CHAPTER THIRTEEN

Impact of Forest Management on Coho Salmon (*Oncorhynchus kisutch*) Populations of the Clearwater River, Washington: A Project Summary

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ABSTRACT In 1972, declining coho salmon production and visible forestry impacts on coho habitats prompted the initiation of an ongoing fisheries research project in the Clearwater River basin of the Olympic Peninsula. Heavy fishery catches have resulted in a general underseeding of the basin, as demonstrated by stocking experiments and inventories of potential habitat. Because of the resulting lack of a reservoir of surplus juveniles, the number of smolts produced is more sensitive to natural and forestry-related impacts.

Forestry-related mortality in the Clearwater basin is primarily due to an increased sediment load and to alterations in the riparian environment that reduce refuge habitat during winter storms. Increased sediment loads come primarily from landslides and surface erosion on heavily used logging roads, while reductions in winter refuge capacity are caused by stream blockages or by destruction of the refuge habitat.

Field and laboratory experiments demonstrate that (1) survival of eggs and alevins decreases as the percentage of fine sediments in spawning gravels increases, (2) suspended sediments cause stress to juveniles during summer, (3) disruption or blockage of small winter refuge channels can reduce smolt survival, (4) aggradation of coarse sediments can cause loss of summer rearing habitats, and (5) streambed stability may be locally reduced by removal of large woody debris.

Since the depressed state of Clearwater River coho stocks has resulted from the combined effects of overfishing and forestry-caused habitat degradation, an integrated approach to natural resource management is needed that includes recognition of both the independent and combined impacts of the-fishery and forestry industries. Within a drainage basin, resource management programs must provide for the protection of the full range of habitat types used by the fish.

Much of the economy of the Pacific Northwest is based on two industries whose raw materials are inextricably linked, fishing and logging. If these industries are to remain compatible, both must be managed to minimize the impact on the other. Such management requires a basic understanding of stream productivity and ecology, the effects of timber removal on streams, and the economic realities of the forest industry. To determine what the requirements are for protection of fisheries habitat we need a thorough understanding of that habitat and of the population dynamics of the fish. Ultimately, we need to be able to answer the question: "How much of a difference to fish populations will a given land use practice make?"

Studies are now under way in the Clearwater basin of the Olympic Peninsula to define the forestry-related impacts on the production of anadromous fishes. This project was initiated in response to the visible impacts of forestry on fisheries resources on land managed by the Washington State Department of Natural Resources (DNR). Anadromous fish populations on the Clearwater River basin had declined radically over previous decades, and massive landsliding from logging roads was thought to be directly responsible for sedimentation of salmon spawning and rearing habitats and thus for the decline of fish populations (Deschamps 1971). Consequently, the DNR contracted with the University of Washington Fisheries Research Institute (FRI) to document the reasons for the declining populations. Because of the funding schedules, the project took the form of a series of short-term studies. This strategy has the advantage of flexibility, but sacrifices the potential for long-term planning. Additional research by the Washington State Department of Fisheries (WDF) and the Quinault Tribe has provided information on adult spawning escapements and systemwide smolt yield.

APPROACH

The general approach for the project has been (1) to determine which biological or physical factors are limiting for each life stage of coho salmon (*Oncorhnchus kisutch*), (2) to determine the nature of the controls on each actor, and 3) to evaluate the effects of various management practices on each control.

Along the coast of Washington the abundance of coho salmon is controlled by natural mortality, exploitation by fisheries, and logging-associated mortality. Each of these influences contributes to reducing the potential fry recruitment. If some minimum number of fry must survive the intragravel and rearing environments in order to achieve full seeding, then the degree to which a particular impact reduces the probability of reaching this minimum is a measure of its effect. Full seeding is defined as the number of fry needed to maintain the population at or near maximum smolt yield.

The impact of forestry on fish populations is realized through changes in the physical and biologic stream environment during the life stages in which they are resident in or downstream of forested areas. Since each life stage has different habitat requirements, the potential impact of a land use practice will vary with the age of the fish (Table 1). The focus of the Clearwater study has been to investigate the effects of forest management on coho salmon reproduction and rearing success, and to assess the significance of these impacts collectively on the basinwide population. To meet this goal it was necessary (1) to define the characteristics of the local coho population and (2) to determine experimentally how and to what extent forestry-related changes cause mortality at each stage of juvenile development.

Table 1. Potential effects of timber harvesting on factors influencing survival of various life stages of coho salmon.

Life Stage	Limiting Factor	Influence of Forestry	Cause*
Egg and alevin	Intragravel flow	Increased fine sediments	S
	Gravel porosity	Increased fine sediments	S
	Scouring	Hydrologic changes, decreased organic debris	HR
	Stranding	Hydrologic changes, coarse sediment influx	SH
Fry and smolt	Temperature	Altered canopy cover, shallowed channels	RHS
	Predation	Decreased organic debris, pool depth, and overhead. cover	RHS
	Turbidity	Increased fine sediments	S
	Food	Altered benthic community (altered canopy cover, bed stability, organic debris, and channel morphology)	SRH
	Winter refuge	Destruction of wall-base channels and ponds, decreased organic debris and pool depth	RHS
Spawner	Migration barriers	Logging debris	R
	Predation	Decreased cover, pool size; but decreased population of predators	RHS
	Suitable gravel	Altered character of sediment input	S
	Suitable sites	Altered channel morphology	HS

* H = hydrologic change. R = change in riparian environment.
S = change in sediment input.

DESCRIPTION OF THE STUDY AREA

The Clearwater River drains a 375 km^2 basin on the western slope of the Olympic Mountains in western Washington, and empties into the Queets River 9 km above its mouth (Figure 1). The Clearwater basin is an area of steep, forest-covered slopes underlain by Tertiary marine siltstones and sandstones of the Hoh Lithic Assemblage. Soils are classified as silt clays, silt loams, and silt-clay loams, and contain abundant coarse fragments on steeper slopes. Rainfall averages about 3,500 mm per year and is strongly seasonal, falling mostly between November and March, and snow remains on the ground for more than a few days only in the highest parts of the basin.

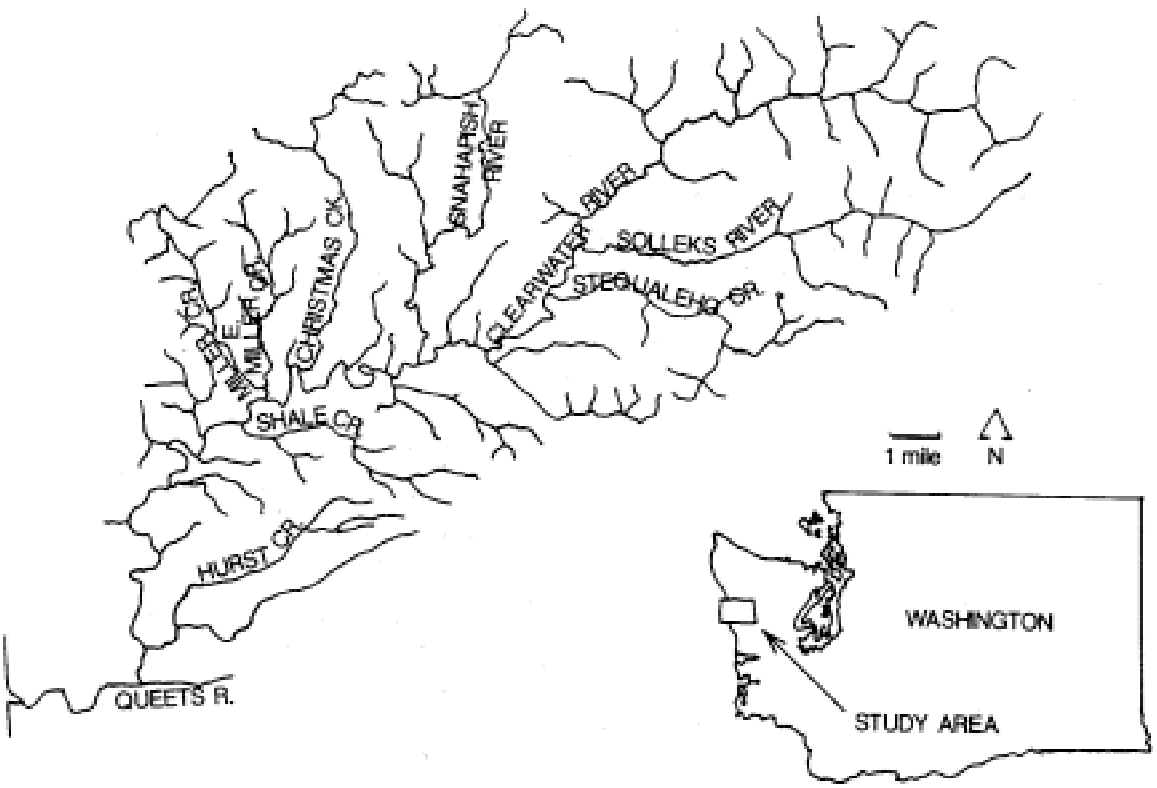

Figure 1. Clearwater River basin.

Over 80% of the Clearwater basin is publicly owned, and is managed by the DNR on a 60- to 80-year sustained-yield cutting cycle. Logging systems generally use high-lead techniques, resulting in a road density of under 3 km/km² in the most intensively clearcut part of the basin. Since 1975 most forest roads in steep terrain have been constructed on full benches to minimize sidecast, and road drainage is escorted through culverts and flumes to stream channels in order to maintain slope stability. Old-growth buffer strips 10 to 100 meters wide are usually left along streams larger than third order to protect the aquatic environment and provide corridors for recreation and wildlife. Currently about 60% of the basin has been logged at least once.

