CUMULATIVE EFFECTS OF LOGGING ROAD SEDIMENT ON SALMONID POPULATIONS IN THE CLEARWATER RIVER, JEFFERSON COUNTY, WASHINGTON[1]

by

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ABSTRACT

The nature of sediment production from logging roads and the effect of the resulting sediment on salmonid spawning success in the Clearwater River drainage have been studied for eight years. The study includes intensive and extensive analyses of field situations, supplemented by several controlled experiments. It was found that significant amounts (15-25 percent) of fine sediments (less than 0.85 mm diameter material) are accumulating in spawning gravels of some heavily roaded tributary basins. This accumulation is highest in basins where the road area exceeds 2.5 percent of the basin area. Tributaries of relatively steep gradient are less likely to accumulate high levels of fines. The survival of salmonid eggs to emergence is inversely correlated with percent fines when the percentage of fines exceeds the natural levels of 10 percent. There is a rapid decrease in survival to emergence for each 1 percent increase in fines over natural levels. The presence of 2.5 km/km2 of gravel-surfaced roads undergoing an average distribution of road uses is found to be responsible for producing sediment at 2.6-4.3 times the natural rate in a drainage basin. Sixty percent of the road-related sediment production is caused by landslides while erosion on road surfaces accounts for an additional 18-26 percent. If fine sediment alone is considered, production from road surfaces and landslides is nearly equal. The tributaries of the Clearwater River may be underseeded for coho salmon due to heavy harvest rates in the commercial and sport fisheries. This underseeded condition becomes significant when the efficiency of the spawning environment in producing recruits is lowered by logging-caused sedimentation.

Keywords: salmonid, sediment, erosion, landslides, logging.

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CUMULATIVE EFFECTS OF LOGGING ROAD SEDIMENT ON SALMONID POPULATIONS IN THE CLEARWATER RIVER, JEFFERSON COUNTY, WASHINGTON

INTRODUCTION

Pacific coastal streams have complex environments which have caused the evolution of a variety of distinct and once abundant salmonid resources. Even with increasing artificial propagation our natural populations still contribute a major portion of the catch. The natural populations have recently declined in some areas, largely due to overharvest and to a gradual but continuing loss of freshwater habitat from assorted land use practices which include logging.

On the west coast of the Olympic Peninsula sedimentation of salmonid spawning habitats from logging road activities has caused concern for fisheries resources of the Clearwater River. In 1971 a series of massive landslides, including both logging road sidecast failures and natural slides, occurred in Stequaleho Creek, a tributary of the Clearwater River. Investigations by the Washington State Department of Fisheries (WSDF) determined that some of these landslides came from logging roads on land administered by the State Department of Natural Resources (DNR). The surveys of Stequaleho Creek by Deschamps (1) led him to state: "The heavy siltation (from the landslides) severely depleted the supply of fish food organisms and covered coho spawning gravel." Soon after Deschamps' report was published the DNR contracted with the University of Washington Fisheries Research Institute (FRI) to investigate these and other sediment sources throughout the basin to determine their effects on the fisheries resources.

Hydrologic investigations have shown that the logging roads are principal contributors of sediment to streams; however, most of the studies were concerned with suspended sediments and total sediment load (2,3,4,5, 6). Although it is generally accepted that high levels of sedimentation result in lowered salmonid production (7,8,9,10), it has not been shown how logging roads affect the composition of spawning gravels and how the resulting lowered survival to emergence affects the production of salmon for a large river system.

Considerable research has been done on the effects of sedimentation of the intragravel environment on the survival and fitness of salmonid embryos and fry incubated and emerging from this environment (11,12,13, 14,15). Fry survival and fitness are lowered when the spawning gravels become laden with "fine" sediments (less than 6 mm diameter), but the most serious diameter of "fines" will vary depending on regional lithology, hydrology, soils, vegetation, and general stream dynamics (11,16,12,17). We have determined that the particle size class most detrimental to coho salmon survival to emergence in the Clearwater River system is less than 0.850 mm diameter (17,18,19); this size class will be referred to as "fines" in this paper.

The processes causing mortality of eggs and fry in the intragravel environment are principally two: a) oxygen deprivation due to reduced permeability (20,21,22,10); and b) entombment of fry within the interstices of the gravel (10,23). Also, sedimented gravel can impose strong selective pressures on emerging fry that can affect stock characteristics in future generations (13).

The purpose of this paper is to present experimental data on logging-road-caused sedimentation sources and the resulting effects on intragravel survival of coho salmon, and to discuss how these impacts, in conjunction with a significant fishery harvest, could have cumulative effects on coho life history in the Clearwater River system. We also make some recommendations of ways to minimize logging-road-caused sedimentation, based on DNR experiences in the Clearwater River system.

THE STUDY AREA

The Clearwater River, a fairly typical north coastal stream, flows west from the foothills of the Olympic Mountains on the western coast of the Olympic Peninsula (Fig. 1). The watershed is 375 km^2 in this area, and the main river is fed by several salmon-bearing tributaries. The principal salmonid species are chinook (Oncorhynchus tshawytscha) and coho (O. kisutch) salmon and steelhead (Salmo gairdneri cutthroat (S. clarki) trout. There are approximately 70 km of main-stem river and 110 km of tributary open to anadromous migration, while the steeper headwater streams are inhabited by resident cutthroat trout. The Clearwater River has a mean annual flow of approximately 28 m^3/sec and is the largest tributary of the Queets River.

There is an intensive gillnet fishery by the Queets Indian Tribe located below the confluence of the Queets and Clearwater Rivers. The fishery annually harvests chinook, coho and steelhead. There is a minor river sport fishery within the Clearwater on these same species. Clearwater salmon stocks are also subjected to extensive ocean commercial and sport harvests by both U.S. and Canadian fisheries.

The Clearwater basin is under intensive old-growth timber management by the DNR, which manages over 80 percent of the drainage basin. At present the basin is 40 percent logged in the clearcut manner and the road system is over two-thirds complete. In recent years the rate of cutting and road building has been high, with the remainder of the timber scheduled to be cut by 1992. There are over 650 km of logging road in the basin now, and over half were built with sidecast construction in steep country. Since 1975 many new and stable roads have been built, and about a fifth of the road surface is asphalt-paved.

