scanned for KRIS

North American Journal of Fisheries Management 17:947-963, 1997
© Copyright by the American Fisheries Society 1997

Response of Juvenile Coho Salmon and Steelhead to Placement of Large Woody Debris in a Coastal Washington Stream

C. J. CEDERHOLM

Washington Department of Natural Resources
Resource Planning and Asset Management Division
Post Office Box 47014, Olympia, Washington 98504-7014, USA

R. E. BILBY

The Weyerhaeuser Co., Technology Center
32901 Weyerhaeuser Way South, Federal Way, Washington 98003, USA

P. A. BISSON

U.S. Forest Service, Pacific Northwest Research Station
3625 93rd Avenue Southwest, Olympia, Washington 98512-9193, USA

T. W. BUMSTEAD

River Masters Inc., Pullman, Washington 99163, USA

B. R. FRANSEN

The Weyerhaeuser Co., Technology Center

W. J. SCARLETT

Washington Department of Natural Resources
Resource Planning and Asset Management Division

J. W. WARD

The Weyerhaeuser Co., Technology Center

Abstract.-Many fish habitats have been altered in Pacific Northwest streams and rivers over the past century by a variety of land use practices, including forestry, urbanization, agriculture, and channelization. There are research and management needs for evaluation of the effectiveness of rehabilitation projects intended to enhance stream fish habitat recovery. The response of populations of juvenile coho salmon *Oncorhynchus kisutch* and steelhead *O. mykiss* to addition of large woody debris (LWD) was tested in North Fork Porter Creek (NFPC), a small coastal tributary of the Chehalis River, Washington. The NFPC was divided into three 500-m study sections; two sections were altered with two approaches (engineered and logger's choice) to adding LWD, and the third was kept as a reference site. Immediately after LWD addition, the abundance of LWD pieces was 7.9 times greater than the pretreatment level in the engineered site and 2.7 times greater in the logger's choice site; abundance was unchanged in the reference site. Subsequent winter storms brought additional LWD into all three study sites. In the years that followed, the amount of pool surface area increased significantly in both the engineered and logger's choice sites, while it decreased slightly in the reference site. After LWD addition, winter populations of juvenile coho salmon increased significantly in the engineered and logger's choice sites, while they remained the same in the reference site. There were no significant differences in the coho salmon populations during spring and autumn within the reference, engineered, or logger's choice sites. The coho salmon smolt yield from the engineered and logger's choice sites also increased significantly after LWD addition, while it decreased slightly in the reference site. After LWD addition, the reference site and the engineered site both exhibited increases in age-0 steelhead populations; however, the population in the logger's choice site did not change. There was no difference in age-1 steelhead abundance among sites, or before and after enhancement during any season. Winter populations of juvenile coho salmon and age-0 steelhead were related inversely to maximum and mean winter discharge.

Fish habitat in Pacific Northwest streams and rivers has been altered over the last century by a variety of land use practices, including forestry (Wendler and Deschamps 1955; Salo and Cundy 1987; Hicks et al. 1991), pioneer settlement and subsequent urbanization (Sedell and Luchessa 1982; Sedell et al. 1988; Booth 1991), agriculture (Elmore and Beschta 1987; Platts 1991), and modification of stream channels (Kramer 1953; Cederholm 1972; Salo and Jagielo 1983). These activities have resulted in dramatic reductions in abundance of large woody debris (LWD) in stream channels (Sedell and Luchessa 1982; Grette 1985; Bilby and Ward 1991).

Large woody debris (i.e., organic material longer than 2 m and having a diameter of at least 10 cm) performs a variety of functions in streams. It is often the most important pool-forming agent in smaller systems (Bisson et al. 1987); it stores gravel, fine sediment, and organic matter (Beschta 1979; Bilby and Likens 1980; Cederholm et al. 1989); and it dissipates the energy of flowing water (Heede 1976). These processes have important effects on fishes living in streams, in that they create spawning and rearing habitat, increase nutrient and organic matter retention (which increases food production in the system), and provide refuge from predators and cover during high winter flows (Bustard and Narver 1975; Lestelle 1978; Lestelle and Cederholm 1982; McMahon and Hartman 1989; Hicks et al. 1991). Several studies in the Pacific Northwest have indicated that availability of low-velocity habitat within the main channel, sheltered from the effects of winter flood flows, is often an important factor in retaining juvenile coho salmon within the stream channels over winter, these fish later contribute to stream smolt production (Mason 1976; Reeves et al. 1991). The LWD is important in creating this type of habitat (Bustard and Narver 1975; Bisson et al. 1987).

There is a need for evaluation of the effectiveness of restoration projects intended to enhance stream and fish habitat (Koski 1992). Numerous efforts to increase the abundance of LWD in streams where it is considered deficient have been undertaken over the last decade (Duff and Banks 1988; House et al. 1988; Sheng 1993). However, Frissell and Nawa (1992) found that many large and costly salmon habitat restoration projects have been implemented by federal and state agencies with little or no analysis of the response of the targeted stream biota. In addition, much of the LWD placed in streams during these projects failed to perform as intended or was damaged or removed from the system by high flows. Some projects have shown benefits to salmonid fish populations, but, in many cases, evaluations and monitoring have been noticeably lacking.

Increases in numbers of anadromous (Ward and Slaney 1981; House and Boehne 1995) and non-anadromous (Gowan and Fausch 1995) fishes after addition of LWD to a stream have been demonstrated. These results are cited widely as justification for enhancement projects which involve the introduction of LWD. However, further examination of both published and unpublished information on the effectiveness of various enhancement efforts suggests that numerous projects have had no impact or negative impacts on fish populations (Hall and Baker 1982; Hamilton 1989). The need for careful evaluation of enhancement efforts has become widely recognized (Hall and Baker 1982; Reeves and Roelofs 1982; Everest and Sedell 1984; Hall 1984; Klingeman 1984; Platts and Rinne 1985).

Our study evaluated the changes in habitat and the response of juvenile coho salmon ***Oncorhynchus kisutch*** and steelhead ***0. mykiss*** to two approaches of introducing LWD to a stream. One section of stream was treated by placing logs in the channel using heavy equipment and securing the wood in place, a relatively expensive approach which has been applied widely in the Pacific Northwest. The other approach involved simply cutting and felling trees into the stream channel and cabling them to their stumps, an inexpensive technique commonly used.

Methods

Study Area

We evaluated LWD placement in North Fork Porter Creek (NFPC), located west of Olympia, Washington, in the state-owned Capitol Forest 46°59′N, 123°14′W (Figure 1). North Fork Porter Creek is a third-order tributary to the Chehalis River, draining an area of 25 km^2.

The study area was located approximately 0.5 km upstream from the mouth of the NFPC. Average bank-full channel width is about 10 m and channel gradient is 2%. Average annual discharge is approximately 1 m^3/s with summer low flow of 0.05 m^3/s and an estimated 50-year return interval flow of 51 m^3/s (Orsborn 1990).

The climate in the watershed is characterized by warm, dry summers and cool, wet weather the rest of the year. Annual precipitation ranges from 127 to 178 cm, occurring primarily as rain (McMurphy and Anderson 1968). Snow may accumulate and persist for several weeks during winter at higher elevations within the watershed. Air temperatures are moderated by marine influence of the nearby Pacific Ocean. Annual mean temperature is 10.4°C with recorded extremes from – 18.3°C to 39.5°C (Phillips 1964).

The NFPC watershed is underlain by bedrock of the Crescent Formation, consisting of basalt