The river has been an important producer of anadromous fish, supporting runs of coho salmon, chinook salmon (O. tshawytscha), steelhead trout (Salmo gairdneri), and cutthroat trout S. clarki. Over the past three decades a high proportion of the coho salmon from the Clearwater River has been harvested by U.S. and Canadian commercial and sports fishermen in the ocean, and by Quinault tribal fishermen in the lower Queets River.

While resident in the Clearwater River system, coho salmon are dependent on a sequence of habitat types. Adults enter the river from October through November, and spawning lasts through the middle of January. There are over 170 km of accessible spawning habitat in the system, but only about 130 km of tributaries and upper main river are used in any significant degree. After hatching, the yolk-sac fry (alevins) reside in the streambed gravels for two to three months; emergence of fry from the gravels begins in March and lasts through May (Tagart 1976). After emergence, the fry disperse downstream, and fry can be seen distributed along the stream margins and in pools throughout the tributaries and main river. The extent to which fry disperse varies between tributaries. Those tributaries that lack abundant coho summer rearing habitats apparently disperse a greater percentage of their emergent fry population to the main river, while those with good on-site rearing habitat retain more fry within them for summer rearing.

By the summer low-flow period in August and September, the fry have become well established in their summer rearing habitats, and at this stage do not venture far from their home territories. But during the first main freshets of October and November, fish once again begin to disperse downriver. During this redistribution, fish immigrate into a variety of small tributaries on the lower river floodplain (Figure 2), and these streams provide refuge from high discharges in the main-stem river (Peterson and Reid 1984, Cederholm and Scarlett 1982). By the time a one-year-old smolt leaves these refuges the following April and May, it may have already traveled as far as 30 km downriver from where it was spawned.

STATUS OF THE COHO SALMON POPULATION

To understand why there are fewer coho in the Clearwater River than in the past, we must first define the present adult run size and seeding levels and compare them with potential production for the river system. The necessary data are available from fisheries statistics and the results of stocking experiments in the Clearwater system.

Catches of adult coho salmon in the Queets River tribal fishery downstream of the Queets-Clearwater confluence show a steady decline during the two decades preceding 1970 (Cederholm et al. 1981, Wood 1984), and this trend coincides with major improvements in fishing gear and increased marine catches. These trends suggest that high marine fishing rates have contributed to depressed populations of spawning fish in the Queets-Clearwater basin and other nearby rivers over this period. More recently, restriction of catches at the Queets River mouth and in Washington marine waters has resulted in increased escapement, but estimates of spawner escapements are still well below the goal of 5,800 to 14,500 fish set for the Queets River by a panel of fisheries scientists (Lestelle et al. 1984). Since 1973, escapements in the Queets-Clearwater basin have fallen below the minimum recommendation of this panel in 75% of the cases (Figure 3). It is evident that the restraint shown by the Washington fisheries alone is not sufficient to rebuild these stocks, and that some form of international cooperation that includes Canadian fisheries is necessary to protect them.

Spawning escapements in the Clearwater River were the lowest on record between 1973 and 1978, when they averaged an estimated 560 adults, and showed improvement between 1979 and 1984, averaging 1,900 adults (Wood 1984; Wood, pers. comm.; L. Lestelle, Quinault

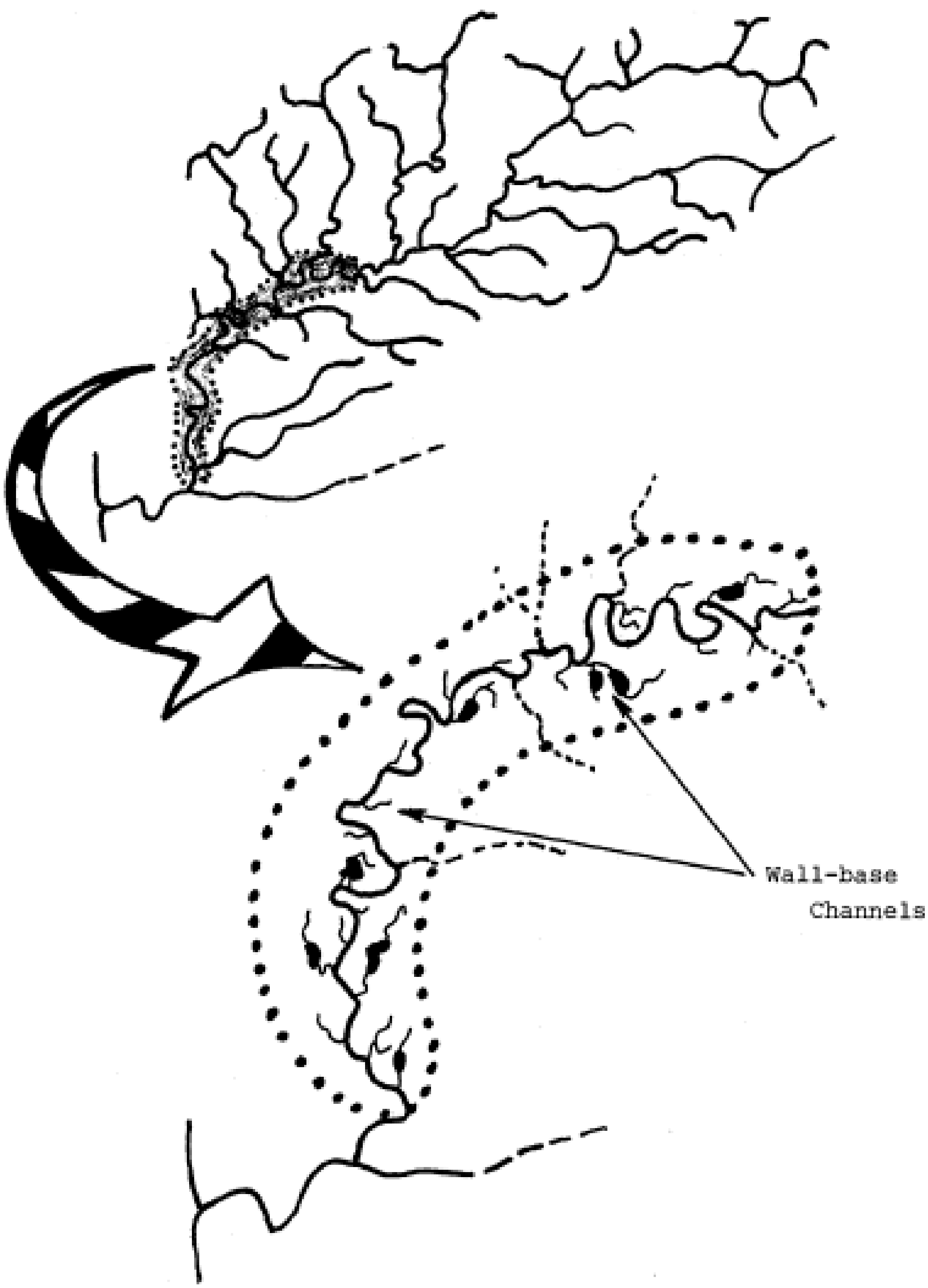

Figure 2. Location and distribution of riverine wall-base channels in the lower 34 km of the Clearwater River (adapted from Peterson and Reid 1984).

