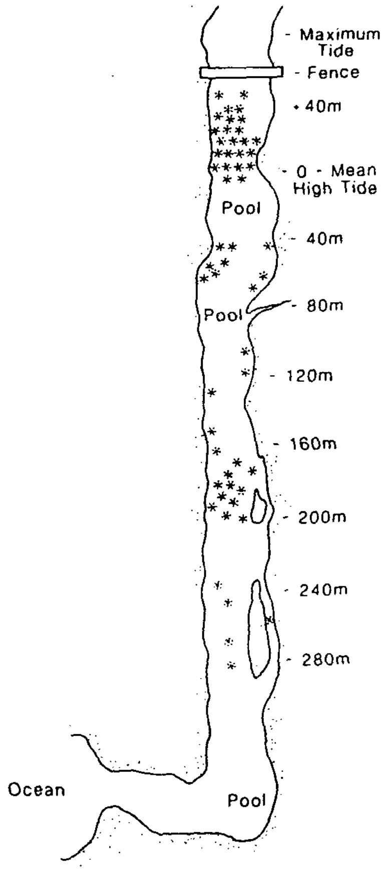

FIG. 63. The distribution of chum salmon redds (* = 20 redds) is shown for the estuary of Carnation Creek after the spawning of 2 500 adults during 1985.

(>20 ‰) that was flushed out during low tides (Scrivener 1988a). Although chum salmon never spawned in the saline pools, they did spawn at sites where saline water persisted during low flow periods (Fig. 63 ; -100 to -140 m, -240 to -280 m). These marginal habitats contained more redds when spawner densities exceeded 2400 (Groot 1989).

Emergence of fry

The period of movement through the counting fence, an indicator of chum and coho salmon fry emergence, occurred earlier following logging. Chum salmon fry appeared earlier at the fence during 1977–86 (logging and postlogging periods) than during 1971–76 (prelogging ; Fig. 64A). Their numbers also peaked annually after April 15 from 1971 to 1976, but they peaked before April 15 from 1977 to 1986, in all years except 1979 and 1985. Timing of the downstream movement of coho fry was similar to that of the chum salmon. The first coho fry were captured at the counting fence within 2 days of the time that the first fry were noted by swimmers doing distribution surveys 0.5–2 km upstream. The first stages of active coho fry movement through the fence occurred after April 15 during prelogging years (1971–76), thereafter they occurred prior to April 15 (Fig. 64B).

Short term fluctuations in the numbers of fry moving through the counting fence were not necessarily indicative of the day-to-day patterns of emergence. Daily numbers of chum and coho salmon fry moving downstream varied (Fig. 64A and 64B) because much of the movement occurred during freshets (Hartman et al. 1982). After late May, coho fry at the fence were larger (FL) than fry that had recently emerged. Therefore, the latter half of the fence counts were not indicative of the terminal phase of coho fry emergence. The size of chum fry did not change within each emigration period so fence counts appeared to mirror the general pattern of emergence.

The timing of emergence of trout fry was more difficult to determine because they were caught during stream population surveys and not at the counting fence. Study section surveys each year (Table 5) during May 17 to June 28 and during July 22 to August 1 provided evidence of the timing of trout fry emergence. The earliest capture of cutthroat or steelhead fry was June 20 during the prelogging period (1970–76), and May 31 during the postlogging period (1981–86). Trout that were captured in the May–June surveys were 0.6 % fry prior to logging, and 11.1 % fry after the intense logging treatment in 1977 (Andersen 1983, 1984, 1985, 1987). Cutthroat fry were never obtained in study section IX, upper Carnation Creek (Fig. 9), during the May/June survey. Trout fry were always abundant in the stream during the late July survey. We concluded that trout fry emerged earlier during postlogging than prelogging years, and that they emerged earlier in the lower main channel and tributaries (June 5–July 10) than in upstream reaches (June 28–July 15).

The size of emerging coho and chum salmon fry was smaller following logging. Coho fry that had recently emerged were 37.8 mm FL (SE = 0.18) during the prelogging period. Size declined to 37.3 mm (SE = 0.18) during the logging period (1977–81) and to 36.2 mm (SE = 0.32) during the postlogging period (1982–86). The size of chum fry also declined from 42.1 mm (SE = 0.16) during prelogging to 42.0 mm (SE = 0.12) during logging and to 41.4 mm (SE = 0.63) during postlogging years (Scrivener 1988b).

Distribution and movement of juvenile salmonids

Distribution and movement of young fish within the drainage varied among and within species. Recently emerged chum salmon moved almost directly to sea from the locations of egg deposition.

Juvenile coho salmon occupied a wide range of different stream habitats (Fig. 65), and their movement and distribution exhibited four basic life history strategies in Carnation Creek.

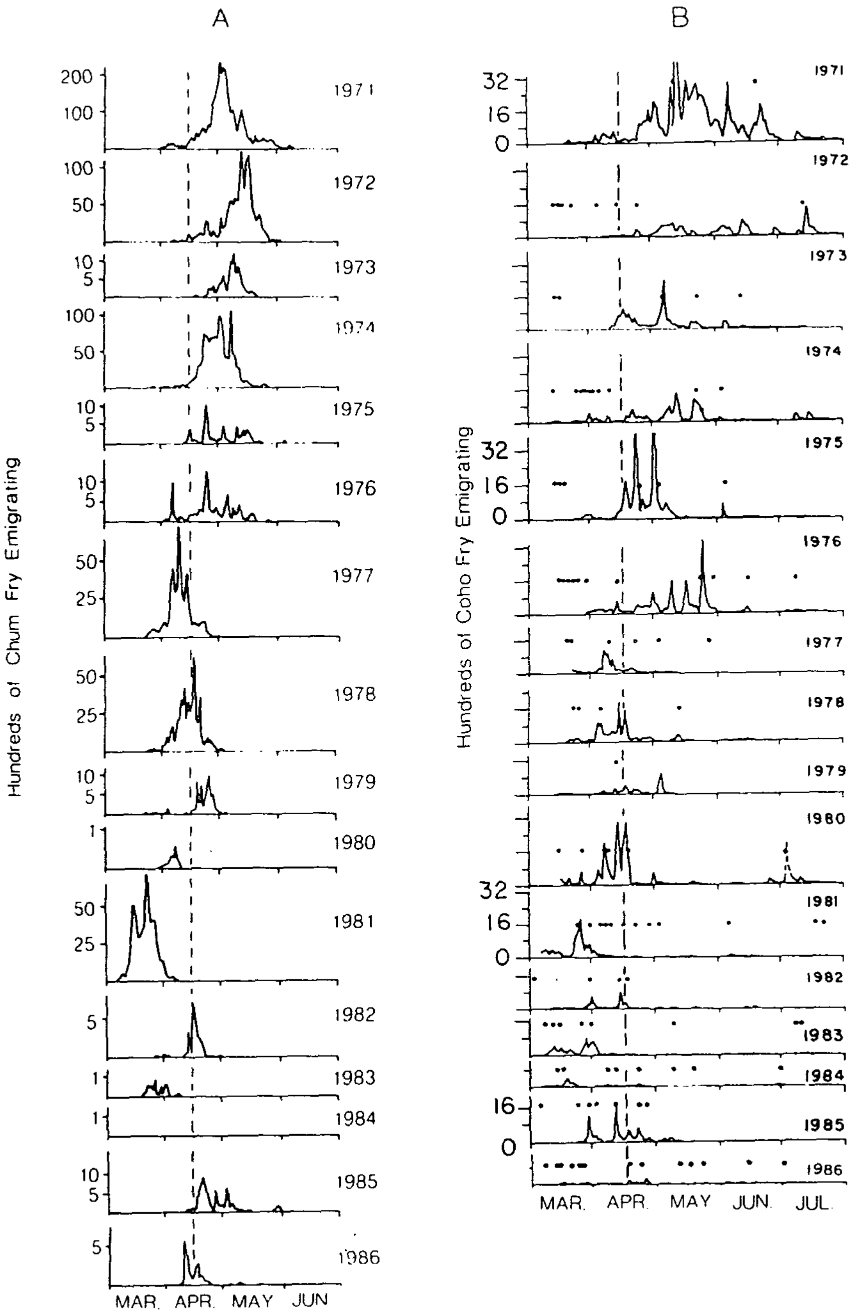

FIG. 64. Timing of downstream movement of (A) chum ; and (B) coho salmon fry in Carnation Creek as an index of emergence time. Dots above coho numbers represent freshets larger than 1.8 $m^3 \cdot s^{-1}$.

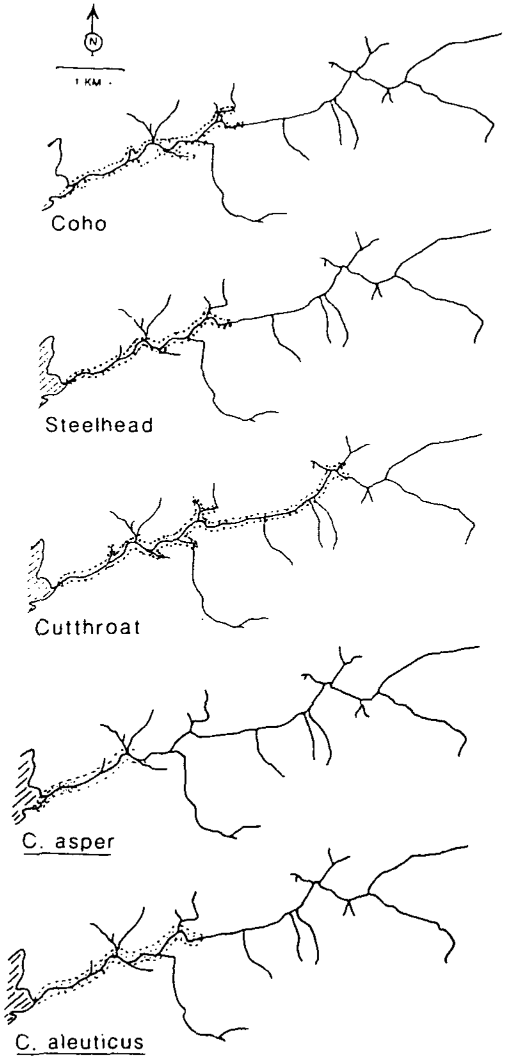

FIG. 65. Distributions of juvenile salmonids and sculpins (*Cottus asper* ; *C. aleuticus*) observed in Carnation Creek. Resident and sea-run cutthroat trout cannot be clearly separated.

1. Many of the recently emerged fry moved downstream each spring (1971–86 ; $\bar{x}$ = 46 %, SD = 14). The peaks of downstream movement coincided with freshets (Hartman et al. 1982). In years when coho fry numbered 20 000 – 120 000 (1971–76 ; Fig. 66a), it was presumed that most went to sea and were lost. A substantial proportion of fry still moved downstream during years (1984, 1986) when few of them emerged (Table 11).
2. Each year, up to 5000 fry that moved downstream in the spring remained within the estuary of the stream (Tschaplinski 1982). By autumn as many as 2400 of these juvenile coho were still present in the estuary and 50 % of them had reached 70 mm FL. These fish tolerated high salinities and it is presumed that many of them migrated to sea in September and October (Tschaplinski 1982). Data from recent studies suggested that 15 % of these fish reentered an adjacent stream to overwinter (T.G. Brown, Pacific Biological Station, Nanaimo, pers. comm.). Few coho remained overwinter in the estuary because there was no protection from winter freshets in this area (Tschaplinski 1982).
3. Many age 0+ coho remained in the mainstem of the stream during the spring and summer (Table 11) and then 17 % (mean of 4 yr) moved into small swamps and tributaries on the flood plain during the first autumn storms (Bustard and Narver 1975 ; Tschaplinski and Hartman 1983 ; Brown and Hartman 1988). Of the coho that entered flood plain habitat, many overwintered there and emigrated as age 1+ smolts the following spring (Tschaplinski and Hartman 1982 ; Brown 1985 ; Brown and Hartman 1988).
4. The remainder of the coho fry stayed within the mainstem of the stream and went to sea as age 1+ or 2+ smolts.

Steelhead trout were more restricted in their distribution than were coho salmon (Fig. 65). Steelhead hatched in the mainstem of the creek and reared there. A few of them entered the small flood plain tributaries (Hartman and Brown 1987), but the precise

TABLE 11. Numbers of coho fry estimated at emergence and during stream surveys in the lower 3 070 m of Carnation Creek (1971–82 data from Scrivener and Andersen 1984). Standard deviation (SD) about the means are also shown.

	Population at emergence		Population estimate period					
			Late May-early June		Late July		Late September	
1970	—		—		16 004		14 129	
1971	157 400		37 030		29 188		11 842	
1972	50 320		33 556		15 578		9 223	
1973	38 600		18 357		10 776		9 071	
1974	37 420		17 580		14 589		12 460	
1975	44 770		14 605		14 092		11 482	
1976	58 800		46 662		19 173		12 327	
Mean(SD)	64 550	(46 160)	27 965	(12 975)	17 057	(5 905)	11 505	(1 813)
1977	23 460		15 767		14 338		10 602	
1978	39 825		26 148		23 120		10 927	
1979	30 400		26 437		19 702		13 227	
1980	48 625		—		25 756		20 953	
1981	17 200		6 743		6 995		6 088	
1982	12 450		8 648		8 890		7 337	
1983	27 650		17 304		11 720		10 184	
1984	6 700		3 209		4 466		3 423	
1985	15 000		12 589		12 303		6 824	
1986	4 150		2 692		—		2 916	
Mean(SD)	22 546	(14 325)	13 282	(8 940)	14 143	(7 320)	9 248	(5 290)

numbers that did so could not be determined because steelhead and cutthroat less than 80 mm FL could not always be distinguished with certainty.

Resident and anadromous cutthroat trout spawned and reared in the mainstem and small tributaries. Resident cutthroat trout occurred in the upper reaches of Carnation Creek and in Tributary-C, -J, -1600, and -2600 (Fig. 65). Three or four cutthroat trout that were marked in the upper part of Carnation Creek have been captured below the impassible log-jam. The distributions of resident cutthroat and progeny of anadromous cutthroat therefore overlap, and only fry and adults (age 3+ or 4+) can be separated. The anadromous trout were larger.

Numbers of juvenile salmonids

Chum salmon fry which emerged below the fence could not be counted although catches in emergence traps provided information on time of exit from the streambed and the size of fry at emergence. Counts of chum fry at the fence provided estimates of production per adult in the stream.

The number of coho salmon fry that were produced declined during the study. Annual estimates of total coho fry production were calculated by summing the number of fry in the May–June population estimate and the number of fry moving downstream before the estimate date. Mean fry production was 64 550 annually, during the prelogging period, which declined to 22 546 following logging (Table 11). An irregular decline in the abundance of young coho was also indicated when numbers of fry moving downstream (Fig. 66a) and numbers in autumn (Fig. 66b) were examined. Average numbers of juvenile coho in the stream were smaller for all three population estimate periods after logging was begun. The magnitude of the inter-annual variability, as shown by standard deviations, was greater after logging than during the prelogging period (Table 11). Ratios of the largest estimated population to the smallest were also 2–4 times greater following logging (Table 12).

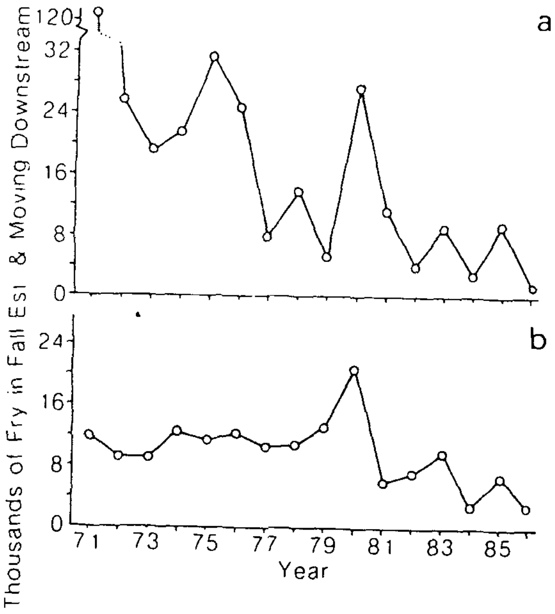

FIG. 66. Numbers of age 0+ coho salmon (a) moving downstream in Carnation Creek from 1971 to 1986 ; (b) in autumn population surveys from 1971 to 1986 in the lower 3.1 km of Carnation Creek.

Trout numbers in the main channel also declined and annual variability increased following logging. Combined numbers from steelhead and cutthroat trout of all ages were greater during the prelogging period (1970–76) than during later years (1977–86) for all three population estimates (Table 13). Ratios of the largest to the smallest populations indicated greater variability following logging as they were twice the prelogging values for all three population surveys (Table 12). Standard deviations about mean numbers were ~34 % of their means during 1970–76 and ~51 % of their means during 1977–86 (Table 13).

Interpretation of changes in trout numbers was possible despite the mixture of steelhead and cutthroat stocks. Trout in the main channel were not separated by species prior to 1977, because objective criteria permitting the separation of juveniles aged 4–18 mo were not applied consistently until 1978 (Fig. 67). There were few age 0+ trout in the late May–early June population estimates so numbers peaked annually during July after fry emergence (Table 13). Age 0+ trout were 85–90 % of the summer and autumn populations (Fig. 67).

TABLE 12. Variation in the magnitude of estimated coho and trout numbers as indicated by the ratio of the largest number estimated to the smallest number estimated within the prelogging (1971–76) and postlogging periods (1977–86). Number of population surveys are in parentheses.

	Coho			Trout		
	May–June	Late July	Late September	May–June	Late July	Late September
prelogging	3.1 (6)	2.7 (7)	1.6 (7)	3.5 (6)	2.4 (6)	2.4 (7)
postlogging	9.8 (9)	5.8 (9)	7.2 (10)	5.2 (9)	4.9 (9)	5.7 (10)

TABLE 13. Population estimates of all trout, 0+ to 3+ age-groups, in the lower 3 070 m of stream prior to and following the first major logging operation (winter 1976–77). Standard deviation (SD) about the means are also shown. Fry emerged after the May–June population estimate.

	Population estimate period					
	Late May early June		Late July		Late September	
1970	—		—		2 771	
1971	767		9 523		4 008	
1972	888		3 951		2 298	
1973	1 320		9 581		5 492	
1974	396		5 802		4 038	
1975	376		6 541		3 346	
1976	696		8 206		3 311	
Mean(SD)	741	(350)	7 267	(2 235)	3 609	(1 038)
1977	272		576		834	
1978	516		1 669		1 437	
1979	300		880		396	
1980	—		432		737	
1981	648		2 105		2 243	
1982	584		1 357		1 390	
1983	413		653		697	
1984	124		1 355		1 555	
1985	206		2 054		1 060	
1986	147		—		891	
Mean(SD)	357	(192)	1 231	(631)	1 124	(540)

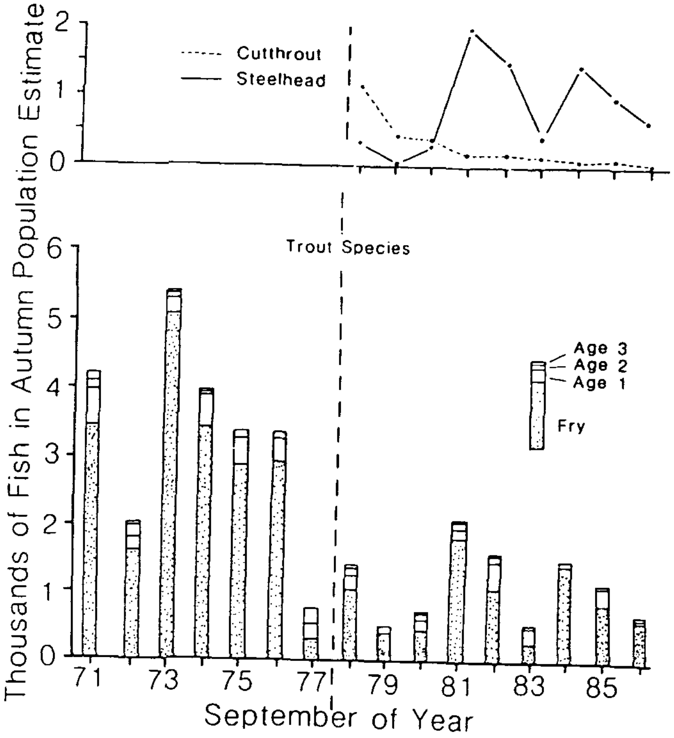

FIG. 67. Numbers of trout in the lower 3.1 km of Carnation Creek during autumn from 1971 to 1986. Numbers of cutthroat and steelhead trout were combined until 1978 and separated thereafter.

Survival of coho during summer

Multiple regression models were used to determine the relative influences of stream flow, fish density, stream temperature, and streambank vegetation on the survival of juvenile coho during the summer. The proportion of stream bank vegetated, July density of coho fry, number of 5-d periods when minimum daily stream flow exceeded 2.8 $m^3 \cdot s^{-1}$, and maximum temperature on the date of minimum annual flow accounted for 95 % (R^2) of the summer loss rates of age 0+ coho (Holtby and Hartman 1982). Streambank vegetation accounted for 39.8 %, density accounted for 23.6 %, flows exceeding 2.8 $m^3 \cdot s^{-1}$ accounted for 16.3 %, and maximum temperature accounted for 15.1 % of the variation. Stream-side logging affected vegetation cover, fish density (Fig. 62 ; Table 11), and stream temperatures (Fig.27).

Loss rates of age 1+ coho in summer were affected most by stream discharge at B-weir. The number of days when minimum daily flow exceeded 2.8 $m^3 \cdot s^{-1}$ accounted for 44.1 % of the variation in numbers during September ; and the proportion of time that stream flow was less than 0.028 $m^3 \cdot s^{-1}$ accounted for a further 12 % of the variation (Holtby and Hartman 1982).

Coho and trout sizes and growth

The size of coho salmon and trout in the autumn was greater following logging. Comparisons between years were possible after mean fork lengths (FL) of coho salmon and trout were adjusted to a uniform date, September 30, by using the average daily size increments (growth rate) between July and September. The FL of age 0+ coho were significantly greater following logging (1977–86) than before logging (1970–76 ; Mann–Whitney *U*-test, $P < 0.001$), despite their smaller size during 1978 and 1980 (Fig. 68). Age 0+ trout in the lower 3.1 km of the main channel were also larger following logging (Mann–Whitney, $P < 0.001$), despite their smaller size during 1985 (Fig. 69). The older age-groups of both coho (Fig. 68) and trout (Fig. 69) were also larger in size following logging, but most of the 11 mm increase for coho and 18 mm increase for trout had been attained by the end of their first summer.