The western Olympic Peninsula has a typical maritime climate with wet, relatively mild winters and humid, cool summers. Weather is dominated by air masses from the nearby Pacific Ocean. Orographic lifting of moist air approaching the Olympic Mountains results in an average of over 350 cm annual precipitation over the watershed, with the majority falling between November and March. Snowfall at lower elevations remains

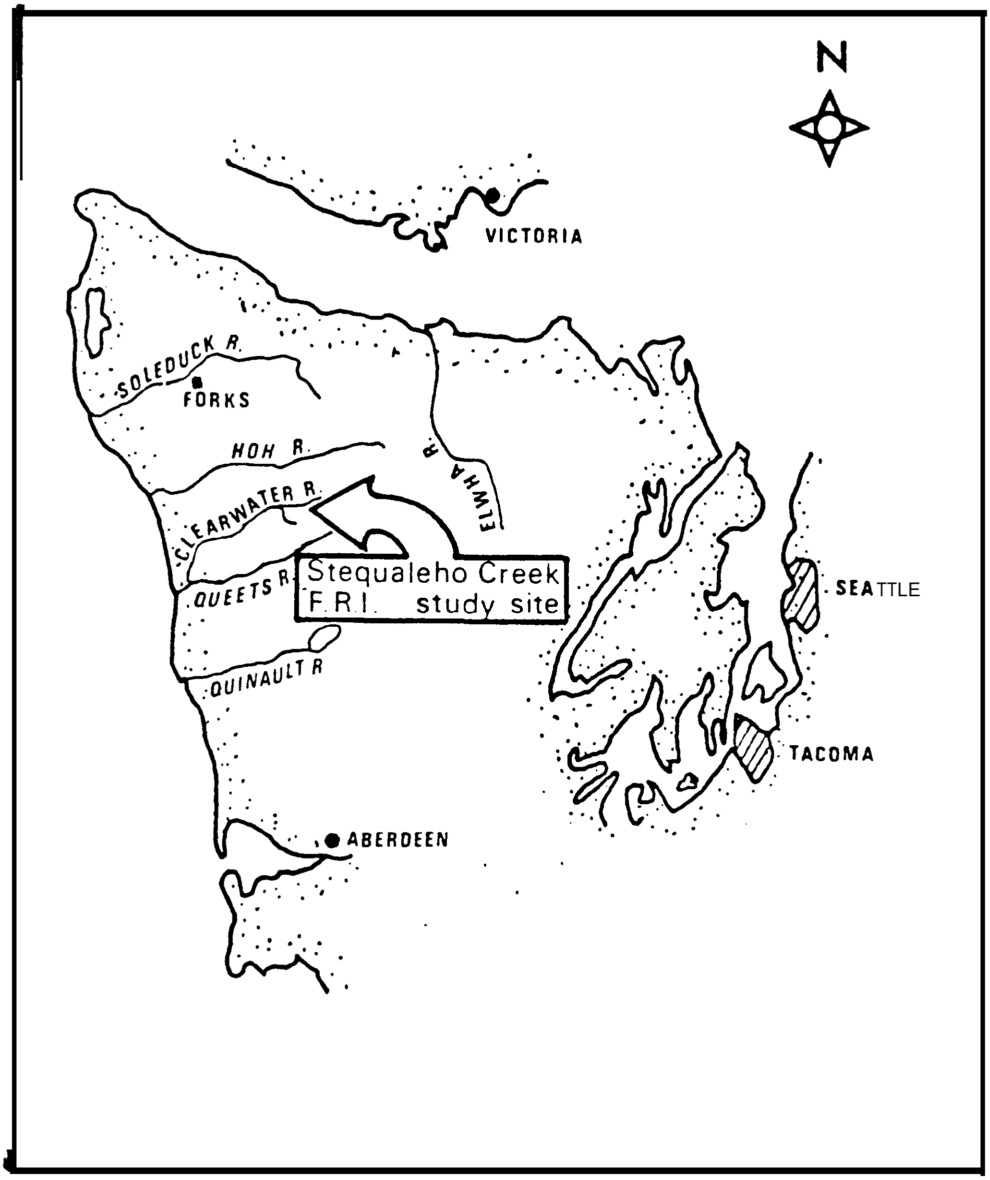


Fig. 1. Location of Clearwater River.

on the ground for only a few days, but headwater ridges may accumulate up to a meter or more of snow which may persist through May (24).

The bedrock in the Clearwater basin is characterized by Tertiary marine sediments composed of shale, siltstone, sandstone, and graywacke. There is some evidence of glacial influence along the ridge tops, caused by encroachment of valley glaciers from the neighboring Hoh and Queets river systems (25).

METHODS

Samples of spawning gravel were collected with a 15.2 cm diameter by 22.9 cm deep FRI hand coring device, using a plunger to capture the particles 0.106 mm in diameter and smaller. The samples were analyzed by a wet-sieve procedure with the gravel divided into four size ranges: 77 mm to 26.9 mm, 26.9 mm to 3.36 mm, 3.36 mm to 0.850 mm, and smaller than 0.850 mm diameter. Data were reduced using a modified version of the computer program FRS 062, FRI, University of Washington (19).

An eyed-egg planting experiment was carried out to test the effects of the sedimentation from the 1971 landslides on intragravel survival of cutthroat trout in Stequaleho Creek. In this experiment 54 individual perforated incubation boxes of 100 eggs each were planted in six locations throughout Stequaleho Creek: 27 boxes above the landslide influence (control), and 27 boxes below the landslide influence (experimental). The boxes were each buried in small hand-made redds 15 cm deep. Spawning gravel composition samples were taken near the test sites after emergence was complete (18).

During the winter of 1975 there was a massive logging road failure which deposited several thousand cubic meters of sediment and organic debris in upper East Fork Miller Creek. To test the effects of this sedimentation on coho salmon intragravel survival, another eyed-egg plant experiment was conducted in 1977 (19). In this test, 24 individuai nylon mesh envelopes of 200 eggs each were planted in eight locations of East Fork Miller Creek: 9 envelopes at three locations above the landslide influence (control), and 15 envelopes at five locations downstream of the landslide influence (experimental). Each envelope was buried in a small 15-cm deep hand-made redd, as in the cutthroat experiment. Spawning gravel samples were also taken in this experiment after emergence was complete.

We conducted a study in the winters of 1973-74 and 1974-75 to investigate the effects of varying gravel composition on natural coho salmon survival to emergence and to develop a predictive equation for survival at various concentrations of fines (17). Nylon nets were placed over 19 natural coho salmon redds in various tributaries of the Clearwater River. The emerged fry were counted and measured before releasing them back into the stream. We had previously developed a linear regression of fork length against fecundity for Sol Duc River coho females, so the potential egg deposition could be estimated for each redd based on the length of the respective spawnout female. The survival to emergence of fry in each redd could then be computed from the egg deposition and the number of fry that emerged. After emergence was complete a series of gravel samples was removed from each redd.