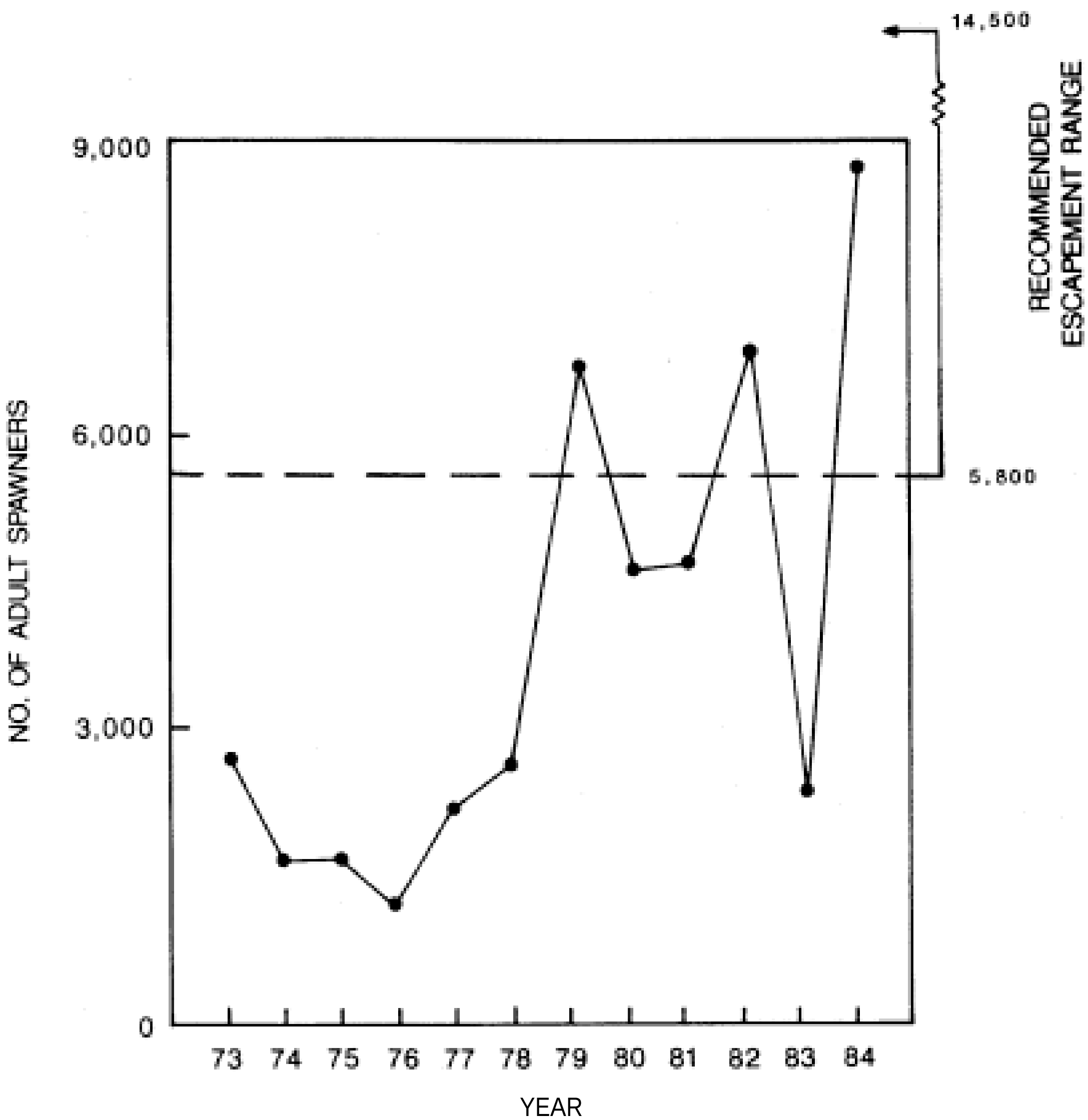

Figure 3. Queets River adult coho spawning escapement estimates and recommended escapement goal range.

Department of Natural Resources, pers. comm.). Using resource assessments we calculate that an escapement of 3,850 adults is necessary to fully seed the Clearwater system. This is based on 130 km of tributaries having 404,500 m^2 of pool rearing space at summer low flow, a seeding at emergence of 5 fry/m^2 of pool, a natural survival-to-emergence of 350, a female fecundity of 3,000 eggs, and a 1:1 adult sex ratio on the spawning beds (Cederholm, unpublished data).

Our summer censuses of juvenile coho standing crop during the mid-1970s suggested that the Clearwater system was underseeded (Edie 1975; B. Edie, WDF, unpublished data). Juvenile biomass averaged 0.78 g /m^2 of total water surface area in seventy-eight sections studied over a period of five years. This value is 45% of the 1.75 g/m^2 found in

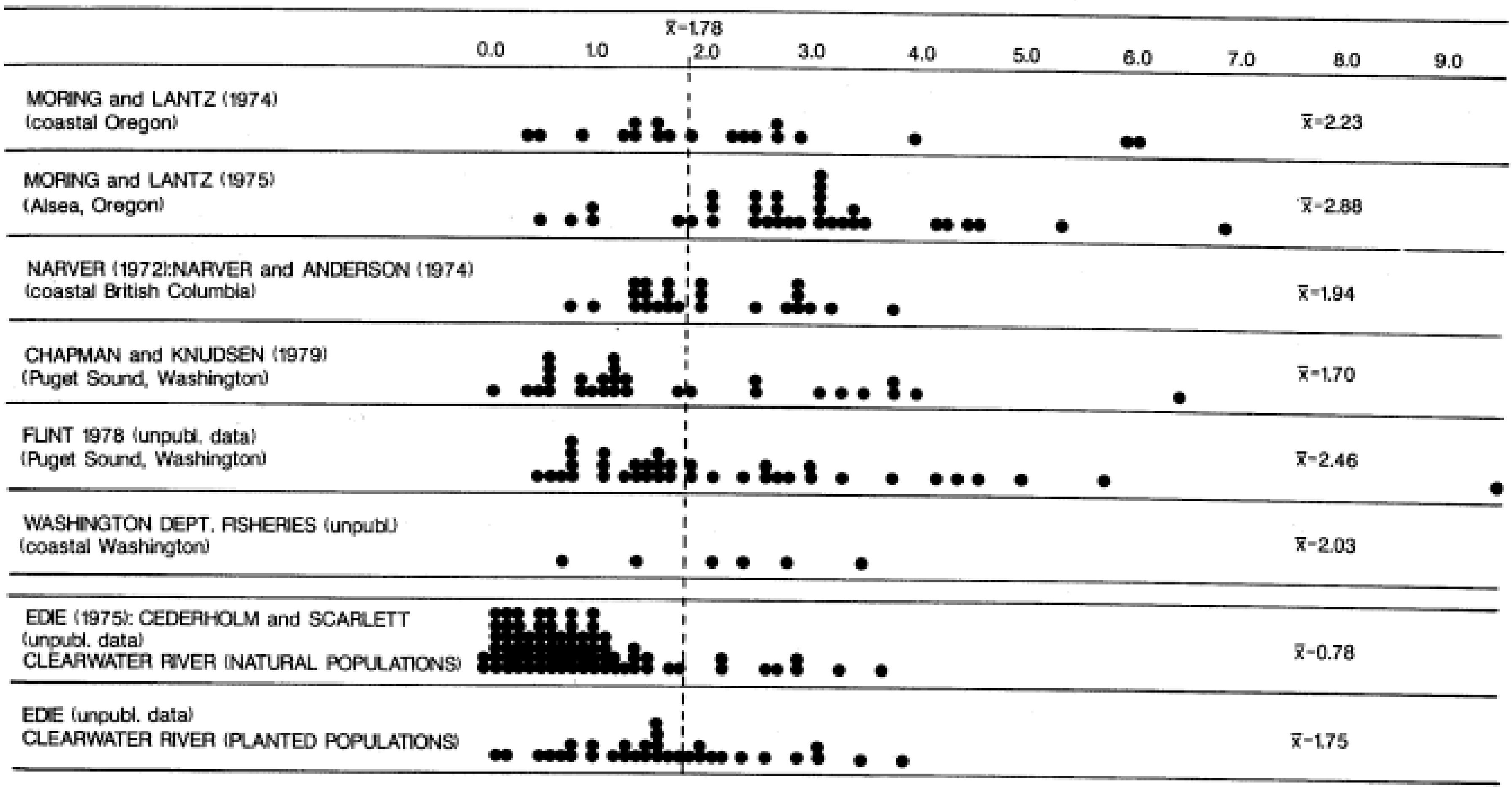

Figure 4. Comparison of the relative biomass of coho salmon in eight studies carried out throughout the Pacific Northwest (g/m^2). Each dot represents one complete study section electrofished between August and October, 1973-79 (adapted from Cederholm et. al. 1982).

Table 2. Estimated Clearwater River coho smolt yield based on the amount of summer low-flow pool, and winter "wall-base channel" rearing habitats during an average year.

Habitat Type	Smolt Yield
Valley-wall Tributaries:	
Typical summer habitat having low gradient, abundant woody debris, and cover	54,700
Atypical summer habitat having high gradient, boulders, and minimal cover	28,300
Wall-base channels and some main river winter rearing	35,000
	118,000

Sources: Typical and atypical habitat production was based on unpublished data collected by Edie and Cederholm. Wall-base channel habitat production was based on Peterson 1982, 1985, and unpublished data collected by the Quinault Department of Natural Resources, the Washington State Department of Fisheries, and Cederholm.

thirty-three artificially fully seeded study sections, and 35% of the average of published values for other Pacific Coast streams (Figure 4). The results of other studies of artificially seeded tributaries were highly variable, but averaged a 20% increase in smolt yield over natural conditions (Edie, unpublished data). During underseeded conditions in two small tributaries, Scarlett and Cederholm (1984) found a 9% increase in size of coho at summer low flow, but whether this increase in size was enough to compensate for low initial seeding is doubtful.

Additional evidence for underseeding comes from an extensive inventory of the summer low-flow rearing habitat throughout the Clearwater basin, combined with our experimentally derived estimates of carrying capacity as a function of habitat type (Edie, WDF, unpublished data). Using these data we estimate a potential smolt yield of 118,000 from the system during years of average summer streamflow (Table 2); estimates of actual smolt yields based on data from a trap near the mouth of the Clearwater have averaged 60,000 between 1981 and 1985 (D. Seiler, WDF, pers. comm.), a period of improved escapements. Since 1981, the number of smolts produced by the system showed no relation to the number of spawners available during the brood year, indicating that mortality from egg to smolt stages is a strong control on smolt production.

Evidence from adult and juvenile population surveys and fry seeding experiments thus indicates that the Clearwater system is underseeded. The populations are depressed primarily because of high fishing rates, and the resiliency of the stock as a whole is reduced (Cederholm et al. 1981). There are no longer any surplus fish to compensate for inordinate losses due to landslide disasters or scouring during large storms; therefore, impacts such as these become more devastating to the local populations.

FORESTRY-RELATED CONTROLS ON COHO POPULATION

To minimize logging-related impacts, we must determine the types of impacts most harmful to the fish and identify the life stages that are most sensitive. These impacts are either direct physical alterations of the local environment or indirect changes brought about by alterations of the input, character, and transport of water, sediment, and organic matter through the stream system. In the first case, effects may be localized around the disturbance; for example, banks may be broken down and streams shallowed by yarding logs across them. In some cases, excessive deposition of coarse sediment below landslides and debris torrents has forced streams to percolate through their channel-bed gravels during low flows, turning them into ephemeral channels. In the second case, effects tend to be more widely distributed, because any site downstream of the logging may be affected. Changes may include increased scouring of redds due to increased peak discharges, or entombment and suffocation of eggs due to sedimentation, or loss of pool habitat due to a decreased contribution of large organic debris. Specific controls on survival are listed in Table 1, and these can generally be attributed to changes in hydrologic regime, riparian environment, and sediment input.