The size of age 0+ coho in autumn was dependent upon the length of the spring/summer growth period and the rate of growth. Regression models indicated the relative importance of various physical and biological influences on these two factors (Holtby and Hartman 1982 ; Holtby 1988). The duration of the period of summer growth, which was extended by earlier emergence of fry, had the greatest positive effect on fry FL and weight in the autumn. Day-of-the-year when 50 % of the fry had emerged was strongly correlated with their size in autumn ($r = -0.96$, $n = 16$, $P < .001$). Day-of-the-year of 50 % emergence was also correlated with stream temperature during egg incubation, e.g., thermal summation of daily means of stream temperature (Hartman et al. 1984 ; Scrivener and Andersen 1984). Warmer winters led to earlier emergence and a longer growing season. The growth rate of coho fry was negatively density dependent (FL, $r = -0.56$, $n = 16$, $P < 0.05$; weight, $r = -0.83$, $n = 16$, $P < 0.001$; Holtby 1988) for the whole stream, and for each study section (Scrivener and Andersen 1984). The number of days with stream flow <0.028 $m^3 \cdot s^{-1}$ also affected growth of coho fry, i.e., the greater the duration of low summer flow periods the smaller the growth rate (Holtby and Hartman 1982). Finally, stream temperature during the summer, thermal summation of mean daily temperatures at B-weir, was positively correlated with fry FL and weight in the autumn (Holtby 1988). All of these factors were affected by clearcut logging.

An apparent discrepancy appeared when the mean FL of age 1 + coho in autumn was greater following logging (Fig. 68), but the growth rates were smaller during the second summer for age 1 + coho (Holtby and Hartman 1982). The apparent discrepancy was

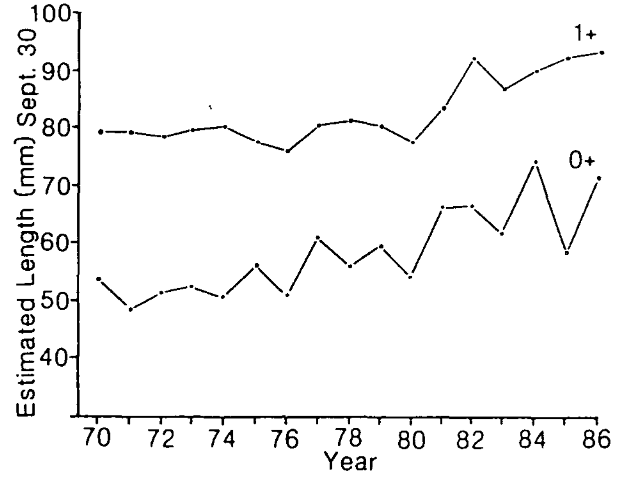

FIG. 68. Mean length (FL) of age 0+ and 1+ coho salmon on September 30 from 1970 to 1986.

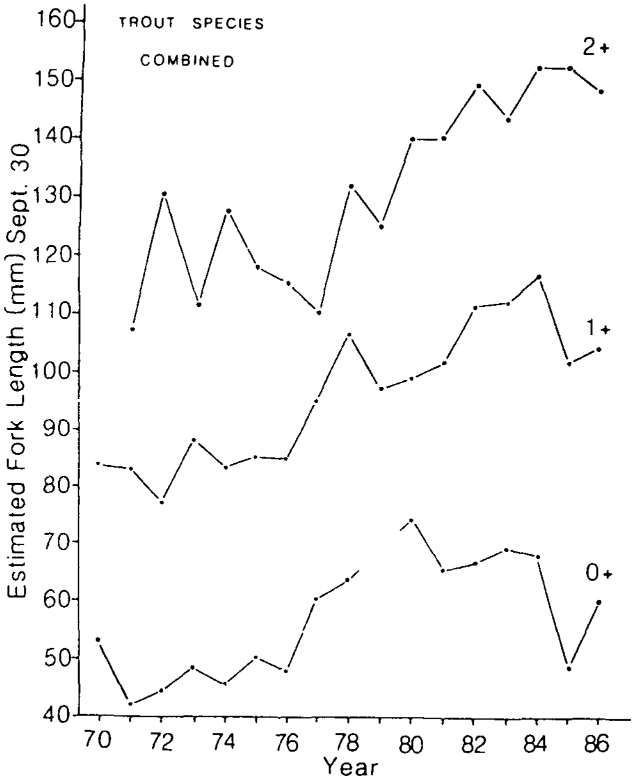

FIG. 69. Estimated mean lengths on September 30, of age 0+, 1+ and 2+ trout in the main stream (data for steelhead and cutthroat trout combined) from 1970 to 1986. No steelhead fry were caught during September 1979.

clarified when five results were evaluated :

1. Size (FL) of age 1+ coho salmon in autumn depended upon their size during the previous autumn at age 0+ ($r = 0.65$, $n = 17$, $P < 0.01$).
2. Size and growth rate of age 1+ coho were independent of the density of age 0+ or 1+ coho during the summer, unlike the situation with age 0+ coho (Holtby 1988).
3. The growth rate of age 1+ coho was negatively correlated with thermal summation during summer in contrast with age 0+ coho (Holtby 1988).
4. The growth rate of age 1+ coho during the summer was positively correlated with the proportion of stream side that was vegetated. This was not the case with age 0+ coho (Holtby and Hartman 1982).
5. The growth rate of age 1+ coho during the summer was negatively correlated with the duration of stream flows <0.028 $m^3 \cdot s^{-1}$, as was the case with age 0+ coho.

We speculate that food supply was reduced following logging when stream-side vegetation was removed (reduced - leaf litter, Fig. 53, and terrestrial food) and when low flows prevented transport of food from riffles to coho in the pools. Stream temperatures were also higher and the food required for growth and maintenance was greater than during the prelogging period. A multiple regression model indicated that the proportion of the stream bank that was vegetated explained 46 % of the reduction of summer growth rate for age 1+ coho, while the duration of low stream flow (no. of <0.028 $m^3 \cdot s^{-1}$ days) explained another 19 % of the reduction (Holtby and Hartman 1982).

Increasing stream temperature and decreasing trout density in the lower 3.1 km of Carnation Creek caused trout size to increase following logging (Fig. 69). As with coho fry, the size of age 0+ trout in autumn was dependent upon stream temperature during the incubation period (spring ; Table 14) and density of trout during the summer (Fig. 70).

TABLE 14. Mean size (FL) of age 0+, 1+, and 2+ trout (steelhead and cutthroat) on September 30 regressed against thermal history at B-weir (thermal summation of mean daily stream temperatures) and against trout numbers during July in the lower 3.1 km of Carnation Creek. Periods of summed stream temperature included the egg incubation or spring growth periods (Mar. 1 – May 31), the summer growth period (June 1 – Sept. 30) and the total thermal history (TTH) for age 0+ (Mar. 1 – Sept. 30), for age 1+ (Mar. 1 – Sept. 30 yr + 1), and for age 2+ (Mar. 1 – Sept. 30 yr + 2).

Thermal history	No. of years	r	P	Equation
Age 0+				
Mar.–May	16	0.88	<0.001	FL = 0.072•(°C) + 11.89
June-Sept.	16	0.74	<0.001	FL = 0.042•(°C) − 3.30
TTH	16	0.82	<0.001	FL = 0.028•(°C) − 2.74
Age 1+				
Mar.–May	17	0.85	<0.001	FL = 0.081•(°C) + 45.21
June–Sept.	17	0.85	<0.001	FL = 0.056•(°C) + 14.09
TTH	16	0.88	<0.001	FL = 0.016•(°C) + 17.54
Age 2+				
Mar.–May	17	0.60	0.01	FL = 0.069•(°C) + 89.37
June–Sept.	17	0.75	<0.001	FL = 0.066•(°C) + 33.60
TTH	15	0.84	<0.001	FL = 0.011•(°C) + 39.07
Trout numbers				
Age 0+	16	−0.86	<0.001	FL = −19.59$\log_{10}$(No.) + 123.0
Age 1+	17	−0.66	0.004	FL = −18.62$\log_{10}$(No.) + 158.2
Age 2+	17	0.38	0.12	

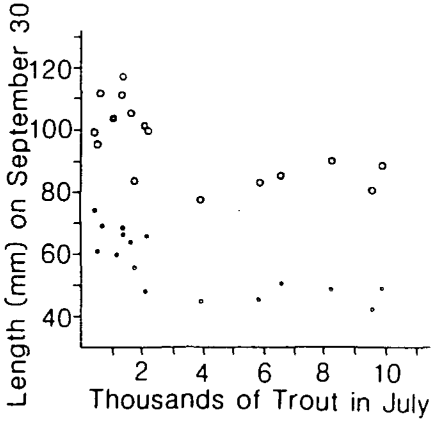

FIG. 70. Relationships between mean lengths (FL) of age 0+ (dots) and 1+ (circles) trout on September 30 (1971–87) and density during July. A population estimate was not obtained in the stream during July 1986.

Trout size in September was not related to coho density ($r = -0.24$, $n = 16$, $P = 0.42$). Mean size could have been affected by the small species shift to cutthroat trout (Fig. 60), but young cutthroat fry were smaller than steelhead fry and trout size increased following logging. September FL of age 0+ cutthroat trout was also correlated with stream temperature during their incubation period (Apr.–May) in Tributary-C (unlogged) and study section IX (Fig. 71).

The relationship between trout density in July and FL in September was not linear (Fig. 70). Trout numbers greater than 3000 appeared to have no further influence on trout size in September. Trout numbers were >3000 from 1971 to 1976 so annual variability of density did not influence trout size during these years (Fig. 70). The greater trout sizes that were observed after 1977 might reflect the higher stream temperatures and might, only coincidentally, appear to be a density effect. This is unlikely because stream temperatures were strongly correlated with time ($r = 0.85$), while trout numbers were more variable ($r = -0.72$) and more strongly correlated with trout size in September ($r = -0.86$; Table 14).

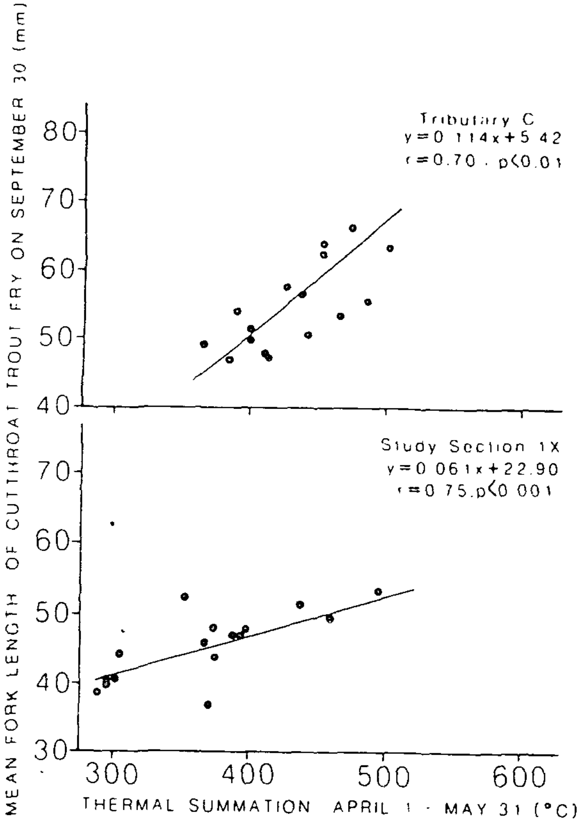

FIG. 71. Relationships between summation of mean daily water temperature during the egg incubation period and mean lengths of age 0+ cutthroat trout on September 30. Mean length on the date of the September population estimate was incremented to September 30 with the average daily increase in size (Sept. size–June or July size/No. days between).

Growth rates of steelhead fry also increased during enclosure experiments where stream temperatures had been increased by logging of the stream side (deLeeuw 1982). Weight gains were similar for age 0+ steelhead that were held from August 4 to September 10 in unlogged sections of Carnation and Ritherdon creeks (~0.15 g). Weight gains of fish held for the same period in logged sections of Carnation and Ritherdon creeks were 0.7 and 1.18 g, respectively. There were no significant differences in food supply (insect drift) between the logged and unlogged sections (deLeeuw 1982).

The rate of egg incubation and the timing of fry emergence had a stronger influence on trout size in September than did growth rate during the summer. Sizes of age 0+ trout in September were more strongly correlated with stream temperatures during egg incubation than during summer rearing in the lower main channel (Table 14), in Tributary-C (Table 15), and in upper Carnation Creek (study section IX, Table 15). Slopes of the relationships were also lower for summer rearing temperatures than for incubation temperatures (Tables 14 and 15). If trout size in September was controlled more by stream temperature during the summer, and consequently elevated growth rates during that period, then those relationships should have produced the significantly stronger relationships.

The size of older trout in autumn was correlated with their size during the previous September, with trout density, and with stream temperatures. Size (FL) during September was strongly correlated with size the previous autumn for age 1+ ($r = 0.80$, $n = 16$, $P < 0.001$) and for age 2+ trout ($r = 0.85$, $n = 17$, $P < 0.001$) in the lower 3.1 km of Carnation Creek. Size during September was negatively correlated with total numbers during July for age 1+ trout, but they were not correlated for age 2+ trout (Table 14). The influence of density on summer growth rates declined with age and it no longer significantly affected the growth of 2-yr old trout. Correlations between size and summed stream temperatures persisted for trout in the main channel, but they tended to weaken as the trout got older (Table 14). These correlations tended to disappear for older cutthroat trout in Tributary-C and the upper reaches of Carnation Creek (Table 15).

Our results suggested that stream temperatures and secondly fish densities had the greatest influence on the size of coho and trout fry. The effect of both declined as the

TABLE 15. Correlations between summed thermal history (CTU) during four life stages of cutthroat trout and their mean length adjusted to September 30 in Tributary-C and upper Carnation Creek (Section IX). Life history stages were incubation period (April 1 – May 31), age 0+ summer (June 1 – September 30), age 1 through September and age 2 through September for years 1972 to 1987, 1973 to 1987, and 1974 to 1987 for age 0+, 1+ and 2+ fish, respectively.

	No. of years	r	P	Slope	Maximum CTU
Tributary-C					
Age 0+					
Apr.–May	16	0.70	<0.01	0.114	508
June–Sept.	16	0.64	<0.01	0.063	1523
Age 1+					
CTU total	15	0.54	<0.05	0.017	4674
Age 2+					
CTU total	14	0.52	0.06	0.016	7818
Study Section IX					
Age 0+					
Apr.–May	16	0.75	<0.001	0.061	496
June–Sept.	16	0.70	<0.01	0.044	1581
Age 1+					
CTU total	15	0.18	0.52	0.004	4504
Age 2+					
CTU total	14	0.63	<0.05	0.017	7158

fish aged. Stream temperature influenced fish size mainly by shortening the egg incubation period ; thus lengthening the growth period during their first summer. Stream-side logging increased stream temperatures and decreased fish densities ; thus promoting greater size among juvenile coho salmon and trout.

Over-winter survival of coho and trout

The over-winter survival of yearling coho, i.e. from eggs layed 12–14 mo earlier, was dependent on their size in autumn. Survival during the first winter was positively correlated with size, both length (Fig. 72), and weight ($r = 0.88$, $n = 14$, $P < 0.001$; Holtby 1988). Over-winter survival of yearling coho salmon was independent of density, but it was positively correlated with stream temperatures. However, since both winter and early spring temperatures were higher after 1976 than before 1976 during most years (Fig. 27), Holtby (1988) suggested that the positive relationship between stream temperature and survival of the first winter might simply reflect a shorter period of egg incubation (leading to larger size in autumn, Fig. 68 ; and consequently a higher over-winter survival), than of actual stream temperature during winter. Any relationship between over-winter survival and main-channel density may have been masked by the tendency of yearling coho to use off-channel habitat.

The survival of 2-yr old coho salmon during their second winter in the stream was greater than it was during their first winter (Holtby and Hartman 1982), but their survival was not correlated with their size at age 1 + during the previous autumn (Hartman et al. 1984). Survival of 2-yr-old coho was not dependent on winter levels of stream flow, but it was negatively density dependent. The effects of density were only significant when the analysis included the prelogging years which had extremely large populations.

High quality winter habitat for 2-yr-old coho may have been limited (Holtby and Hartman 1982). A mechanism for such a habitat effect was demonstrated by Bustard and Narver (1975) who showed that during the winter larger and older coho salmon sought locations nearer to cover and they were lower in the water column than younger and smaller fish. The survival rate of the 2-yr-old fish might be affected more by the presence of deep pools and dense cover than by fish size (Holtby and Scrivener 1989).

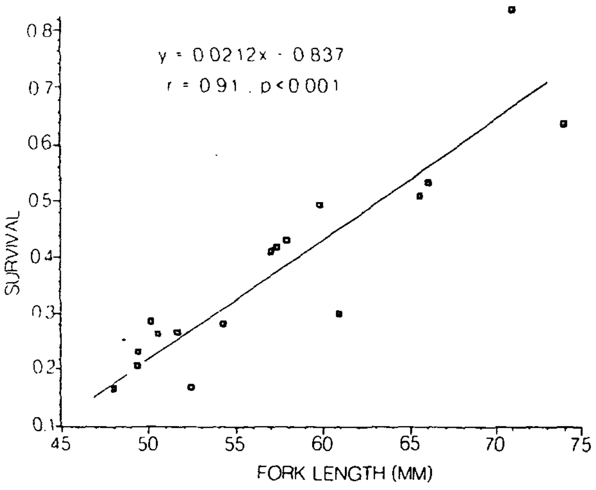

FIG. 72. The relationship observed for length of age 0+ coho salmon in the autumn versus survival rate during the subsequent winter from 1970 to 1987.

The survival rates of the different age classes of trout in Carnation Creek have not been determined. The FL of age 0+ and 1+ trout were affected by stream temperatures and by trout density in a manner similar to that shown for coho salmon. Further analysis is required to determine how trout size, trout density, and habitat conditions affect winter survival.

Smolt sizes, numbers, and emigration timing

The size and numbers of age 1 + coho smolts increased after logging was begun. Smolt data from 1977 was included with the prelogging years because logging activities could have influenced these fish for only their final few months in the stream. Mean weight of coho smolts increased by 1.5 g or 33.3 % after 1977, while smolt FL increased by 8.4 mm or 11 % after 1977 (Fig. 73). The average numbers of 1 + coho smolts increased from 1250 during 1971–77 to 2977 during 1978–87 (Fig. 74).

The size of age 2+ coho smolts was unchanged, but their numbers declined after 1977. Their average weight increased <0.4 g or <4 % of the average weight from 1971

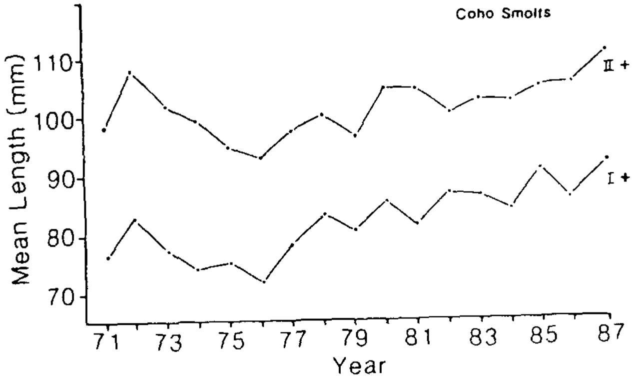

FIG. 73. Mean lengths (FL) of age 1 + and 2 + coho smolts migrating from Carnation Creek from 1971 to 1987.

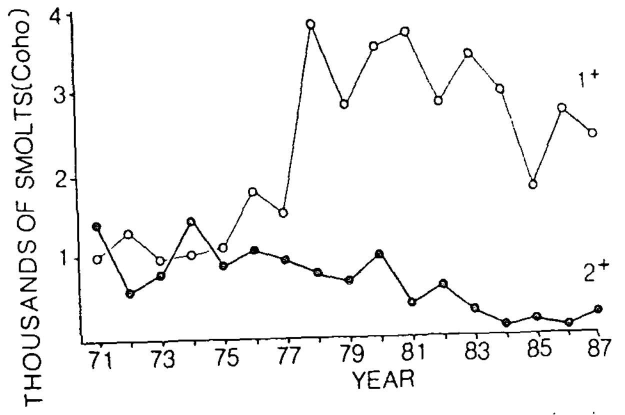

FIG. 74. Numbers of age 1 + and 2 + coho salmon smolts migrating from Carnation Creek from 1971 to 1987.

to 1977, while FL was not significantly different after 1977 (Mann–Whitney *U*-test, $0.1 > P > 0.05$; Fig. 73). The number of 2+ coho smolts averaged 1012 annually during 1971–77 and 440 annually during 1978–87 (Fig. 74).

The increased size of juvenile coho salmon was an important factor in the observed shift of smolt age composition towards a predominance of yearlings (Fig. 74). The proportion of age 1+ coho that underwent smoltification in spring was correlated with their size the previous autumn (Holtby 1988). The underyearling coho which were destined for earlier smolt transformation following logging experienced shorter periods of egg incubation, longer periods of summer growth, larger size in autumn (Fig. 68), and greater survival rates in winter (Fig. 72). The net effect was an approximate doubling of smolt numbers from 1978 to 1983 (Fig. 76). Smolt numbers and mean size declined after 1983 as age 2+ smolts became rare (Fig. 74), as spawning adults decreased (Fig. 59), and as egg-to-fry survival decreased (Fig. 62).

The median date of coho smolt migration and the patterns of migration were similar for both age groups of smolts, but their timing was earlier following logging (Holtby 1988). The median date was May 9 for age 1+ smolts and May 12 for age 2+ smolts from 1971 to 1977. The median date of smolt migration moved back in time by an average of 12 d (Apr 28) after the intensive logging treatment of 1977. A negative relationship between smolt migration timing and stream temperatures in spring explained 76 % (r^2) of the variation of the median day of migration (Holtby 1988).

The sizes of the smolts of steelhead and cutthroat trout were unchanged following logging. The year-to-year variation of their size (Fig. 75) was much greater, however, than for coho smolts (Fig. 73). The FL of age 0+ and 1+ trout in autumn had increased from 1977 to 1984 and 1+ trout were ~20 mm longer after 1977 (Fig. 69). This apparent conflict among the data can be explained by an age shift in the smolt production similar to that observed for coho salmon. Steelhead smolts were usually age 2+ or 3+ from 1971 to 1987. However, small changes in the numbers of very large smolts (189.5 mm ; age 4+) and very small smolts (92.4 mm ; age 1+) tended to shift mean size annually and to increase mean size variability of the few hundred emigrants from the stream (Fig. 76). Age 4+ smolts became rare after 1978 (total = 3 fish), while age 1+ became more common (Andersen 1983, 1984, 1985, 1987).

The number of steelhead smolts declined, but cutthroat numbers were unchanged following logging (Fig. 76). Smolt production averaged 275 steelhead and 60 cutthroat trout annually during 1971–77 and 65 steelhead and 49 cutthroat trout annually during 1978–87.