To investigate the survival to emergence of coho in varying gravel compositions under controlled conditions and again to develop a predictive equation for survival at various levels of fines, eyed eggs were planted in troughs (19). The troughs measured 1.8 m long by 0.38 m wide by 0.24 m deep and contained a mixture of gravel (based on Clearwater River gravel compositions) treated with varying percentages of fines. This experiment was carried out in 31 tests over a two-year period. The troughs allowed us to control variables encountered in the natural redd environment (i.e. egg deposition, female superimposition, streambed scour). An average of 1,500 eggs was buried in each gravel trough. The emerging fry were caught with a small nylon net trap at the outlet of each trough, and the survival was calculated. After emergence was complete, the gravel composition in each trough was sampled and analyzed.

To study the relationship between logging road density and downstream spawning gravel composition in natural tributary basins we chose 45 subbasins in the Clearwater, Queets, Hoh and Quillayute River systems (19). At these 45 tributary basins we collected and analyzed the particle size distribution of over 900 gravel samples. The logging road area was determined from aerial photos. The percent of a basin in road area (independent variable) was expressed as the product of the road length and a mean road width (measured horizontally from the top of the cut bank to the toe of the sidecast slope) divided by total basin area above the gravel sampling site. Simple linear regression analysis was used to determine the relation between road area per basin area and the percent of fines in the gravels.

Sediment production rates from the major road-related sediment sources were then measured. Preliminary field work resulted in the identification of road surface erosion, backcut erosion, landslides, debris flows, gullies, sidecast erosion, rills, and secondary erosion on landslide scars as dominant sources (26). Additional sources of sediment such as channel destabilization by road drainage and tree-throw along road rights-of-way were recognized but were not evaluated.

Road surface and backcut erosion were evaluated by sampling effluent from road culverts located on ten segments of logging road undergoing various intensities of use. Road segments were chosen to conform to the average road gradient of 4.5° to 6.5° and average length of 150 to 250 m, and included roads subjected to heavy use (more than 4 trucks per day), moderate use (1 to 4 trucks per day), light use (light vehicle use only), and no use. Heavy-use roads are actually in use or within six hours of having been used for only 43 percent of the heavy-use period. During the remaining 52 percent of the time they are considered to be in a temporary non-use category. Sediment concentrations, measured by weighing filtered water samples, were plotted against corresponding water discharge measurements to construct a sediment rating curve for each surface condition

(Fig. 2). Measurements of water discharge also allowed construction of unit hydrographs for various surface conditions. By using the unit hydrograph a continuous record of culvert discharge could be constructed from precipitation measured in the basin during the 1977-1978 water year, a year of average precipitation. A computer was then used to combine the continuous discharge records with the sediment rating curves to calculate the sediment lost from a road segment of each type. Because sediment discharge increases with water discharge to a positive power, the sediment yield from a road segment during a year of average precipitation will be less than the average yearly sediment yield. However, a strong relationship exists between the total sediment yield and total precipitation for a storm, allowing the calculation of sediment yields for years for which only records of daily total precipitation were available. These additional 10 years of data make possible the calculation of average annual sediment yield from road segments of each type.

Large-scale sediment sources related to roads were located and evaluated in a 40 km2 area. Road-related landslides, debris flows, areas of sidecast erosion, and gullies were identified, their areas measured, and the proportion of the displaced sediment available for fluvial transport estimated using aerial photographs. On-site measurements of volumes of 42 of the 170 identified landsTides and gullies verified the aerial photo measurements and made possible the definition of an average failure depth. These measurements then allowed the calculation of landslide volumes.

RESULTS

Mortality Rates of Salmonid Eggs Planted in Areas Affected by Landslides

Stequaleho Creek

During the late winter of 1972 we conducted an experiment determining the survival of cutthroat trout eggs in Stequaleho Creek one year after the occurrence of the landslides. We found no significant difference in the survival of the eggs between the affected (experimental) and unaffected (control) groups. The mean survival to hatch for the experimental group was 78.3 percent (range 6-96 percent) and the control was 76.0 percent (range 16-90 percent) (Fig. 3, Table 1). The mean percent fines was 10.9 percent in the experimental area and 8.0 percent in the control (18).

East Fork Miller Creek

Eyed-egg planting experiments in the East Fork of Miller Creek demonstrated a noticeable lowering of survival to hatching and to the button-up stage of fry development in the experimental group, compared with the control. The relationship was significant (1 percent level) for the lowering of survival to button-up stage but not survival to hatch. The mean survival for the experimental group was 24.7 percent to hatching and 2.6 percent to button-up (Fig. 3). The mean survival for the control was 57.2 percent to hatching and 25.6 percent to button-up (Table 2) (19). The mean percent fines was 23.7 percent in gravels of the experimental