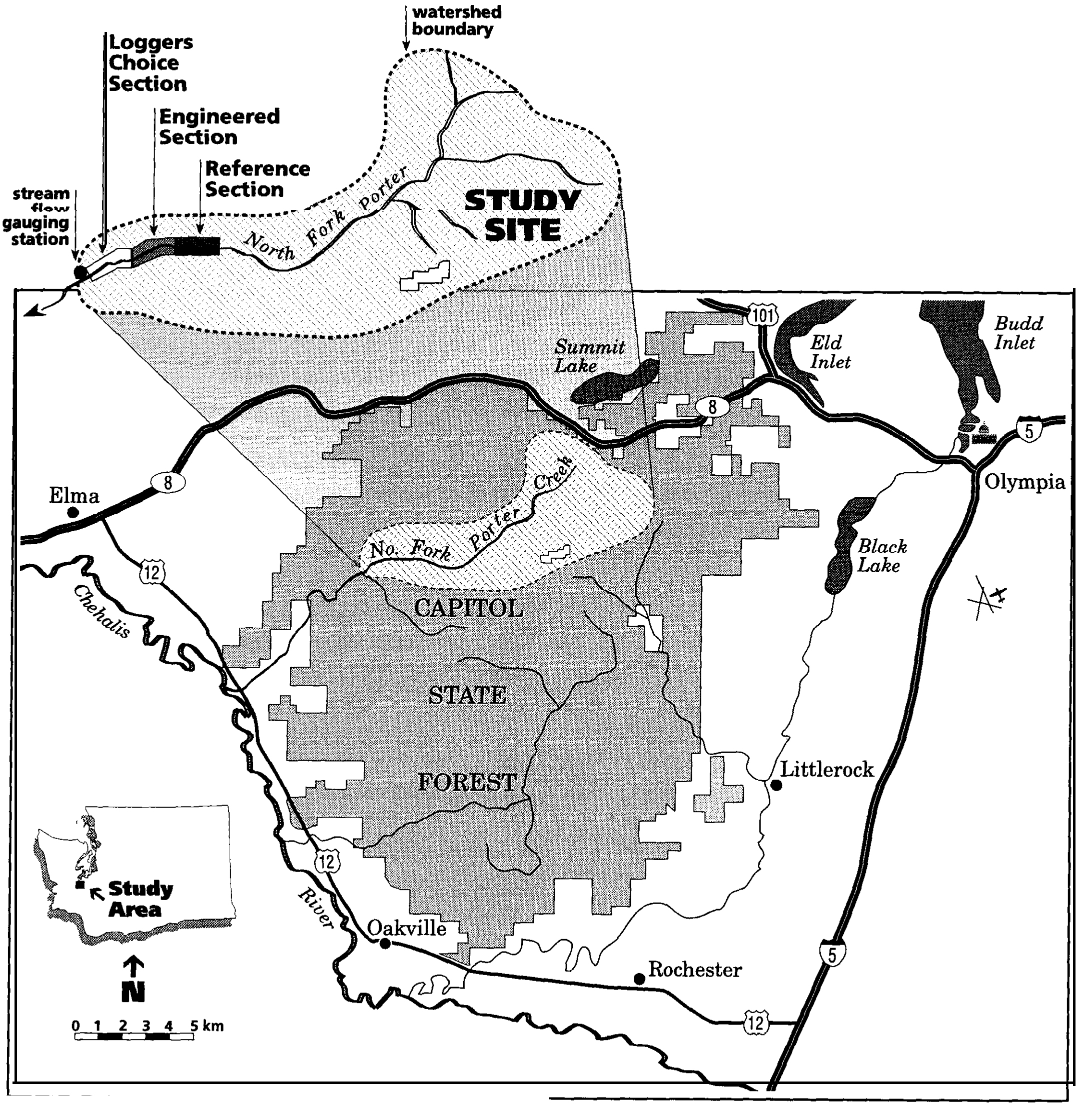

FIGURE 1.-Location of the Porter Creek watershed, Washington, showing the location of the reference and experimental sections.

flows deposited during the early and mid-Eocene and sedimentary deposits from the Oligocene and Miocene. Soils formed from this bedrock in areas of low relief are deep, well-drained silt and clay loams while soils in steeper terrain are shallower and contain more gravel (Pringle 1986).

About 8 km of the stream is accessible to anadromous fishes which include coho salmon, steelhead, coastal cutthroat trout ***O. clarki clarki*** and Pacific lamprey ***Lampetra tridentata.*** Resident (nonanadromous) species occupying the study site include several species of sculpin ***Cottus*** spp. and cutthroat trout.

Land Management History

The Capitol Forest was originally logged between 1920 and 1940 (Carman et al. 1984) and the NFPC watershed was logged during the latter part of this period. Timber harvested at this time was removed from the forest by railroad, as evidenced by abandoned grades and trestles near the study site. No forest practice regulations were in effect at that time, and impacts on the stream and the riparian area were severe.

During the 1970s about 35 km of stream within the Capitol Forest were cleared of nearly all LWD to eliminate possible blockages to anadromous fish migration. The NFPC was included in this treatment.

Logging of second-growth timber in the NFPC watershed has been ongoing since 1975. The primary harvest method is clearcutting of blocks ranging in size from 40 to 100 ha. Streams have received varying levels of protection from logging depending on the size of the stream and the regulations in effect at the time the area was harvested. A buffer of standing trees was retained along the NFPC following logging in the early 1980s. The buffer ranges 8-25 m in width. The predominant overstory species in the buffer is red alder *Alnus rubra,* a common early successional species in forests of western Washington. A few Sitka spruce *Picea sitchensis,* Douglas-fir *Pseudotsuga menziesii,* western hemlock *Tsuga heterophylla,* western redcedar *Thuja plicata,* and bigleaf maple *Acer macrophyllum* also were included in the buffer.

Experimental Design

The study sites for this project were established on one stream to minimize between-stream physical and biological variability. It would have been helpful to have study sites on several streams, but the costs involved proved to be prohibitive. The 1,500-m study area on NFPC was separated into three, 500-m sites-reference, engineered, and logger's choice-to provide enough stream area for physical and biological response to LWD placement (Figure 1). Statistical inferences derived from our treatments would have been much more powerful if replicate treatment sites on the NFPC could have been established; nonetheless, our design permitted us to compare the response of physical habitat features and fish populations to our treatments at these sites and to better understand the processes responsible for the observed changes.

Large woody debris addition to the two treatment sites began in late summer 1990 and was finished in late summer 199 1. Two years were required because construction activity in the stream was permitted only during August and September. The goal for the treated sites was to increase the size and frequency of pools and amount of LWD cover during winter, and to positively influence the number of overwintering juvenile salmonids within the two treatment sites.

Reference site.-The reference site was deliberately not altered during this study, and was located upstream of the two treated sites to minimize influences resulting from installation of the enhancement structures at the treated sites. Although no LWD was purposefully added to this site, 48 pieces entered the site between 1991 and 1994 during winter storms and some changes in habitat characteristics did occur over the 6-year study.

Engineered site.-The center site was labeled the engineered site because of the methods used to introduce LWD at this location. A thorough survey of the area and a detailed analysis of the hydrology of NFPC were completed prior to developing plans (Orsborn 1990). Introduction of LWD was accomplished with labor-intensive techniques involving heavy equipment and anchoring of wood added to the channel. Logs and boulders used in the project were transported to the channel with a tractor and placed with a tracked loader with a thumbed bucket. Large woody debris abundance was increased to levels typical of streams in forests where no timber harvest had occurred (Bilby and Ward 1989). In all, 133 structures containing 200 logs were added to the engineered site.

Logs were arranged into five different configurations at the engineered site (Figure 2A). In general, the full-crossing structures were intended primarily to control stream gradient while the partially crossing, parallel, pyramid, and logjam structures were intended to provide cover and habitat for the fish. Most of the logs used for these structures were cut from a stand of large conifers approximately 1 km from the study area. Conifer logs decompose more slowly than hardwood logs of similar size (Harmon et al. 1986), which increases the longevity of the structures. To create access to the area for heavy equipment, some red alder, Douglas-fir, and Sitka spruce had to be removed from the adjacent riparian stand; many of these trees were placed and anchored in the channel.

Several methods were used to anchor the logs in the channel (Figure 2A). Full-crossing logs were placed in narrow trenches excavated in each bank, boulders were placed on the ends of the log and covered with soil. A length of 1.8-m high cyclone fencing was stapled from bank to bank along the upstream side of the full-crossing logs; and covered with black fiberglass fabric to prevent the stream from undercutting the logs. One end of the partial-crossing logs was similarly buried in streambanks; however, the free end was anchored to the streambed using cable and epoxy cement. Parallel structures also were attached to the streambed with cable and epoxy cement. This procedure involved drilling a pair of holes into a buried boulder and wrapping a 14-mm steel cable

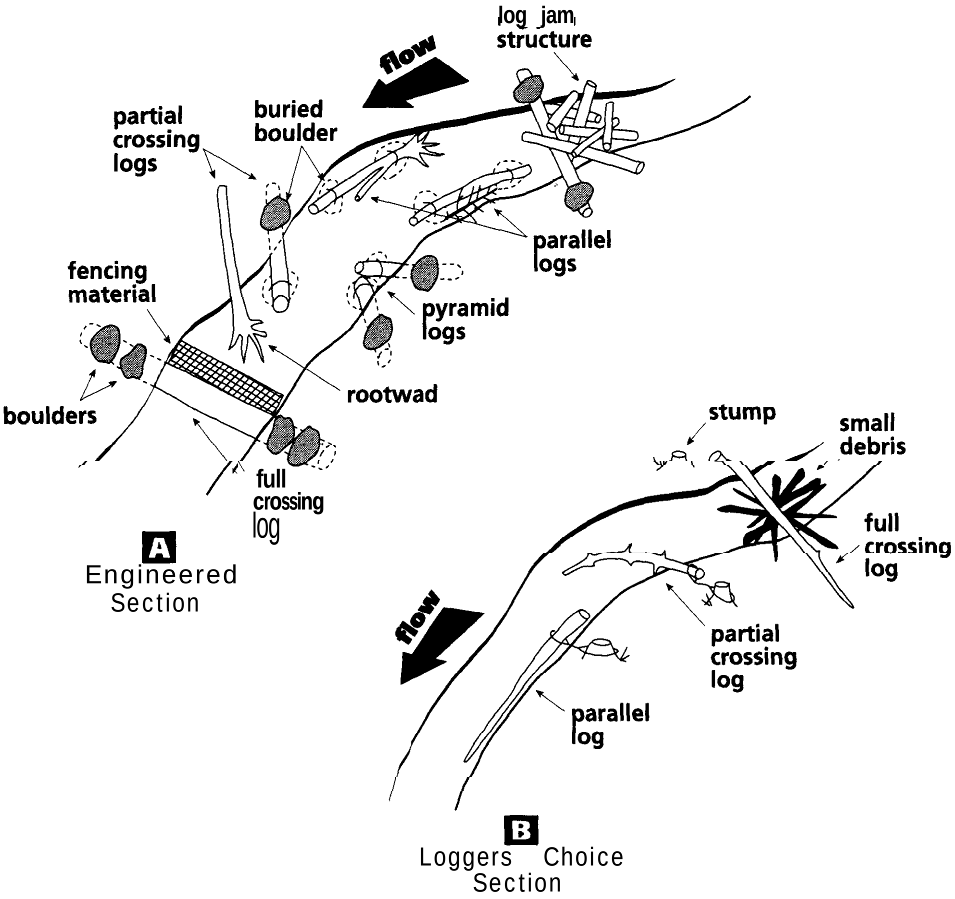

FIGURE 2.-Types of woody debris structures added to the (A) engineered and (B) logger's choice stream sections.

around the log and cementing the cable into the holes. In most cases, the boulder attached to the log was buried purposefully in the streambed. Other partially crossing logs were secured by wedging one end between two live trees on the streambank, and the free end was allowed to move in the current. Wherever two logs came into contact with each other (i.e., in the logjam), they were drilled and pinned together with a length of 13-mm diameter steel reinforcing rod.