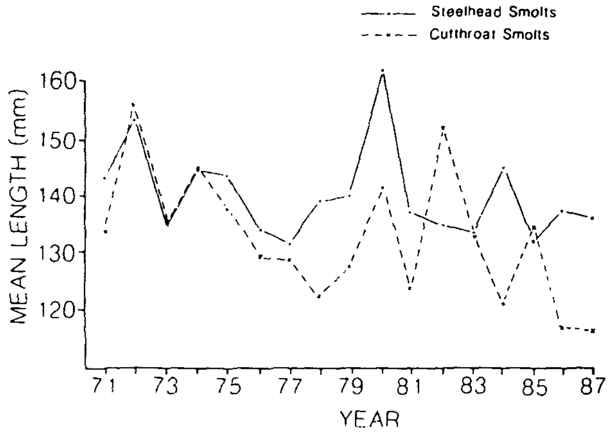

FIG. 75. The mean lengths (FL) of steelhead and cutthroat trout smolts migrating from Carnation Creek from 1971 to 1987.

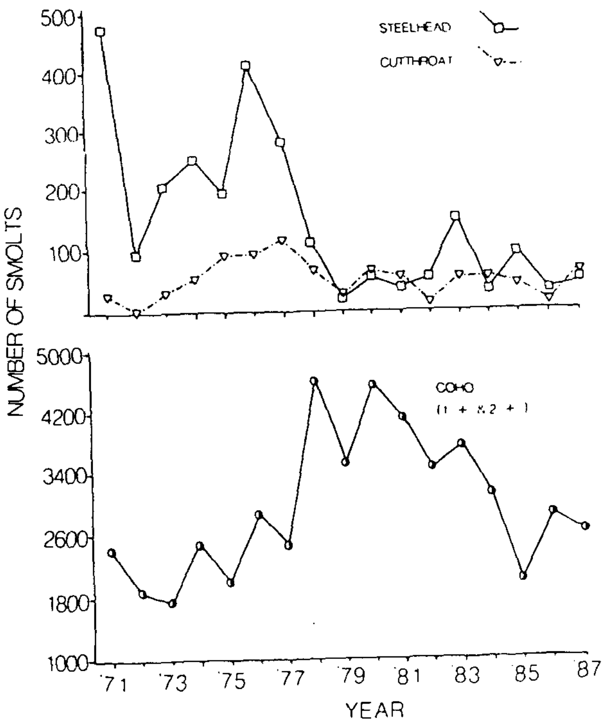

FIG. 76. The numbers of cutthroat and steelhead trout smolts and total numbers of coho salmon smolts leaving Carnation Creek from 1971 to 1987.

In summary, regional climate variability and logging induced changes in stream temperature, produced larger salmonids, and caused life history changes for trout and coho salmon. Larger coho salmon and trout in autumn and larger age 1+ coho smolts were correlated with winter and spring stream temperatures, with shorter periods of egg incubation, and longer periods of summer growth. The early beneficial effects of higher stream temperatures were lost during the second and third years of stream residence. At first, numbers of coho smolts increased in response to these effects and an age shift occurred that produced younger smolts. Later, smolt numbers began declining as egg production and egg-to-fry survival declined.

Marine survival and movement of salmon

It was essential to separate freshwater and marine impacts on anadromous salmonids in order to truly assess logging impacts on adults returning to a fishery. Chum and coho salmon spend >50 % of their lives in the ocean which has the final influence on them. Some logging impacts could also carry over into the marine environment. Therefore, we included a discussion of the ocean life history of Carnation Creek salmonids.

The marine survival of chum salmon was correlated with sea surface salinity for April (Fig. 77) or for the spring months (Mar.–June ; Scrivener 1988b) at Amphitrite Point.

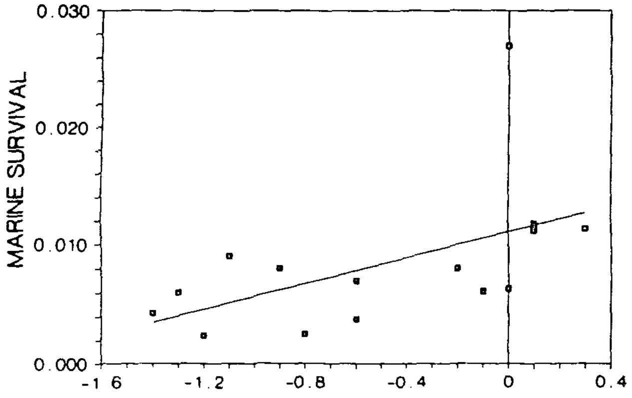

FIG. 77. The relationship between the marine survival of Carnation Creek chum salmon and the April salinity anomaly of the sea surface at Amphitrite Point. The anomaly was the 50-yr mean salinity for April (1934–84) minus the mean of daily salinities for April each year.

The salinity anomaly was calculated from the 50-yr mean for April (1934-84) minus the mean of daily salinity for April each year (Dodimead 1984). Salinity was an indicator of the distribution of predators and of areas of upwelling and high plankton productivity in the nearshore zone off the west coast of Vancouver Island (Fulton and LeBrasseur 1985). In years of extremely low salinities (negative anomalies), the plankton rich subarctic boundary between the Alaska gyre with its coastal current and the California current shifted northward. Very low survivals were obtained for chum fry that entered the ocean during those springs (Fig. 77). The marine survival of chum salmon was also related positively to fry size and migration timing (Scrivener 1988b ; Holtby and Scrivener 1989). Both were affected by logging.

Marine survival of coho salmon was related to smolt size, emigration timing, and ocean conditions (Holtby and Scrivener 1989). Indicators of ocean conditions at Amphitrite Point were the average salinity anomaly during the spring (Apr.–June) of smolt migration and average sea surface temperatures during the winter following smolt emigration (Oct.–Feb.). Small size and early migration of coho smolts produced relatively poor survival in the ocean. A multiple regression model that incorporated smolt size, migration timing, and these spring and winter ocean conditions explained 71 % (R^2) of the variance in adult returns to the fishery (Holtby and Scrivener 1989).

Recovery of adults with coded wire tags (CWT) indicated that estuary reared coho contributed to the spawning population and the commercial fishery. Recoveries from the 1980 brood year (CWT Sep 1981) included two jacks in October 1982 at the Carnation Creek fence and two adults from the 1983 troll fishery. The troll caught fish were obtained in Area 26 (Kyuquot Sound) during the 2-wk of July and in Area 25 (Nootka Sound) during the 4-wk of July. Coho salmon appeared to migrate down the west coast of Vancouver Island during July and August when returning to spawn in Carnation Creek. Only a single jack was recovered from the 1982 brood year (CWT Aug 1983). It was caught at the fence on October 5, 1984. Marine survival of the 1982 brood year was the lowest obtained to date (Holtby and Scrivener 1989).

The recovery of only five mature fish from a total release of 680 CWT (0.74 %) indicated that estuary reared coho contributed fewer returns than stream reared coho salmon. In total, 149 adults and 82 jacks were recovered at the fence from the 16 823 juveniles that were present in the stream during September of 1981 and 1983 (1.37 %). Another 223 adults were probably caught in the troll fishery assuming a 60 % exploitation rate (Holtby and Scrivener 1989).

Salmonids in other streams

During the last 15 yr (1971–85), total salmonid biomass ranged from 1.0 to 3.3 g·m^{-2} in South Pachena, Useless, and Carnation creeks (Fig. 78). S. Pachena and Useless creeks were streams in Barkley Sound that served as controls for Carnation Creek. Inter-annual changes in biomass were in the same direction during 9 of the 13 yr for all three streams (data were not available for all streams during 1971 and 1986, see Table 6). The direction of inter-annual change in biomass in Carnation and S. Pachena creeks were similar during 11 of 14 yr (Fig. 78). We concluded that environmental factors were influencing all three populations in a similar manner during most of the study period.

Similar trends in salmonid biomass were observed for the three streams between 1974 and 1983, but thereafter, the biomass in Carnation Creek declined relative to the other streams (Fig. 78). Biomass was near the minimum during 1976–78 and then increased during the early 1980's in all three streams. Salmonid biomass then declined to ~1 g·m^{-2} after the January 1984 freshet in Carnation Creek. It remained at 1.5 g·m^{-2} in Useless Creek and at >2.0 g·m^{-2} in S. Pachena Creek.

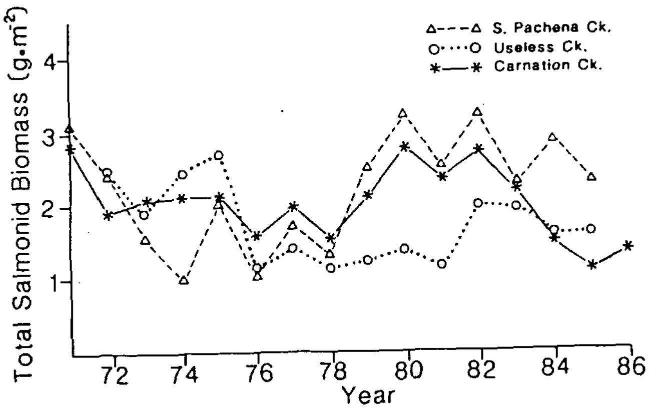

FIG. 78. Salmonid biomass in September is shown for three Barkley Sound streams from 1971 to 1986. Population estimates were not obtained for Useless Creek in 1971 or 1986, or for S. Pachena Creek in 1986.

Sculpin Populations

Two sculpin species (*Cottus asper* and *C. aleuticus*), which differed in distribution, abundance, and micro-habitat use, were found in Carnation Creek (Ringstad 1982). *C. asper* occupied the lower 1.5 km of Carnation Creek, while *C. aleuticus* occurred throughout the lower 3.1 km of stream (Fig. 65). Both species of cottid occupied benthic habitat and larger individuals (>80 mm, age 4+ or older) were located in the deeper pools. *Cottus asper* preferred pool areas where water velocity was low and LOD abundant. *Cottus aleuticus* occupied pools with faster flowing water and with less LOD (Ringstad 1982). Mean numbers of *C. asper* in September were 400 during the prelogging (1971–76), 237 during the logging (1977–81), and 132 during the postlogging periods

(1982–87). *Cottus aleuticus* averaged 3840 during prelogging, 2178 during logging, and 1445 during postlogging periods. These population estimates did not include sculpin fry or spawning adults which were in the estuary.

During the summer, about half the sculpin population was in the estuary, while the remainder was in the stream. *Cottus asper* is catadromous and adults migrated downstream at night during March and April to spawn in the estuary (Ringstad 1982). Planktonic larvae of both species appeared there during July. They metamorphosed into fry which reared in the estuary until age 1 + (40 mm). Adults and yearlings of both species migrated upstream during August to October each year.

The sculpin populations in Carnation Creek did not appear to suppress salmonid numbers or growth. Only one cottid containing salmonid remains was obtained during stream surveys or feeding studies in summer 1971, 1972 and 1973 (Ringstad 1982). Although cottids and salmonids consumed the same aquatic macroinvertebrates, cottid densities of 2.5 times typical stream densities were required before significant reductions in either macroinvertebrate densities or coho growth occurred in experimental troughs (Ringstad 1982). Terrestrial food was also excluded from these troughs.

Stream-side logging caused the sculpin populations to decline. Mean September numbers of *C. asper* declined from 400 during prelogging to 132 during postlogging years (Mann–Whitney U-test, $U = 7$, $P = 0.043$). *C. aleuticus* numbers declined from 3840 to 1445 during the same periods (Mann–Whitney, $U = 4$, $P = 0.013$). The downstream migration of adults in spring also declined after logging (Ringstad 1982). The greatest reductions were observed in study sections V and VI where LOD was destabilized by logging (Table 8) and the stream channelized by major freshets in November 1978 (Fig. 41) and January 1984 (Powell 1988).

Chapter 7. Drainage Basin Processes and Process Complexity

Introduction

To manage and harvest natural ecosystems one must understand the processes that affect the production of its renewable components. However, the processes and changes which follow major physical alterations are complex. Management would be easier if this were not so, but natural systems have not evolved with anthropocentric goals, i.e. of being easy for man to understand or to manage. Simplicity and ease of management are economic considerations for humans but not ecological realities for natural systems. In the following subsections on complexity, we will put considerable emphasis on processes in drainage basins.

Forest harvest within a watershed causes a number of physical changes which effect a spectrum of biological processes. These physical changes and their indirect effects are the kinds of impacts that the manager seeks to use or ameliorate.

Forest harvest is not a unitary activity. It involves a spectrum of activities ; road construction, falling, yarding, post-harvest burning etc., and each of these activities has specific physical impacts and biological consequences. The effects of which may either enhance or diminish biological production in the stream ecosystem. Whether or not they enhance or diminish fish or ecosystem productivity will depend upon the nature and severity of the activity, upon the type of stream system and upon the time since impact. The effects of forest harvest activities on organisms such as fish may also depend on the species and life stage of the fish. Therefore, predicting the net effect on salmonids returning to a fishery would be impossible without an understanding of the physical and ecological processes.

Forest Harvest Activities — Diversity of Impact

At Carnation Creek, forest harvest activities involved road construction, falling, yarding and hauling. They were followed by silvicultural activities such as prescribed burning, scarification, and herbicide use (Table 1). The different impacts of each of these activities are summarized in a matrix (Fig. 79). The most important impacts were caused by falling and yarding in the stream-side zone.

Different activities alter different sets of conditions in the system (Fig. 79) and some activities have compound effects. For example, stream-side cutting let sunlight into the stream, increased stream temperature and altered channel structure. The physical changes caused by some activities set processes in motion which are apparent immediately and are continued for years. The impacts of other activities such as reforestation may not be apparent for at least a decade (Fig. 79). Logging activities at Carnation Creek have chiefly affected :

1. stream temperatures (Holtby 1988 ; Hartman et al. 1984, 1987) ;
2. debris and stream channel structure (Toews and Moore 1982 ; Harris 1986 ; Powell 1988 ; Scrivener and Brownlee 1982, 1989) ;
3. light and nutrient entry to the stream (Stockner and Shortreed 1976, 1978 ; Shortreed and Stockner 1983 ; Scrivener 1975, 1982, 1988c) and effects on macroinvertebrates (Culp and Davies 1983, 1985 ; Culp et al. 1983, 1986 ; Culp 1986 ; Scrivener and Carruthers 1989).

Logging did not generate hydrological changes that had readily detectable effects on biological processes in the drainage. However, the extremes of natural hydrological conditions were clearly related to changes in debris, channel and stream biota stability (Hartman et al. 1982 ; Holtby and Scrivener 1989 ; Scrivener and Andersen 1984 ; Scrivener and Brownlee 1989).

FOREST HARVEST ACTIVITIES

EFFECTS ON STREAM ECOSYSTEM		ROAD		FALLING		RDING		SILVICULTURE		
		CONSTRUCTION	USE	STREAM SIDE	UP SLOPE	STREAM SIDE	UP SLOPE	SLASH BURNING	HERBICIDE USE	TREE RE-GROWTH
TEMPERATURE	LIGHT TO STREAM			■					■	□
	TEMPERATURE OF STREAM			■	■				■	□
	TEMPERATURE OF SLOPE SOILS & WATER				■				■	□
HYDROLOGY	WATER YIELD				■					
	TIME FROM PEAK PRECIPITATION TO PEAK FLOW	□					○			
	WATER ROUTING	○					○			
CHEMICAL & NUTRIENT FLUX	NUTRIENT RELEASE			■	■		■	■		□
	LITTER INPUT			□					□	■
DEBRIS & CHANNEL CONDITION	SMALL DEBRIS · VOLUME			■		■	■			
	LARGE DEBRIS · VOLUME			□		□	▽			
	· STABILITY			□		□	▽			■
	· DISTRIBUTION			○		○	▽			
	CHANNEL · WIDTH			■		■				
	· DEPTH			□		□				
	SCOUR POTENTIAL			■		■	▼			
	GRAVEL QUALITY	□	▽	□		□	▽			

□ – DECREASE
■ – INCREASE
○ – CHANGE
▽ – DECREASE -- OTHER STUDIES
▼ – INCREASE " "

FIG. 79. A matrix of logging activities and changes in physical conditions at Carnation Creek. Some effects of logging activities from studies in the Queen Charlotte Islands (Poulin 1986) and the Olympic Peninsula (Cederholm et al. 1981), indicated by triangles, are included to illustrate difference between geographic areas.

To integrate logging activities, the physical changes caused by such activities and the effects on biological conditions in the stream, we have grouped them into hydrological, fluvial-debris, temperature, and ecological categories. They illustrate our perceptions of the major processes in the system and they include effects on fish production.

Hydrological Processes — Slope Drainage and Water Yield

The high precipitation and rapid runoff at Carnation Creek created natural freshets with 200-fold discharge increases and decreases in a single day. Before any logging effects on water yield or peak flows, these freshet extremes had important impacts on physical and biological processes within the stream.

Forest harvest activities had complex and different effects on hydrological processes within the Carnation Creek drainage (Fig. 80). In Tributary-H, water yield, time from peak rainfall to peak runoff, and peak flows were all changed when >90 % of the 12 ha drainage was clear cut in 1 yr. Logging increased the water yield in 6 of 7 yr (Fig. 34a, 34b), raised summer low flows by 78 % in 2 of 3 yr and increased peak flows in early autumn (Hetherington 1982, 1988). Road construction in the sub-basin reduced the time from peak rain to peak-flows by re-routing ground-water flow through ditches to the stream (Fig. 80 ; Hetherington 1982 ; Cheng 1988). Mineral soil disturbance and the closure of openings to macro-channels was suggested as the process which slowed the rate of water channelization at some sites on the slopes. However, this slowdown of water movement was masked by the increased rate of movement of re-routed water at other sites (Hetherington 1982).

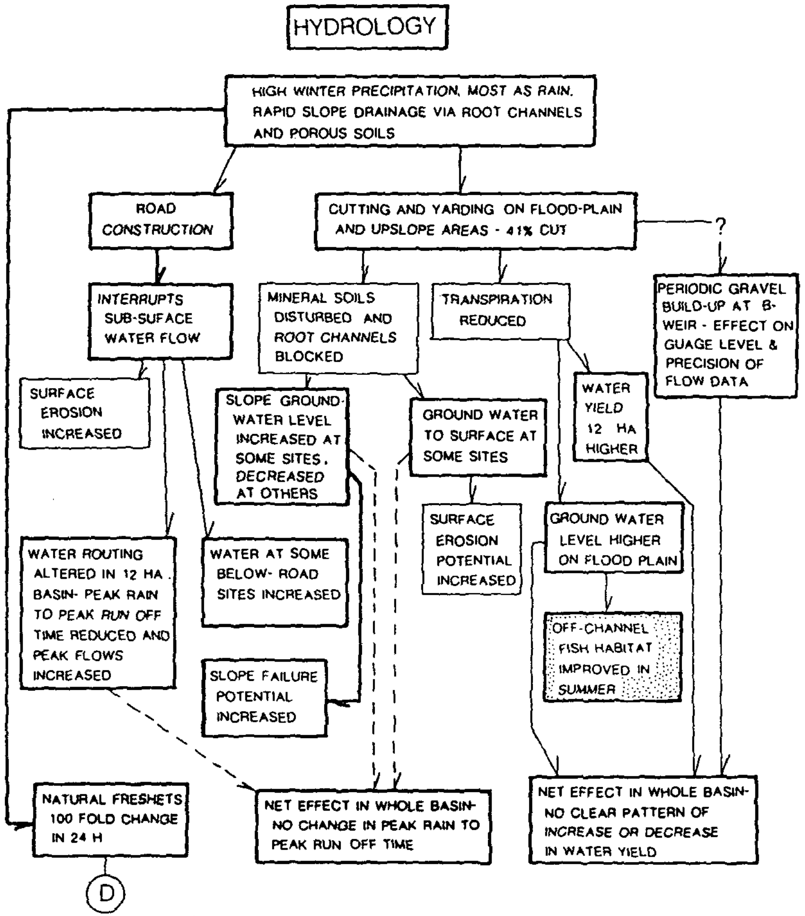

FIG. 80. A schematic diagram outlining hydrological relationships and responses to road construction and logging within the Carnation Creek basin. The D in the circle on the figure indicates an important point of connection between hydrological processes and debris related processes. A heavy line around a statement about responses or a heavy line arrow relating one response to another indicates that the responses and relationships have been documented at Carnation Creek. A light line or dotted line indicates that the responses and relationships have *not* been firmly demonstrated or they have been inferred from work published on drainages other than Carnation Creek. Stippling within a box indicates a response that directly involves fish or fish production.

Changes in soil water movement and distribution increased the potential for slope failures (Fig. 80). One slope failure in H-watershed was believed to be caused by re-routed water and increased ground water saturation. The suggestion that increased groundwater levels and re-routed water caused the slope failures is speculative, but it would be consistent with results from other drainages (Swanson et al. 1987).

The effects on the total basin area were less clear than those on Tributary-H. The area logged and the rate of cut were probably not large enough to produce the same effects at B-weir (Fig. 34c. 34d). Clearcutting 41 % of the total basin reduced transpiration and interception. This contributed positively to the basin water yield and also elevated groundwater levels in the flood plain (Fig. 33). Gravel accumulation at weir sites after logging may have reduced the reliability of stream gauging. Changes in water yield were not detectable at B-weir because counteracting effects occurred, measuring precision was impaired and only 41 % of the basin was logged (Fig. 80).

Water levels in the small tributaries and ponds on the flood plain were positively related to the groundwater levels (Brown 1985). We speculate that the elevation of groundwater levels on the flood plain improved summer habitat for age 0+ cutthroat trout and coho salmon rearing in the intermittent tributaries.

The discussion of hydrological processes is based on analysis of 1971–86 data. Analysis of more recent data, and particularly impacts of rain-on-snow freshets, will clarify interpretations of hydrological processes. We stress again that natural extremes of discharge influence other processes such as debris movement, channel morphology change or gravel scour and deposition whether or not logging effects on hydrological processes occurred at detectable levels.

Fluvial, Geological, and Debris Changes in the Stream

Changes involving large organic debris (logs, LOD) and channel morphology occurred during the logging and postlogging periods. They occurred as sudden catastrophic changes or as gradual changes over a number of years. The first set of processes involved debris and sediment in the valley wall tributaries, and the steeper gradient canyons of the main channel (Zones 1 and 3, Fig. 4). The second set of processes involved LOD, channel morphology and gravel quality in Zone 4, where the effects of the three different streamside treatments were assessed. Events which occurred in the steep tributaries and canyons had impacts that were visually obvious not only in these locations but also in the areas immediately downstream.

Steep slope tributaries and canyons

Logging activities, including cutting to the stream bank, caused three changes in basins of the valley wall tributaries :

1. It reduced the stability of the debris and sediment that was in the channel prior to logging.
2. It removed the trees from the stream side, weakened root structure and added logging debris to the channels.