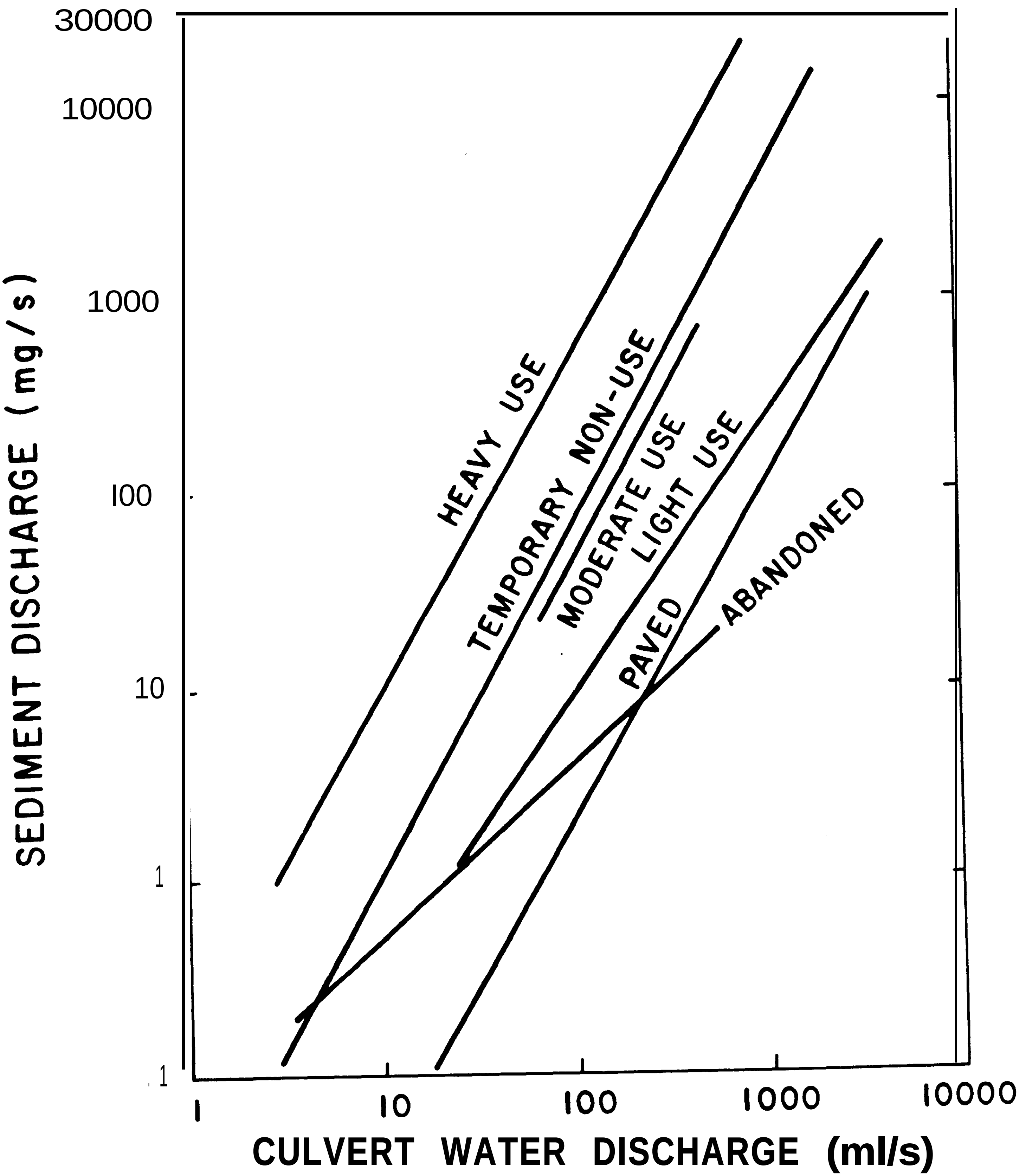


Fig. 2. Sediment rating curves for culvert flow from paved and from gravel surfaced forest roads sustaining different levels of traffic use. (See text for definition of use levels).

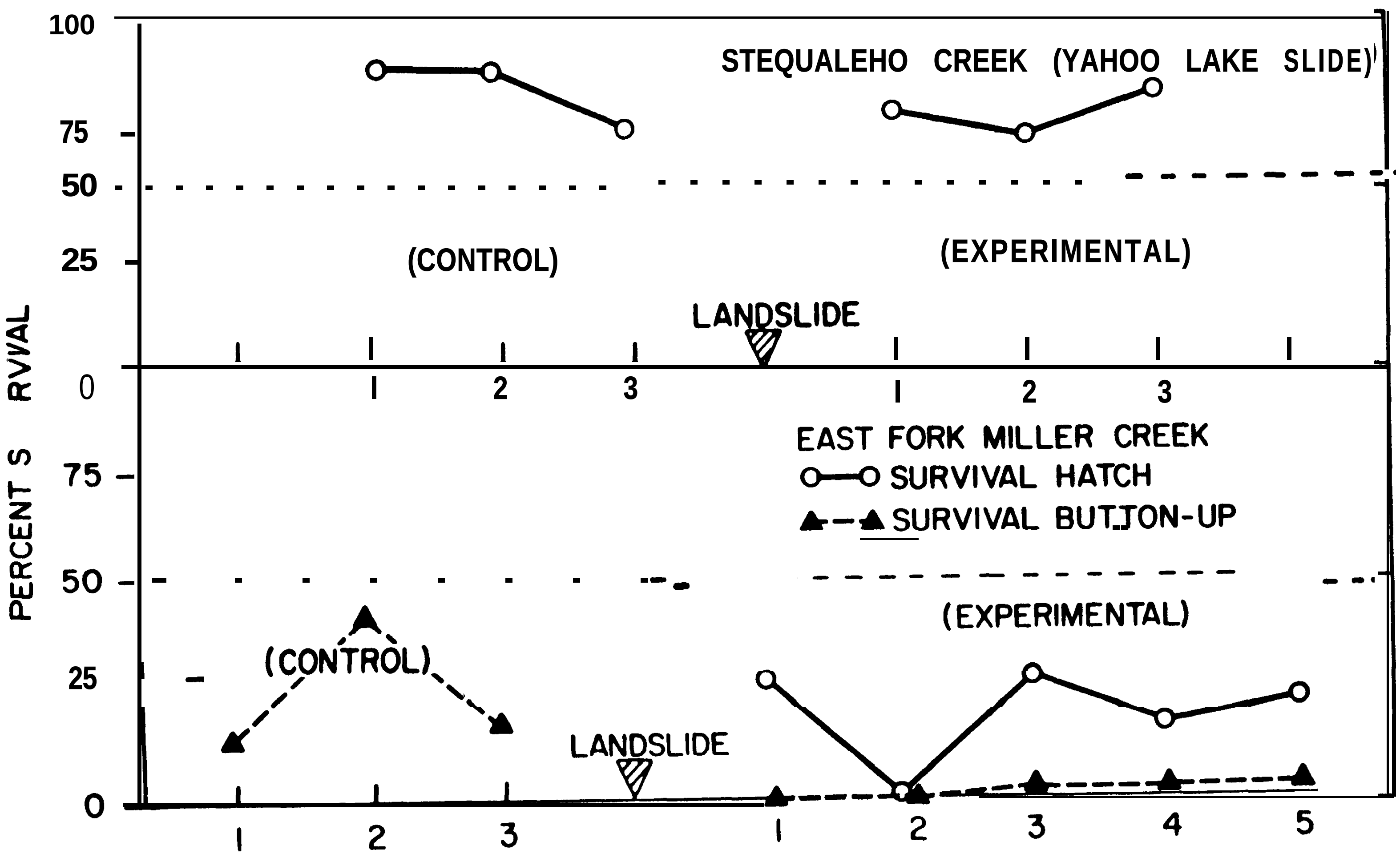


Fig. 3. Effects of landslide sedimentation on cutthroat trout survival (Stequaleho Creek) and coho salmon survival (East Fork Miller Creek).