Effects of Hydrologic Change

Increased incidence of scour is expected to result from forestry-related hydrologic changes, although data are not yet available to determine whether such changes have occurred in the Clearwater basin. Five years of data from smolt traps suggest that smolt yield is partly controlled by the severity of winter storms, and we have begun to monitor depth and frequency of scour at ninety sites throughout the Clearwater and adjoining basins. Observations during the particularly severe winter of 1979 indicate that 40 to 50% of the previously constructed redds were destroyed by streambed scour and deposition (W. Wood, WDF, pers. comm.). The sensitivity to hydrologic conditions is further supported by a measured inverse correlation between chinook fry populations during the summer in some rivers of the northwest coast and maximum peak discharge of the previous winter (W. Wood, pers. comm.). Thus small increases in the frequency or magnitude of peak discharges could have an effect- on survival of eggs and alevins. Information is needed on the distribution and significance of forestry induced hydrologic changes and their effects on spawning bed stability.

Effects of Altered Riparian Environment

The streamside environment is of critical importance in determining water temperature, bank stability, and the contribution of large organic debris to the streams. Litter fall from the canopy contributes nutrients to instream food webs, and underbrush and overhanging limbs provide shelter and vantage points for predators and a source of terrestrial insects (Martinet al. 1981).

In the Clearwater basin, riparian zones on DNR land are protected by 10- to 100-meter-wide buffer strips of old-growth forest on most streams larger than third order (Type 1, 2, and 3 waters, as defined in the Washington State Forest Practices Handbook, 1976), so changes in the riparian environment are not expected to be major. Data from fifteen stream-years of measurement on tributaries of various sizes indicate that summer water temperature is increased in streams downstream of clearcuts, and in the Clearwater system the increases encountered are expected to enhance the growth rates of the fish. Given the underseeded conditions in the basin, increased growth rates are probably beneficial for the fisheries resource.

Introduction of easily transported logging debris can contribute to the formation of logjams which block adult migration. However, this has not been found to be a significant problem in the Clearwater system. Over the last thirteen years, logjams have temporarily blocked on average only 2.6% of the 130 km of tributary channels used by coho.

On the other hand, limited streamside protection zones on private land and overzealous stream clean-out practices have resulted in a decrease in the number of large, immobile logs in some streams, and this condition will persist until sources for new logs are established (Grette 1985). This large organic debris is an important element in the stream ecosystem, helping to maintain channel stability by anchoring the location of plunge pools and holding bed material in place during winter storms, and providing overhead cover and organic inputs to the food web (Bisson et al., this volume). Channel stability imparted by natural debris may be of critical importance both in protecting redds from scour and in providing refuge for juvenile fish during storms. A Clearwater tributary experimentally cleared of natural debris in 1972 continues to show reduced pool depths and cover and depressed populations of salmonids thirteen years after clearing.

Recent studies carried out along the Clearwater River show that low-order channels formed on floodplains and terraces are very important winter refuges for juvenile coho (Peterson 1982, Peterson and Reid 1984, Cederholm and Scarlett 1982). These sites are often overlooked, and they are not consistently identified on the Washington State stream-type maps used to design logging plans. Approximately 10 to 25% of the smolts produced from the entire Clearwater system overwinter in these channels and associated ponds, despite the almost complete absence of spawning along them (Cederholm and Scarlett 1982, Peterson and Reid 1984). Because floodplains and terraces are the most convenient locations for roads, gravel pits, and lumber-mill waste dumps, these refuge streams are particularly vulnerable to forestry related impacts. We are currently experimenting with rehabilitation and enhancement of several existing sites in the Clearwater basin in order to increase smolt production (Peterson 1985).

Effects of Sedimentation

The Clearwater project has focused on the effects wrought by altered rates of sediment production to streams, both because evidence for the changes is readily observed and because it is generally accepted that high levels of sedimentation lower salmonid production (Gibbons and Salo 1973, Iwamoto et al. 1978, Everest et al., this volume). In addition, preliminary observations suggested that other logging-related effects described above were of secondary importance in the Clearwater system.

Accelerated sedimentation can be deterimental to several growth stages of coho. Since survival of eggs is dependent on a continuous supply of well-oxygenated water through the streambed gravels, the infiltration of fine sediments into spawning gravels can lead to suffocation of eggs (Wickett 1954, 1958, Koski 1966, 1975, Hall 1984). Once the eggs have hatched, the alevins must make their way up through the gravels to the open stream. If intragravel passages are blocked with fine sediment, emerging fish are trapped (Phillips 1965, Koski 1972). Increases in sediment on and within the aquatic substrate have been shown to be deterimental to both the macroinvertebrates and the primary producers: clogging of gravel interstices may decrease the flow of oxygenated water within the gravel bed (Ziebell 1960) ; suspended sediments may abrade or clog gill membranes (Usinger 1971); and heavy sediment loads may prevent photosynthesis by blocking light penetration to the streambed (Hynes 1960).

High levels of suspended sediment can abrade and clog fish gills, and may lead to death. For example, caged rainbow trout were killed within twenty days in the Powder River, Oregon, when the suspended sediment concentrations were 1,000 to 2,500 ppm (Campbell 1954).

Alteration of the rate of input of coarse sediment may also decrease smolt production. Altered sediment loads may lead to changes in channel morphology, affecting the distribution and frequency of pool habitat and the stability of the bed material (Sullivan et al., this volume). A decrease in the average size of sediment on the streambed may lead to increased frequency and depth of scour, and may result in a redistribution of available spawning gravels.

In some cases, excessive aggradation can cause streams to dry up during summer months. For example, a tributary of the Clearwater has become ephemeral since a debris torrent and streamside salvage logging caused heavy sediment deposition. As a result, smolt production from the tributary has been reduced from 350 to 1,000 per year to 50 to 400.

The relative importance of the sediment-related impacts described above depends on such factors as regional lithology, hydrology, soils, vegetation, and stock genetics. We thus needed to determine the types of impacts present within the Clearwater area and to identify the forest practices responsible for them. In addition, since many of the studies reported in the literature have been carried out under artificial conditions or in different regions with widely diverse climates, geology, and stream size, the applicability of the results to the Clearwater basin is unclear. Part of the goal of the Clearwater project is thus to validate experimental results for a large Washington river system.

Effects of Sedimentation on Eggs and Alevins. Our field and laboratory experiments show that coho eggs and alevins of the Clearwater system are most severely affected by particles smaller than 0.85 mm. Particles in this category are referred to as "fines" in this paper. To determine the extent of sedimentation, we periodically collected gravel samples at twenty-five known spawning areas in the upper Clearwater River and its major tributaries and, with the help of the Quinault Department of Natural Resources, at additional riffles along five undisturbed streams of Olympic National Park. Several samples were removed from each riffle using a hand coring device known as the McNeil cylinder (McNeil and Ahnell 1964, Koski 1966). Samples were

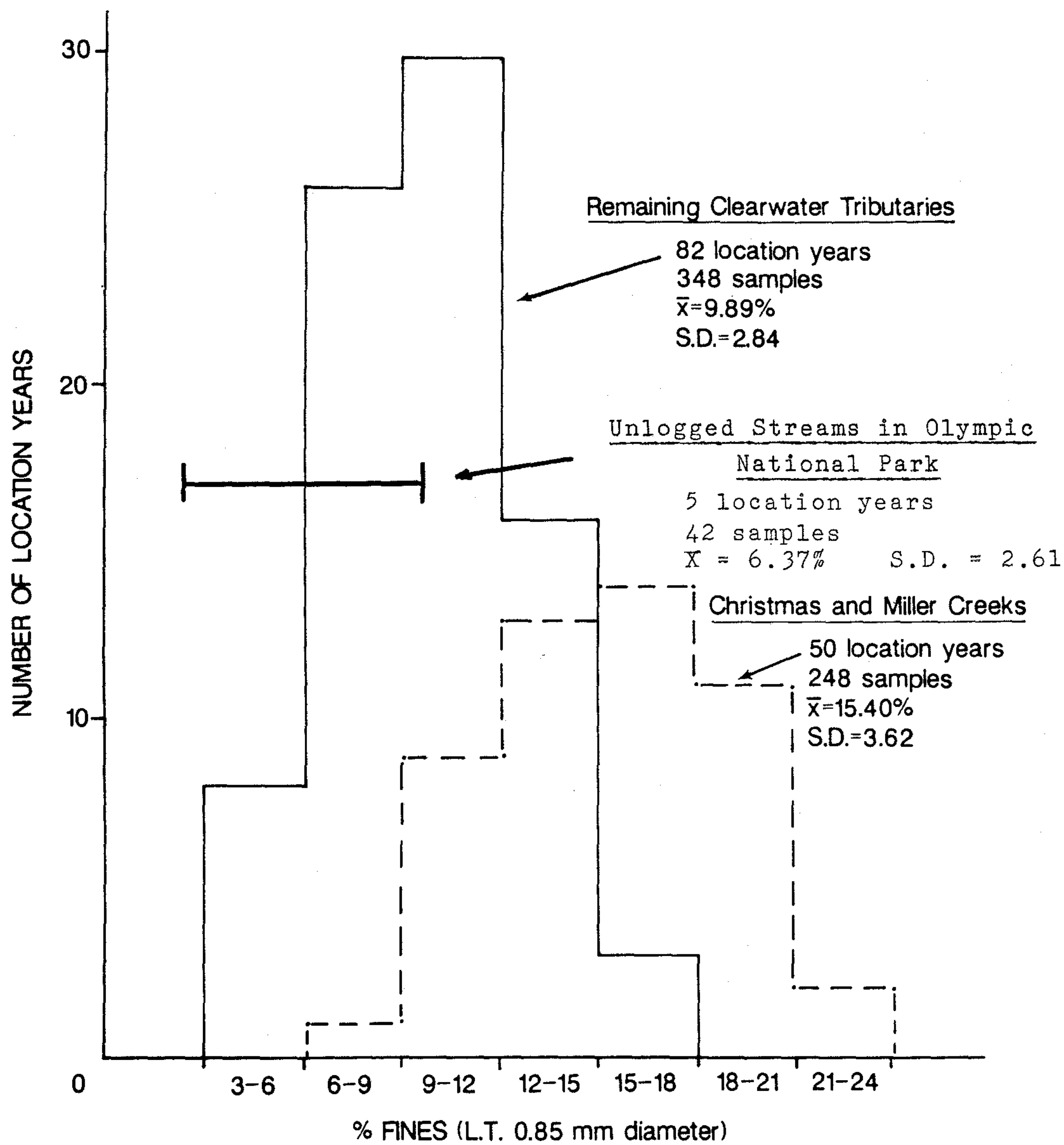

Figure 5. Spawning gravel composition in Christmas and Miller creeks and the remaining Clearwater tributaries, 1972-83.