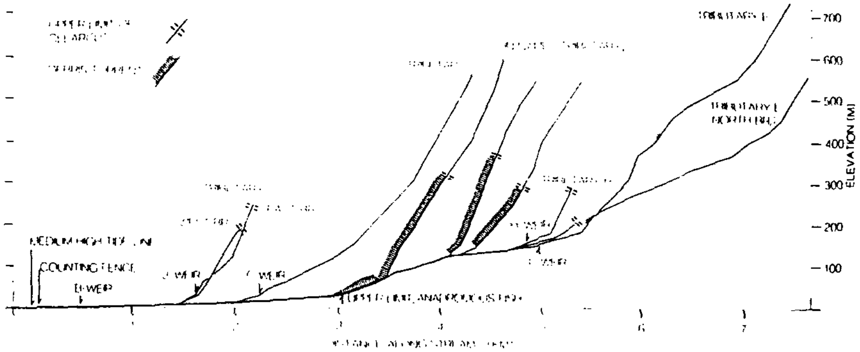

FIG. 81. Gradient profile of Carnation Creek and main tributaries, and locations of debris torrents.

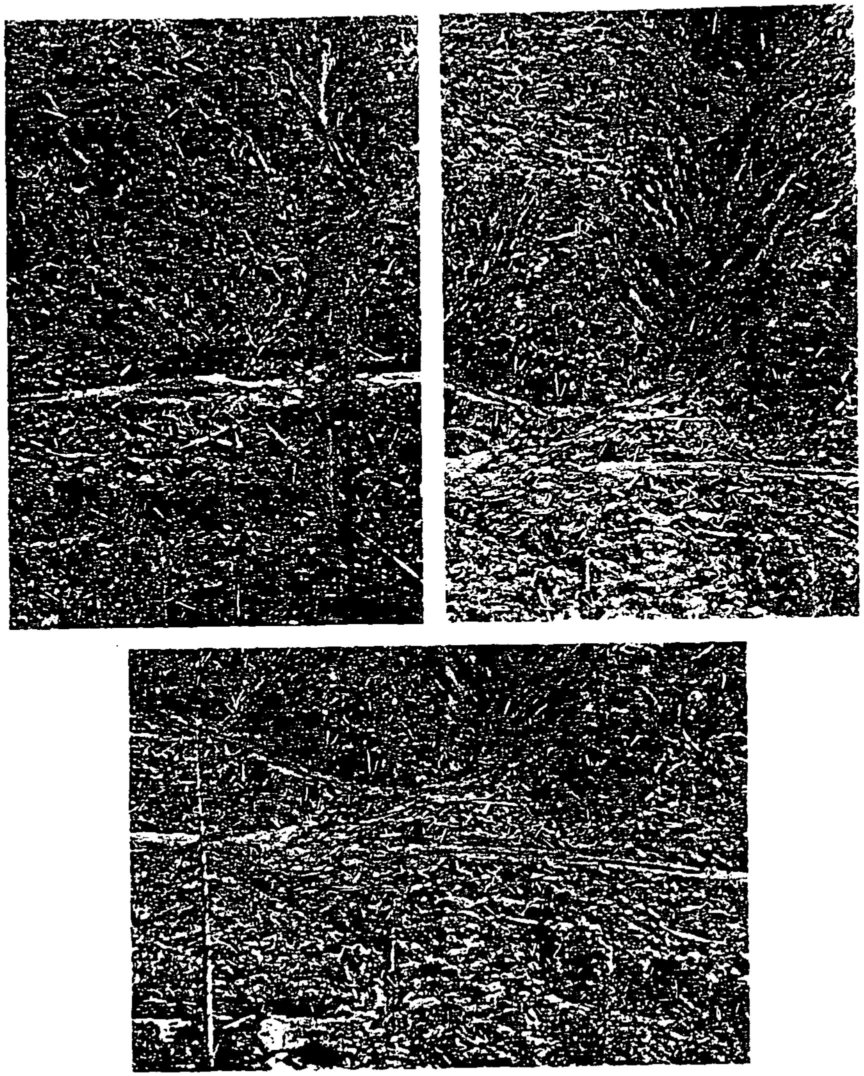

FIG. 82. Scoured channels and material deposited by debris torrents in the lower ends of unnamed tributaries 1 and 2.

3. It exposed more mineral soil which could be eroded and transported into the active channels of the tributaries. 8-10 in

During an unusually large storm (January 3–4, 1984), in which 22–26 cm of rain fell at various stations in 24 h ; water, sediments and woody material formed debris torrents in three unnamed tributaries on the south side of Carnation Creek (Fig. 81, 82).

During the same storm, slides occurred in the canyon section of Zone 3 and all LOD and gravel in 100 m of stream channel was swept from the canyon in a single debris flow (Fig. 83). We speculate, but cannot prove, that movement of logging debris from

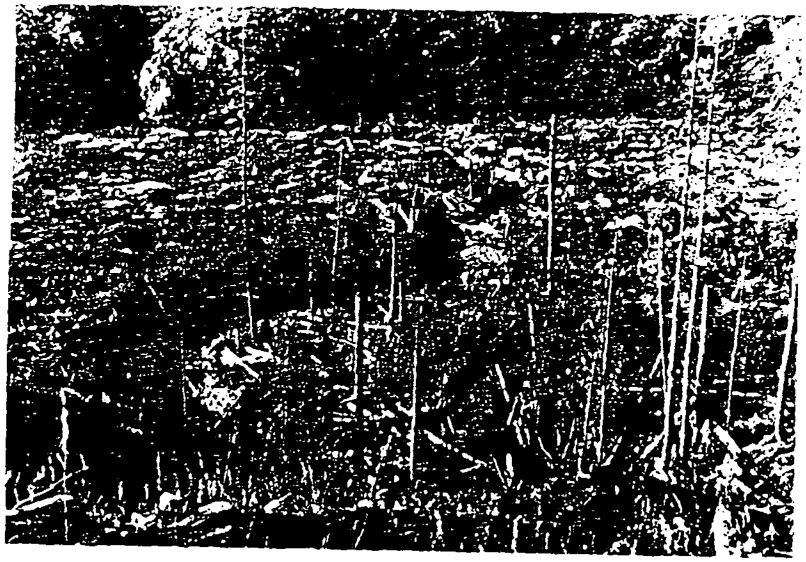

FIG. 83 Deposition of woody debris on the outsides of stream bends and across the stream between 2 600 m and 2 900 m upstream from the mouth of Carnation Creek

stream-side areas below E-weir, slides in the lower canyon (Fig. 84) and the debris torrent in the canyon were all interrelated events triggered by one severe storm. We believe that debris and sediment were destabilized by logging in the tributaries and along the main creek and that a severe storm removed this unstable material. The following points support this speculation

1. Debris torrents did not occur in unlogged Tributary-C or -E, both of which had steep sections with LOD and sediment in them and a large enough drainage area to generate ~10 $m^3 \cdot s^{-1}$ of water during the freshet
2. Piles of debris like those deposited in the January 3–4, 1984 storm were not evident prior to logging. Had such an earlier torrent occurred in the main canyon during the last 40 yr, material would still be evident. A freshet of this magnitude occurred once in 20 yr (Hetherington 1988).
3. Torrents in the unnamed tributaries were initiated at or below the upper boundaries of the clearcuts and not in standing timber (Fig. 81)
4. Material from the debris torrent in the lower unnamed tributary (Fig. 81) extended to the stream edge after the storm

During the debris flow in the canyon, pieces of LOD were deposited ~ 3.5 m above the level of low stream flow. A combination of very wet bank soils, high water levels and debris abrading the banks caused the slope failures within the canyon and the consequent release of sediments into the stream

Processes which took place in the valley wall tributaries and the lower canyon affected channel conditions on the flood plain. The debris flow removed most of the LOD from the upper 250 m of the careful stream-side treatment (400–650 m above study section VIII). It deposited three piles of LOD on the banks in the next 300 m reach of stream (100–400 m above section VIII, Fig. 83). The freshet deposited gravel bars, up to 1 m deep, immediately above study section VIII. It also dislodged LOD in study section VIII and moved it ~20 m downstream (Fig. 42, first apparent in 1984 survey)

FIG. 84 Land-slide in the lower canyon of Carnation Creek. *Upper photo*, view downstream of south side of the stream. *Lower photo*, view into the stream from a higher elevation. Note that some material slid across the stream and was deposited on the north side of the channel

Main channel sections and the flood plain

The careful and intensive stream-side treatments caused decreases in the amount, size, and stability of LOD, and they caused increases of small woody debris (<3 m in length) in the stream. These changes had a marked effect on channel morphology, fish cover and streambed composition. Ultimately they affected fish production. The processes involved in these changes are shown in a generalized schematic diagram (Fig. 85). The careful and intensive logging methods caused three changes that affected the stream bank and channel dynamics :

1. Tree roots in the stream bank were killed or weakened in both the careful and intensive treatment areas.
2. Small debris was added to the channel, particularly from the intensive treatment, which added limbs and needles that destabilized large decaying logs in the channel.

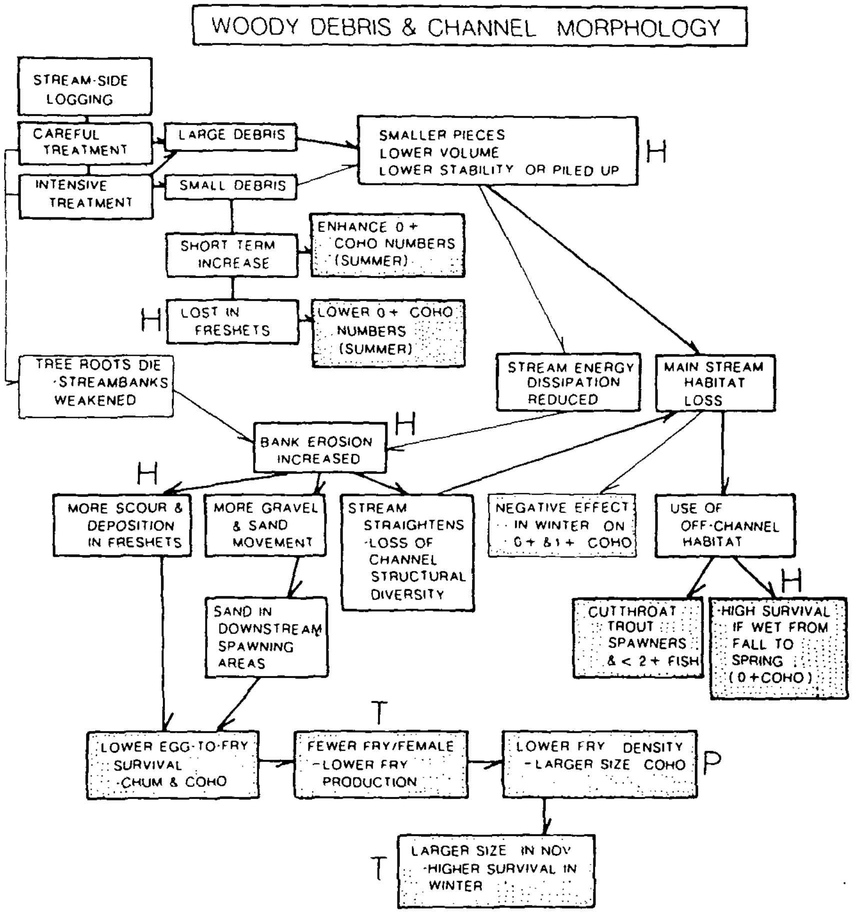

FIG. 85. A schematic diagram outlining the effects of logging activities on debris and the subsequent effects of debris changes on channel condition, gravel quality and fish. The letters P, T, or H indicate important points of connection between debris and channel-related processes on fish production, temperature-related processes or hydrological processes. See caption of Fig. 80 for explanation of width of lines and stippling.

3. LOD was disturbed directly by being broken or removed in the intensive treatment area.

Changes in the volume of small debris, and the volume, stability and mean piece size of LOD occurred within a year in the intensive treatment area (Toews and Moore 1982) and the effects of these changes on fish were immediate (Scrivener and Andersen 1984). The addition of branches and other small debris initially made the stream habitat more complex. Consequently, it supported relatively more coho fry per unit of area of stream

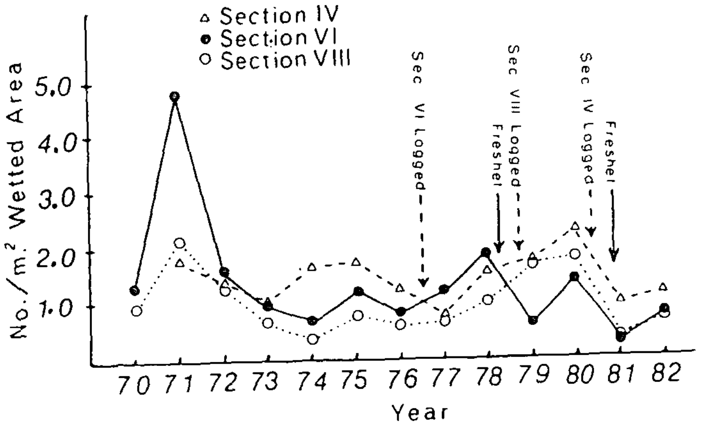

FIG. 86. Late July densities of coho salmon fry in Carnation Creek study sections IV, VI, and VIII. The winters, during which logging occurred adjacent to the sections, are indicated as are major freshets (from Scrivener and Andersen 1984).

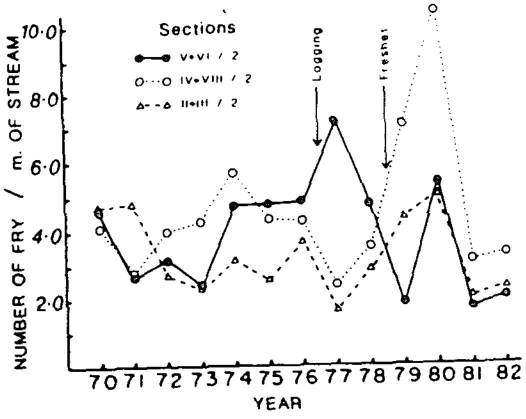

FIG. 87. Relative abundance of fry through time among study sections II + III, IV + VIII, and V + VI in Carnation Creek during late September. Values were calculated for 1973 section VIII and for 1981 section II because storm flows interrupted population estimates at these sites (see Table 5). Five-year relationships were established between the proportion of total population in the section and an estimate of total stream population (Table 11) for section VIII (1971–75) and for section II (1979–83 ; both $n = 14$, $r = 0.87$, $P < 0.001$).

(Fig. 86) and per unit length of stream (Fig. 87). However, enhanced summer carrying capacity in study sections V and VI did not last (Fig. 87). The first major freshet following the intensive treatment occurred in November 1978 (44 $m^3 \cdot s^{-1}$) and it flushed away much of the small debris. From 1979 to 1982 sections V and VI supported fewer fry than control sections IV and VIII (Scrivener and Andersen 1984). The loss of the small debris during the November 1978 storm appeared to cause the dislocation of fish and their movement to more stable winter cover if they could find it. The addition of small debris had a short term positive effect on summer carrying capacity for age 0+ coho salmon.

The loss of stream LOD reduced the stability of the channel micro-topography, the amount of cover, and the complexity of stream habitat. It also reduced the capacity of the stream channel to dissipate the hydraulic energy of flowing water (Fig. 85).

Loss of summer and winter habitat for young coho salmon and trout occurred (Fig. 85) when LOD was reduced in both the intensive and careful treatment areas (Toews and Moore 1982 ; Schultz International Ltd. 1981 ; Harris 1986). The existence of LOD and under bank habitat was a critical factor in the maintenance of juvenile coho salmon and steelhead parr in the main creek during winter (Bustard and Narver 1975 ; Tschaplinski and Hartman 1983). Coho salmon were not found during winter in sections of the stream that were devoid of LOD. Over 90 % of the young fish that remained in the main creek were located in debris piles and under bank cover (Tschaplinski and Hartman 1983).

In drainages like Carnation Creek, which have side-channels, ephemeral swamps, and intermittent tributaries on the alluvial flood plain, the use of such habitat can buffer fish populations against the effects of habitat loss in the main creek (Fig. 85 ; Brown and Hartman 1988). During the first autumn storms, age 0+ coho salmon moved into the ephemeral swamps and intermittent tributaries (Fig. 88). Cutthroat trout were dependent on LOD in the main stream during winter, but they also entered the intermittent tributaries during the autumn (Hartman and Brown 1987). Several age classes of trout resided in this habitat during winter and some adults spawned in it during spring (Fig. 88).

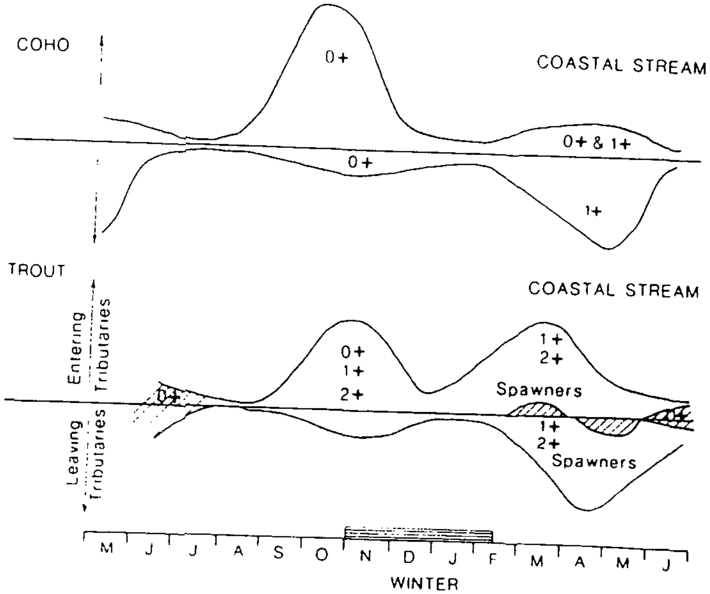

FIG. 88. Generalized pattern of movement of coho salmon and cutthroat trout into and out of flood-plain tributaries of a coastal stream such as Carnation Creek. The ages are indicated of non-spawning fish, age 0+ to 2+ which are moving. The pattern of cutthroat spawner movement, March to May, is indicated by hatch marks. The movement in June and July, of trout fry that were produced by spawners within or near the tributaries, is indicated as cross-hatching over 0+ fish. The horizontal bar indicated a typical residence time.

The choice of use or non-use of off-channel habitat, as a life history strategy of young coho salmon, entails a degree of survival risk. During springs when rainy periods were frequent, and water levels were high during coho emigration from off-channel habitat, survival rates of juvenile coho from such habitat were much greater than in the main creek. During warm dry springs, survival in the off-channel habitat was lower than during wet springs and mortality by stranding has been observed (Brown 1985 ; Brown and Hartman 1988).

The decrease in stream LOD had important effects on fluvial geomorphological processes in the stream, in addition to its effects on survival and distribution of salmonids (Fig. 85). The reduction in hydraulic energy dissipation, i.e. the increased stream velocity that accompanied the debris losses (Toews and Moore 1982), and the weakening of roots in the stream banks (as documented in other systems by Burroughs and Thomas 1977) resulted in increased bank erosion (Fig. 45), increased channel scour and deposition (Fig. 43), and decreased structural complexity (Toews and Moore 1982 ; Harris 1986). The erosion processes had four kinds of impacts (Fig. 85) on the stream and the fish within it :

1. The channel was straightened and the riffle-pool diversity was reduced causing a loss of fish habitat in the main creek.
2. Scour and deposition during freshets reduced egg-to-fry survival (Holtby and Scrivener 1989).
3. Downstream movement and deposition of sand altered spawning gravel quality and reduced egg-to-fry survival (Hartman et al. 1987 ; Scrivener and Brownlee 1989).
4. Bedload deposition in some areas filled the channel (Fig. 44b), thus reducing the stream wetted area and summer rearing habitat of fish.

Reduced size of emerging fry of chum and coho salmon was also related to the reduction of mean particle size of spawning gravel (Scrivener 1988b ; Scrivener and Brownlee 1989). Egg size, which is influenced by female size, had the largest effect on the FL of emerging fry (chum $r = 0.63$, $n = 15$, $P < 0.01$; coho $r = 0.72$, $n = 16$, $P < 0.001$). However, after adjusting for the egg size influence, the positive relationship between mean particle size of spawning gravel and fry FL was improved for coho salmon ($r = 0.81$, $n = 14$, $P < 0.001$) and for chum salmon ($r = 0.71$, $n = 13$, $P < 0.01$; Scrivener and Brownlee 1989). Reduced chum fry size was correlated with reduced ocean survival (Holtby and Scrivener 1989).

Percentages of both chum and coho salmon eggs that survived to fry were correlated with the geometric mean particle size of the spawning gravel (Fig. 89). Survival declined as sand and pea gravel accumulated in the streambed. The additional sand in the spawning gravels prevented the fry from emerging, thus entombing them in the streambed (Scrivener 1988d). Sand also reduced the flow of inter-gravel water and hence gas and metabolite exchange was diminished at the egg surface (Scrivener and Brownlee 1982, 1989).

Our data do not permit evaluation of egg-to-fry survival of trout. However, cutthroat trout spawned during March and April in the small tributaries on the flood plain, while steelhead trout were spawning in the main channel. Storms and freshets had become less frequent by April (Fig. 30), so trout may have been less subject to gravel scour impacts than coho and chum salmon.

Changes in both the ocean and the stream channel contributed to the reduced coho fry (Table 11) and chum fry (Fig. 64a) production after 1980. Declining marine survival reduced the number of returning adults (Fig. 77 ; Holtby and Scrivener 1989). The consequences of reduced egg-to-fry survival in the stream was fewer live fry per female and lower total fry production.

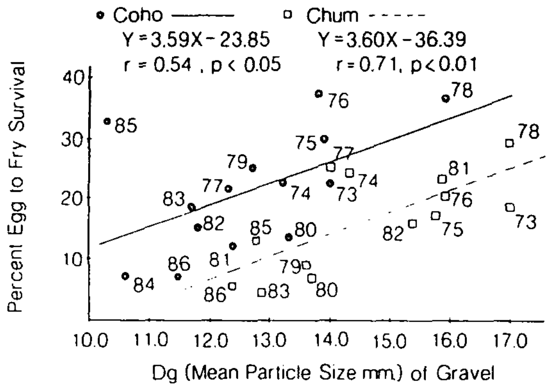

FIG. 89. The relationships between egg-to-fry survival of chum and coho salmon and mean particle size of gravel used by spawners.

Increased rates of growth and rearing survival compensated for the reduced production of coho fry. Instantaneous growth rates were higher at lower densities (Scrivener and Andersen 1984) and this contributed to the production of larger autumn fry which had higher over winter survival (Fig. 72). Survival rates were also higher at low population densities. In a multiple regression analysis 23.6 % of the variation in mortality of fry during summer was explained by a density function (Holtby and Hartman 1982). Both of these population responses helped a greater proportion of coho salmon attain the size necessary for smoltification at age 1 + during the postlogging than the prelogging period (Holtby 1988).