Table 1

Percentage survival to hatching of planted eyed cutthroat trout eggs in landslide-affected (experimental) and unaffected (control) areas of Stequaleho Creek, 1972

SITE NO.	EXPERIMENTAL			CONTROL		
1	84	83	63	83	77	76
2	80	86	84	82	79	87
3	82	81	85	86	83	76
4	79	88	85	79	79	79
5	87	84	84	87	38	84
6	89	85	80	78	65	88
7	77	59	48	79	76	77
8	87	74	96	85	73	89
9	87	93	6	16	64	90
$\overline{X}$	84	81	70	75	70	83

$\overline{X}$ = 78.3 (experimental) $\overline{X}$ = 76.0 (control)

Table 2

Percentage survival of planted eyed coho salmon eggs in landslide-affected (experimental) and unaffected (control) areas of East Fork Miller Creek, 1972

SITE NO.	EXPERIMENTAL										CONTROL					
	1		2		3		4		5		1		2		3	
	H	BU	H	BU	H	BU	H	BU	H	BU	H	BU	H	BU	H	BU
a	0	0	0	0	47	0	39	0	32	8	73	31	83	74	47	12
b	32	0	0	0	3	1	21	2	0	0	57	9	66	48	65	56
c	67	0	0	0	53	13	2	5	50	7	48	0	42	0	34	0
$\overline{X}$	33	0	0	0	34	5	21	2	27	5	59	13	64	41	49	23

H = Hatch
BU = Button-up

Experimental:
Mean hatch = 24.71
(SD = 23.99)
Mean button-up = 2.57
(SD = 4.11)

Control:
Mean hatch = 57.22
(SD = 15.86)
Mean button-up = 25.56
(SD = 27.89)

area and 16.1 percent in the gravels of the control area. This 7.6 percent increase in fines was probably the cause of the high mortality rates in the experimental area.

Survival from Egg Deposition to Emergence

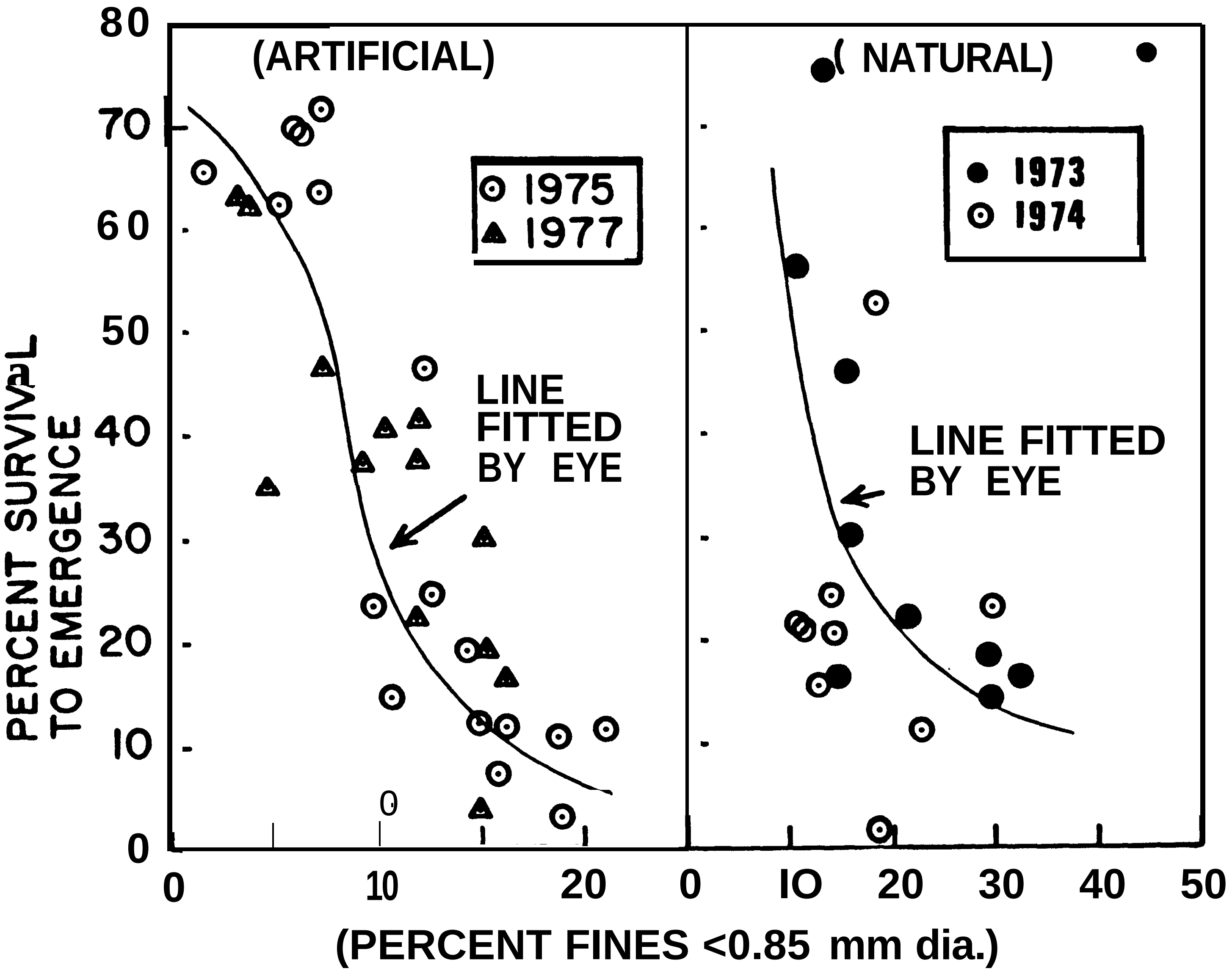
Natural Stream Environment

Coho salmon spawning in the Clearwater River lasts from October through early January, with the peak usually occurring the first week of December. During the 1973 and 1974 spawning seasons we measured and inspected for egg retention 27 spawnout coho females as part of a study of natural survival from egg deposition to emergence. The females had a mean fork length of 74.7 cm and retained an average of 7 undeveloped eggs. We measured and staked out the redds of 19 of these females for later study. It was determined that the survival to emergence in these redds ranged from 0.9 percent to 77.3 percent. The mean survival of the egg-to-fry stage was 37.4 percent in 1973 and 21.4 percent in 1974. Mean survival for both years was 29.9 percent. During the month of June in both years a total of 72 gravel samples was collected from inside and outside the redds under study. When the percentage of fines was linearly regressed against percent survival to emergence a significant relationship was found for the 1973 data (excluding one redd that we suspected had a superimposition of spawners) but not for the 1974 data. When survival data for both years are plotted against the percent fines, the range of survival for observations where fines make up less than 20 percent of the gravel bed is large, extending from 0.88 percent to 75.0 percent (Fig. 4). However, when fines are greater than 20 percent of the gravel bed, the range in survival is much less, 11 percent to 30 percent. Mean survival for the groups with less than 20 percent fines is 31.9 percent, while the mean survival for the groups with greater than 20 percent fines is 17.7 percent. The variances of these two groups are significantly different (5 percent level) (17).

In the 1973 data, a positive correlation between good gravel (percent of gravel between 26.9 mm and 3.36 mm diameter) and survival was observed. Plotting correlation coefficients of each gravel category, i.e. material stopped by a specific sieve, with survival, produces a curve with a characteristic positive bulge in the area of good gravel. Although these correlations were not all significant, a consistent trend appears (17).