TABLE 1.-Expenses incurred in implementation of the two large woody debris addition techniques compared in this study.

Expense	Engineered section	Logger's choice section
Engineering and design	$14,600.00	0.00
Heavy machinery	$33,000.00	0.00
Hand labor	$12,600.00	$2.700.00
Logs and rock	$17,000.00	$3,000.00
Other materials	$3,050.00	$750.00
Pumps	$2,000.00	0.00
Total	$82,250.00	$6,450.00
Cost/m of channel		
	$164.50	$12.90

Additional cover was provided at some of the parallel and partially crossing structures by nailing whole, 3-4 m long conifers (approximate diameter of 10 cm) to the shoreline side of the parallel log structures (Figure 2A). The approximate cost for treating the engineered section was $82,250 (Table 1). Twenty-nine additional pieces of LWD entered the engineered site between 1991 and 1994 during winter storms.

Logger's choice site.-A much less expensive approach, called logger's choice, was used to add LWD to the downstream-most site. Logs added to this site were all red alder cut from the streambank and dropped into the channel. Felling crews were instructed to cut 60 trees larger than 30 cm in diameter and distribute them as evenly as possible along the 500-m stream reach. The trees were tethered to their respective stumps with 14-mm-diameter steel cable to prevent transport downstream and possible damage to bridges, roads or private property (Figure 2B). Approximate cost of this treatment was $6,450 (Table 1). Thirty-two additional pieces of LWD entered the logger's choice site between 1991 and 1994 during winter storms.

Evaluation of Habitat and Fish Populations

Juvenile coho salmon and steelhead populations, coho salmon smolt yield, and physical habitat of the three stream sites were evaluated beginning in June 1988. Measurements were collected seasonally through spring 1994. Coho salmon and steelhead were much more abundant than cutthroat trout at all three sites and, thus, were the focus of our study. The low densities of cutthroat trout prevented us from evaluating the response of this species to habitat enhancement efforts. We did not sample the sculpins and Pacific lampreys, and we assumed they would have a consistent influence on salmonid abundance in all study sections.

Salmonid populations were surveyed by selecting representative habitat units of each type present in a study site, isolating the unit with nets, and collecting the fish with an electroshocker. Approximately 20% of the water surface area of each study site was sampled directly on any given sampling date. Each habitat was fished three times and total population in the unit was estimated using a removal-summation calculation (Carle and Strub 1978). Fishes collected during electrofishing were identified to species, and fork length (FL) was measured for each individual.

The total population of a fish species within a treatment was estimated by multiplying the average fish density for a given habitat type by the total area of that habitat type present in the entire treatment site. Ninety-five percent confidence limits about the whole-site population estimates were determined using a bootstrapping method (Efron and Tibshirani 1993). This technique produces asymmetrical confidence intervals about the population estimate. We considered populations among treatment sites, or before and after enhancement within a treatment site, to be significantly different when overlap of the 95% confidence intervals was less than 10% of the smaller interval.

Large woody debris was added to the treated stream sites in 1990 and 1991. Less than half the wood added was placed in autumn 1990; the remainder of the wood and all the cover structures were added in autumn 199 1. Therefore, habitat enhancements from LWD addition were not expressed fully until winter of 1991-1992. Thus, we consider data collected from spring 1988 through smolt migration in 1991 to represent preenhancement conditions, and data collected from spring 1991 through smolt migration in 1994 to represent postenhancement conditions.

Habitat surveys and fish population estimates were conducted in late winter (March), spring (June) and autumn (late September). The sample times were established to provide us with information about changes in population levels over the low-flow summer period and over the winter, when frequent periods of high discharge occurred.

Habitat was assessed three times each year, in conjunction with determination of fish populations, using the method of Bisson et al. (1982). This technique entails the identification of individual habitat units and measurement of width and length of the water surface. Habitat units in the NFPC study sites consisted of four types of pools (scour pools, plunge pools, dam pools, and backwaters), and three types of fast water (riffles, cascades, and glides).

Large woody debris in the channel prior to enhancement was inventoried in 1989. The length and diameter of each piece was measured and each piece was marked with a numbered steel tag. Large woody debris was reinventoried after wood was added to the treated stream sections, both in 1992 and 1994.

In order to ensure that sufficient juvenile coho salmon were present at the study sites to take advantage of any improvement in habitat, fed coho salmon fry (approximately 1 g each) were released at the sites during 3 of the 6 years. An average of 19,000 unmarked fry were stocked throughout the study sites during early April of 1989, 1990, and 1991. The fry were distributed evenly throughout, and for about 100 m upstream of the study sites, to ensure that sufficient fry seeding occurred during the study. In retrospect we believe that, because of the large size of these fry, they may have left the site soon after planting. At the time of seeding, resident fish were much smaller than planted fish. Lack of availability of fry during the final 3 years prevented us from stocking the sites during the latter half of the study. However, population census of the coho salmon juveniles during the spring and late summer of stocked versus unstocked years indicated that stocking had no discernible effect on density of the fish. This suggests that natural reproduction by coho salmon in the NFPC was sufficient to fully seed the sites. Thus, the fact that stocking was not done during all 6 years should not affect our results.

Coho salmon smolts produced in each of the three study sites were collected each year from early April through mid-June. In some years the traps did not begin fishing until mid-April. Because of the variable time of trap installation, an uncounted number of presmolts and smolts may have emigrated from the stream prior to trapping onset. Total counts of smolts were made with traps similar to the one described by Armstrong (1978), consisting of temporary small-mesh screen weirs that direct downstream migrating fish into a live box. Traps were located at the downstream end of each of the study sites, and a fourth trap was placed at the upstream end of the reference site to intercept smolts produced above the study area. Traps were emptied daily. Captured smolts were identified, measured (FL), transported below the lower study site and released. Nonsmolting undersized (< 135 mm FL) steelhead and cutthroat were released directly into the next downstream study site.

During occasional periods of high flow the traps became inoperative. These periods were rare, accounting for only 3% (11 days) of the total 370 fishing days over the 6 years of sampling. However, this was a problem when it occurred during the peak smolt migration. The most troublesome period of smolt trap inundation occurred on 8 May 1993, when a high-intensity rain storm caused the NFPC to rise and overflow the smolt traps for a 24-h period. While the traps were inundated, downstream migrating fish were able to move freely between the study sites. In order to correct for this problem, a factor was developed from the average proportion of smolts caught between all four traps during the l-week period prior to inundation. This average was used to reproportion the total summed trap catches for the week following inundation. Experiments with marked fish indicated that the time needed for a smolt to swim through all three study sites was about a week. For example, on 8 May 1993 an unknown number of smolts probably moved into the reference and engineered study sites, causing a disproportionate number of smolts to be caught in their respective traps. Therefore, during the 7-day period after 8 May, the total catch of all four traps was summed and reapportioned based on the preinundation week's intertrap proportions. This allowed us to reallocate the fish that had moved into the reference and engineered sites, and add them back into their respective traps. The proportions used for this calculation were 84.4% caught in the uppermost trap, 3.5% caught in the reference site trap, 9.1% caught in the engineered site trap, and 3.0% caught in the logger's choice site trap.

Although our electrofishing population surveys indicated that substantial numbers of age-l steelhead used the NFPC, we captured few steelhead smolts in the traps. It is likely that they left the system earlier than the coho salmon. Because high flows prevented us from installing the traps earlier than about 1 April, data on steelhead smolt yield was judged too incomplete to report.

A discharge recording station was installed on the NFPC about 75 m below the downstream end of the study sites in 1988 (Figure 1). Floods altered the channel at the gauging station in 1989, and the instrument was subsequently relocated about 50 m upstream. Instrumentation at the station operated more than 95% of the time. However, on several occasions malfunctions left gaps in the data. These gaps were filled by correcting flows at our station on the NFPC with simultaneous data collected at a Washington Department of Natural Resources (WDNR) station on lower Porter Creek (Jim Ryan, WDNR, unpublished data). When data from the WDNR recorder were not available, NFPC flows were corrected with data at a U.S. Geological Survey station on nearby Schaefer Creek. Flow data were used to examine the effect of discharge on fish populations before and after enhancement.