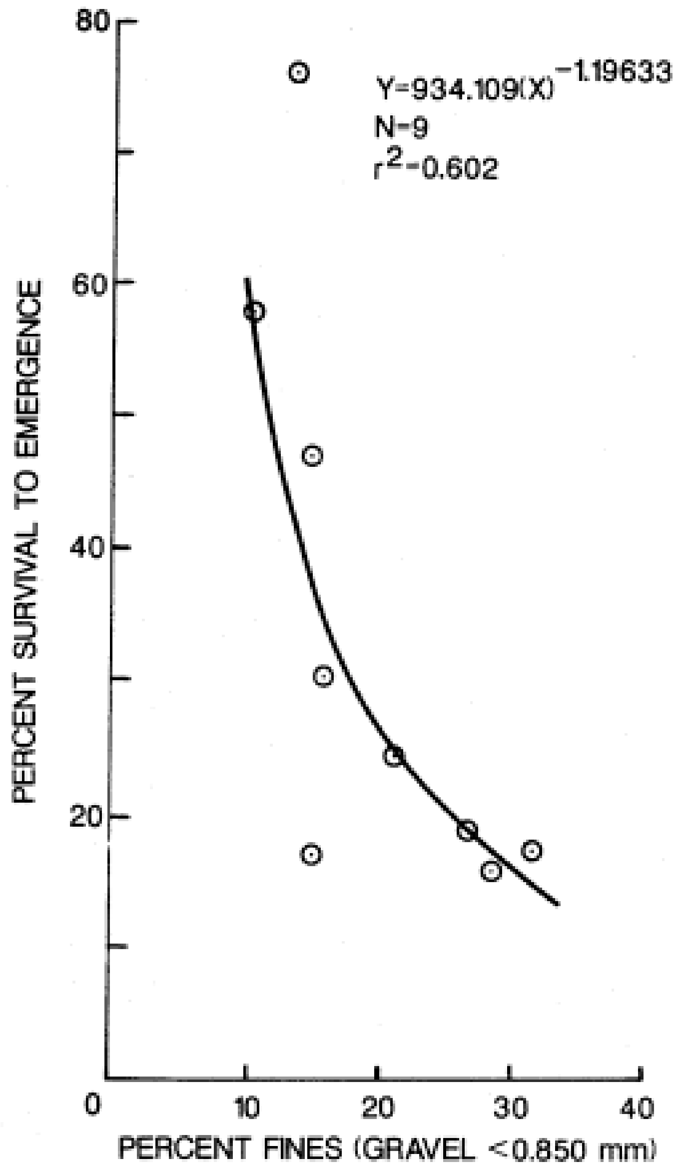

Figure 6a. Relationship between the percent fines (fraction of the gravel <0.850 mm in diameter) and estimated survival from egg deposition to emergence for nine naturally spawned coho salmon redds trapped during 1973-74 (adapted from Tagart 1984).

combined to provide a single characterization of the riffle. Repeated measurements over a thirteen-year period show a range of means of 6 to 23% fines in Clearwater tributaries, and 3 to 10% in undisturbed streams. Gravels contain significantly more fines in the managed basins, and those basins with the greatest amount of clearcutting and roads (Christmas and Miller Creek basins) show the highest proportion of fine sediments in the gravels (Figure 5).

The next step was to determine whether the measured differences in gravel composition were significant to the survival of salmon. During the 1973-74 and 1974-75 spawning seasons, we trapped nineteen

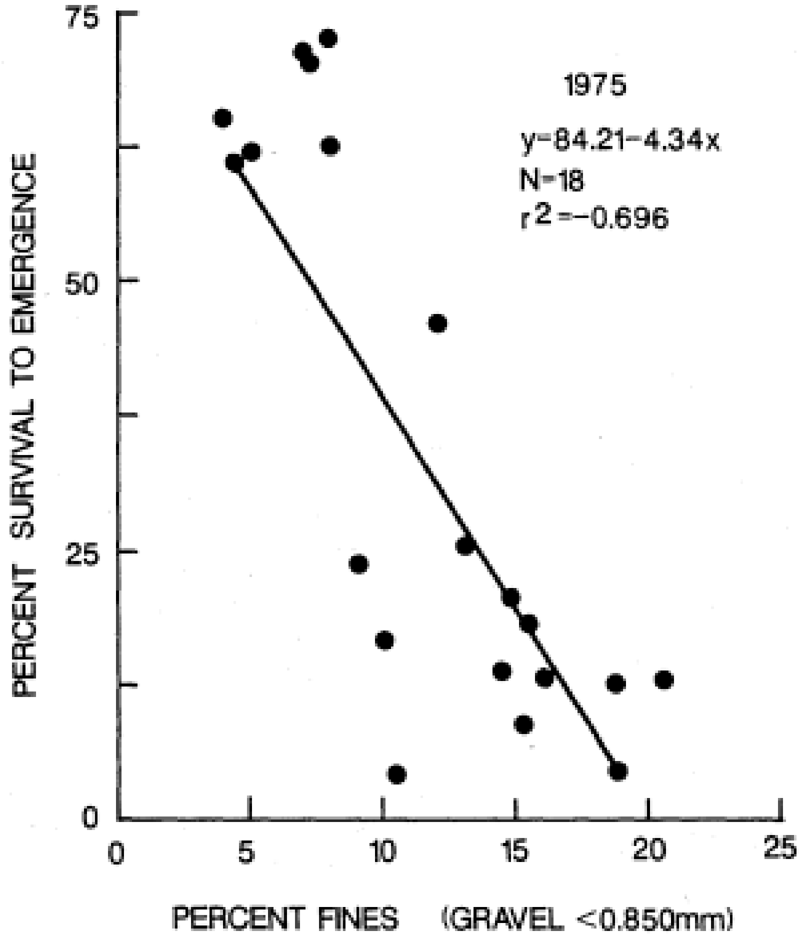

Figure 6b. Coho salmon egg trough experiments on survival from egg deposition to emergence, 1975 (adapted from Cederholm and Salo 1979)

naturally spawned coho salmon redds located in several tributaries of the Clearwater River and sampled the gravel in the redds (Tagart 1976, 1984). Survival-to-emergence estimated using these data ranged from 0.88 to over 75%, and was significantly correlated to the percentage of fine sediment in the gravels (Figure 6a). Tagart's work also indicates that larger fry are less likely to survive to emergence as sedimentation increases. To substantiate the results of the field studies, we buried an average of 1,500 eggs in each of thirty-one troughs loaded with gravel of various compositions (Cederholm and Salo 1979). In this case, too, survival-to-emergence was inversely correlated with the percentage of fines (Figure 6b).

Comparison of the percentage of fine sediments measured in Clearwater spawning riffles with the results of the survival experiments indicates that survival-to-emergence is expected to be significantly reduced from natural values in the more heavily sedimented tributaries. By averaging the predicted survivals from Figures 6a and 6b, we estimate that average intragravel survival has been reduced by 50% in Christmas and Miller creeks, indicating that spawning gravel sedimentation has significantly reduced the viability of the coho substocks in these two tributaries. Because these subbasins provide approximately 40% of the potential smolt yield in the entire river system, this change is expected to be responsible for a 20% decrease in survival-to-emergence for the Clearwater River basin as a whole.

Effect of Sedimentation on Juvenile Fish. Juvenile salmonids depend on macroinvertebrates as a food source. Our earlier work on the influence of gravel-bed siltation on the abundance of benthic macroinvertebrates suggested a decline in these populations in streams affected by landslides (Cederholm and Lestelle 1974, Cederholm et al. 1978). However, we were unable to distinguish the effects of the landslides from those of increasing stream size and discharge.

To clarify the effects of sediment, we conducted a series of studies to determine the influence of streambed composition on benthic fauna in four Clearwater River tributaries (Martin 1976). Benthos samples were collected with a Neill cylinder (Neill 1938) on a monthly schedule for a year, and gravel compositions were measured. It became clear as the experiment progressed that the influence of sediments was not independent of other environmental factors. For example, when silt enters a stream in the Clearwater River system, its residence time on the substrate surface is likely to be short term, since it is rapidly removed by frequent small storms. When sediment is present, benthos are reduced by poor substrate habitat, but they rapidly recolonize substrate surfaces cleaned by the freshets. At the levels present in the Clearwater system, the effects of sedimentation on benthic macroinvertebrates are short term, and are probably insignificant to fish populations feeding on them.