Temperature Change and Related Processes

Temperature changes in Carnation Creek resulted in a mosaic of effects on fish. These effects were different for different species, life history stages and, in some instances, for different individuals within the same life stage. Temperature-dependent responses at one stage also had important consequences later in the life of the fish. We have summarized the main effects of the observed temperature changes in a schematic diagram (Fig. 90). In this section, we will provide a narrative and references for the observations that support the generalizations indicated within the diagram.

In Carnation Creek, increases in monthly mean stream temperatures were attributable to logging and regional climate trends. Holtby (1988) modelled stream temperatures for Carnation Creek using multiple regression analysis and a linked series of models that partitioned the observed variability between climate and logging related effects. Thus, the proportion of an effect attributable to logging could be quantified. The main variables that predicted stream temperature in the model were mean daily air temperatures (averaged over weekly intervals) and the proportion of the watershed that had been logged. Logging effects on stream temperature were the differences between observed temperatures (logging effect included) and predicted temperatures from the models with the logging-effect terms set to zero (Holtby 1988). Logging-related increases of stream temperature occurred at all times of the year, but the mechanisms causing these increases might not be the same in winter and summer (Fig. 90). Hartman et al. (1982, 1987) speculated that up-slope cutting and postlogging slash burning may increase stream temperatures during winter by causing ground water, which is replaced during the first autumn rains, to be warmer. If this effect occurred as speculated, it would cause stream temperatures (during low flow) to be warmer during winter, when this warmed ground water was being

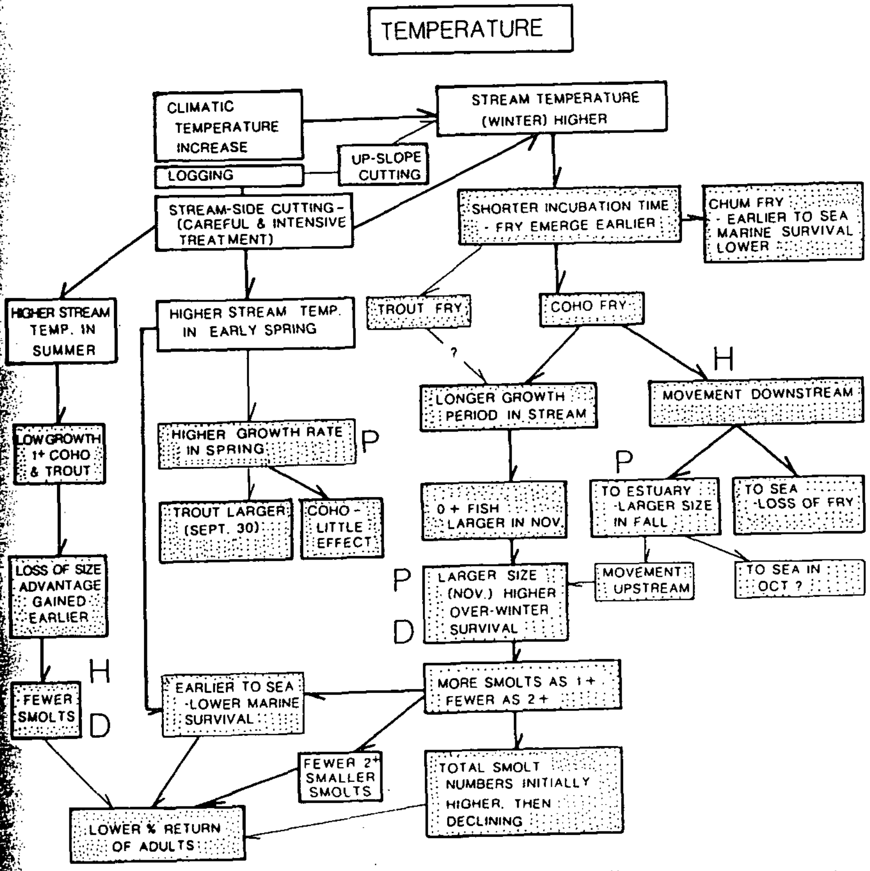

FIG. 90. Schematic diagram outlining the effects of logging and climate on stream temperature regimes, and the subsequent effects of temperature changes on fish production. The letters P, H, or D indicate important points of connection between temperature related processes and fish food production, hydrological processes, or debris processes. See caption of Fig. 80 for explanation of width of lines and stippling.

discharged. Stream temperature increases during the spring and summer periods, following logging, were presumed to have been caused by short wave solar heating of the water and streambed.

Thermal summations (Fig. 91), based, (1) on measured stream temperatures, (2) on predicted stream temperatures using the model and (3) on predicted stream temperatures had logging not occurred, indicated the scale of the logging effect. The summations also indicated the effect of regional climate change. The analysis in Fig. 91 was designed to illustrate logging and climate related effects on thermal summation during three periods :

1. the period of egg incubation for chum and coho salmon (Nov.–Feb.) ;
2. the period of summer growth for resident salmonids (June–Sept.) ;
3. and the period during smolting of salmonids and during egg incubation of trout (Mar.–Apr.).

The smallest increase in thermal summation occurred during the Nov.–Feb. period, but this winter increase in stream temperature shortened the incubation period and therefore

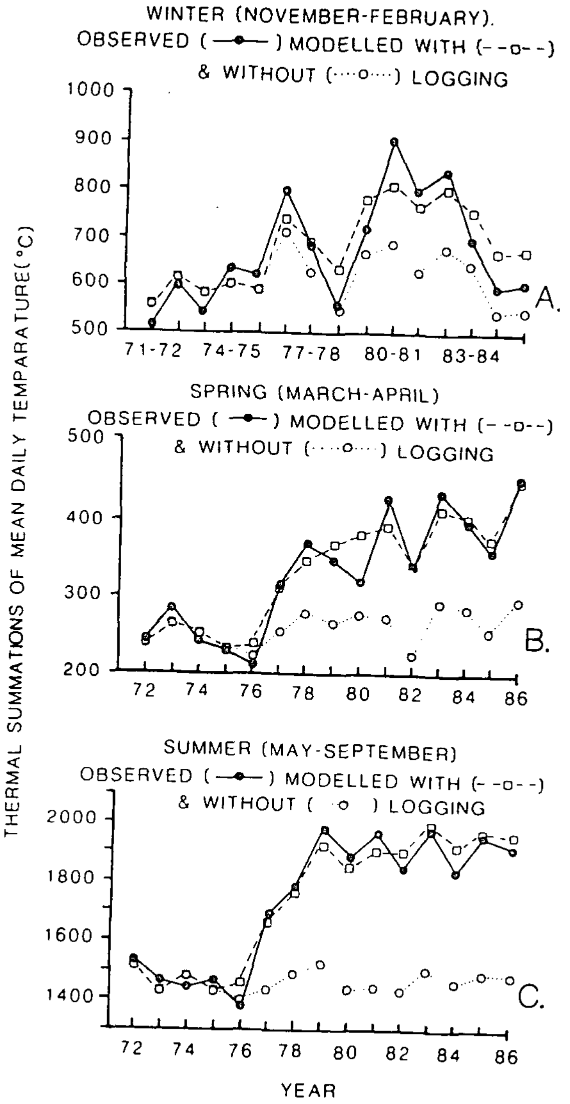

FIG. 91. Thermal summations (CTU) of water temperature in Carnation Creek for three periods of the year (A, B, C) from 1972 to 1986. Summations based on observed temperatures and those based on a model, assuming logging or no logging, are shown. See Holtby (1988) for original analysis.

chum and coho salmon fry emerged earlier (Fig. 64a, b ; Scrivener and Andersen 1984 ; Scrivener 1988b). Thermal summation based on measured stream temperatures explained most of the inter-annual variability in emergence and emigration timing among salmon fry (Fig. 92), but at least two other factors probably influenced the timing.

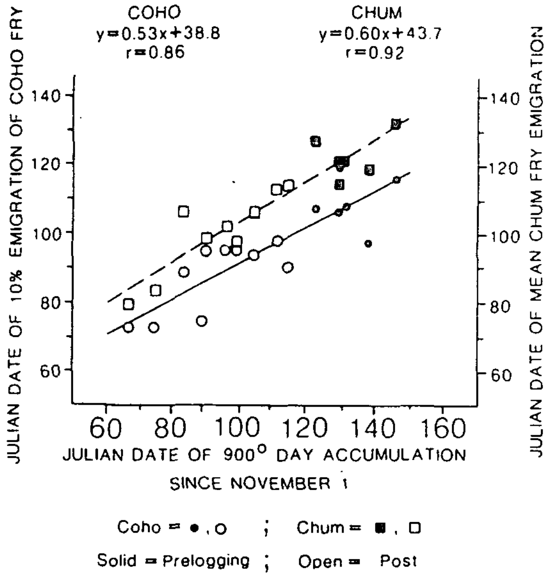

FIG. 92. Relationships between water temperatures during winter (i.e., the number of days required to reach 900 CTU), the Julian dates of the first decile of coho fry output and the mean date of chum fry emigration from Carnation Creek (1971–86). Circles, coho salmon ; squares, chum salmon ; solid, prelogging ; clear, logging and postlogging. For fry of coho salmon, the first decile date was deemed more indicative of emergence than the date of mean emigration of fry (Scrivener and Andersen 1984). No chum salmon fry were caught at the counting fence during 1984.

First, the timing of adult spawning explained another 10 % of the annual variability of fry emigration. Each year, chum salmon spawned en masse within ± 7 d of November 1, and thermal summation of daily mean temperature from the annual date of mass spawning improved predictions for the time of chum fry emergence (Scrivener 1988b). Female coho salmon usually entered Carnation Creek after November 1 and the annual variability of entry was greater than for chum salmon (Holtby et al. 1984). Inclusion of thermal summation data from the annual date of 70 % entry of females also improved predictions of the emergence date for coho fry.

Second, some salmon redds were likely influenced by warmer ground water upwelling in the stream. Inter-gravel temperatures during winter were 1°C higher than open water temperatures at a few sites in the stream (Fig. 29). Thermal summations of 850–1000°C are usually required for the incubation of salmonid eggs (J. Jensen, Pacific Biological Station, Nanaimo, pers. comm.), but 50 % of the chum fry had emigrated during 6 of 15 yr, and 10 % of the coho fry had emerged during 13 of 16 yr before summations of mean daily stream temperature had apparently reached 900°C (Fig. 92). Groundwater influences varied the incubation temperatures for salmon eggs in Carnation Creek, thus broadening the timing of fry emergence each year. The effect was probably smaller on the inter-annual variability of emergence timing, because these influences persisted throughout the study.

Indirect evidence indicated that trout fry also emerged earlier, but we do not have accurate information about the timing of their emergence. We concluded that logging effects on the time required for the incubation of salmon and trout eggs were similar, because logging of the stream side had an even greater influence on stream temperatures in March and April than during the winter (Fig. 91), because the trout spawned during March and April, and because the FL of 0+ trout in the stream during September was positively correlated with March-through-May temperatures before emergence (Table 14 and 15).

The earlier emergence of young chum salmon appeared to have reduced their survival rate during the period immediately after entering the sea (Hartman et al. 1987 ; Holtby and Scrivener 1989 ; Scrivener 1988b). In contrast, the earlier emergence of coho fry affected various groups of the year-class differently. Some coho fry were swept by freshets into the ocean where they were presumed to have perished. Some were redistributed into estuarine habitat where they reared during the summer. Other fry remained in the stream where the longer growing season enhanced survival during the following winter and rate of smoltification at age 1+ (Fig. 90).

There was an important connection between thermal and hydrological conditions in the watershed, and the survival and distribution of young coho. Each year, 50–90 % of the recently emerged coho salmon fry moved downstream (Table 11, Fig. 66a), often during or immediately before freshets (Hartman et al. 1982). Earlier emergence that was induced by higher stream temperatures exposed the fry to risks from freshets which were more probable earlier in the spring (Hartman et al. 1984). They probably needed time to orient themselves to living in a stream. This speculation of displacement by freshets was supported when negative relationships were obtained between stream flow and both the number of days between first and third quartile migration dates of fry (Fig. 93) and the number of days between first decile and third quartile migration dates ($r = -0.69$, $n = 16$, $P < 0.01$). Many of the fry which moved downstream are presumed to have perished each year in the ocean.

Some of the coho fry survived in the estuary. About 4000 fry in 1979 and 6000 fry in 1980, which moved downstream, remained in the brackish water of the estuary during July (Tschaplinski 1982). These fish grew more rapidly than those which remained in the stream, and by late September, they were 70–75 mm long. The 800 coho salmon that still remained in the estuary by early October either re-entered the stream or moved to sea during October (Tschaplinski 1982). Recently, 15 % of these October residents of the estuary were shown to enter Dick Creek, an adjacent stream that was dry during the summer (location in Fig. 9 ; T. G. Brown, Pacific Biological Station, Nanaimo, pers. comm.).

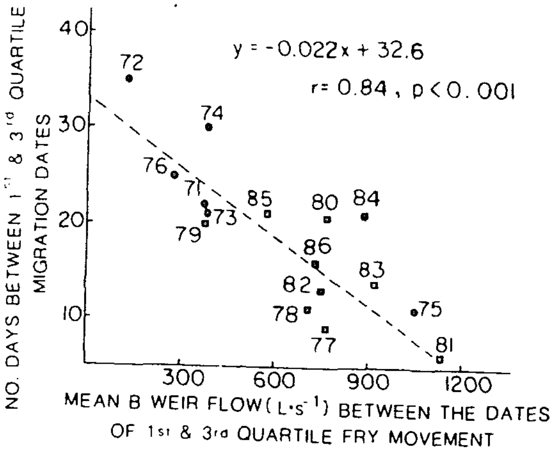

FIG. 93. Relationship between mean stream flow and the number of days between the first quartile (25 %) and the third quartile (75 %) of the coho fry counts through the main fish fence on Carnation Creek. Round and square symbols represent prelogging and logging years, respectively.

The coho fry that did not move into the sea or the estuary and remained within the stream, had a longer growing period, because of their early emergence, than did fry of prelogging years. As a consequence, they were larger in late September (Fig. 68 ; Holtby 1988). The larger size of coho in the autumn was almost entirely due to a longer period of growth rather than to higher stream temperatures during summer (Hartman et al. 1984). There was a strong positive relationship between fry size November 1 and their survival during the subsequent winter (Fig. 72, 90). Holtby (1988) also suggested that fry which reached a critical size in the late autumn would smolt at age 1+ in the following spring. As a result of higher overwinter survival of 0+ coho salmon and an increase in the fraction of such fish that became smolts both the number and the proportion of age 1+ coho smolts were dramatically increased (Fig. 74, 90). The fraction of 2+ coho smolts declined because more of them left the stream at age 1+ and because survival did not improve for fish that remained a second winter in the stream despite their increased size. The analysis by Holtby (1988) showed that the numbers of coho smolts increased initially (1978 to 1984) because of these temperature processes (Fig. 90).

Two processes have operated over time to reduce coho smolt production since 1983–84. These involved changes in egg-to-fry survival and reduction in the number of returning adults (egg deposition). Egg-to-fry survivals have been lower during all winters since 1977 except for the winter of 1984–85. During the 1984–85 winter, discharges in the stream were more stable than in other years. This contributed to the high egg-to-fry survival during that winter.

The time of smolt migration to sea, which was strongly correlated with thermal summation during March and April, has advanced by up to 2 wk since logging began. The advance in smolt migration timing, 81 % of which was accounted for by logging based on predictive models, reduced the marine survival of both age 1+ and 2+ migrants (Holtby 1988).

Actual returns of fish were even lower than those predicted by the model of Bilton et al. (1982) due to further marine mortality (Holtby 1988). The predicted returns of Carnation Creek coho with the Bilton model were 14.3 % for age 1+ coho smolts and 15.6 % for age 2+ coho smolts between 1971 and 1976. The predicted returns for both groups fell to 10.7 % for 1977–84 (Holtby 1988). The change in migration timing in part negated the earlier effects of increased smolt production. The net increase in predicted return of adults was 19 % for 1977–84. The use of more recent data and models that partition logging impacts and climatic variability predicted a small negative effect from logging on returning adult numbers (– 5 %, Holtby and Scrivener 1989). Most of the observed reduction in adult returns since 1980 (Fig. 59) was attributed to poor ocean conditions.

The effects of temperature changes on trout production formed a less clear scenario than was the case with coho. Trout probably emerged earlier owing to increased thermal summations in the Mar.–Apr. periods after 1977, but emergence timing was poorly documented. The sizes of trout in Carnation Creek were correlated with thermal summations for fish in the lower main creek, (Table 14), upper main creek and a small tributary (Fig. 71, Table 15). Therefore, we concluded that during spring and summer, there was a positive effect of stream temperature on trout size at least during their first year. This was also demonstrated for trout fry in a series of enclosure experiments (de Leeuw 1982).

The relationship between stream temperature and trout size tended to weaken with age (Table 14 and 15). Actually, average daily increments of FL declined for 1- and 2-yr-old trout after logging was begun (Mann–Whitney *U*-test ; age 1+, $P < 0.01$, age 2+, $P < 0.05$). They also declined in relation to the higher stream temperatures (Fig. 94).

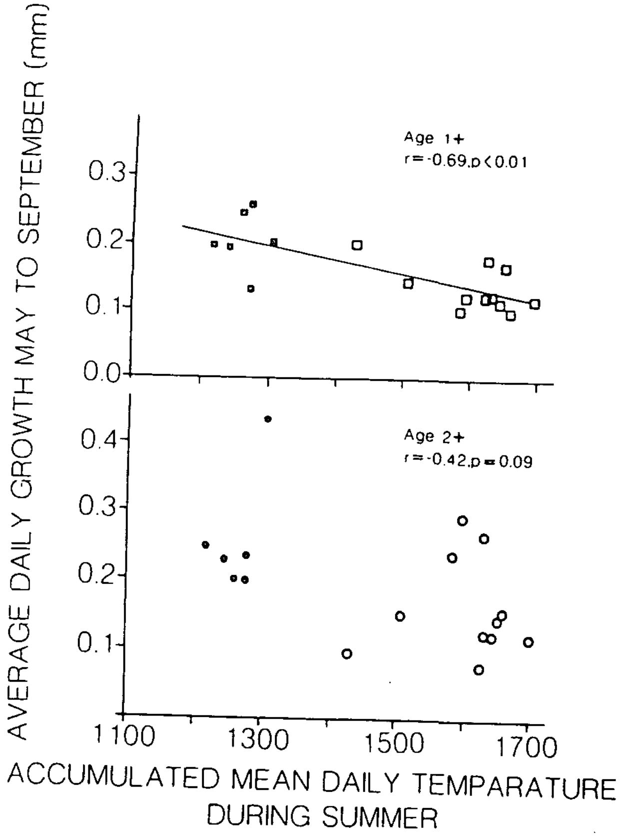

FIG. 94. Year class relationships between the average daily increase in length of trout (June–Sept.) and the total of mean daily stream temperatures from June 1 to September 30 in Carnation Creek (solid symbols, prelogging ; open, logging and postlogging years).

Relative growth among trout that were older than 1 year was not related to total trout density (1+, $r = 0.46, P = 0.09$; 2+, $r = 0.32, P = 0.21$) or to coho salmon density ($r = 0.32$, $P = 0.21$). Summer trout numbers, salmon numbers and relative growth rates all declined over time (trout, $r = -0.75$, $P < 0.001$; coho, $r = -0.60$, $P < 0.01$; trout growth, $r = -0.58, P < 0.05$), which would tend to mask any negative relationship between growth and density (Table 14 and 15).

Although estimated September 30 trout lengths were greater after 1977 in the lower 3.1 km of Carnation Creek (Fig. 69), the size of smolts leaving the system were not correspondingly larger (Fig. 75). We can infer a beneficial effect of stream temperature on size of trout during their first year of residence. However, over the next 1.5 or 2.5 yr (until smolting) its influence was detrimental (Fig. 94). Other factors such as a higher mortality amongst older or larger fish may also have negated the early benefit of higher stream temperatures. This was observed for age 2+ coho salmon (Holtby 1988 ; Holtby and Scrivener 1989). Evidence has already been presented indicating a small age shift towards younger trout smolts (see Smolt sizes, numbers, and emigration timing, Chapter 6).

The processes summarized in Fig. 90 show that a temperature increase during a particular period of the year could affect the production of a species or age groups of a single species in a positive, negative, or neutral manner. A temperature increase in winter had negative effects on chum salmon and either positive or negative effects on coho salmon or trout. Figure 90 also demonstrates that impacts of temperature changes in one season may still be affecting survival 1-yr or 2-yr later (see Smolt sizes, numbers, and emigration timing ; Marine survival, Chapter 6). Finally the process summary indicates that other factors, such as debris stability, gravel quality and food production in the system enter the process, and may moderate or accentuate the effects of temperature changes.

Physical Changes and Trophic Responses

Figure 95 integrates physical impacts of logging activities, and trophic responses. The most reliable information about nutrient effects on primary production, the role of detritus in macroinvertebrate production and the effects of sand on insects came from trough and enclosure experiments (see Stream macroinvertebrates, Chapter 6). The schematic diagram is an integration of experimental and field data in which we attempted to show some of the main features of the stream production processes, but it is not based on a cohesive analysis as was the case with temperature related processes and coho salmon production (Holtby 1988).

Three different logging activities had the potential to affect litter input and periphyton production and hence macroinvertebrate abundance. The physical impacts of the activities were different and the mechanisms through which they affected production processes were different (Fig. 95).

Although increased light at the stream surface and elevated stream temperatures, following logging, had the potential to increase periphyton biomass, the change did not occur. Periphyton biomass before and after logging was similar in six out of nine cases (3 sites measured for 3 yr ; Shortreed and Stockner 1983). We infer a weak positive effect, if any, of light and temperature increase on periphyton biomass (Fig. 95). Nutrients, particularly phosphorus, limited periphyton production in Carnation Creek (Stockner and Shortreed 1989). In lower Carnation Creek, phosphorus levels were not elevated following logging and slash burning (Fig. 38). The level of phosphorus was insufficient, or the timing of its release was inappropriate, to cause an increase in primary production because an increase of periphyton biomass was higher only three of nine times after logging (Fig. 51). If there was enhancement of periphyton growth, resulting from light, temperature and nutrient changes, their effects may have been masked by losses resulting from freshets, increased sand movement and consequent scour of accumulated biomass (Fig. 95 ; Shortreed and Stockner 1983). Phosphorus levels increased for ~18 mo after application of the herbicide (Scrivener 1989) which led to increased periphyton only during 1985 (Holtby and Baillie 1989a).

Leaf litter input and the production and processing of detritus is the second route by which macroinvertebrates may be influenced (Fig. 95). Two effects of stream-side cutting on litter input and retention are implied in Fig. 95 :

1. The loss of LOD appeared to cause reduced retention of leaf litter and detritus in the main stream because it promoted instability of the streambed (Fig. 43). Such an effect was demonstrated in an Appalachian stream by Bilby and Likens (1980).
2. The removal of stream-side trees resulted in the short term reduction of leaf litter input (Fig. 53, 54). However, if alder trees and salmon berry shrubs were allowed to continue to grow at the stream margin (not treated with herbicides), leaf litter input increased 10-fold within 8 years of clearcutting (see Leaf litter, Chapter 6 ; Holtby and Baillie 1986b).