Results

Changes in LWD Abundance and Habitat

Large woody debris abundance changed in all three study sites after enhancement (Table 2). Abundance of LWD in the reference site more than doubled after enhancement of the two treated sites. This increase was attributable to input from the riparian area or wood transport from upstream during winter storms. Increases in LWD number and volume in the engineered and logger's choice sites were due to both deliberate addition of wood to the channel and the subsequent accumulation of wood during winter storms. By the end of the study in 1994, the number of pieces of LWD in the engineered site was 8.9 times the pretreatment level, while in the logger's choice site it was 3.6 times the pretreatment level. The number of LWD pieces increased 2.3-fold in the reference site.

Wood added during the enhancement project had little impact on average LWD diameter (Table 2). However, average piece length at both the engi-

TABLE 2.-Woody debris amounts and characteristics in North Fork Porter Creek before treatment (1989), immediately after treatment (1991), and in 1992 and 1994 in the reference, engineered, and logger's choice sites. Two hundred pieces of large woody debris (LWD) were added to the engineered site during enhancement, and 60 pieces to the logger's choice site. Changes in LWD amount over time at the reference site, and changes not accounted for by deliberate additions of wood at the two treated sites were caused by natural inputs of LWD during winter storms.

	Reference				Engineered				Logger's choice			
LWD characteristics	1989	1991	1992	1994	1989	1991	1992	1994	1989	1991	1992	1994
Number of pieces	36	36	84	84	29	229	251	258	35	95	95	127
Median diameter (cm)	29		28	28	35		32	32	26		32	31
Median length (m)	4.0		2.9	3.0	3.0		5.7	5.5	3.4		10.0	8.4
Median volume (m^3)	0.3		0.2	0.2	0.2		0.5	0.4	0.3		0.8	0.6
Total volume (m^3)	30		69	69	15		197	188	25		84	101

neered and logger's choice sites increased significantly following enhancement (t-test, $P < 0.05$). Increased piece length and abundance resulted in a 11.5-fold increase in total wood volume in the engineered site and a 3.0-fold increase in the logger's choice site. The reference site exhibited a 1.3-fold increase of total wood volume as a result of natural input. However, the wood entering the reference site was small- and medium-sized, as piece lengths and volume decreased between 1989 and 1992. This material had little impact on channel morphology, as described below.

TABLE 3.-Habitat characteristics before and after enhancement by treatment. Values represent the average proportion of stream surface area in each habitat category for surveys conducted for three years before and three years after enhancement. Miscellaneous (misc.) habitats include backwaters, secondary channels, and glides. These habitats never accounted for more than 10% of the total surface area at any site during any survey.

	Reference		Engineered		Logger's choice	
Habitat type	Before	After	Before	After	Before	After
Spring						
Riffle	0.33	0.57	0.37	0.34	0.36	0.46
Cascade	0.15	0.04	0.29	0.00	0.17	0.03
Scour pool	0.45	0.35	0.33	0.32	0.40	0.46
Dam pool	0.00	0.02	0.00	0.16	0.00	0.02
Plunge pool	0.00	0.00	0.00	0.11	0.01	0.00
Misc. habitats	0.07	0.02	0.01	0.07	0.06	0.03
Autumn						
Riffle	0.34	0.47	0.45	0.23	0.30	0.29
Cascade	0.11	0.03	0.14	0.00	0.18	0.08
Scour pool	0.47	0.46	0.34	0.40	0.46	0.58
Dam pool	0.00	0.00	0.00	0.23	0.00	0.00
Plunge pool	0.01	0.00	0.04	0.11	0.00	0.00
Misc. habitats	0.07	0.04	0.03	0.03	0.06	0.05
Winter						
Riffle	0.44	0.50	0.44	0.39	0.38	0.43
Cascade	0.06	0.07	0.14	0.00	0.12	0.00
Scour pool	0.41	0.39	0.34	0.39	0.38	0.43
Dam pool	0.00	0.00	0.00	0.01	0.02	0.05
Plunge pool	0.01	0.00	0.04	0.16	0.00	0.01
Misc. habitats	0.08	0.04	0.04	0.06	0.10	0.08

Pool area increased in both the engineered and logger's choice sites following enhancement (Table 3). The engineered site displayed the most dramatic increases in pools, with the proportion of the water surface composed of pools increasing from 33%, 38%, and 38% in spring, autumn, and winter, respectively, to 59%, 74%, and 56%. Most of the increase in the engineered site was due to the creation of dam and plunge pools associated with the full-crossing LWD structures placed in the stream. The logger's choice site exhibited increases of 7% to 12% in proportion of pool areas, due almost entirely to creation of additional scour pools. Very few of the LWD pieces added to this site fully blocked the stream, because pieces floating in the channel were swept to the margins during winter high flows. Because fully blocking pieces of LWD usually are needed to form dam or scour pools, these habitats remained rare in the logger's choice site after enhancement. The reference site displayed slight decreases in proportion of the water surface area composed of pools after enhancement during all seasons.

Fast-water habitats decreased at the two enhanced sites (Table 3). In the engineered site, riffles decreased and cascades were eliminated after completion of enhancement. In the logger's choice site, riffles increased during spring and winter, but stayed relatively constant during autumn before and after enhancement. The proportion of cascades decreased by more than 10% during all three seasons in the treated sites. Fast-water habitats increased at the reference site.

Although we did not quantify changes in substrate characteristics, large amounts of gravel accumulated at the structures added to the two treated sites. We frequently observed coho salmon and steelhead spawning in the treated sites after en-

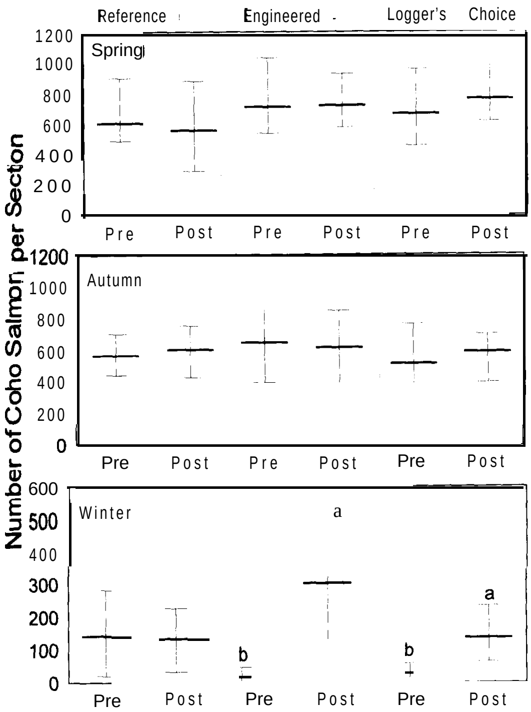

FIGURE 3.-Average juvenile coho salmon abundance seasonally before (Pre) and after (Post) addition of large woody debris to the engineered and logger's choice stream sections. Error bars represent 95% confidence intervals. An "a" above the error bar indicates a significant difference in numbers of coho salmon before and after treatment at a site. A "b" indicates a significant difference in numbers of coho salmon between the reference and treated section.

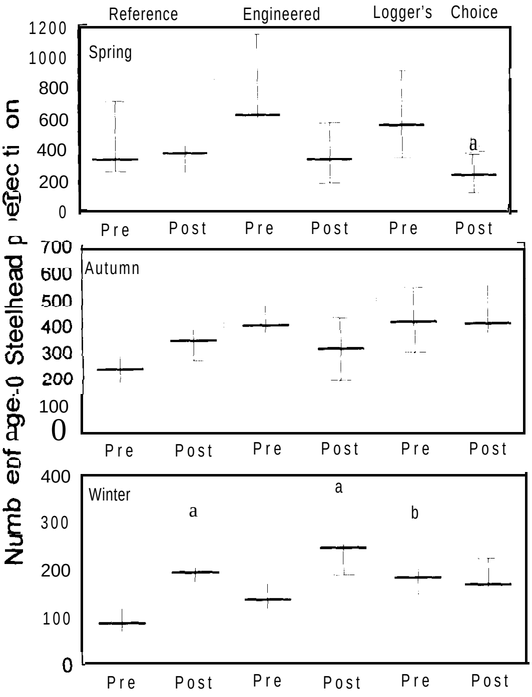

FIGURE 4.-Average age-0 steelhead abundance seasonally before (Pre) and after (Post) addition of large woody debris to the engineered and logger's choice stream sections. Error bars represent 95% confidence intervals. An "a" above the error bar indicates a significant difference in numbers of age-0 steelhead before and after treatment at a site. A "b" indicates a significant difference in numbers of age-0 steelhead between the reference and treated section.

hancement, whereas before enhancement, few coho salmon or steelhead were observed spawning within the entire study area.

Fish Response to Habitat Enhancement

Stocking of fish in 1989, 1990, and 1991 had no apparent effect on spring population densities of coho salmon (Figure 3). Stocking took place in early April. However, population estimates in June did not differ significantly between stocked and unstocked years (stocked = 0.25, SE = 0.065 coho/m^2, not stocked = 0.16, SE = 0.044 coho/m^2; t-test P = 0.331). Therefore, stocking coho salmon fry during 3 of the 6 years of this study should have had little impact on the responses exhibited by the fish to the enhancement projects.