To determine the effects of high suspended sediment concentrations on coho behavior, we constructed two artificial stream channels which allowed us close control of sediment concentrations and habitat conditions, and used static bioassay tanks to detect the effects of experimental conditions on physiology and mortality (Noggle 1978). When the coho were given a choice of clear water (O mg/1), medium (1,000 to 4,000 mg/1), and high concentrations (4,000 to 12,000 mg /1) of suspended sediments in a Y-trough, fish increasingly preferred clear and medium sediment conditions as concentrations increased, and avoided high concentrations, though at low concentrations the fish were observed to use the turbid water as a form of cover. When exposed to high concentrations, the coho experienced noticeable signs of stress (i.e., rapid opercular and cough rates), and sediment accumulated on the ends of gill filaments, apparently interfering with respiration. Tests of plasma glucose in the blood indicated that significant sublethal stress was occurring when fish were temporarily exposed to either medium or high concentrations. Feeding tests carried out in increasingly turbid conditions showed a significant decline in prey capture success at relatively low concentrations of 100 to 400 mg/1 (Figure 7). Static bioassays indicated a thirtyfold increase in tolerance of suspended sediment between August (1,200 mg /1) and November 35,000 mg/1), when naturally occurring concentrations are expected to be high (Figure 8).

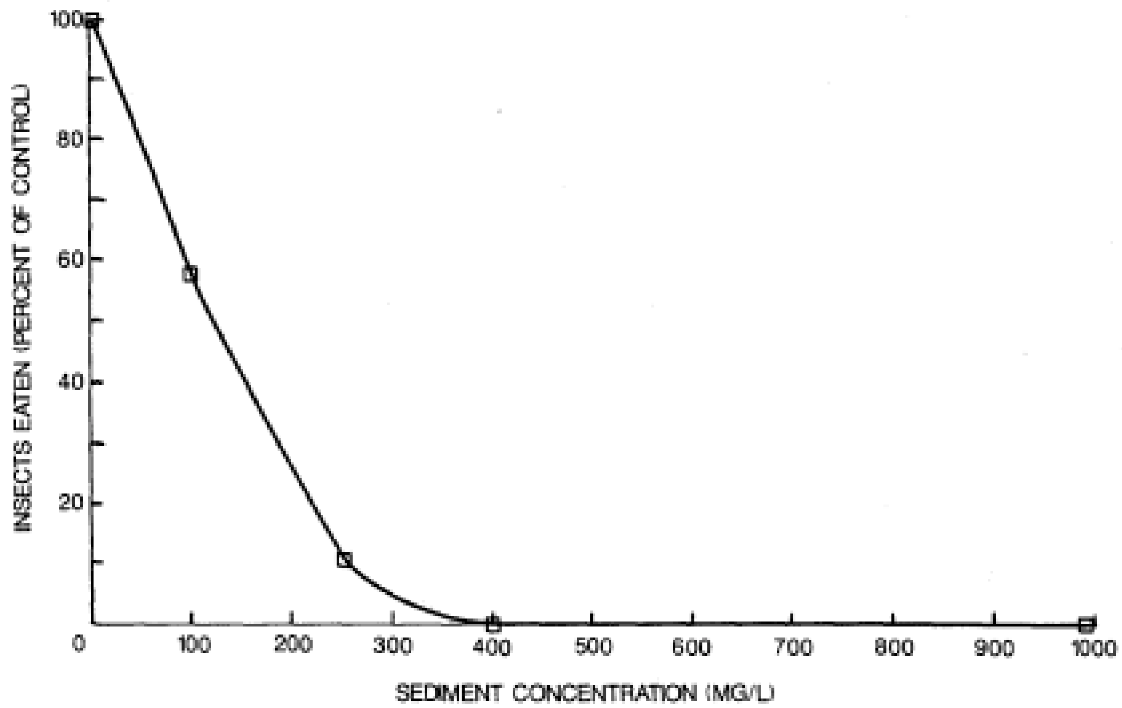

Figure 7. Feeding efficiency of coho smolts versus suspended sediment concentration (adapted from Noggle 1978).

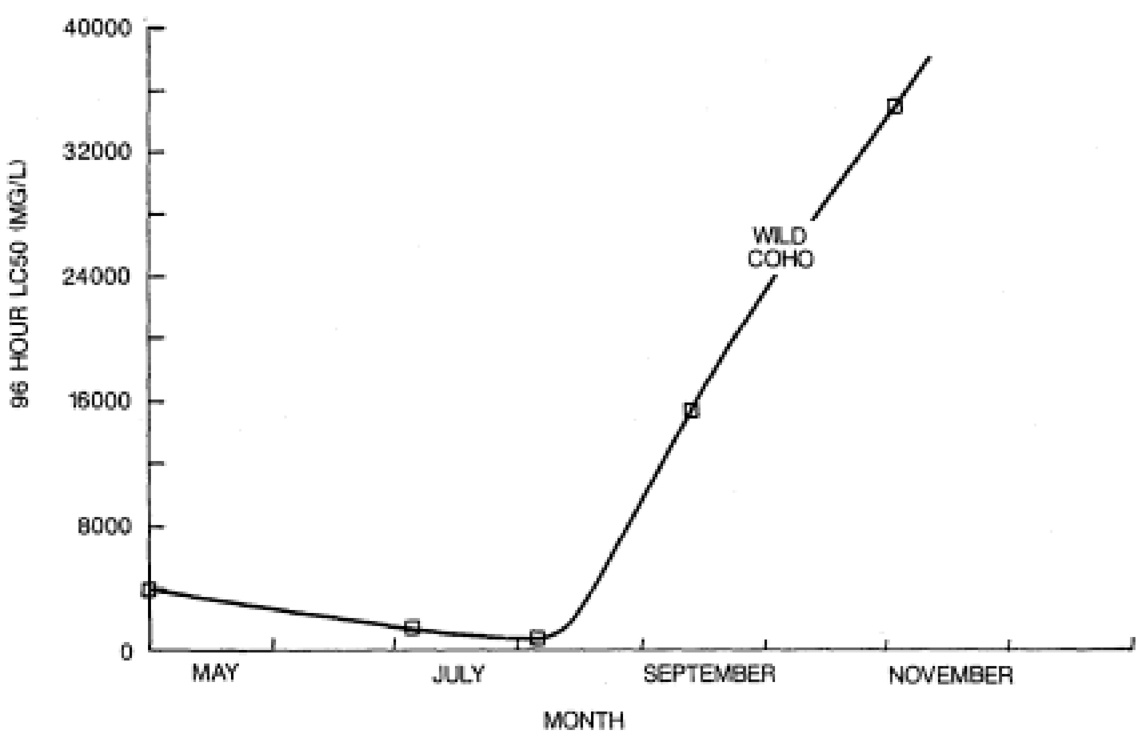

Figure 8. Seasonal change in lethal sediment concentrations of wild coho (adapted from Noggle 1978).

The levels of suspended sediment encountered in the Clearwater basin are generally below those used in the experiments. We have measured concentrations of up to 1,680 to 4,380 mg /1 at a few sites downstream of landslides (Cederholm and Lestelle 1974), but typical high concentrations during winter storms seldom exceed 1,500 mg /1 and are of short duration (Wooldridge et al. 1975). The results from the laboratory experiments indicate that although suspended sediment concentrations are sublethal, they may be introducing significant stress and thus lead to lower survival at some sites. In addition, road use and construction may produce uncharacteristically high sediment loads during small storms in the late summer and early autumn, when tolerance is low, and temporary localized impacts may occur.

Identification of Sediment Sources. To alleviate the documented impacts of sedimentation on survival-to-emergence, we must determine the sources of logging-related sediment, and identify the factors controlling the rate of sediment production. Investigations carried out in the past have shown that forest roads are principal contributors of sediment to streams (Brown and Krygier 1971, Megahan and Kidd 1972). To determine if a correlation exists between logging road density and gravel composition in the Clearwater system, we regressed the measured area of logging road surface above our gravel sampling locations against the percentage of fines in the spawning gravels. The resulting relationship demonstrates that when the road area exceeds 3% of basin area, there is a significant increase in percentage of fines over natural conditions (Figure 9).

Logging roads contribute sediment to streams by erosion of unpaved surfaces, cut banks, and sidecast, and from associated gullies, landslides, and debris torrents. The relative importance of these sources was determined for the Clearwater basin by measuring the rate of sediment production from each source and combining the results to construct a sediment budget for the area (Reid 1981, Reid et al. 1981).

The contribution from road-surface erosion was evaluated by sampling effluent from culverts located on eight segments of gravel-surfaced logging road undergoing various intensities of use, and the input from cut banks was isolated by carrying out similar measurements on two paved roads. Because erosion rates are closely correlated with use level and the amount of runoff from the road surface, construction of a simple runoff model allowed computation of the sediment yield from a road surface for each use level for any storm. In a typical 40% clearcut tributary basin with a road density of 2.5 km/km^2, road-surface erosion would contribute 49 t/km^2 per year, while cut-bank erosion is responsible for only 2 t/km^2 per year (Reid and Dunne 1984).