Artificial Stream Environment

Survival from the eyed stage of embryonic development to emergence was tested in 31 gravel troughs over two winters. Survival ranged from 2.9 percent to 95.4 percent over the two-year period. Mean survival to emergence for 18 troughs in 1975 was 33.0 percent, and for 13 troughs in 1977 it was 35.1 percent. This was, however, a controlled experiment, and the gravel composition was mixed to reflect a survival distribution throughout the range found in the Clearwater tributaries (3.5 to 21.0 percent fines). A significant (1 percent level) inverse relationship was



Fiq. 4. Relationship between percent fines and coho salmon survival to emergence under natural and artificial stream conditions.

found between percent fines and survival to emergence (Fig. 4). During this 1977 experiment there was an apparent intragravel stress on the pre-emergent yolk sac fry which resulted in an emergence of 32 percent of the fry as alevins. These fry were subtracted from the full-term survivors to arrive at the overall percent survival for 1977 (19).

Percentage of Basin in Road Area vs. Downstream Spawning Gravel Composition

During the years 1972 through 1976 we collected and analyzed over 900 spawning gravel samples within 39 sub-basins of the Clearwater, 2 basins in the Hoh, 3 basins in the Queets, and 1 basin in the Quillayute River systems. The mean percentage of fine material in all the basins combined was 10.9 percent and the range was 3.1 percent to 22.0 percent. The sub-basins were found to have a mean of 2.9 percent of their areas in logging road area, with a range of 0.0 (in the National Park) to 7.2 percent (in a heavily roaded area). The sub-basins in the Clearwater River alone ranged from a low of 0.5 percent to 6.1 percent. There was a significant (1 percent level) positive relationship between percent of basin area in logging road area and levels of fines in downstream spawning gravels (Fig. 5). The coefficient of determination (r^2) was 0.62. There was no significant relationship when road area was regressed against the three larger gravel categories. It was concluded that when the area of logging roads in a basin in the area of study exceeds 2.5 percent of the basin area, fine sediments begin to accumulate in downstream spawning gravels (19).

Sediment Production from Gravel-Surfaced Logging Roads

A tabulation of average sediment production areas from road-related sources (Table 3) reveals an average sediment production rate to streams from landslides, sidecast erosion, and gullies of 50 + 15 tons/year per km of road in the northern part of the basin (the indicated confidence interval represents the standard error). In the steeper, higher, southern portion of the Clearwater basin the corresponding value is 85 ± 31 tons/road-km-year. Only 0.8 percent of this sediment is produced by formation of gullies and 1.3 percent by sidecast erosion. Examination of aerial photos taken in 1971, 1975 and 1977 discloses no evident temporal pattern in the initiation of the failures and suggests that those landslides identified represent virtually all of the road-related failures that have occurred since road construction began in the basin (26).

Debris flows contribute sediment to streams only insofar as they erode sediment from valley walls; sediment contributed from the original slope failure has already been considered as part of the landslide contribution, and that derived from the channel bed had already been introduced into the stream at some time in the past. Erosion depths on valley walls were measured in the field at 33 locations, allowing calculation of the volume of sediment eroded from the measured area of the debris flow tracks. A total of 29 debris flows were identified, producing an average of 4.5 ± 0.6 tons/road-km-year in the north part of the basin and 16.2 ± 2.1 tons/road-km-year in the south part of the basin. In the case of

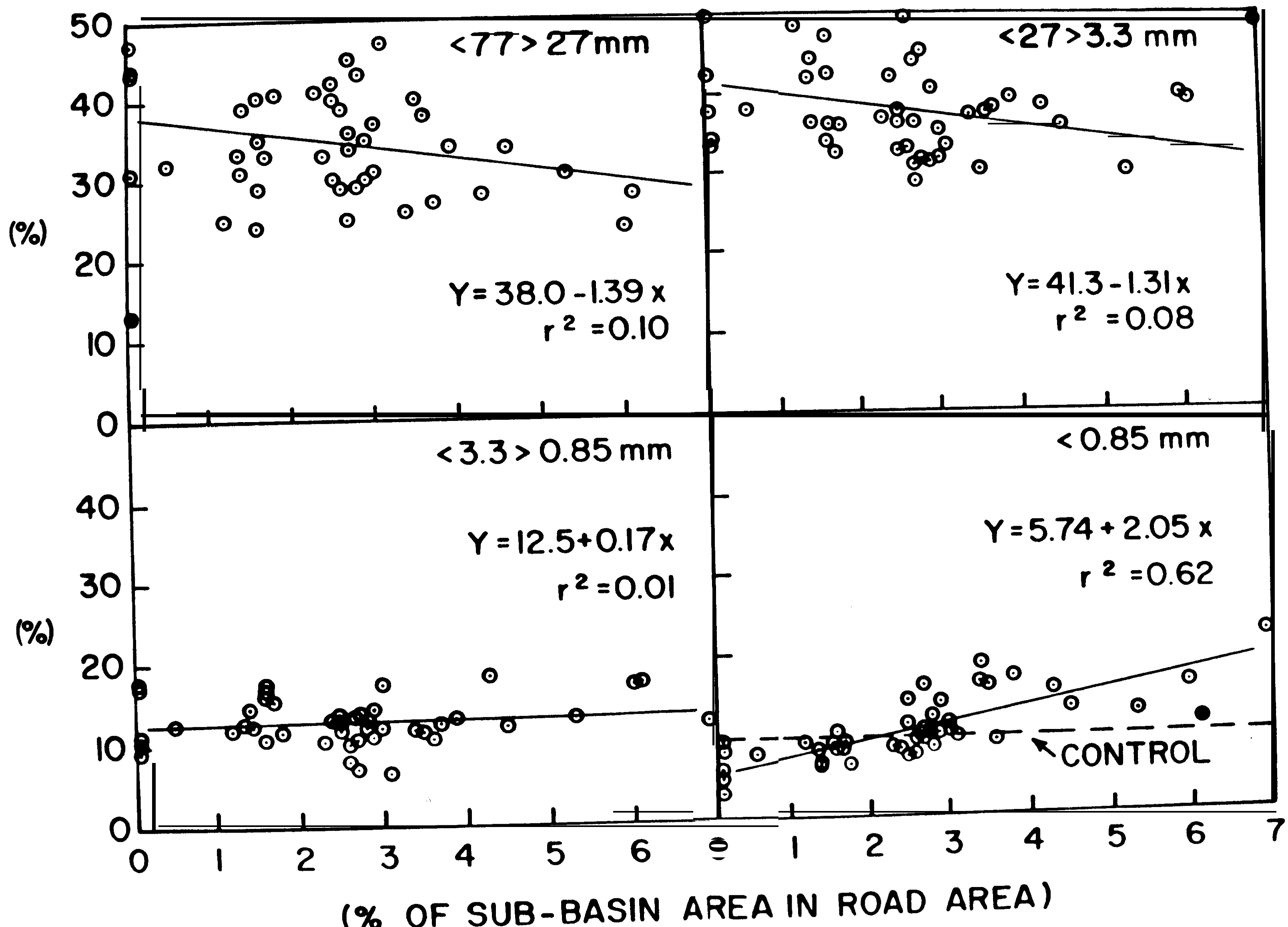


Fig. 5. Relationship between percent of sub-bisin area in logging road area and downstream spawning gravel compositicn.