Abundance of coho salmon during spring and autumn sampling periods showed no response to enhancement (Figure 3). Average spring populations ranged from 550 to 750 fish/site while autumn population levels varied from 500 to 650 fish/site. There were no significant differences among sites or among years during spring and autumn.

Juvenile coho salmon populations did respond to enhancement during winter (Figure 3). Prior to enhancement, the reference site supported nearly 10 times the number of presmolt coho as the two treatment sites. After enhancement, coho abundance increased 20-fold in the engineered site and 6-fold in the logger's choice site. The reference site exhibited no change in coho abundance after treatment of the other two sites.

There were no significant differences in age-0 steelhead abundance during spring among the sites prior to enhancement (Figure 4). After enhancement, no change was observed in the reference or engineered sites in spring; however, age-0 steelhead abundance declined significantly in the logger's choice site. During autumn, no changes among sites before and after enhancement were noted. During winter before enhancement, the log-

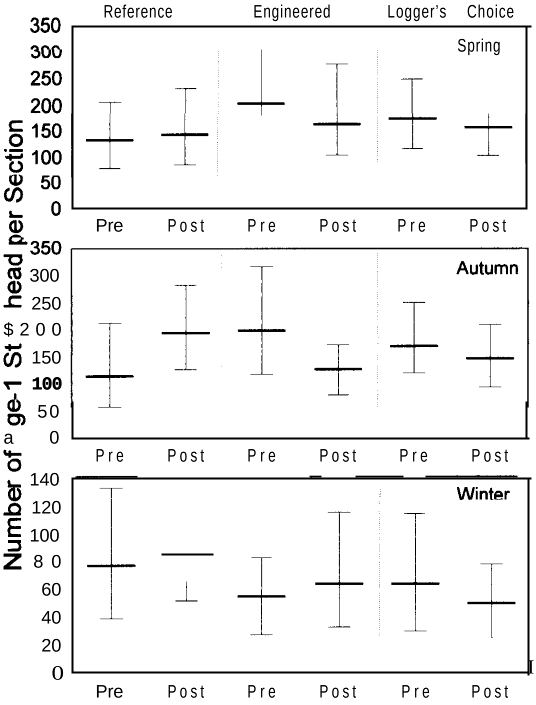

FIGURE 5.—Average age-1 steelhead abundance seasonally before (Pre) and after (Post) addition of large woody debris to the engineered and logger's choice stream sections. Error bars represent 95% confidence intervals.

ger's choice site supported higher populations of age-0 steelhead than the reference site. After enhancement, age-0 steelhead increased during winter in both the reference site and the engineered site; however, the population in the logger's choice site did not change after enhancement.

Age-1 steelhead abundance was similar among sites and before and after enhancement during all seasons (Figure 5).

The number of coho salmon smolts migrating from the engineered and logger's choice sites increased following enhancement (Figure 6). An average of 117 smolts/year emigrated from the engineered site prior to enhancement, and 55 smolts/year emigrated from the logger's choice site, by far the lowest number for the three sites. Following enhancement, average annual yield increased to 370 smolts/year from the engineered site and 142 smolts/year from the logger's choice site. Smolt production at the reference site remained relatively unchanged before and after enhancement of the two other reaches, 134 smolts/year before and 109 smolts/year after enhancement. The number of coho salmon smolts produced upstream from the experimental area averaged 2,534 smolts/year prior to enhancement and 3,016 smolts/year afterwards. Changes in number of emigrating coho salmon smolts from the engineered and logger's choice sites before and after treatment are statistically significant (t-test, $P < 0.005$ and $P = 0.036$, respectively), but no significant changes occurred

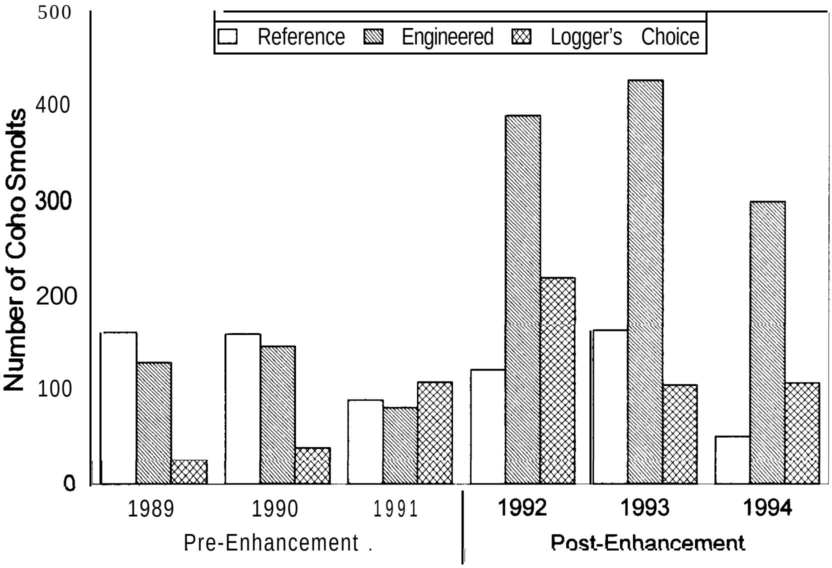

FIGURE 6.—Production of coho salmon smolts in the three study sections before (pre-enhancement) and after (post-enhancement) addition of large woody debris to the engineered and logger's choice sections.

TABLE 4.-Mean lengths of coho salmon smolts captured from 1989 through 1994 on the North Fork Porter Creek.

	Reference			Engineered			Logger's choice		
		Length (mm)			Length (mm)			Length (mm)	
Year	N	Mean	SD	N	Mean	SD	N	Mean	SD
1989	144	114	8.2	113	115	8.0	24	113	6.5
1990	153	119	6.6	144	121	7.0	35	122	7.8
1991	86	121	6.7	77	120	7.5	101	122	7.2
1992	228	117	8.5	564	115	6.4	264	115	3.7
1993	372	117	6.8	436	116	8.1	125	117	6.7
1994	56	118	7.2	294	116	6.6	105	115	6.2

in emigration from the reference site or from the reach upstream of the experimental area.

The estimated number of juvenile coho salmon using the engineered site of the NFPC during winter prior to enhancement was considerably lower than the number of smolts ultimately produced (Figures 3, 6). This discrepancy likely is due to the fact that one pool in the engineered site was too deep to sample. This single pool could have contained enough juvenile coho salmon to account for the difference. After enhancement, many habitats with characteristics similar to the large pool were created. We were able to sample many of these new habitats. Thus, estimates of abundance in the engineered site likely were more accurate after enhancement, as indicated by the closer agreement with the eventual smolt numbers. Winter population and smolt yield estimates at the other two study sites were similar.

The mean lengths of coho salmon smolts were similar among the three sites for any year, but differed among years (ANOVA, $P < 0.05$; Table 4). This information may have been biased due to presmolt movements before the traps were installed, and during the temporary trap inundation of 8 May 1994.

Discharge in the NFPC ranged from less than 0.2 m^3/s during summer to more than 17.0 m^3/s during a storm in late November 1990. Peak winter discharges exceeded 10 m^3/s during the winters of 1989-1990, and 1990-1991, both preenhancement winters. Supplemental discharge data collected during the winter of 1994-1995 indicate an additional storm of magnitude greater than 10 m^3/s. Over the course of this study only three log structures moved, and this occurred during the 1990-1991 storm; four cyclone fence log aprons were scoured out of position during the 1994-1995 storm.

Winter population levels of juvenile coho salmon and age-0 steelhead were related to mean winter discharge and maximum winter discharge (Figure 7). Coho salmon populations decreased more rapidly with increasing mean winter discharge than did age-0 steelhead. However, populations of both species, at all three sites, were very low when mean winter discharges exceeded 1.5 m^3/s and when peak daily discharge exceeded 10 m^3/s. This pattern was evident both before and after enhancement.

Discussion

The proportion of stream surface represented both by pools and by LWD abundance increased following treatment of the engineered and logger's choice sites of the NFPC. The treated sites also exhibited increased coho salmon populations during winter and increased smolt yield. Juvenile coho salmon are found most commonly in deep pools during winter (Hartman 1965; Chapman and Bjornn 1969; Bustard and Narver 1975; McMahon and Hartman 1989), and those pools that contain an abundance of LWD are preferred over habitats with lesser amounts of wood (Tschaplinski and Hartman 1983; Grette 1985; Martin et al. 1986; Murphy et al. 1986). This behavior has a number of potential advantages, including conservation of energy, avoidance of predators, and protection from high current velocity during freshets. Greater availability of the type of habitat preferred by coho during winter, such as pools with abundant LWD, is the most probable cause of the response by the fish in the treated sites. We assumed that the presence of resident nonsalmonids such as sculpins and juvenile Pacific lamprey did not affect the abundance of salmonids among sections differentially.