Landslides, debris torrents, gullies, and areas of sidecast erosion were identified on aerial photographs, and one-third of those identified were examined in the field to determine their age and volume of sediment they displaced. Table 3 indicates that landslides are responsible for the major proportion of sediment introduced by Clearwater roads. However, if the grain size of the sediment is considered, road-surface erosion is seen to be nearly as important as landslides in introducing

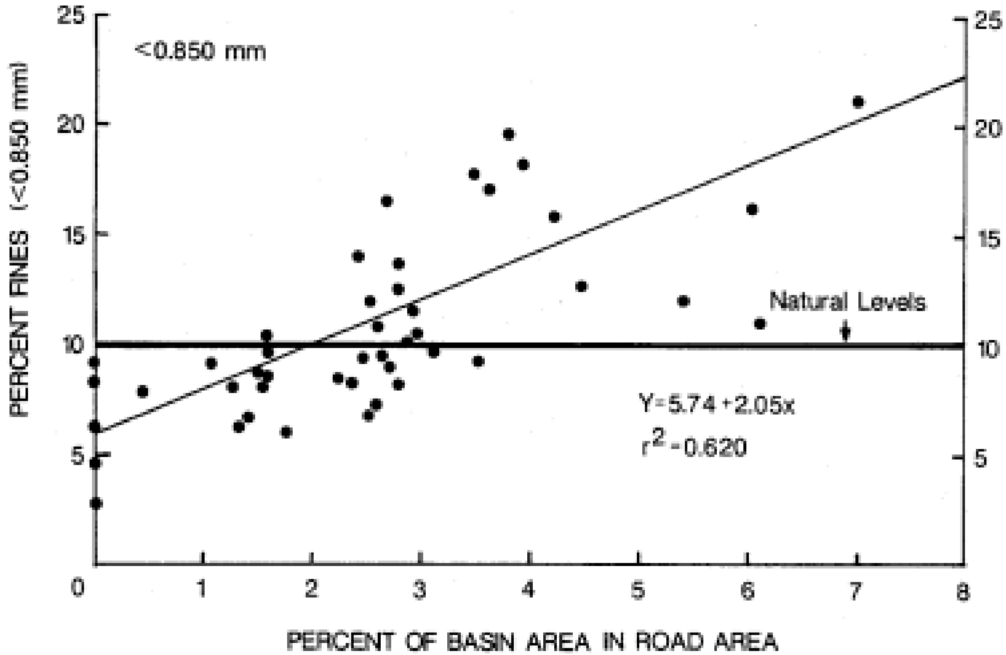

Figure 9. Relationship between percentage of basin area in road area and the percentage of fines in spawning gravels of forty-three basins. Natural levels represent the highest mean level of fines that were found in gravels unaffected by logging roads (adapted from Cederholm 1982).

Table 3. Annual sediment production from road-related sources.

Sediment Source	Rate of Sediment Production (t/road-km)	Sediment Production in Basin (t/km^2)	
		Total	<2 mm
Landslides	66	160	54
Debris flows	10	26	7
Gullies	0.4	1	0.3
Sidecase erosion	1.2	3	3
Road-surface erosion:			
Heavy use	500	36	36
Temporary nonuse	64	5	5
Moderate use	40	5	5
Light use	2	2	2
Abandoned*	0.51	0.6	0.6
Backcut erosion	1.8	2	2
Total		250	120

*Value for abandoned road includes backcut erosion.

fine-grained sediment, though much of the coarse-grained sediment produced by landslides will break down to smaller sizes during transport through the stream system.

Total sediment production from road-related sources in a typical Clearwater tributary basin is approximately 250 t/km^2 per year, while field measurements in the Clearwater basin (Reid 1981) and published values from similar West Coast basins (Brown and Krygier 1971, Larson and Sidle 1980, Rice et al. 1979) provide an estimated sediment production rate of 80 t/km^2 per year under natural conditions. The presence and use of roads alone is thus expected to increase sediment production rates by a factor of four over natural conditions, and sediment finer than 2 mm will be produced at six times the natural rate. Clearcutting is also expected to contribute to higher rates of sediment production, but our preliminary analyses show that sediment sources on clearcuts are relatively less significant than those related to roads.

Factors Governing the Rates of Sediment Production. Once the most important sources o sediment are identified, an understanding of the factors controlling production rates from each source can be used to plan ways of decreasing forestry-related erosion, and the most important sources can be targeted for control. In the Clearwater area, the most important sediment sources are road-related landslides and road-surface erosion, and these were evaluated to determine the variables controlling their rates of sediment production.

The rate of road-surface erosion is found to be most strongly dependent on the intensity of road use, and secondarily on how much water. runs along the surface. Thus 84% of the road-surface sediment is produced from the average of 6% of the road length in a tributary basin that is undergoing heavy use, while the 50% of the roads that are abandoned produce only 1% of the sediment. Road gradient and segment length compensate for each other and are of minor significance. These results indicate that sediment control programs should be focused on road segments that undergo heavy use.

Landslide frequency is most closely controlled by the gradient of the hillslope on which the road is built, and by the age of the road. Thus 95% of the slides are located on the steepest 10% of the slopes, those over 35 degrees, and landslide frequency is at least ten times higher during the two years following road construction than it is ten years after construction. Future landsliding could be nearly eliminated by laying out roads to avoid the steepest slopes. The close relation to road age, however, suggests that this is a sediment source of primary concern only where new roads are being built. Now that most of the road network is already constructed throughout the Clearwater basin, the relative importance of this source will decrease.

DISCUSSION

Studies carried out in the Clearwater basin suggest that intrusion of fine-grained sediment into spawning gravels is the most significant forestry-related impact in the basin. In addition, some winter refuge habitat is being lost by disruption or blockage of small channels on floodplains; aggradation of coarse sediment results in loss of summer habitat; suspended sediment can cause stress to fingerlings; and streambed stability may be locally decreased by removal of large woody debris.

Juvenile coho suffer mortality as a result of naturally occurring floods, landslides, streambed scour, drought, and other causes of temporary habitat loss, but stable populations of salmon compensate for this natural mortality through resilience mechanisms such as excess spawners and abundant fry. In the Clearwater River, stocks are experiencing a loss of resiliency because of the combined effects of overfishing, forestry-caused habitat degradation, and natural mortality. Until recent years the fishery of Queets-Clearwater coho stocks has been excessive, resulting in generally underseeded conditions within the basin. Juvenile populations have been below the levels that would allow maximum smolt yield to be achieved on a regular basis, and this has made these populations vulnerable to habitat degradation caused by logging and natural environmental fluctuations.

By comparing the gravel compositions of the Clearwater watershed with relationships between gravel composition and intragravel survival, we estimate that survival-to-emergence has been lowered by 50% in the two most intensively roaded tributary basins. This impact has lowered basinwide intragravel survival by 20%. In years of marginal spawner escapement or severe environmental conditions, this reduction in intragravel survival could weaken stocks significantly.

Natural events such as floods and droughts can further reduce effective seeding; consequently, the necessary spawning escapement for one year may be inadequate for another (Salo and Bayliff 1958). During the rebuilding of depressed stocks, it would be wise to allow the stock as wide a margin of spawners as is practical as a buffer against adverse environmental conditions. This practice would prevent the development of weak brood cycles such as occurred in 1979 in the Clearwater River. During the 1979-80 spawning season, scour and deposition from major floods destroyed 40 to 50% of the redds (Wood, WDF, pers. comm.), and subsequently the 1981 smolt yield was low (52,000 smolts). In contrast, the relatively mild winter of 1981-82 produced the highest smolt yield on record (95,000 smolts), although the number of spawners for that brood was 30% less than in 1979 (smolt yield data supplied by D. Seiler, WDF, pers. comm.).

If the Clearwater were receiving sufficient spawners, natural and forestry-related mortality would probably be compensated for by the provision of a buffer of excess fry and fingerlings, and the maximum smolt yield could be achieved on a more regular basis. However, overfishing, forestry-related impacts, and natural climatic fluctuations have combined to depress the coho salmon population of the Clearwater River. The interaction of different causes of mortality may have a far greater effect on the viability of Northwest stocks than is generally recognized, and may partly explain the declines of wild coho and other salmonid species that have been reported along the West Coast.

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LITERATURE CITED

Brown, G. W., and J. T. Krygier. 1971. Clear-cut logging and sediment production in the Oregon Coast Range. Water Resour. Res. 7(5):1189-1198.

Campbell, H. J. 1954. The effect of siltation from gold dredging on survival of rainbow trout and eyed eggs in Powder River, Oregon. Oregon State Game Commission. Mimeographed report. 3 p.

Cederholm, C. J., and L. C. Lestelle. 1974. Observations on the effects of landslide siltation on salmon and trout resources of the Clearwater River, Jefferson County, Washington, 1972-1973. Final report: Part 1. FRI-UW-7404. Fisheries Research Institute, University of Washington, Seattle. 89 p.

Cederholm, C. J., L. C. Lestelle, B. G. Edie, D. J. Martin, J. V. Tagart, and E. 0. Salo. 1978. The effects of landslide siltation on the salmon and trout resources of Stequaleho Creek and the main Clearwater River, Jefferson County, Washington, 1972-1975. Final report: Part 2. FRI-UW-7804. Fisheries Research Institute, University of Washington, Seattle. 53 p.

Cederholm, C. J., L. M. Reid, B. G. Edie, and E. 0. Salo. 1982. Effects of forest road erosion on salmonid spawning gravel composition and populations of the Clearwater River, Washington. In Habitat distrubance and recovery: Proceedings of a symposium, p. 1-17. California Trout, Inc., San Francisco, California.

Cederholm, C. J., L. M. Reid, and E. 0. Salo. 1981. Cumulative effects of logging road sediment on salmonid populations in the Clearwater River, Jefferson County, Washington. In Proceedings from the conference Salmon-Spawning Gravel: A Renewable Resource in the Pacific Northwest? p. 39-74. Rep. 39. State of Washington Water Research Center, Pullman.