Low levels of alder detritus attracted few macroinvertebrates. The weight of detritus that was added to substrate containers in the streambed was positively correlated with

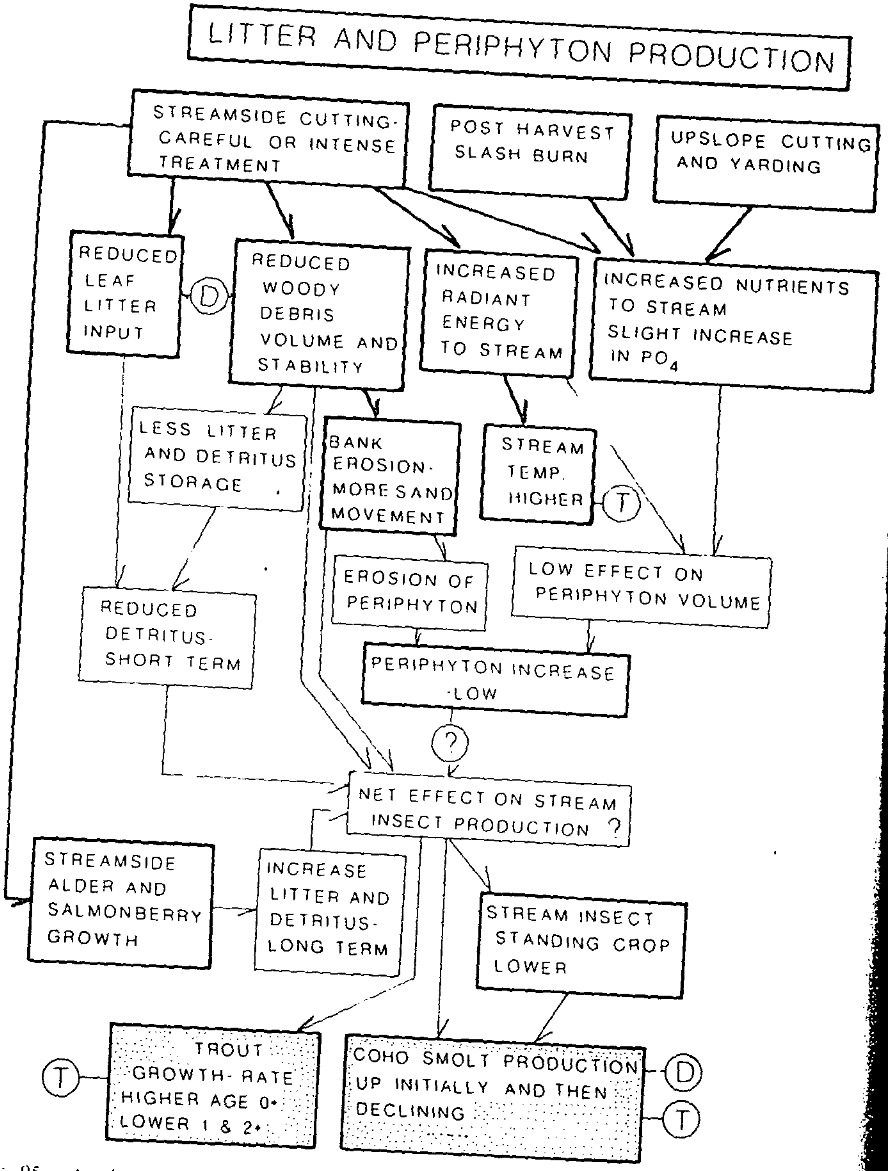

FIG. 95. A schematic diagram outlining the effects of logging activities on leaf litter input and periphyton accumulation rate, and the subsequent effects of changes in these conditions on macroinvertebrates. The capitals *D* or *T* indicate an important point of connection between processes affecting litter input and periphyton accumulation, and debris or temperature related processes. See caption of Fig. 80 for explanation of width of lines and stippling.

macroinvertebrate colonization rates in Carnation Creek (Culp and Davies 1983). In addition, increases in the amount of sand in the substrate and moving over it reduced macroinvertebrate standing crop and elevated the level of insect drift (Fig. 56).

Culp and Davies (1983) have shown that macroinvertebrate standing crops were lower in stream sections which were clear cut to the bank than in those with leave strips. They have also shown that macroinvertebrate standing crop was lower in both leave strip and clearcut stream sections after logging. Culp and Davies concluded that a reduction of detritus input and storage, combined with the effects of sand intrusion into the substrate and movement over it, caused a net reduction of macroinvertebrates in the stream below the intensive treatment area (Fig. 95).

In Carnation Creek, the accumulation of periphyton and litter input are seasonal events (Fig. 96). The combination of periphyton production, and deciduous and coniferous litter inputs created greater food resources over more of the year for macroinvertebrates than any single source could provide (see Leaf litter, Chapter 6). Much more analysis of Carnation Creek macroinvertebrate data is needed to reveal the relative importance of allocthonous (detritus) and autochthonous (periphyton) material to insect production, but few changes to community composition were observed (Culp and Davies 1983). An analysis of the growth rates of stream insects is needed to reveal whether temperature increases affected size or life history patterns. Figure 95 suggests an effect of insect production on trout and coho salmon growth. Because the standing crop of macroinvertebrates was lower, we infer that fish growth should be adversely affected if fish are dependent on this source of food.

In Carnation Creek, trout and coho salmon utilized slightly different food resources. Like trout, coho salmon depended mainly on aquatic organisms (drift), but terrestrial insects and winged adults of aquatic origin were common in their diet (Table 16). Unlike

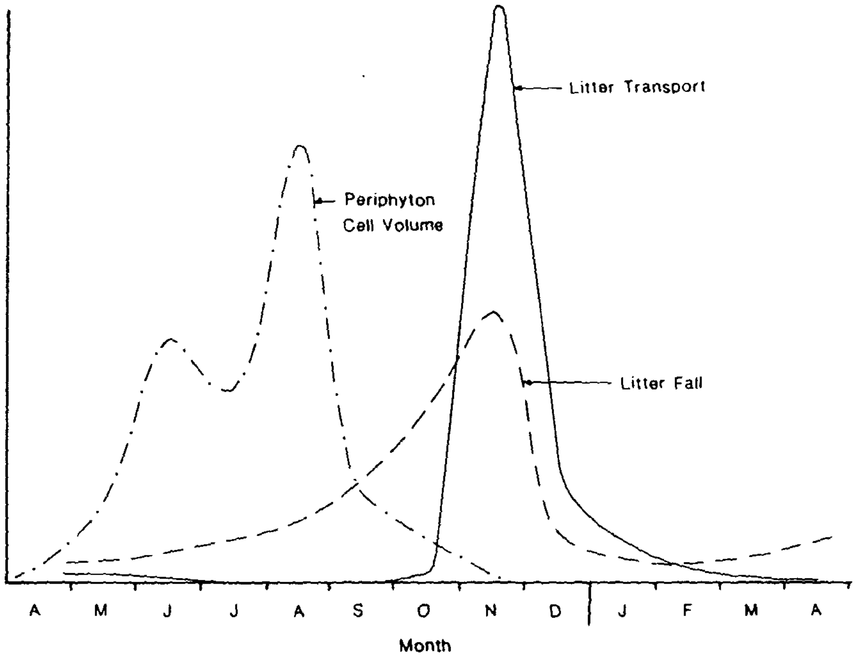

FIG. 96. Generalized diagram showing the annual pattern of periphyton accumulation, litter fall, and litter export in Carnation Creek.

TABLE 16. Sources of food as a percentage of total organisms contained in the stomachs of coho salmon and trout from 10 feeding studies at Carnation Creek. Each month contains data from ~100 coho salmon and ~20 trout that were obtained between June 1971 and May 1974.

	May	June	July	August	September
Coho					
% aquatic drift	75.2	67.2	77.4	46.8	69.8
% aquatic adults (surface feeding)	8.5	17.2	7.5	28.4	5.9
% terrestrial	16.3	15.6	15.1	24.8	24.3
Trout					
% aquatic drift	96.3	96.9	96.0	85.5	
% aquatic adults (surface feeding)	0.3	0	2.0	2.7	
% terrestrial	3.4	3.1	2.0	11.8	

trout, coho salmon fry became more dependent on food of terrestrial origin later in the summer. These differences in diets probably reflected different feeding behaviours. Coho salmon fry tended to feed at the surface of water (Chapman 1966), while trout tended to feed in the water column (Lowry 1966). Age 1+ coho salmon tended to occupy the deeper water and behaved in a manner similar to trout at least during the early autumn (Bustard and Narver 1975 ; Tschaplinski and Hartman 1983).

The tendency of coho fry to be less dependent on aquatic food resources might in part explain the different size and growth responses that were observed for coho fry and the older age classes of both coho salmon and trout. Older coho and trout had to contend with a declining food resource and higher water temperatures (greater metabolic rate) after logging. Meanwhile, coho fry depended on terrestrial sources for as much as 25 % of their food (Table 16). Removal of the forest canopy along the stream reduced some of these terrestrial organisms (e.g. spiders, leaf hoppers and springtails), but the total number of aerial insects around a stream usually increased after removal of the stream-side canopy (Mundie 1974 ; Nelson 1965).

Interaction of Temperature, Debris, Hydrological, and Production Processes

The physical changes produced by different forest-harvest activities had separate and different effects on the processes that determined stream temperature, LOD, channel morphology, and spawning gravel characteristics. These in turn had different effects on fish food production, and on the growth, survival, distribution, and numbers of fish. There were some positive effects, some negative effects, and others that were either neutral or undetected (Fig. 85, 90, 95).

We believe that the logging related temperature and nutrient increases pushed the system toward higher fish growth and production during the freshwater stages of their life histories. By contrast, logging related changes in LOD, channel morphology and streambed stability and composition, exacerbated by the natural hydrological variability, depressed fish survival and production. These changes in the stream are easier to understand if they are examined in terms of :

1. logging activities,
2. physical changes in the system,
3. effects of physical changes on fish by species and life stage.

In Fig. 79 and Chapter 5, we illustrated which physical characteristics in the stream system were affected by logging activities. However, this Figure matrix only indicated whether or not a physical characteristic was changed and what the direction of the change was (e.g., temperature increase, debris volume decrease, nutrient level increase). The matrix in Fig. 97 has the same format as the one in Fig. 79, however, in Fig. 97 we have indicated the effect of the impacts on different species and life history stages of chum salmon, coho salmon, steelhead trout and cutthroat trout. The matrix summarized results from Chapters 5 and 6. We will not discuss each sub-matrix ; however, there are seven major conclusions that may be drawn from the figure.

1. Most logging activities produced a multitude of effects in the system (e.g. stream-side falling produced responses in most categories).
2. A few activities had no effects on physical conditions in many categories (e.g., road construction had no effect on light, temperature and nutrient flux in the stream).
3. Activities could change the physical conditions, but the effects on fish could be neutral or undetectable (e.g., peak precipitation to peak flow times or water routing in the small 12 ha sub-basin).
4. Activities such as stream-side falling increased small debris and scour which had clear negative effects for a single life stage of all species (egg incubation in the streambed), while upslope logging had positive effects on water yield and on all fish rearing in the stream during summer.
5. Activities that increased stream temperature produced positive effects at one life stage (1st summer and winter) and negative effects at another stage (2nd summer and winter) of a single species (coho salmon).
6. Physical changes caused by a logging activity could have a positive effect on some individuals and a negative effect on others, within the same species and life stage, depending on how they behaved : (e.g. Increases in stream temperatures during winter caused early emergence of coho fry and increased the probability that such fry would be exposed to one or more late winter freshets. Fry moved to sea with these freshets and were presumed to be lost, others that did not move experienced a longer growing season, a larger size and a greater survival rate).
7. Logging activities generated physical changes which occurred over different time scales. Falling, yarding and slash burning, for example, caused temperature changes that occurred immediately, while physical changes of the channel required 2-3 yr to appear. Re-growth of trees, (planted or wild) is anticipated to cause water temperatures, water yield, and nutrient decreases within a decade.

Temperature regime, debris characteristics, gravel quality, stream hydrology and food production interacted to affect fish production. Although we considered their impacts separately in schematic models (Fig. 80, 85, 90, 95) we will now attempt to integrate their effects on fish production. Models based on empirical information have been developed for integrating the various effects of temperature, debris, gravel quality and food production changes on the populations of coho and chum salmon (Holtby and Scrivener 1989), but integration of these effects is conjectural or inferential for trout.

Chum salmon

Changes in both channel condition and temperature regime had negative impacts on chum salmon production (Holtby and Scrivener 1989 ; Scrivener 1988b). Within the stream, changes in the stability of large woody debris (LOD) and channel condition and the consequent decrease in gravel quality and stability reduced egg-to-fry survival and size of emerging fry (see Emergence of fry, Chapter 6). Reduction of chum salmon survival was also caused by changes in the thermal regime during the incubation period, and by the consequent early emergence of fry. Smaller fry going to sea early experienced a lower survival after entry into the marine environment (Scrivener 1988b).

A long time series of data was required to distinguish logging-related effects from natural variability (Scrivener 1988b). Logging effects were masked by the inter-annual variability of adult returns of chum salmon (Fig. 58), that was caused in part by the

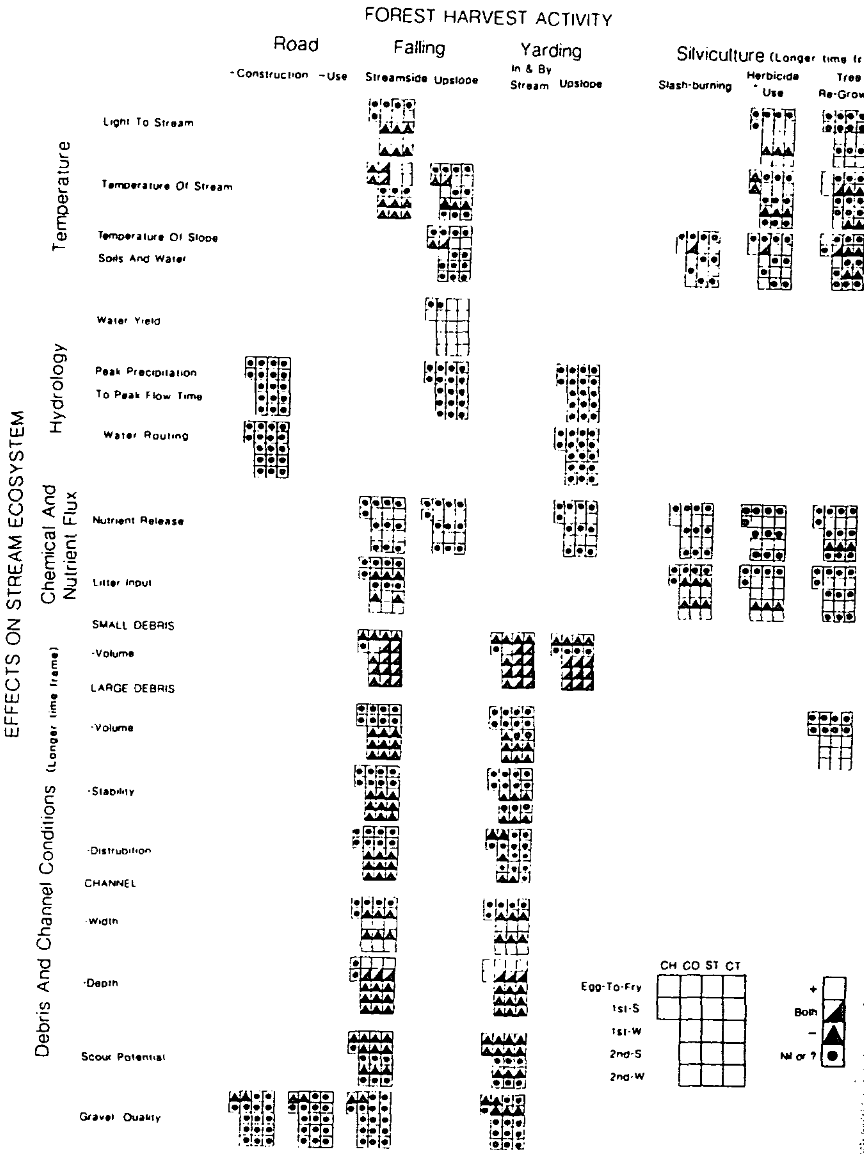

FIG. 97. The nature of responses of different species and different life stages of salmonids to changes in various habitat conditions caused by different logging and silvicultural activities. The sample sub-matrix, lower right, indicates the species of fish (CH — chum, CO — coho, ST — steelhead, CT — cutthroat) and the life stage (egg-to-fry, 1ST-S = first summer, 1ST-W = first winter, 2ND-S = second summer, 2ND-W = second winter). The nature of response at each life stage, if known, is indicated beside the sample sub-matrix.

natural variability of physical and meteorological conditions in the freshwater and marine environment. Responses of the stock were also slow to appear because the species has a 4-yr life cycle.

Using a sequentially linked series of regression models, the roles of climate, logging and fishing were explored for recruitment of adult chum salmon to Carnation Creek. Model inputs were observed time series of climatic variables from Carnation Creek (17 yr), and the Barkley Sound area (50 yr), and local fishing mortalities (Holtby and Scrivener 1989). A correlation coefficient of 0.78 was obtained between observed and predicted recruitment when the observed database of spawner numbers and physical data was used. Holtby and Scrivener (1989) concluded that :

1. Inter-annual variability in chum salmon numbers appeared to be equally attributable to variation of freshwater and marine factors ;
2. Logging effects had reduced adult returns by an average of 26 % and contributed to an increased inter-annual variability in fish abundance ;
3. Differences in fishing pressure were not an important contributor to inter-annual differences in fish abundance, although exploitation at historically high levels (35–40 %) produced variability of numbers that were 2–3 times greater than at moderate levels of exploitation ;
4. A collapse of the stock occurred when the cumulative effects of habitat disturbance, adverse oceanic conditions, and high exploitation rates prevailed.
5. The stock did not recover until at least 2 of the 3 factors were very favourable to chum salmon production.

Coho salmon

The numbers of coho salmon smolts (Fig. 74, 76) were affected by the interaction of changes of stream temperature, LOD, channel morphology, and spawning gravel quality (positive and negative effects) in the freshwater environment. The numbers of adult spawners (Fig. 59) were also affected by a period of adverse oceanic conditions. Juvenile coho salmon exhibited behaviour patterns that buffered the effects of crowding and habitat loss (e.g., downstream movement during freshets and use of off-channel habitat).

Logging and a warming climate had a positive influence on the number of smolts between 1978 and 1981. They caused stream temperatures to increase during winter and spring which improved survival and growth of fry and smolting rates of 1-yr-old juveniles. The large number of smolts (~80 %, age 1+ ; Fig. 74) was not attributable to an increase in egg deposition (see female number for the autumn of 1976, 1977 and 1978 ; Fig. 59). Egg-to-fry survival of fry emerging in 1977, 1978, and 1979 (Fig. 62) was also within the range observed during the prelogging period (23–37 %). The intensive and careful treatment areas held relatively more fish in the summers from 1977 to 1980 because stream-side logging introduced fine debris which created a structurally diverse habitat (Scrivener and Andersen 1984). Densities of fry in recently logged sections of Carnation Creek were high relative to unlogged sections (see 1977 and 1978 in the intensive treatment sections ; 1979 and 1980 in the careful treatment section ; Fig. 87).

Logging had a positive influence on the size of coho fry in September (Fig. 68) and on the size of age 1+ smolts during the following spring (Fig. 73). They were ~10 % larger during the logging period (summer 1977 to spring 1981) and 15–20 % larger during the postlogging period (summer 1981 to spring 1987) than during the prelogging period (1970–76). This increased size was caused primarily by the earlier emergence of fry and extension of the growing season (Holtby 1988), but low densities also influenced the size of coho during the postlogging period. Summer growth rates of fry were negatively correlated with density for the whole stream (Holtby 1988) and for each study section (Scrivener and Andersen 1984). We suggest that the structural diversity of habitat caused by fine logging debris kept densities up and growth rates down in the intense treatment during 1977 and 1978, and in the careful treatment during 1979 and 1980 (Fig. 87). Densities were also high (Table 11) and growth rates low during 1980, because of the large number of spawning females during autumn 1979 (Fig. 59). These were the returns from the 1976 brood year, the first generation that benefitted from logging. Densities declined and growth rates increased when freshets removed the fine logging debris and channelized the stream in the intense treatment during November 1978 and in the careful treatment during December 1980 (Table 7). Densities also declined and growth rates increased as egg-to-fry survival (Fig. 62) and egg deposition (Fig. 59) declined during the postlogging period.

Logging of the stream side caused fry numbers to decline during the postlogging period. After the freshet in November 1978, erosion in the stream channel increased (Toews and Moore 1982) and the quality of spawning gravel declined (Hartman et al. 1987 ; Scrivener and Brownlee 1989). Increased sand in the streambed and increased gravel scouring reduced egg-to-fry survival of coho salmon (Fig. 62), therefore numbers of age 0 + coho were lower in the autumn (Fig. 66b). An exception occurred during summer 1980, when the exceptional egg deposition of autumn 1979 (Fig. 59) offset the poor egg-to-fry survival of winter 1979–80. Coho fry moved seaward during freshets throughout the study and did so even during years when densities were below those that the stream had accommodated during prelogging years (Fig. 66a). Changes in the streambed and the response of fry to freshets both reduced their numbers in the stream.

Total smolt numbers increased after logging (Fig. 76), but smolts now consisted of a single age group and they were smaller in size because large 2-yr-olds were rare. Over-winter survival increased due to the larger juveniles in autumn (Fig. 72). The large size of juveniles also caused an increased number of 1-yr-old coho salmon to smolt (Fig. 74). Therefore, total smolt production was not affected by the increased mortality during a second year of stream life (see Over-winter survival, Chapter 6).

The behaviour of moving to flood plain habitat buffered the impacts of winter habitat deterioration in the main creek. Physical changes in LOD and channel structure had the potential to reduce over-winter survival of age 0 + coho salmon. However, many 0 + coho moved to small ponds and tributaries on the flood plain during winter. Survival in this flood plain habitat was high and as much as 24 % of the smolt production came from it (Brown and Hartman 1988).