Large woody debris abundance at our reference site also increased during our study, due to natural input from the red alder-dominated riparian stand. However, the pieces of LWD added to this section of stream were much smaller than those placed in the two treated sites (Table 2). Small pieces of wood are less likely to maintain position and have a lesser effect on channel form than larger pieces

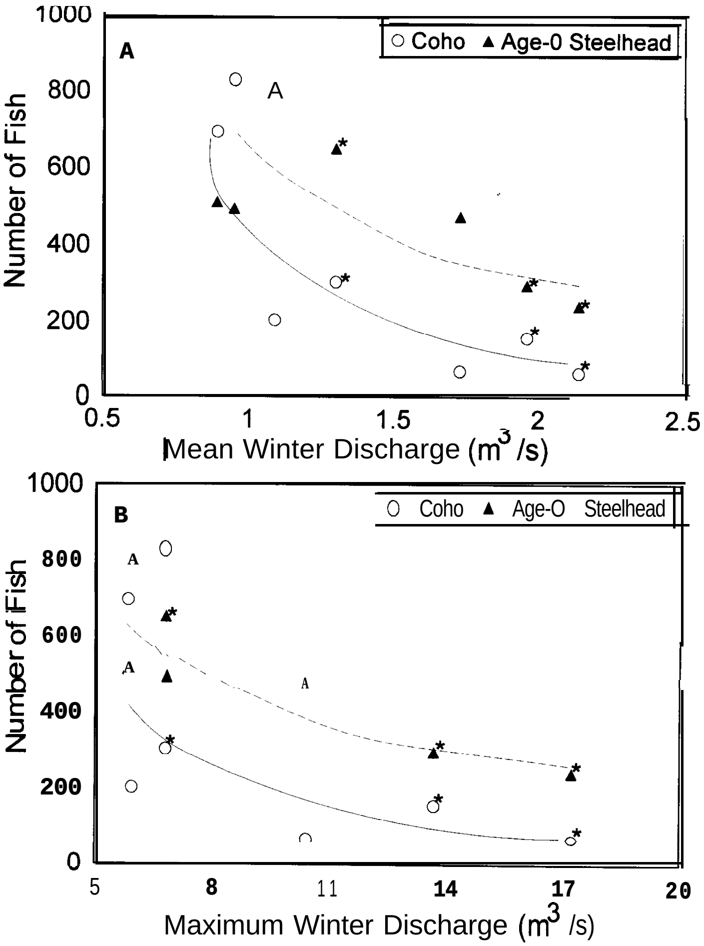

FIGURE 7.-Relationships between winter coho salmon (solid line) and age-0 steelhead (dashed line) abundance and (A) mean annual winter discharge (November-March) and (B) maximum daily winter discharge. Fish abundance values represent totals for all three study sections. Data points marked with an asterisk (*) indicate preenhancement values. Regression equations for mean winter discharge: log(number of coho salmon) = -2.48 log(mean flow) + 2.68 (r^2 = 0.79); log(number of steelhead) = -0.86 log(mean flow) + 2.78 (r^2 = 0.54). Regression equations for maximum winter discharge: log(number of coho salmon) = − 1.76 log(max flow) + 4.01 (r^2 = 0.59); log(number of steelhead) = -0.87 log(max flow) + 3.49 (r^2 = 0.83). All regressions are significant ($P < 0.05$).

(Bilby and Ward 1989). Thus, despite the increase in LWD abundance at the reference site, no change in pool frequency or size and no change in fish populations were observed at that site.

The lack of response by the coho salmon population during spring and autumn suggests that availability of pools and LWD during summer were not critical in determining population levels. This same observation was reported by Grette (1985) for several small streams on Washington’s Olympic Peninsula. Hartman and Scrivener (1990) found increases in juvenile coho salmon populations both in July and September at Carnation Creek soon after the input of logging debris; however, this benefit was lost after winter storms. Summer population levels, however, may not be an important determinant of smolt production for a given site. If the availability of winter habitat is very low, the capacity of the system to generate coho salmon smolts will be low, regardless of summer populations at the site (Mason 1976). The increased winter populations and smolt production we observed in response to LWD addition, with no corresponding increases in spring or autumn population levels, indicate that the availability of suitable winter habitat likely was a major limiting factor of coho salmon production in our study area.

There is the problem that more smolts were produced from the engineered and logger's choice sections than were estimated by electrofishing during the preconstruction winter period. This may be explained by the fact that the removal-summation method of fish population estimation tends to underestimate the actual size of the population (Peterson and Cederholm 1984; Thompson and Rahel 1996). Also, some atypical deep pools could not be sampled in these sections, and may have held a disproportionate number of juvenile coho salmon.

Although we observed increased coho salmon abundance in winter and increased smolt production at our enhanced sites, we cannot estimate what impact these increases had on overall coho salmon smolt production from the Porter Creek watershed. Improved habitat conditions at our enhanced sites did retain fish over the winter. However, these fish possibly could have found suitable overwinter habitat elsewhere in the watershed. Thus, improved habitat at the treated sites may not have increased smolt output from the whole watershed. However, if suitable conditions were not available elsewhere, or if these habitats were already fully occupied, improved winter habitat conditions at our study site would have added to the smolt production from Porter Creek.

Increased populations of juvenile steelhead in response to habitat enhancement of the type we conducted have been noted in other studies (House and Boehne 1985). However, we saw little response. Age-l steelhead displayed no change in population levels during any season in any of our study sites. Age-O steelhead did decrease significantly in spring following LWD addition to the logger's choice site. The cause of this decline could not be determined. A shift in habitat composition may have contributed, because age-0 steelhead prefer riffle habitat (Bisson et al. 1982), and this habitat type decreased in the logger's choice site (Table 3). However, no change in age-0 steelhead abundance was observed in the engineered site, in which riffle habitat was also reduced by the addition of LWD. Another possibility is that the larger number of coho salmon presmolts occupying the logger's choice site following enhancement increased predation on age-0 steelhead. The greater abundance of LWD in the engineered site may have provided adequate cover for steelhead fry to prevent increased predation, despite higher numbers of presmolt coho salmon. Regardless, the population levels of age-0 steelhead in the logger's choice site were not different from the reference or engineered sites later in the summer. Nor did abundance of age-l steelhead differ in the following year.

Winter flow was an important factor in determining winter population levels of coho salmon and age-0 steelhead. Abundance of both species was low during winters with high average discharge or with high daily maximum discharge, both before and after enhancement. This relationship suggests that habitat enhancement efforts in the NFPC were most effective during winters of low or moderate flow, but were of little benefit during winters with elevated flows. Apparently, the pools created by LWD placement in the two treated sections did not offer sufficient protection from periods of elevated discharge.

Comparing the two approaches to enhancement on a cost-per-smolt basis requires an estimate of the longevity of the two treatments. The logger's choice site exhibited significant signs of deterioration by 1994. Many of the red alder logs added to the logger's choice site were swept to the side of the channel during the high flows in 1991 and 1994. In addition, many of these logs had decayed by 1994 and were broken by high flow and lost from the study area. We estimated that the habitat in the logger's choice site would approach the pretreatment condition within 5 years of treatment. No evidence of decay was observed in coniferous LWD added to the engineered site, and very little damage to structures was experienced by repeated exposures to elevated flows. These structures were designed to persist for 25 years or more. Harmon et al. (1986) estimated that some large pieces of old-growth conifer debris may take hundreds of years to decay. Grette (1985) estimated a longterm average of 0.5% annual loss rate of old-growth conifer debris, but a much faster rate of loss for smaller, less rot-resistant, second-growth debris. This loss is attributed to wood decay, breakage, and displacement during high flow periods. Hartman et al. (1996) wrote of the structural and habitat changes caused by the loss of LWD in streams, which occurs over a long time period, and they found a 59% reduction of LWD volume in a 70-year period.

The cost of the two methods of enhancement evaluated in this study was considerably different (Table 1). However, when considered in terms of cost per additional coho salmon smolt produced, the greater longevity of structures added to the engineered site offsets the higher initial cost (Table 5). In addition, there are insufficient numbers of trees next to the channel to sustain the logger's choice method at 5-year intervals. Therefore, any

TABLE 5.—Cost per additional coho salmon smolt of the logger's choice and engineered approaches to stream habitat enhancement. Additional number of coho smolts produced is based on the average increase observed in the two treatment sections following LWD addition.

Variable	Logger's choice	Engineered
Total cost	$6,450	$82,250
Additional smolts/year	87	253
Longevity of treatment	5 years	25 years
Additional smolts over life of the project	435	6,325
Cost/additional smolt	$14.82	$13.00

long-term benefits to coho salmon smolt production would require transport of wood to the stream, which would increase the cost and further enhance the economic advantage of the engineered approach. The logger's choice approach for adding LWD may be most appropriate where conifer trees can be felled into the channel. The large size and decay-resistance of conifererous LWD would increase longevity of the treatment and enable the added pieces to maintain position better during high flows. The increased longevity of coniferous LWD would substantially reduce the cost per additional coho calculated for our logger's choice treatment (e.g., an increase from 5 years to 10 years would reduce the cost per smolt by half).

The cost per additional coho salmon smolt for both methods of LWD addition at NFPC was relatively high. Survival rate from smolt to adult varies annually. Holtby et al. (1990) reported smolt survival rates ranging from 5% to 22% for Carnation Creek, Vancouver Island, British Columbia. In order to compare our treatments, we assumed a survival rate from smolt to adult of 10% our engineered treatment would produce an additional 25 adult coho salmon/year and the logger's choice approach would produce 8 additional adult coho salmon/year at costs of $130 and $150/adult, respectively. However, application of these techniques in stream segments with a higher potential for increased coho smolt production than our study sites could generate more dramatic results. Juvenile coho salmon occupy low-gradient, small streams with relatively stable discharge at high densities, especially during winter (Skeesick 1970; Scarlett and Cederholm 1984; Brown 1985). Our study area had a gradient of about 2% and exhibited rapid rises in discharge in response to rainfall. Thus, the potential for increased production of coho salmon smolts at our study sites in response to LWD addition probably was limited by the nature of the system. By implementing enhancement activities where flow, gradient, and other physical characteristics of good winter coho salmon habitat exist, the increase in smolt production could be much greater than was observed in our study.