Cederholm, C. J., and E. 0. Salo. 1979. The effects of logging road landslide siltation on the salmon and trout spawning gravels of Stequaleho Creek and the Clearwater River basin, Jefferson County, Washington, 1972-1978. FRI-UW-7915. Fisheries Research Institute, University of Washington, Seattle. 99 p.

Cederholm, C. J., and W. J. Scarlett. 1982. Seasonal immigrations of juvenile salmonids into four small tributaries of the Clearwater River, Washington, 1977-1981. In E. L. Brannon and E. 0. Salo (eds.) Proceedings of the Salmon and Trout Migratory Behavior Symposium, p. 98-110. School of Fisheries, University of Washington, Seattle.

Chapman, D. W., and E. Knudsen. 1979. Channelization and livestock impacts on salmonid habitat and biomass in western Washington. Trans. Am. Fish. Soc. 109:357-363.

Deschamps, G. 1971. A report of siltation in Stequaleho Creek. Washington Department of Fisheries, Management Research Division. Mimeographed report. 7 p.

Edie, B. G. 1975. A census of juvenile salmonids of the Clearwater River basin, Jefferson County, Washington, in relation to logging. M.S. thesis, College of Fisheries, University of Washington, Seattle. 86 p.

Flint, T. 1977. Juvenile coho population estimates determined by electrofishing in twelve Puget Sound streams, August-October, 1976. Washington Department of Fisheries Prog. Rep. 32. 18 p.

Gibbons, D. R., and E. 0. Salo. 1973. An annotated bibliography of *the effects* of logging on fish of the western United States and Canada. USDA For. Serv. Gen. Tech. Rep. PNW-10. Pac. Northwest For. and Range Exp. Stn., Portland, Oregon. 145 p.

Grette, G. B. 1985. The role of large organic debris in juvenile salmonid rearing habitat in small streams. M.S. thesis, University of Washington, Seattle. 105 p.

Hall, T. 1984. A laboratory study of the effects of sediments of two different size characteristics on survival of rainbow trout (Salmo gairdneri) embryos to fry emergence. Tech. Bull. 429. National Council of the Paper Industry for Air and Stream Improvement. 49 p.

Hynes, H. B. N. 1960. The biology of polluted waters. Liverpool University Press, Liverpool, England. 202 p.

Iwamoto, R. N., E. 0. Salo, M. A. Madej, and R. L. McComas. 1978. Sediment and water quality: A review of the literature including a suggested approach for water quality criteria. U.S. Environmental Protection Agency, Region 10, Seattle. 151 p.

Koski, K V. 1966. The survival of coho salmon (Oncorhynchus kisutch) from egg deposition to emergence in three Oregon coastal streams. M.S. thesis, Oregon State University, Corvallis. 84 p.

___________. 1975. The survival and fitness of two stocks of chum salmon (Oncorhynchus keta) from egg deposition to emergence in a controlled stream environment at Big Beef Creek. Ph.D. thesis, University of Washington, Seattle. 212 p.

Larson, K. R., and R. C. Sidle. 1980. Erosion and sedimentation data catalog of the Pacific Northwest. USDA For. Serv. R6-WM-050-1981. Pacific Northwest Region, Portland, Oregon. 64 p.

Lestelle, L. C., G. S. Morishima, and T. D. Cooney. 1984. Determining spawning escapement goals for wild coho salmon on the Washington North Coast. In J. M. Walton and D. B. Houston (eds.) Proceedings of the Olympic Wild Fish Conference, p. 243-254. Fisheries Technology Program, Peninsula College, Port Angeles, Washington.

Martin, D. J. 1976. The effects of sediment and organic detritus on the population of benthic mactoinvertebrate: in four tributary streams of the Clearwater River, Washington. M.S. thesis, College of Fisheries, University of Washington, Seattle. 79 p.

Martin, D. J., E. 0. Salo, S. T. White, J. A. June, W. J. Foris, and G. L. Lucchetti. 1981. The impact of managed streamside timber removal on cutthroat trout and the stream ecosystem. FRI-UW-8107. Fisheries Research Institute, University of Washington, Seattle. 65 p.

McNeil, W. J., and W. H. Ahnell. 1964. Success of pink salmon spawning relative to size of spawning bed materials. U.S. Fish and Wildlife Service Spec. Sci. Rep., Fish. 469. 15 p.

Megahan, W. F., and W. J. Kidd, Jr. 1972. Effects of logging roads on sediment production rates in the Idaho batholith. USDA For. Serv. Res. Pap. INT-123. Intermountain For. and Range Exp. Stn., Ogden, Utah. 14 p.

Moring, J. R., and R. L. Lantz. 1974. Immediate effects of logging on freshwater environments of salmonids. Res. Div. Proj. AFS-58. Final Rep. Oregon Wildlife Commission, Portland. 101 p.

___________. 1975. The Alsea Watershed Study: Effects of logging on the aquatic resources of three headwater streams of the Alsea River, Oregon. Part 1: Biological studies. Fish. Res. Rep. 9. Oregon Department of Fish and Wildlife, Portland. 66 p.

Narver, D. W. 1972. A survey of some possible effects of logging on two Eastern Vancouver Island streams. Fish. Res. Board Can. Tech. Rep. 323. 55 p.

Narver, D. W., and B. C. Andersen. 1974. Fish populations of Carnation Creek and other Barkley Sound streams, 1970-1973: Data record and progress report. Fish. Res. Board Can. MS Rep. 1303. 115 p.

Neill, R. M. 1938. The food and feeding of the brown trout in relation to the organic environment. Trans. Royal Soc. Edin. 59:481-520.

Noggle, C. C. 1978. Behavioral, physiological and lethal effects of suspended sediment on juvenile salmonids. M.S. thesis, University of Washington, Seattle. 87 p.

Peterson, N. P. 1982. Immigration of juvenile coho salmon (Oncorhynchus kisutch) into riverine ponds. Can. J. Fish. Aquat. Sci. 39:1308-1310.

__________. 1985. Riverine pond enhancement project, October 1982 - December 1983. Washington Department of Fisheries and Department of Natural Resources Prog. Rep. 233. 48 p.

Peterson, N. P., and L. M. Reid. 1984. Coho riverine habitat: Its evolution, distribution, and use. In J. M. Walton and D. B. Houston (eds.) Proceedings of the Olympic Wild Fish Conference, p. 215-225. Fisheries Technology Program, Peninsula College, Port Angeles, Washington.

Phillips, R. W. 1965. Effect of fine materials on salmon and trout redds. Meeting on Erosion and Sedimentation. Water Supply and Water Pollution Control Subcommittee, Columbia River Interagency.

Reid, L. M. 1981. Sediment production from gravel-surfaced forest roads, Clearwater basin, Washington. FRI-UW-8108. Fisheries Research Institute, University of Washington, Seattle. 247 p.

Reid, L. M., and T. Dunne. 1984. Sediment production from forest road surfaces. Water Resour. Res. 20(11):1753-1761.

Reid, L. M., T. Dunne, and C. J. Cederholm. 1981. Application of sediment budget studies to the evaluation of logging road impact. N.Z. J. Hydrol. 20:49-62.

Rice, R. M., F. B. Tilley, and P. A. Datzman. 1979. A watershed's response to logging and roads: South Fork of Caspar Creek, California, 1967-1976. USDA For. Serv. Res. Pap. PSW-146. Pac. Southwest For. and Range Exp. Stn., Berkeley, California. 12 p.

Salo, E. 0., and W. H. Bayliff. 1958. Artificial and natural production of silver salmon, Oncorhynchus kisutch, at Minter Creek, Washington. Washington Department of Fisheries Res. Bull. 4. 75 p.

Scarlett, W. S., and C. J. Cederholm. 1984. Juvenile coho salmon fall-winter utilization of two small tributaries of the Clearwater River, Jefferson County, Washington. In J. M. Walton and D. B. Houston (eds.) Proceedings of the Olympic Wild Fish Conference, p. 227-242. Fisheries Technology Program, Peninsula College, Port Angeles, Washington.

Tagart, J. V. 1976. The survival from egg deposition to emergence of coho salmon in the Clearwater River, Jefferson County, Washington. M.S. thesis, University of Washington, Seattle. 101 p.

__________. 1984. Coho salmon survival from egg deposition to fry emergence. In J. M. Walton and D. B. Houston (eds.) Proceedings of the Olympic Wild Fish Conference, p. 173-182. Fisheries Technology Program, Peninsula College, Port Angeles, Washington.

Usinger, R. L. 1971. Aquatic insects of California. University of California Press. 508 p.

Washington State Forest Practices Board. 1976. Washington forest practices handbook: Rules and regulations. 100 p.

Wickett, W. P. 1954. The oxygen supply to salmon eggs in spawning beds. J. Fish. Res. Board Can. 11(6):933-953.

__________. 1958. Review of certain environmental factors affecting the production of pink and chum salmon. J. Fish. Res. Board Can. 15(5):1103-1126.

Wood, W. A. 1984. Trends in historic abundance and present status of natural stocks of north coastal Washington coho and chinook salmon. In J. W. Walton and D. B. Houston (eds.) Proceedings of the Olympic Wild Fish Conference. Fisheries Technology Program, Peninsula College, Port Angeles, Washington.

Wooldridge, D. D., A. G. Larson, and A. R. Wald. 1975. Hydrologic data summary Clearwater River basin, water year 1973-74. College of Forest Resources, University of Washington, Seattle.

Ziebell, C. D. 1960. Problems associated with spawning and growth of salmonids in Northwest watersheds. Proceedings, Seventh Symposium on Water Pollution Research. U.S. Department of Health, Education and Welfare, Portland, Oregon.