In summary we suggest the following interacting effects of temperature, substrate composition and debris on numbers of coho salmon :

1. The increased numbers of smolts, 1978 to 1980 were the result of relatively warm water temperatures during egg incubation, high egg-to-fry survival levels, and high summer carrying capacity because of fine debris in three study sections of the stream.
2. A large smolt production occurred during 1981 when an exceptional number of females returned from the first brood year that was affected by logging.
3. The sizes of the fry in autumn were larger because fry emergence was early from 1977 to 1986 and because low densities produced high growth rates from 1981 to 1986.
4. The negative effect of deteriorating quality of spawning gravel, reduced summer and winter habitat, and declining adult returns after 1980 (Fig. 59) partially offset the benefits of warmer stream temperatures. These factors and the rapid decline of 2-yr-old smolts after 1980 (Fig. 74) caused coho smolt production to begin declining.
5. When young coho moved into flood plain habitat during autumn to over-winter, higher survival occurred in such habitat on wet years and it buffered negative effects of habitat loss in the main channel.
6. Warmer early spring temperatures caused coho salmon to undergo smolting earlier in the year. Marine survival of such early migrants was lower than that of prelogging smolts (see Marine survival and movement of salmon, Chapter 6). This contributed to the trend of declining adult returns and egg deposition (Holtby 1988).

The roles of climate, logging, and fishing on recruitment of adult coho salmon were also explored using a sequentially linked series of regression models (Holtby and Scrivener

1989). The model explained 66 % (r^2) of the variance in returns for fish spending 18 mo in freshwater and 71 % of the variance for fish spending 30 mo in freshwater, when the observed time series of physical variables and numbers of spawners were used as inputs. Holtby and Scrivener (1989) concluded that :

1. Inter-annual variability of returning coho salmon was equally attributable to freshwater and marine factors, although the impacts of some freshwater factors did not affect survival until the fish entered the ocean.
2. The temperature benefits attributable to logging were almost entirely lost because coho smolts emigrating early in the spring at a small mean size (2-yr-olds were rare) had poor marine survivals. The net effect of logging was a 6 % reduction in adult returns, but inter-annual variability in fish abundance increased.
3. After 1981, most of the observed reduction in recruitment of adult coho salmon was attributed to climatic differences in the ocean.
4. The cumulative effects of habitat disturbance, adverse oceanic conditions and sustained high exploitation (>65 %) led to increased levels of variability at very reduced abundances of coho salmon.

Steelhead trout

How steelhead smolt production was adversely affected has not been clearly demonstrated, but both coho salmon and steelhead trout were similarly influenced by many of the same factors. Temperature increases had a positive effect on the sizes of age 0 + and 1 + steelhead and cutthroat trout over the course of the study (Fig. 69 ; Table 14 and 15). Larger size, on September 30, in the latter part of the study was a composite effect of increased incubation temperatures (and hence longer growth period), of warmer water temperatures during their first spring in the stream, and of lower densities of trout. These positive effects were not exhibited by the number (Fig. 76) or size (Fig. 75) of steelhead smolts when they emigrated to the ocean. The larger size of juvenile trout in autumn did not appear to improve their over-winter survival. Smolt size did not increase over the course of the study because the early benefits were almost entirely lost through poorer growth during the second and third summer of stream residence. These observations were similar to those that were described for 2-yr-old smolts of coho salmon (Holtby 1988). A slight shift towards younger trout smolts may also have affected their size (see Smolt sizes, numbers, and emigration timing, Chapter 6).

We speculate that the decrease in the volume of LOD and the increase in the degree to which it collected in single locations throughout half (1600–3100 m) of the stream, reduced winter habitat for steelhead parr over one year of age. Increased scour and deposition of the streambed where the stream bank was logged also reduced the winter habitat for age 0 + trout. The interaction of temperature effects and stream channel changes determined, in part, the pattern of change of steelhead numbers (Fig. 76).

The behaviour of young steelhead also made them more vulnerable than coho salmon or cutthroat trout to changes in the main creek. Steelhead trout were not inclined to occupy small tributaries and swamp habitat (Hartman and Brown 1987 ; Hartman and Gill 1968 ; Cederholm and Scarlett 1981) so they were more vulnerable to the type of physical changes which occurred in the main channel of Carnation Creek.

Could changes in steelhead numbers in Carnation Creek reflect coastwide patterns of abundance ? The trends of steelhead smolt (Fig. 76) and adult numbers (Fig. 60) in Carnation Creek do not follow those of the Keogh, Gold or Somass rivers on Vancouver Island (Fig. 98). Therefore, steelhead population trends in Carnation Creek were not typical of a coastwide pattern and the decline in numbers after 1977 were due to factors that were particular to Carnation Creek.

In summary, we suggest that temperature changes caused steelhead sizes to increase until spring of their first year. Thereafter, they declined in size in a manner similar to that demonstrated for coho salmon (Holtby 1988). Changes in LOD and channel stability

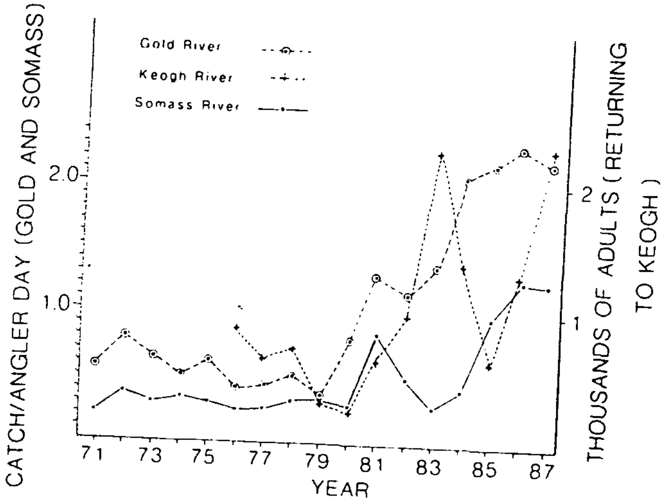

FIG. 98. Indicators of coast-wide abundance are shown for wild steelhead (Vancouver Island). Catch per angler day for Somass and Gold rivers and numbers of steelhead entering the fish counting facility on the Keogh River are used (data of angler catch of steelhead from statistics of the Government of British Columbia).

caused decreases in the winter survival of steelhead parr so that numbers of smolts declined.

Cutthroat trout

The negative impacts from logging were less pronounced on cutthroat trout than on steelhead trout because of behavioural and distribution differences between the species. Numbers of cutthroat smolts varied from 4 to 117 between 1971 and 1987 (Fig. 76) indicating little or no net effect from logging. Stream temperature increases caused by logging had similar influences on both trout species because the FL of all age 0+ and 1+ trout in the lower main channel were positively correlated with temperature (Table 14), and because the FL of age 0+ cutthroat trout in a tributary and upper Carnation Creek were also positively correlated with stream temperature (Table 15). Larger fish on September 30 were presumed to be the effect of early emergence (longer growth period) and more rapid growth until age 1+. The changes in debris volume and distribution, and channel morphology had no apparent negative effect on cutthroat smolt numbers. Like coho salmon, parr of cutthroat trout are more inclined than steelhead trout to occupy small ponds (Cederholm and Scarlett 1981) or small tributaries and sloughs. The highest densities of cutthroat trout were found in two intermittent tributaries on the floodplain (Hartman and Brown 1987). Cutthroat were also inclined to spawn in tributaries, while steelhead trout spawned in the main stream. Although the adult counts of returning searun cutthroat trout represented minimum numbers only, they suggested that spawner numbers were maintained undiminished into the logging period longer than those of steelhead trout.

In summary, we suggest that elevated stream temperatures had positive effects on the size of cutthroat trout until 18 mo of age and negative effects during the remainder of their lives. The capacity of cutthroat trout to rear and spawn in small tributaries, and to move into and out of them may have buffered this species from the deterioration of habitat in the main channel.

Chapter 8. Ecosystem Perspectives : Time, Similarities, and Diversity

There are limitations in the Carnation Creek study, which preclude full understanding of processes within the system. These reflect the funding and logistic problems of accurately measuring and analyzing enough variables within the system to fully understand it. In addition to these study limitations our data series covers only a short period within one forest rotation and only a fraction of the time required for measurable geomorphic processes. This study reveals many important conditions and processes within one basin, but it does not reveal the diversity among systems. However, the understanding of processes will help us to understand the cause of diversity when we observe it.

The importance of time, as an element of change within ecosystems is discussed in the following subsection of this chapter. The last subsections deal with some of the overriding common features of coastal stream systems in British Columbia as well as diversity among these streams.

Time

Resource users and managers tend to view situations in terms of time scales that reflect only the most immediate concerns. Most individuals currently involved in research and management, do not expect to be here 50 yr from now and although they might do so, are not inclined to view ecological processes in the time scale which may be required for understanding.

Ecosystems which have been subjected to events such as dam construction, major fires or logging may continue to respond to them for decades or centuries (Bormann and Likens 1979 ; Petts 1980 ; Dale et al. 1986). The projected long-term responses, so often ignored, are complex and important to society. Strayer et al. (1986) in a review of the design, operation and importance of "long-term studies" pointed out that such studies may be the only way to detect slow processes, rare events and subtle changes. They may also be the only way of understanding cumulative impacts both natural and man-induced.

Only one of 15 long-term studies have extended beyond the reorganization phase in a logged watershed. Hall and Knight (1981) listed 13 extended studies of fish populations or ecosystems. The list did not include the Nashwaak study in New Brunswick or the Hubbard Brook study in New Hampshire. Including these, only one of the studies, the Hubbard Book project, extended or was planned to extend beyond 20 yr. The reorganization phase is an immediate post-disturbance period characterized by drastic changes in hydrologic, ecological, energetic and biogeochemical processes (see Bormann and Likens 1979). This phase is also a period in which there is loss of biotic regulation causing increased variability. Within this phase, however, there are also strong homeostatic mechanisms that come into play and move the system toward more constant and predictable conditions (Bormann and Likens 1979).

At present most fisheries/forestry studies compare disturbed systems, in the reorganization phase, with undisturbed systems or they examine processes in the reorganization phase only. In reality, there are no long-term ecosystem studies being carried out in North America. Petts (1980) stated :

> "The environmental scientist should anticipate the consequences of human impacts over 50-, 100-, or perhaps even 500-yr time-scales, as well as those of immediate significance."

We subscribe to this view and believe that there is great need for an appreciation of the effect of time with regard to past disturbances of river systems (see Sedell and Luchessa 1982 ; Sedell and Froggatt 1984 ; Grette 1985 for studies that reveal such appreciation). There is also a need for a better perspective on future patterns of change in disturbed

Bormann and Likens 1979 ; Dale et al. 1986 ; Triska and Cromach 1980 ; Triska et al. 1982 as examples).

Extended time series of data, either case history ecosystem or stock re-construction studies, have permitted analyses of complex patterns of interaction among habitat change, fishing pressure and management decisions that would not otherwise be possible. For example, with an 80-yr data base, Hyatt and Steer (1987) were able to demonstrate and separate effects of fishery allocation decisions, habitat management programs and climatic cycles on sockeye salmon of Barkley Sound. Holtby and Scrivener (1989) required a 50-yr meteorological data base to partition the effects of climatic variability, logging, and fishing on numbers and sizes of adult coho and chum salmon returning to Carnation Creek. Mysak (1986) presented patterns of sea level and salinity changes which were only evident with a 20–40 yr data base. Without such time series Mysak (1986) would not have been able to produce such a powerful and holistic analysis of El Niño-southern oscillation phenomena. Shorter data series would not have permitted such analyses. We believe, that variability in conditions may obscure important long-term patterns of change within a system.

These discussions of historical perspective and the use of long-term data bases do not mean that Carnation Creek should be studied continuously for 200–300 yr. It would be difficult to apply such information, after the fact, to management. We do suggest, however, that there is need to study processes over an extended time in a series of systems that were logged 40, 60, and 100 yr ago. Information from such work would have a bearing on management decisions. There is also an urgent need to predict where possible what the management problems of the future might be and to initiate research in these areas (e.g. future logging will occur in second-growth forests).

Carnation Creek — Future Patterns of Change

In the absence of research on other stream systems that were logged 40–100 yr ago, we may project the patterns of change in the Carnation Creek drainage into the future. This cannot be done with accuracy, although the approximate timing of stages of forest succession are known. The changes in vegetation will determine the degree of solar input to stream areas. They will also determine the characteristics of evapotranspiration, water yield and nutrient flux in the watershed. The pattern of loss of old-growth woody debris and accumulation of second growth woody debris in streams on the Olympic Peninsula has been described (Grette 1985). The role of LOD in retaining sediments, leaf litter, and particulate organic matter in stream channels has been reviewed by Bilby and Likens (1980), Triska et al. (1982), and Swanson et al. (1982). Based on such information from other watersheds and our knowledge of the initial responses within Carnation Creek we will speculate about the nature of future changes. We provide a series of projections of long-term changes that will likely occur and we emphasize their importance to stream productivity.

The initial responses in Carnation Creek have been published elsewhere and are reviewed in this manuscript. We will briefly summarize them again :

1. Light intensity on slopes and stream surface doubled or more than doubled following forest harvesting.
2. Diurnal and seasonal variability of stream temperature increased and mean temperatures were 3°C higher during summer and 0.5°C higher during winter for the first decade following logging.
3. Nutrient levels increased 40–80 % at least during high flows for 2–4 yr following logging and for 1–2 yr following herbicide application.
4. Water yield increases were detected in tributary watersheds (>95 % clearcut), but they were not significant for the total basin (41 % clearcut). Groundwater levels increased on the flood plain. Duration of the period of higher groundwater levels is at least a decade.
5. Fine woody debris increased in the stream, but it was lost within 2 yr.
6. Large woody debris (LOD) became clumped and it was reduced to ~30 % of prelogging volume within 2 yr in areas that were logged to the stream bank. Stability and piece size of LOD decreased within 2 yr. Instability continues for at least a decade.
7. Channel erosion and change of channel location began within 4 yr of onset of logging and it is continuing.
8. Litter input to the stream was reduced to 25–50 % of prelogging levels after logging and silvicultural treatments. About half of this loss had recovered within a decade.
9. Pea gravel and sand content of the streambed had doubled during the decade since cutting. Changes were still occurring.
10. Macroinvertebrate densities were reduced 40–50 % following stream-side logging and silvicultural treatments.
11. For the coho salmon population : Egg-to-fry survival, numbers of age 0+ coho in autumn, and numbers of 2-yr-old smolts declined after logging ; fry emerged earlier producing a longer period for growth and a larger size for parr ; numbers of smolts (age 1+) and female adults increased then decreased at double the prelogging inter-annual variability.
12. For the chum salmon population ; egg-to-fry survival, fry size, and adult returns were reduced and more variable following logging and the fry emigrated earlier to the ocean. The 90 % reduction of adult chum salmon was caused by poor ocean conditions (64 %) and by logging (26 %).
13. The steelhead population decreased, while the cutthroat population was unchanged.

Conditions recorded within Carnation Creek watershed were consistent with those that represent the reorganization phase after disturbance (see Bormann and Likens 1979). The increase in light and stream temperatures, the imbalance in geochemical conditions (nutrient loss, erosion and reduction in transpiration), the loss of biotic stability (poor coupling of nutrient release and primary productivity), and the increased variability of fish numbers all indicated instability of a reorganization phase.

In Fig. 99 we present a series of diagrams indicating the long-term patterns of change which we speculate will occur in a system such as Carnation Creek. We stress that the patterns in Fig. 99 are qualitative, and only the first decade shown is based on empirical Carnation Creek data. We believe, however, that the nature of potential changes indicates the need for research scientists and managers to consider them in planning future studies and in making decisions about ecosystems.

The re-growth of the forest sets the clock for most of the critical processes involved in the long, slow transition back to stability after disturbance. The patterns, over time, of shading, stream temperature, nutrient flux, water yield and LOD accumulation (Fig. 99) are all closely tied to forest re-growth. Bormann and Likens (1979) projected century long patterns of change in the forest condition. They suggested more stability and less dramatic rates of change after the reorganization phase (1-20 yr). In Fig. 99 we suggest lower rates of change after ~20 years.

Re-shading of the main stream is completed by the end of the reorganization phase, but riparian vegetation continues to change. In Ritherdon Creek, a drainage immediately north of and similar to Carnation Creek, the alder canopy closed over the stream in 16 or 17 yr. Murphy and Hall (1981) found that it took 10–20 yr for riparian vegetation to re-shade first to third order streams (see Strahler 1964). Triska et al. (1982) suggested that alder and willow will grow and re-shade first and second order steams within 10–15 yr of tree removal along western Cascade streams. After 15–25 yr the composition of riparian vegetation along such streams would begin to shift from deciduous to coniferous species. Shading by conifers would be heavy within 80 yr. Swanson et al. (1982) stated

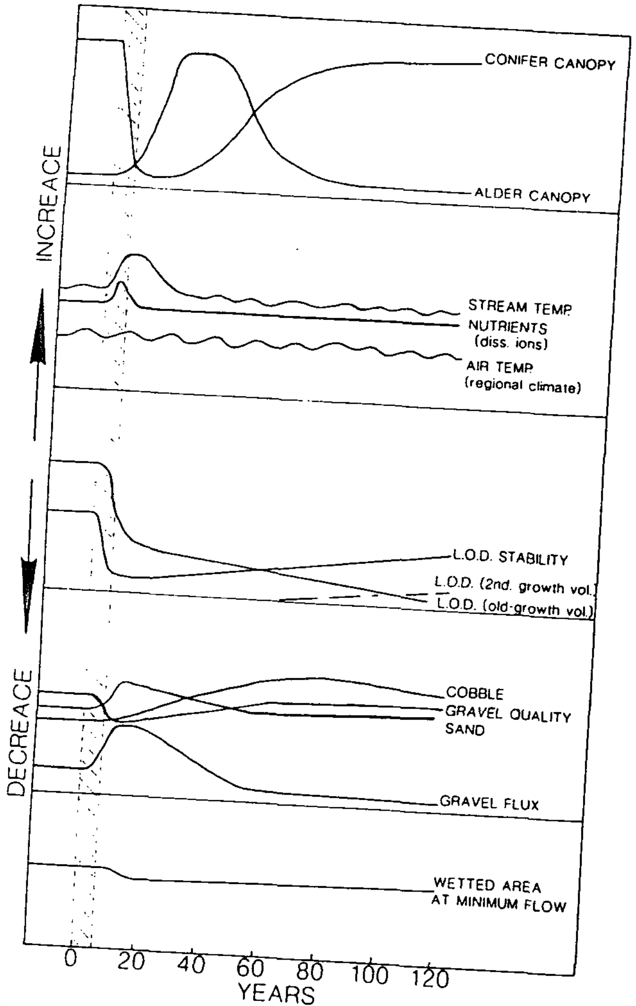

FIG. 99. Anticipated patterns of change in physical conditions in a small coastal stream, like Carnation Creek, following logging (cross hatch). The patterns for stream temperature and stream insolation are presumed to be similar.

that as a Douglas fir stand reached 60 yr of age its canopy would close over small streams and shade water and lower riparian vegetation. We speculate that a rapid development of alder growth and shade at Carnation Creek would be followed by a slow replacement with sitka spruce, hemlock and cedar along the stream side (Fig. 99).

Vegetation on the flood plain will be more variable. Vegetation has again covered 80–90 % of the surface area within a decade as distinct tree, shrub/herb, and forb/moss layers (see Forest regeneration, Chapter 6). Deciduous vegetation will predominate for 60–80 yr thereafter at the sites that are invaded by alder, unless herbicides are used (Kimmins et al. 1989). Regenerating and planted conifers will predominate at many other sites.

In Carnation Creek stream temperatures, during winter, spring and summer, should decline rapidly 15–20 yr after the cessation of logging if the climate warming trend observed during the last two decades (see Meterological record from station A, Chapter 5 ; and Holtby 1988) is the rising limb of a long-term cycle. Stream temperatures will still decline, but they will not return to prelogging levels if the increases at Carnation Creek are being caused by logging effects and a global greenhouse effect. Later changes should occur more slowly as canopy height and shading of the second growth forest increases.

Dissolved ion concentration in the stream rose and fell during a 2 or 3-yr period after forest harvesting, burning and herbicide use in Carnation Creek. The rapid return of ion concentrations to prelogging levels may be caused by the high precipitation and quick flushing of ions through the shallow slope-soils and out of the watershed. As the coniferous forest regrows it will progressively trap more of the dissolved ions in the bio-cycle (soil-vegetation) and fewer nutrients will be lost to the stream (Bormann and Likens 1979 ; Kimmins et al. 1989). Concentrations should decline below prelogging levels for 50–60 yr (Fig. 99). We recognize that leaching of dissolved ions to the stream is not the only source of nutrients. Swanson et al. (1982) outline hypothetical phasing of organic inputs into a small stream for 80 yr after logging. During the initial 20 yr there are rapid changes in the relative rates of input of herb, shrub, alder, and coniferous litter. Our suggestion of a decline in dissolved ion concentrations is consistent with the thinking of Bormann and Likens (1979) who state that during the rebuilding phase more nutrients and water are used by the regenerating forest and less passes through the forest floor to the stream.

Water uptake will increase as the new forest grows. We predict that the water yield from the basin, and consequently stream flows during summer, will decline over 50–100 yr. This time scale may not be conservative (Bosch and Hewlett 1982). Needle and leaf surface area are greater in a growing forest than in a climax forest causing greater water loss by precipitation interception, evaporation, and transpiration (Bormann and Likens 1979 ; Kimmins et al. 1985). Troendle and King (1985) have described subtle impacts on the hydrology of a watershed in Colorado which can be detected in a series of measurements extending 30 yr after timber harvest. These changes cannot be demonstrated with a shorter data base.

We predict that the volume of LOD in the stream will decline over a period of 60–100 yr. The decline of material in logged sections of the stream will be offset in part by movement of material from sections where stream-side trees have been left. In four logged streams in Alaska, LOD increased immediately after logging and then declined for the next 30 yr (Bryant 1985). Conditions in logged study sections of Carnation Creek, for the first decade after logging, are consistent with those reported by Bryant (1985). Volume of LOD declined for half a century in streams on the Olympic Peninsula, but wood from second growth trees had begun to enter the stream a decade later (Grette 1985). Triska and Cromack (1980) state that accumulation of LOD on the floor of a Douglas fir forest must be considered over a period of five centuries if the pattern of accumulation is to be appreciated. LOD accumulations in streams in the western hemlock and western red cedar forests would probably continue for a longer period. Brown and McMahon (1988) speculated that LOD would never return to prelogging levels in Carnation Creek because only 80 yr would elapse before the forests are reharvested.

Channel widths increased after logging in reaches where the stream banks were logged with either the careful or the intensive treatment. The flood-plain channels of streams such as Taylor, Eve, and Elk rivers on Vancouver Island have widened by ≥ 100 % since being logged to the stream bank. The channels are braided and parts of the streambed have filled with gravel (D. Morrison, B.C.M.O.E., Nanaimo, pers. comm.). We have noted that as the stream channel on the Carnation Creek flood plain widened, and straightened, and where the deposition of gravels was increased, more of the water flowed the substrate during periods of low flow. Decreased stability of the streambed, declining water yield during summer as the forest regenerates, and channel widening will lead to a long-term de-watering of the stream where the channel is aggrading and to shallower pools where it is degrading (Fig. 99).