Deliberately adding LWD to streams which are deficient in this material is one aspect of an overall approach to restoring productive stream habitat in the Pacific Northwest. However, manipulation of instream habitat will not be effective if the factors which initially produced poor habitat are not addressed. We suggest a three-step process to aquatic habitat restoration. First, upslope factors that affect stream habitat should be identified and corrected. Improperly located or constructed roads that are prone to generating mass slope failures, practices which accelerate surface erosion and sediment delivery to streams, or other activities that perpetuate poor habitat conditions, should be corrected before attempting to address habitat deficiencies within stream channels.

Second, riparian areas should be managed to encourage natural maintenance of productive stream habitat. Many riparian areas in the Pacific Northwest are dominated by early successional vegetation, the product of past management actions (Bisson et al. 1997). The large conifers necessary to produce large, decay-resistant LWD are rare (Bilby and Ward 1991). Management in these areas should focus on accelerating the development of desired vegetation. However, development of riparian stands dominated by large conifer trees will take decades or centuries in many areas (Grette 1985; Bisson et al. 1987; Sedell et al. 1988; Murphy and Koski 1989; Bisson et al. 1992). Deliberate addition of LWD to streams can be used as an interim measure until the riparian forest begins to deliver adequate amounts of LWD.

Deliberate manipulation of instream habitat is the third component of our approach. However, in view of the considerable expense involved, addition of wood to channels should be limited to those areas where this material is deficient, and where there is a high probability of generating a positive response from the targeted fish species. To achieve the desired results from this type of project, involvement of both fish biologists and hydraulic engineers is essential. For those streams that still retain riparian forests in near-natural conditions, we recommend that sufficiently large areas adjacent to the channel be preserved to ensure that abundant LWD of the appropriate size and species will continue to fall into the channel.

Finally, we realize that there are some problems with this study design, and would hope future researchers could learn from our findings. First, the study sections were continuous on a single stream with downstream effects and no replication. We believed it was preferable to deal with within stream variability rather than between-stream variability, and the high cost of additional study streams was prohibitive. Second, windthrow and floatable LWD was inadvertently added to the three study sites during the study. The reference and engineered sites debris loading caught some natural floating debris before it was able to reach the logger's choice site further downstream. The effect of this problem may have been alleviated if we had used shorter sections (e.g., 100-200 m) in a replicated, randomized-block design with buffer segments between each block. When working under field conditions, one runs the risk of many unanticipated problems; in retrospect, there are many tradeoffs between economics, statistical rigor, and other factors. We hope that others can learn and progress from our experience.

Acknowledgments

We appreciate the funding and research guidance provided for this project by the State of Washington's Timber/Fish/Wildlife Cooperative Monitoring, Evaluation and Research Fish Steering Committee. We thank the Weyerhaeuser Co., the Washington Department of Natural Resources, and the Washington Forest Protection Association for their major funding support. We especially appreciate the efforts of Marty Ereth, Rick Ereth, Mark Chambers, Ted Creviston, and John Heffner as well as the various technicians, students, and equipment operators who assisted during the in-channel log construction work and evaluation monitoring of the project. We thank Larry Dominguez for some helpful comments on a draft of this paper.

References

Armstrong, R. W. 1978. Methods of trapping and marking wild stocks of chinook and coho salmon. Pages l-6 in B. G. Sheperd and R. M. J. Ginetz, editors. Proceedings of the 1977 northeast Pacific chinook and coho salmon workshop. Fisheries and Marine Service, Technical Report 759, Vancouver.

Beschta, R. L. 1979. Debris removal and its effects on sedimentation in an Oregon Coast Range stream. Northwest Science 53:71-77.

Bilby, R. E., and G. E. Likens. 1980. Importance of organic debris dams in the structure and function of stream ecosystems. Ecology 61: 1107-l113.

Bilby, R. E., and J. W. Ward. 1989. Changes in characteristics and function of woody debris with increasing size of streams in western Washington. Transactions of the American Fisheries Society 118: 368-378.

Bilby, R. E., and J. W. Ward. 1991. Characteristics and function of large woody debris in streams draining old-growth, clearcut, and second-growth forests in southwestern Washington. Canadian Journal of Fisheries and Aquatic Sciences 48:2499-2508.

Bisson, P A., and eight coauthors. 1987. Large woody debris in forested streams in the Pacific Northwest: past, present, and future. Pages 143-190 in E. 0. Salo and T. W. Cundy, editors. Streamside management: forestry and fishery interactions. University of Washington, Institute of Forest Resources, Contribution 57, Seattle.

Bisson, P A., J. L. Nielsen, R. A. Palmason, and L. E. Grove. 1982. A system of naming habitat types in small streams, with examples of habitat utilization by salmonids during low streamflow. Pages 62-73 in N. B. Armantrout, editor. Acquisition and utilization of aquatic habitat inventory information. American Fisheries Society, Western Division, Bethesda, Maryland.

Bisson, P A., T. P Quinn, G. H. Reeves, and S. V. Gregory, 1992. Best management practices, cumulative effects, and long-term trends in fish abundance in Pacific Northwest river systems. Pages 189-232 in R. J. Naiman, editor. Watershed management: balancing sustainability and environmental change. Springer-Verlag, New York.

Bisson, P A., G. H. Reeves, R. E. Bilby, and R. J. Naiman. 1997. Watershed management and Pacific salmon: desired future conditions. Pages 447-474 in D. J. Stouder, P A. Bisson, and R. J. Naiman, editors. Pacific salmon and their ecosystems: status and future options. Chapman and Hall, New York.

Booth, D. B. 1991. Urbanization and the natural drainage system-impacts, solutions, and prognoses. Northwest Environmental Journal 7:93-l18.

Brown, T. G. 1985. The role of abandoned steam channels as overwintering habitat for juvenile salmonids. Master's thesis. University of British Columbia, Vancouver.

Bustard, D. R., and D. W. Narver. 1975. Aspects of the winter ecology of juvenile coho salmon (Oncorhynchus kisutch) and steelhead trout (Salmo gairdneri). Journal of the Fisheries Research Board of Canada 32:667-680.

Carle, F. L., and M. R. Strub. 1978. A new method for estimating population size from removal data. Biometrics 34:621-630.

Carman, R. E., C. J. Cederholm, and E. 0. Salo. 1984. A baseline inventory of juvenile salmonid populations and habitats in streams in Capitol Forest, Washington 1981-1982. University of Washington, School of Fisheries, Fisheries Research Institute, Report FRI-UW-8416, Seattle.

Cederholm, C. J. 1972. The short-term physical and biological effects of stream channelization at Big Beef Creek, Kitsap County, Washington. Master's thesis. University of Washington, Seattle.

Cederholm, C. J., D. B. Houston, D. L. Cole, and W. J. Scarlett. 1989. Fate of coho salmon (Oncorhynchus kisutch) carcasses in spawning streams. Canadian Journal of Fisheries and Aquatic Sciences 46: 1347-1355.

Chapman, D. W., and T. C. Bjornn. 1969. Distribution of salmonids in streams, with special reference to food and feeding. Pages 153-176 in P. A. Larkin and N. J. Wilimovsky, editors. Symposium on salmon and trout in streams. H. R. MacMillan Lectures in Fisheries, University of British Columbia, Vancouver.

Duff, D. A., and N. Banks. 1988. Indexed bibliography on stream habitat improvement. U.S. Forest Service, Ogden, Utah.

Efron, B., and R. J. Tibshirani. 1993. An introduction to the bootstrap. Chapman and Hall, New York.

Elmore, W., and R. L. Beschta. 1987. Riparian areas: perceptions in management. Rangelands 9(6):260-265.

Everest, E H., and J. R. Sedell. 1984. Evaluating effectiveness of stream enhancement projects. Pages 246-256 in Hassler (1984).

Frissell, C. A., and R. K. Nawa. 1992. Incidence and causes of physical failure of artificial habitat structures in streams of western Oregon and Washington. North American Journal of Fisheries Management 12:182-197.

Gowan, C., and K. D. Fausch. 1995. Long-term demographic responses of trout populations to habitat manipulation in six Colorado streams. Ecological Applications 6:931-946.

Grette, G. B. 1985. The role of large organic debris in juvenile salmonid rearing habitat in small streams. Master's thesis. University of Washington, Seattle.

Hall, J. D. 1984. Evaluating fish response to artificial stream structures: problems and progress. Pages 214-221 in Hassler (1984).

Hall, J. D., and C. 0. Baker. 1982. Rehabilitating and enhancing stream habitat: review and evaluation. U.S. Forest Service, General Technical Report PNW-138.

Hamilton, J. B. 1983. Performance of rock deflectors for rearing habitat improvement on a tributary of the Mattole River, northern California. Master's thesis. Humboldt State University, Arcata, California.