Table 3

Average sediment production from road-related sources

Source	Total Production (t/road-km-yr) Christmas	Stequaleho	Production of Fines (< 2 mm) (t/road-km-yr) Christmas	Stequaleho
Landslides				
Initial failure	46	77	13	19
Secondary-erosion	3.0	6.0	3.0	6.0
Rills	.9	1.7	.9	1.7
Gullies	.4	.8	.1	.2
Sidecast erosion	.7	1.0	.7	1.0
Debris flows	4.5	16	1.3	4.0
Backcut erosion	1.6	1.6	1.6	1.6
Road surface erosion and backcut erosion				
Heavy use	500		500	
Temporary non-use	67		67	
Moderate use	41		41	
Light use	3.8		3.8	
Paved	2.1		2.1	
Non-used	.5		.5	

both landslides and debris flows, in each area single disturbances account for 25 percent to 36 percent of the sediment production from these sources (26).

Erosion continues after failures occur as rainsplash, sheetwash, and dry ravel transport sediment from the denuded scar. Measurements of ground surface retreat around stationary markers indicate an average erosion rate of 16.1 ± 3.6 mm/year, not significantly different from the measured erosion rate of 16.5 ± 3.4 mm/year due to the same processes on road backcuts. The progress of secondary erosion processes has been implicitly included in the calculations of sediment contribution by landslides, since landslide volumes were calculated using failure depths measured after secondary processes had been active for 1 to 6 more years. Not included in the landslide calculations are rills, which frequently form where road surface wash is diverted onto landslide scars. Volumes of rills were measured on those landslide scars observed in the field. If the resulting erosion rate due to observed rills is extrapolated over the total area laid bare by landsliding, then rilling on road-related landslide scars is responsible for the loss of 1.0 tons/road-km-year in the northern basin and 1.7 tons/road-km-year in the south (26).

Sediment yield at the culvert mouth includes sediment contributed both from road surface and backcut. The effects of these two sources may be separated by assuming that measurements of sediment yield from a paved road segment reflect only the component of sediment introduced from the backcut. The calculation is made by applying the sediment rating curve from a paved segment to a continuous hydrograph using infiltration capacity from a gravel road segment. The results indicate that on a heavily-used road the backcut contributes only 0.4 percent of the sediment yield at the culvert mouth. It should be emphasized that these values are based on measurements made on segments of average length and gradient and not on an actual distribution of road lengths and gradients (26).

Published analyses (27) of soil texture in the Clearwater basin may be used to estimate the proportion of contributed sediment which is of a small enough size to be transported in suspension. Suspendible material is here considered to be less than 2 mm in diameter, the largest grain size to be caught more than once in an utomatic suspended sediment sampler located at the mouth of a 25 km^3 basin. Sediment derived from landslides, gullies, and debris flows reflects the grain size distribution of the whole soil profile, and its volume is thus multiplied by the proportion of the soil volume composed of particles less than 2 mm in diameter. Road surface erosion, rilling, and backcut erosion, on the other hand, provide dominantly fine-grained material, and the total volume of their contribution is considered to be suspendible (26).

Sediment production from road-related sources was calculated for different stages in the development of two basins in the central Clearwater drainage assuming average weather conditions. Christmas Creek drains a 15 km^2 basin in the northern part of the Clearwater drainage, and the 25 km^2 Stequaleho basin is in the steeper, southern portion of the drainage. The resulting tabulation indicates that although road surface erosion accounts for only 18 percent and 26 percent of the total sediment produced by road-related sources in the southern and northern parts of the basin, respectively, this source is responsible for 41 percent and 49 percent of the production of fine-grained sediment, excluding breakdown of coarse material during transport (Table 4) (26).

The significance of sediment production from roads may be gauged by comparing the calculated production rate from roads in a hypothetical basin which has been 40 percent clearcut and has 2.5 km/km^3 of gravel-surfaced road with the expected sediment production rate under natural conditions. The length of road in such a basin is observed to include 6 percent heavily used-road, 5 percent moderately-used road, 39 percent lightly-used, and 50 percent abandoned road; in each case 75 percent of the culverts drain into the stream system. Thirty-seven measurement years (1965 and 1966 water years not included) in five, 0.7 to 5.1 km^2 basins in the Pacific Northwest (28,3) provide an average sediment yield of 72 ± 11 tons/km2-year in undisturbed basins. In the hypothetical basin described above, road-related sources alone would account for 189 tons/km^2-year according to the production rates in the northern portion of the Clearwater basin, and 308 tons/km^2-year in the southern portion of the basin (Table 5). These values represent 2.6 and 4.3 times the expected natural sediment production rates based on the above literature values. Independent measurements and estimates of natural sediment production rates from landslides, debris flows, tree-throw, animal burrows and bank erosion in the Clearwater drainage produce an expected sediment yield of 80 ± 30 tons/km^2-year from undisturbed basins (26).