The quality of spawning gravel in Carnation Creek has declined since 1976. We cannot predict how long the sand and pea gravel in the streambed will continue to accumulate. If the sources of sediment entering the stream are reduced, the streambed will be cleaned by freshets in a decade, first near the surface and later at greater depths (Scrivener and Brownlee 1989). We predict (Fig. 99) that the quality of spawning gravel in the stream will stop declining by 1990. However, the quality, quantity and distribution of gravel, and the distribution of particle sizes will be changing for at least another few decades.

More sediments and unstable LOD were initially recruited to the stream because of bank erosion, channel scour, debris torrents, and erosion of exposed soil on the hillsides. Sediment and debris loading in the main channel increased when debris torrents occurred at four locations in tributaries and the main channel of Carnation Creek following logging. In study section VIII increased sediment and LOD depositions have been recorded. Above study section IV gravel bars in the centre of the stream channel are higher than the vegetated banks. A new channel is forming here when the stream flows over the flood plain during freshets. We predict that sediments and unstable LOD will continue to move downstream until the banks and channel restabilize, probably by the third decade following logging. However, because of the loss of LOD in the channel and reduced dissipation of stream energy, the material will be transported downstream faster. We suggest that as the sediments in the channel are moved out and the inputs decline because of bank and slope revegetation, the amount of gravel in the stream will decline. The gravel that is left in the channel will be transported and sorted, so that upstream areas of steeper gradient will be lined with cobbles and areas downstream will contain progressively more sand and fine gravel toward the stream mouth. We suggest that streambed structure and composition in the system will not return to prelogging conditions until stable large debris is replaced and until prelogging patterns of gravel flux through the drainage are re-established. Such changes may require a century or more.

We have attempted to outline a series of future scenarios regarding different physical conditions in the stream. In combination these changes will maintain the present lower quality of spawning habitat for fish ; and they will produce a cooler, less productive stream for rearing stream biota. A return of stream temperatures to the ranges recorded in the prelogging period will probably benefit chum salmon, but production levels for coho salmon and trout will probably decline. The rate of change will decline with time and our ability to detect change over short-time periods will be inhibited by high annual variation. If the patterns of change about which we have speculated are to be monitored, it will require a long time series of data.

We would like to emphasize the speculative nature of this section. This speculative discussion has focused attention on the role of forest succession on ecosystem processes. Scientists and research administrators must appreciate the value of long-term data bases and long-term ecosystem studies. It is also important that land use planners be aware of the role of succession in ecosystems. The nature and wisdom of management decisions made today will be reflected in the condition of ecosystems decades and perhaps centuries from now.

Common Features

Successful and cost-effective management of west coast watersheds requires that we ecognize both the driving forces that shape common processes within them and the eatures of diversity that may distinguish them.

There are important common attributes of west coast streams and their basins in British olumbia which characterize such systems and play a dominant role in determining their responses to land use activities such as forest harvest. Land use planning should be based on our understanding of these dominant conditions and processes. The common qualitative features that characterize streams lying below 750 m in elevation in the western hemlock-red cedar biogeoclimatic zone (temperate rain forests) are :

1. High precipitation throughout late autumn, winter and early spring ;
2. Most of which falls as rain (>90 %) ;
3. High levels of hydrologic energy (stream discharges may rise and fall 200-fold within 24 h) ;
4. Mild winter conditions (stream temperatures >2°C) ;
5. Cool summer conditions (stream temperatures <16°C) ;
6. Low stream conductivity (nutrient poor water) ;
7. Low primary production and high flushing of epiphyton ;
8. Low macroinvertebrate production of species with opportunistic feeding strategies ;
9. LOD a common feature of undisturbed stream channels ;
10. LOD maintaining structural complexity of the channel and storage of sediment ;
11. Clean well flushed streambed gravel ;
12. Vegetation mainly coniferous in old-growth climax forests.

Most of the streams on the coast are located in areas of steep topography which compounds the influence of high hydrological energy and variability in discharge. Because they are cool, rapidly flushed and low in nutrients, the biotic energy flow through the stream food web is also low. The regulators of fish populations are directly physical : temperature, cover, winter flow conditions. Density of fish has an effect on fish size, but physical environmental factors account for most of the inter-annual variability in abundance. The trophic processes and competitive relationships do not, apparently, play the primary role in population processes. We speculate, however, that if the flow of biotic energy through the system was higher, and hydrological energy lower, population regulation and production would be more regulated by biotic processes. Because the hydrological energy of west coast streams is high, particular attention should be paid to management for :

1. Large woody debris (LOD) ;
2. Channel form ;
3. Gravel budgets ;
4. Temperature regimes.

Diversity among Stream Systems and Potential Responses to Logging

Six sets of conditions may cause a watershed to respond differently than observed at Carnation Creek despite being from the same coastal zone, of similar size (10 km^2) and of similar cut history (41 % clearcut). These are :

1. Different aspect ;
2. Different elevation ;
3. Absence of flood plain ;
4. Presence of lakes ;
5. Different gradient ;
6. Size of estuary.

Streams with different aspect may not exhibit the same temperature changes as those recorded in Carnation Creek. North facing streams should be expected to exhibit smaller temperature increases during summer, following cutting. Streams which are south facing should be expected to exhibit higher temperatures than Carnation Creek following comparable cutting programs (tributary differences, see Stream temperature, Chapter 5).

Streams that originate from higher elevations would be affected more by rain-on-snow events. Winter and spring freshets may be more severe and stream temperatures may change less after logging in such systems. Periods of low stream flows in winter may also be evident.

The absence of flood plains may result in less bank erosion, sand movement and deposition of pea gravel from flood plain sources, but this permits the transport of more sediment directly from roads and slopes to the stream. Such sediment, from up-slope areas, may be finer in texture than that from the frequently washed flood plain. Sediments from the slopes accrete vertically on the flood plain and they become trapped by the soil and vegetation roots (Cordes 1972). The presence or absence of a flood plain may thereafter alter both the source and particle size of sediment. The absence of flood plains and the tributaries on them would also result in fewer life history options for coho salmon and cutthroat trout.

The presence of lakes would reduce the severity of freshets and provide salmonid habitat for other species (e.g. sockeye salmon) and life history options. Lakes would also provide sources of foods downstream from their outlets which are not normally available in streams (Elliott and Corlett 1972). Lakes would also act as sediment and LOD traps.

Progressively steeper gradients would reduce fish access to the stream. Higher gradient streams have increased transport of fines, leaving coarser substrate. Debris torrents tend to be more frequent than in lower gradient streams. They may result in different thermal responses to clear cutting.

Different stream systems may contain different combinations of these features. An enormous amount of research would be required to predict the effects of logging in systems with such combinations of features. Realistically, therefore, the role of research should be to teach resource managers enough about basin processes so that they will understand how different basin features, i.e. aspect, gradient, flood plain, etc., will ameliorate or exacerbate the impacts from the various logging activities.

Examples of Diversity in Temperate Rainforest Drainages

In this section we will briefly discuss situations in which there are differences in geomorphological processes, in movement and distribution of juvenile fish and in fecundity characteristics of chum salmon. The first three of these cases considered separately represent examples of ecological diversity in the biogeoclimatic zone of western hemlock and red cedar. If they are considered together they illustrate the overriding significance of hydrological conditions on streams of this zone.

Example 1 involves a comparison of slope failure frequency between the Carnation Creek basin and the west coast of Queen Charlotte Islands. The physical conditions that determine the probability of slope failure are precipitation, slope steepness, soil-bedrock interface conditions, soil type and soil drainage (Sidle et al. 1985). In the Queen Charlotte Islands most of the high precipitation zones lie in the Queen Charlotte Range where most of the failures were recorded. Although the Queen Charlotte Range occupies only 28 % of the land area, it contains 58 % of the land slides (Poulin 1986). In the Carnation Creek basin the coarse and shallow soils and the topography (benches, flood plain) are such that sediment yields from mass wasting are lower than in the Queen Charlotte Islands (Sidle et al. 1985). All of the slope failures and debris torrents which have occurred in Carnation Creek, however, have also occurred during peak storm conditions. Where their effects have been transmitted downstream, such transmission has been caused by hydrological conditions. Hydrological conditions determine most of the risk and all of the timing of slope failures for both Carnation Creek and Queen Charlotte streams.

In a second example, sedimentation processes are compared for Carnation Creek and parts of the Clearwater River on the Olympic Peninsula, Washington in which different physical responses were driven by similar hydrological events. In Carnation Creek most of the sediment which has been deposited in the spawning gravel has come from the stream banks on the flood plain. The material has been eroded and re-deposited by winter storm events since logging. In Carnation Creek the particles which are eroded and deposited are predominantly in the 1 to 9 mm size range (Hartman et al. 1987 ; Scrivener and Brownlee 1989). In the tributaries of the Clearwater River, erosion and deposition occurred, but the source and the size of the particles were different from those in Carnation Creek. Sediment production was related to road construction and use. Sixty percent of the road-related sediment came from road-side slides and 18–26 % came from erosion of the road surface (Cederholm et al. 1981). The amount of sediment eroding from road surfaces was directly proportional to road use. The size of particles deposited in the gravel was <0.85 mm (Cederholm et al. 1981). In these two situations, topography, soil type, and road location and use determined the type and source of sediment that entered the stream.

Diversity in the mean sizes of eggs among chum salmon stocks are compared in example 3. Common hydrological conditions interacting with different soil types have permitted the evolution of chum salmon which produce 350 mg eggs and 41–45 mm fry at Carnation Creek, while 225 mg eggs and 36–38 mm fry are produced in Olympic Peninsula streams (Scrivener 1988b). The shallow, coarse textured and stable soils, and the frequent freshets have kept fines from the streambed of Carnation Creek and produced clean spawning gravel prior to logging. Large eggs that produce large fry that have better survival to adults (Holtby and Scrivener 1989) were possible for Carnation Creek because they could incubate and easily emerge through the large pore spaces in the coarse gravel. This strategy is not available to chum salmon of the Olympic Peninsula, where eggs must incubate in gravels that are richer in fine sediments.

In Carnation Creek, 17 % of the juvenile coho salmon and an unknown proportion of cutthroat trout move to flood plain habitat in the autumn. There are important variations in their patterns of movement and distribution (see Distribution and Movement of Juvenile Salmonids, Chapter 6). The movements are initiated by hydrological events (autumn freshets), but these behaviours serve to remove fish from exposure to severe winter freshets. The occurrence of this pattern of behaviour depends on the presence of flood plain habitat and its significance within a basin depends on the accessibility of the habitat. The movements to flood plain habitat in the interior of the province (Morice and Coldwater rivers) occurs during June to avoid high runoff or high stream temperatures (Bustard 1985 ; Swales et al. 1986). Movement to off-channel areas on the coast occurs during the Sept.–Nov. period (Bustard and Narver 1975). The timing of movements in different geographical regions is quite different, but in each case it is initiated by hydrological conditions and serves as an adaptive response to either hydrological or temperature conditions.

Coho salmon fry disperse downstream during spring and early summer freshets (Hartman et al. 1982). Many such fry enter the estuary and remain there throughout the summer. Estuarine survival of recent immigrants may be improved by the temporary reductions of salinity during this and later freshets (Tschaplinski 1982). Therefore the number of underyearling coho that occupy the estuary depends upon its size and varies with the frequency of freshets. Both differ among watersheds.

Chapter 9. Application of Long-Term Information in Diverse Systems

Diversity among Pacific Northwest streams is the result of different physical conditions (geology, topography, aspect, etc.) and the interaction between these different conditions and the common climate of the coastal rainforests. Different streams may combine different features and different combinations of features may result in different responses to logging. Because there is diversity among streams along with important common features, we recommend strongly that land managers establish matrices (see Fig. 79) that list logging activities and anticipated changes. By combining experience, site specific information, and knowledge of processes, land use managers may best anticipate the scale and nature of changes that will occur.

The results of long-term process studies in a single system are not rendered inapplicable because of the site specific differences which occur among drainages. Process studies in a single system, provide the land use manager with the means to semi-quantitatively interpret what the significance of site specific physical characteristics may be in a new situation. They can help managers make choices that prevent negative impacts associated with site specific drainage basin features. Land use managers make plans and decisions concerning hundreds of watersheds each year in coastal British Columbia. They should not expect that studies such as the Carnation Creek project, will allow them to predict the precise effect of a particular forestry plan on fish numbers. Usually they do not have enough detailed site specific information to utilize existing models, such as the temperature (Holtby 1988) and stock recruitment models (Holtby and Scrivener 1989) that were developed during the project. Results from projects such as Carnation Creek must be viewed as a useful guide and not as a recipe book.

Woody Debris, Diversity, and the Need for Long-Term Management

The amount and the type of LOD varies between streams and along the lengths of streams (Hartman et al. 1987). Small first and second order streams (see Strahler 1964) contain more wood per unit of area than streams of higher order (Murphy and Hall 1981 ; Harmon et al. 1986). The history of human activities in drainages has resulted in loss of LOD from them (Sedell and Luchessa 1982 ; Sedell and Frogatt 1984). In logged systems the volume of LOD within the channel declined over time for ~50 yr after logging (Grette 1985). Notwithstanding the diversity in the types and volumes of wood in streams of the same order or the differences in volume along a stream system, LOD is a common feature of temperate rainforest streams and its critical role has been discussed previously (Harmon et al. 1986 ; Triska et al. 1982 ; Sedell and Luchessa 1982 ; Sedell and Frogatt 1984 ; Swanson et al. 1982, 1987 ; Bryant 1980, 1985). The function of LOD as fish habitat during winter and responses of woody debris to logging in Carnation Creek has been discussed by Bustard and Narver (1975) ; Toews and Moore (1975) ; Tschaplinski and Hartman (1983) ; Brown and McMahon (1988). In stream systems with high hydrologic energy, large wood determined the structure of the stream channel as a response to the energy in the system, and provided cover which is a habitat imperative in such systems. We therefore re-stress the point that LOD is one of the most consistent features of undisturbed streams in the temperate rain forest. Fisheries habitat managers understand clearly that once the large wood is gone and the stream-side trees are gone there will be no replacement for 50–100 yr. If rotational cutting occurs every 80 yr, large wood from natural sources will be absent for essentially all time. These considerations override those of diversity.

Because the hydrological character of coastal streams is such that the changes which freshets and land use might cause may be long-lasting, there is need for special attention to the time frames over which responses may occur or changes may persist. It is particularly important to plan cutting and silvicultural activities so that the LOD in the channel remains stable and so that there is a future supply of such material.

Gravel Budgets, Flood-Plain Tributaries, and Long-Term Management

It is essential to plan cutting and silvicultural activities so that the rate and pattern of stream erosion is not accelerated. Stream bank structure and LOD determine the channel form. Channels with a variety of habitats (riffles, pools, undercut banks, large wood) are most productive for fish. In the careful and intensive treatment sections of Carnation Creek, the channel has become straighter, wider, and shallower. It is not known for how long the patterns of changes seen during the past decade will continue to occur, but we presume that the channel will not begin to evolve toward a prelogging configuration until stable LOD begins to re-appear.

In undisturbed streams, gravel is progressively moved from the upper reaches downstream. The movement and retention of gravel along the stream length depends on the interplay of freshets, gradient, and LOD. In stream systems where small steep slope tributaries are disturbed and the large wood reduced or lost in the main channel, excess gravel is more likely to be scoured from source areas and from storage in the main channel, and to be flushed and sorted by size down through the system. Reaches up stream may become gravel-poor with low gravel storage and input after this initial period of gravel movement. It is also expected that sorting along the stream may cause coarse gravel or cobbles to dominate the streambed in the steeper gradient sections, while sand and fines are more prevalent in the lowest gradient sections downstream. We stress that comments about gravel budgets are partially speculative. Volumes of gravel that have moved and are currently moving are not accurately quantified. We suggest, however, that planning for the management of gravel supply and movement may be as important in the long term as planning for the maintenance of gravel quality.

We have identified, in Carnation Creek, the importance of flood-plain habitat for fish production (Brown 1985 ; Brown and Hartman 1988). Hartman and Brown (1987) have recommended management and protection measures for off-channel habitat. Three central considerations were proposed :

1. The importance of such habitat must be recognized. Brown and Hartman (1988) showed that up to 24 % of the coho smolts leaving Carnation Creek had reared in the flood-plain habitat. Two flood plain ponds (1.29 and 0.85 ha), adjacent to the Clearwater River on the Olympic Peninsula, produced 1534 and 3613 coho smolts, respectively (Peterson 1980).
2. Many of the flood-plain swamps and ponds which produce coho salmon are dry in summer and so small (holes under logs or trees) that they may be overlooked during summer surveys. Surveys of flood plains should be carried out during winter when these sites contain water and fish. Fish may not be easy to detect visually because they remain close to cover.
3. Flood-plain tributaries which produced both coho salmon and cutthroat trout are so small that they may be easily blocked by land use activities. Natural flow routes and access for fish of all sizes must be maintained.

Variation in Biological Conditions — Application of Research

Under natural conditions, standing crop biomass of salmonids in streams varies widely both spatially and temporally (Hall and Knight 1981). Biomass of salmonids have ranged from 0 to 60 g·m^{-2}. Hall and Knight (1981) list stream flow, habitat quality, food abundance, predation and movement or migration as variables that may differ in space or time, within a stream, and cause such variation in salmonid biomass.

In such diverse natural conditions, efforts to assess the impacts of logging on salmonid growth rates and biomass or on macroinvertebrate abundance have produced inconsistent conclusions. For example, Murphy and Hall (1981) have reviewed a series of articles, some of which demonstrated decreases in cutthroat trout abundance after logging and others of which showed increases in abundance. Dorcey et al. (1980) summarized 21 studies documenting effects of logging on salmonids in western North America. There were 10 cases where biomass of salmonids decreased after logging, and 11 cases where biomass increased (see Table 6.1 ; Dorcey et al. 1980).

Macroinvertebrate studies provide further examples of differences or apparent inconsistencies in logging impacts on living organisms. Murphy and Hall (1981) reported greater biomass and diversity of insects in clearcut than in old-growth streams. Wasserman et al. (1984) found no detectable effects of logging or logging intensity on biomass, number of species, or abundance of functional feeding groups. Culp and Davies (1983) demonstrated that macroinvertebrate abundance in sections of stream bordered by clearcut and leave strips was lower than it was in old-growth sections of stream. The inconsistency of results of biological studies and the inexplicability of their differences is confusing to people in the forest industry. In some cases it may serve as rationale for foresters to ignore biological advice.

We believe that in some cases inconsistency in results may reflect weaknesses in the sampling design of studies, where in fact, conditions other than the treatment were dissimilar. More often, it may reflect the effect of differences in stream-basin conditions or the inability to separate inter-annual variability from logging impacts in the short-term design of the study. The discussion should no longer focus upon which conclusions were correct, but why they were different.

We agree with the idea of Hall et al. (1978) and Hall and Knight (1981) that improved study designs are required to provide more reliable impact assessment in systems, where natural variability is great and where it may mask the effects of disturbance by human activities. We suggest, however, that well designed experiments, which include groups of streams with different aspects, elevation, gradient, valley bottom configuration, natural debris loading or slope failure potential, will produce different results or results that appear to be inconsistent. The reasons for the inconsistency will become apparent if the processes at work in the watershed are understood.

In Carnation Creek, we recorded some positive effects of logging on some species of fish or life history stage and negative effects on others. The positive effects were associated with light, nutrient and temperature changes. The negative effects were associated mainly with changes in LOD condition, channel form, and gravel quality and stability. A greater amount of stream-side cutting or road construction immediately adjacent to the stream would have resulted in a different balance of impacts on salmonid production. If the logging treatment used in Carnation Creek were applied in another drainage, for example, one that had less flood-plain habitat, we suggest that the long-term population responses of coho would have been either negative or not as strongly positive. If a logging treatment similar to the one at Carnation Creek, had been conducted in a north-facing drainage with no flood-plain storage capacity for ground water, we speculate that logging related increases in stream temperature would not have occurred during winter and spring. The growth period of coho would not have been extended in the first year, and any change in age ratio among smolts would not have been as significant. Egg-to-fry survival would have declined, as it did in Carnation Creek, but fry and smolts of salmon would not have migrated to sea earlier, which caused reduced marine survival.

We have speculated about responses of stream systems which differ from Carnation Creek to indicate the types of variant conditions which the land manager should expect. Since few studies have been carried out with the specific intent of comparing the manner in which the effects of forest cutting are modified by, e.g., stream basin aspect, flood-plain characteristics, presence of lakes and stream gradient, we recommend the planning of such research.

The severity of logging treatment and the characteristics of the stream basin both determine the fish population responses to forestry related disturbance. In addition, the population responses of fish may be affected by regional climate responses, which add a temporal dimension to the variability in population responses. We recommend that studies be carried out which elucidate and compare basin processes in different climates. The research in the Alsea River system has provided vital information from a coastal region with lower rainfall, higher air temperatures and a Douglas fir forest (Moring and Lantz 1975). Salmon and trout are produced in streams of variable climatic extremes within British Columbia. Climatically, these differences are greater than differences between Carnation Creek and the Alsea tributaries, but research on the effects of logging on fisheries is required in these different watershed types.

Articles have been published which offer application of this research in fisheries–forestry and other management areas of British Columbia : Hartman (Ed., 1982) ; Hartman et al. (1984) ; Holtby et al. (1984) ; Hartman and Scrivener (1986) ; Hartman et al. (1987) ; Hartman and Brown (1987) ; Brown (1987). This publication will not make detailed recommendations for land-use planning. However, the processes which have been elucidated point to the following :

1. In temperate rainforest areas, such as those in coastal British Columbia, high precipitation and variable stream discharge are characteristics that dominate fisheries forestry interactions.
2. The long-term impacts of changes in LOD, channel, and gravel quality can overcome, within 4–6 yr, the positive effects of temperature increase. Stream basins, stream-side trees and woody debris must be managed for long-term channel stability.
3. Upper slope activities (above fish bearing areas) create impacts downstream. Four conditions prevail from the upper slopes to the delta : (1) LOD and sediment can move from intermittent and non-fish-bearing channels to the creek mainstem in torrents ; (2) debris accumulates at the base of these torrents ; (3) gravels scour below and deposit above the debris piles ; (4) fine gravel and sands are transported and deposited in the lowermost part of the stream. Planning must minimize destabilization of steep tributary channels.
4. Small flood-plain tributaries and ephemeral swamps maintain large numbers of fish during winter. This habitat must be identified before logging is begun, and water sources and fish access must be maintained.
5. Stream temperatures are affected throughout the year by logging, however, the greatest impact on fish occurred in winter, when the smallest change in absolute temperature occurred. Appropriate planning may produce positive effects associated with temperature changes which will last until canopy re-closure over the stream.
6. Many conditions in a stream will undergo a rapid initial alteration following forest harvest. This is followed by a slow change dictated by forest re-growth and geomorphic processes.
7. Physical conditions and fish population characteristics may become unstable after logging. Managing unstable systems is more difficult and risky, when cumulative effects can generate more extremes in fish production, than managing more stable systems. Therefore, it is more important to understand how variability is induced by logging and how to avoid it, than to determine the average impact of logging activities on a fish stock.

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