Harmon, M. E., and twelve coauthors. 1986. Ecology of coarse woody debris in temperate ecosystems. Advances in Ecological Research 15: 133-302.

Hartman, G. E 1965. The role of behavior in the ecology and interaction of underyearling coho salmon (Oncorhynchus kisutch) and steelhead trout (Salmo gairdneri). Journal of the Fisheries Research Board of Canada 22:1035-1081.

Hartman, G. F., and J. C. Scrivener. 1990. Impacts of forestry practices on a coastal stream ecosystem, Carnation Creek, British Columbia. Canadian Bulletin of Fisheries and Aquatic Sciences 223.

Hartman, G. F., J. C. Scrivener, and M. J. Miles. 1996. Impacts of logging in Carnation Creek, a high-energy coastal stream in British Columbia, and their implication for restoring fish habitat. Canadian Journal of Fisheries and Aquatic Sciences 53 (Supplement 1):237-251.

Hassler, T. J. 1984. Proceedings, Pacific Northwest stream habitat management workshop. California Cooperative Fishery Research Unit, Humboldt State University, Arcata.

Heede, B. H. 1976. Equilibrium condition and sediment transport in an ephemeral mountain stream. Pages 97-102 in Volume 6: hydrology and water resources in Arizona and the Southwest: proceedings of the 1976 meeting, Arizona section, American Water Resources Association, and hydrology section. Arizona Academy of Sciences, Tucson.

Hicks, B. J., J. D. Hall, P. A. Bisson, and J. R. Sedell. 1991. Responses of salmonids to habitat changes. Pages 483-518 *in* W. R. Meehan, editor. Influences of forest and rangeland management on salmonid fishes and their habitats. American Fisheries Society, Special Publication 19, Bethesda, Maryland.

Holtby, L. B., B. C. Andersen, and R. K. Kadowaki. 1990. Importance of smolt size and early ocean growth to interannual variability in marine survival of coho salmon (*Oncorhynchus* kisutch). Canada Journal of Fisheries and Aquatic Science 47:2181–2194.

House, R. A., J. Anderson, P L. Boehne, and J. Suther, editors. 1988. Stream rehabilitation manual: emphasizing project design, construction, evaluation. U.S. Bureau of Land Management, and others, Ashland, Oregon.

House, R. A., and P. L. Boehne. 1985. Evaluation of instream enhancement structures for salmonid spawning and rearing in a coastal Oregon stream. North American Journal of Fisheries Management 5:283-295.

Klingeman, P C. 1984. Evaluating hydrologic data needs for design of stream habitat modification structures. Pages 191-213 *in* Hassler (1984).

Koski, K. V. 1992. Restoring stream habitats affected by logging activities. Pages 343-401 *in* G. W. Thayer, editor. Restoring the nation's marine environment. Maryland Sea Grant, University of Maryland, College Park.

Kramer, R. 1953. Completion report by stream clearance unit on Ozette and Big rivers, April, 1953. Washington Department of Fisheries, Stream Improvement Division, Olympia.

Lestelle, L. C. 1978. The effects of forest debris removal on a population of resident cutthroat trout in a small headwater stream. Master's thesis. University of Washington, Seattle.

Lestelle, L. C., and C. J. Cederholm. 1982. Short-term effects of organic debris removal on resident cutthroat trout. Pages 131-140 *in* W. R. Meehan, T. R. Merrell, Jr., and T. A. Hanley, editors. Proceedings, fish and wildlife relationships in old-growth forests symposium. American Institute of Fishery Research Biologists, Ashville, North Carolina.

Martin, D. J., L. J. Wasserman, and V. H. Dale. 1986. Influence of riparian vegetation on posteruption survival of coho salmon fingerlings on the westside streams of Mount St. Helens, Washington. North American Journal of Fisheries Management 6: 1-8.

Mason, J. C. 1976. Response of underyearling coho salmon to supplemental feeding in a small natural stream. Journal of Wildlife Management 40:775-788.

McMahon, T. E., and G. E Hartman. 1989. Influence of cover complexity and current velocity on winter habitat use by juvenile coho salmon (Oncorhynchus kisutch). Canadian Journal of Fisheries and Aquatic Sciences 46: 1551-1557.

McMurphy, C. J., and H. W. Anderson. 1968. Soil survey report of the Capitol Forest area. Washington Department of Natural Resources, Report 14, Olympia.

Murphy, M. L., J. Heifetz, S. W. Johnson, K. V. Koski, and J. F. Thedinga. 1986. Effects of clear-cut logging with and without buffer strips on juvenile salmonids in Alaskan streams. Canadian Journal of Fisheries and Aquatic Sciences 43:1521-1533.

Murphy, M. L., and K. V. Koski. 1989. Input and depletion of woody debris in Alaska streams and implications for streamside management. North American Journal of Fisheries Management 9:427-436.

Orsborn, J. E 1990. Hydrologic analysis of the Porter Creek habitat improvement research site in Capitol Forest. Prepared for Washington Department of Natural Resources, Division of Forest Land Management, Olympia.

Peterson, N. P., and C. J. Cederholm. 1984. A comparison of the removal and mark-recapture methods of population estimation for juvenile coho salmon in a small stream. North American Journal of Fisheries Management 4:99-102.

Phillips, E. L. 1964. Washington climate for these counties: Clark, Cowlitz, Lewis, Skamania, and Thurston. Washington State Agriculture Experiment Station, Report EM-2462, Olympia.

Platts, W. S. 1991. Livestock grazing. Pages 389-423 *in* W. R. Meehan, editor. Influences of forest and rangeland management on salmonid fishes and their habitats. American Fisheries Society, Special Publication 19, Bethesda, Maryland.

Platts, W. S., and R. L. Rinne. 1985. Riparian and stream enhancement management and research in the Rocky Mountains. North American Journal of Fisheries Management 5: 115-125.

Pringle, R. F. 1986. Soil survey of Grays Harbor County, Pacific County, and Wahkaikum County, Washington. U.S. Department of Agriculture, Soil Conservation Service, Spokane, Washington.

Reeves, G. H., J. D. Hall, T. D. Roelofs, T. L. Hickman, and C. 0. Baker. 1991. Rehabilitating and modifying stream habitats. Pages 519-557 *in* W. R. Meehan, editor. Influences of forest and rangeland management on salmonid fishes and their habitats. American Fisheries Society, Special Publication 19, Bethesda, Maryland.

Reeves, G. H., and T. D. Roelofs. 1982. Rehabilitating and enhancing stream habitat: 2. Field applications. U.S. Forest Service, General Technical Report PNW-140.

Salo, E. O., and T. W. Cundy, editors. 1987. Streamside management: forestry and fishery interactions. University of Washington, Institute of Forest Resources, Contribution 57, Seattle.

Salo, E. O., and T. H. Jagielo. 1983. The status of the anadromous fishes of the White-Puyallup River system. Report to U.S. Army Corps of Engineers, Seattle District, Seattle.

Scarlett, W. J., and C. J. Cederholm. 1984. Juvenile coho salmon fall-winter utilization of two small tributaries of the Clearwater River, Jefferson County, Washington. Pages 227-242 in J. M. Walton and D. B. Houston, editors. Proceedings of the Olympic Wild Fish Conference. Peninsula College, Port Angeles, Washington.

Sedell, J. R., P. A. Bisson, E J. Swanson, and S. V. Gregory. 1988. What we know about large trees that fall into streams and rivers. Pages 47-81 *in C.* Maser, R. F. Tarrant, J. M. Trappe, and J. E Franklin, editors. From the forest to the sea: a story of fallen trees. U.S. Forest Service General Technical Report PNW-GTR-229.

Sedell, J. R., and K. J. Luchessa. 1982. Using the historical record as an aid to salmonid habitat enhancement. Pages 210-223 *in* N. B. Armantrout, editor. Acquisition and utilization of aquatic habitat inventory information. American Fisheries Society, Western Division, Bethesda, Maryland.

Sheng, M. 1993. Coho habitat restoration and development in the interior of British Columbia. Pages 318-322 *in* L. Berg and P. W. Selaney, editors. Proceedings of the coho workshop, Nanaimo, British Columbia, May 26-28, 1992. Department of Fisheries and Oceans, Habitat Management Sector, Policy and Information Unit, Vancouver.

Skeesick, D. G. 1970. The fall immigration of juvenile coho salmon into a small tributary. Research Reports of the Oregon Fish Commission 2:90-95.

Thompson, P D., and E J. Rahel. 1996. Evaluation of depletion-removal electrofishing of brook trout in small Rocky Mountain streams. North American Journal of Fisheries Management 16:332-339.

Tschaplinski, P J., and G. E Hartman. 1983. Winter distribution of juvenile coho salmon *(Oncorhynchus kisutch)* before and after logging in Carnation Creek, British Columbia, and some implications for overwinter survival. Canadian Journal of Fisheries and Aquatic Sciences 40:452-461.

Ward, B. R., and P. A. Slaney. 1981. Further evaluation of structures for the improvement of salmonid rearing habitat in coastal streams of British Columbia. Pages 99-108 *in* Hassler (1984).

Wendler, H. O., and G. Deschamps. 1955. Logging dams on coastal Washington streams. Washington Department of Fisheries, Fisheries Research Papers 1(3):27-38.