DISCUSSION

Underseeding

Based on other research carried out on the Clearwater River watershed study (29,30), we have determined that the Clearwater River system has been generally underseeded for coho salmon since the early 1970's. That is, an insufficient number of spawning females have escaped (based on spawning ground redd surveys) the various fisheries to provide emergent fry to fill the available freshwater habitats. When we compare the mean relative biomass of coho in tributaries of the Clearwater (0.78 g/m^2 in 78 study section years) to that of the literature (2.21 g/m^2 in 154 study section years) we can see that the Clearwater levels are 65 percent lower than other comparable areas (Fig. 6). Also, our experiments (30) to determine the rearing potential for Clearwater tributaries, using saturation fry plants (plantings exceeding carrying capacity) have shown the mean potential biomass to be 1.75 g/m (in 35 study section years) which is 2.24 times that in the unplanted natural sections (Fig. 6). This evidence points to an under-utilization of the freshwater habitat of the Clearwater River by juvenile coho at summer low flow

Our calculations show that it would take a coho escapement of 4,200 adults per year to seed the Clearwater River system. This is based on

Table 4

Total sediment production from road-related sources in Christmas (15 km^2) and Stequaleho (25 km^2) basins (values in metric tons)

Source	Christmas total	Christmas <2 mm	Stequaleho total	Stequaleho <2 mm
Landslides				
Initial failure	11400	3170	23300	5710
Secondary erosion	740	740	1810	1810
Rills	230	230	510	510
Debris flows	1110	310	4870	1190
Gullies	90	30	240	60
Sidecast erosion	160	160	300	300
Backcuts*	(400)	(400)	(400)	(400)
Road surface and backcut erosion				
Heavy use	3850	3850	5300	5300
Temporary non-use	560	560	770	770
Moderate use	420	420	720	720
Light use	460	460	550	550
Paved	-	-	10	10
Non-use	50	50	50	50
	18900	10000	38400	17000

* Sediment production rate from backcuts is included under "Road surface and backcut erosion" but is listed separately here to demonstrate relative significance.

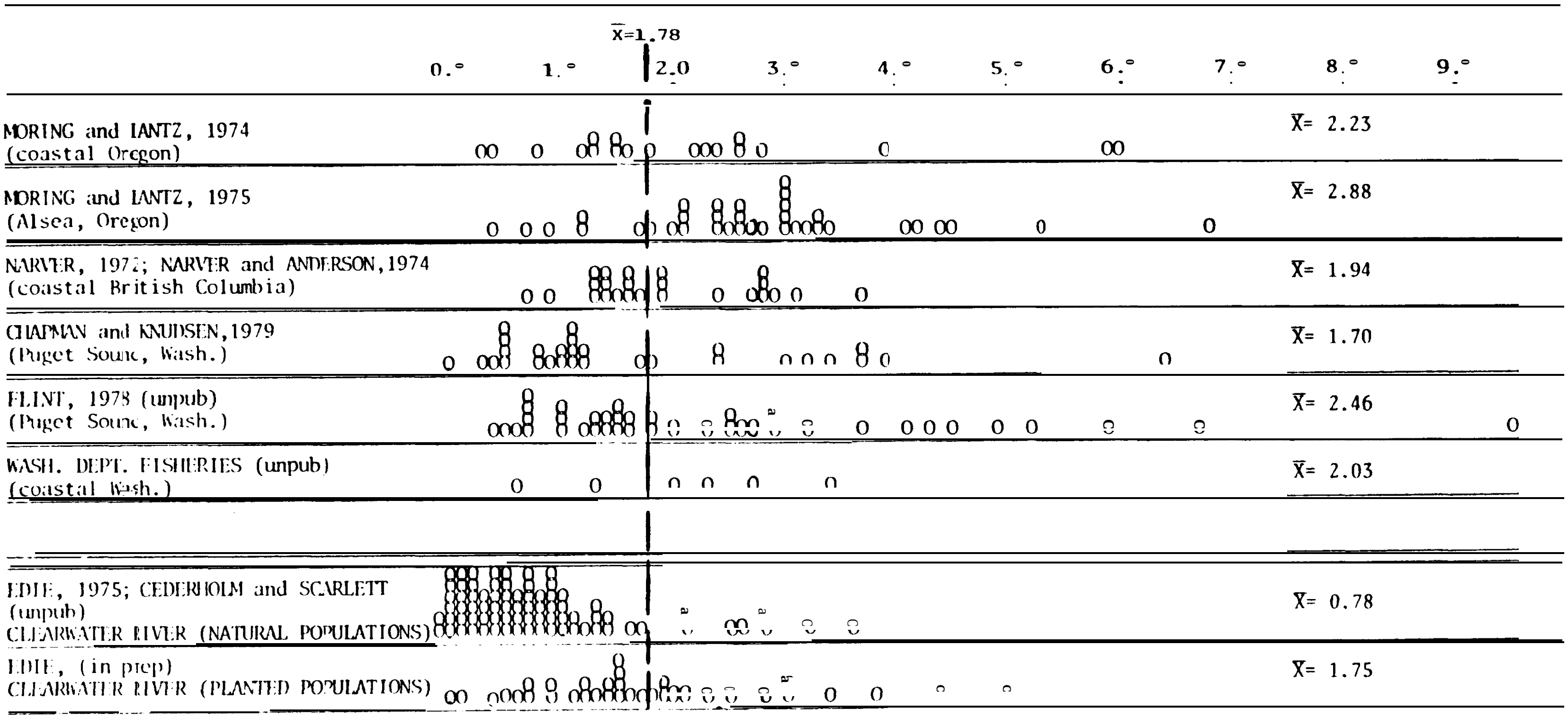
Table 5

Road-related sediment production in two hypothetical 10 km*, 40% clearcut basins with road densities of 2.5 km/km* calculated using rates measured in (A) Christmas and (B) Stequaleho basins

	A. Basin in northwest (t/km*-yr)		B. Basin in southeast (t/km*-yr)	
Source	Total	<2 mm	Total	<2 mm
Landslides				
Initial failure	115	32	193	47
Secondary erosion	7.5	7.5	15.0	15.0
Rills	2.3	2.3	4.3	4.3
Gullies	1.0	.3	2.0	.5
Sidecast erosion	1.8	1.8	2.5	2.5
Debris flows	11	3.2	40	9.9
Backcut erosion*	(4.0)	(4.0)	(4.0)	(4.0)
Road surface and backcut erosion				
Heavy use	36	36	36	36
Temporary non-use	5.2	5.2	5.2	5.2
Moderate use	5.2	5.2	5.2	5.2
Light use	3.7	3.7	3.7	3.7
Non-use	.6	.6	.6	.6
	189	98	308	130

* Sediment production rate from backcuts is included under "Road surface and backcut erosion" but is listed separately here to demonstrate relative significance.

Fig. 6. Comparison of the relative biomass of coho salmon in nine studies carried out throughout the Pacific Northwest (grams/meter^2) (each circle represents one complete study section electrofished between August and October, 1973-1979).



the existing area of pool space at summer low-flow, a seeding of 5 coho fry/m^2 pool at emergence, a survival to emergence of 22 percent, and a 1.5:l.O male-to-female sex ratio on the spawning grounds. The Washington State Department of Fisheries assumes that the Clearwater provides approximately 40 percent of the coho production for the total Queets River system. The coho escapement necessary to seed the entire Clear-water is 4,200 adults annually. However, the escapements of coho to the Clearwater have been estimated to range between 600 and 1,550 adults between 1973 and 1978 (Quinault Indian Fisheries Program). In 1979 the escapement was estimated to exceed 4,000 adults (Quinault Indian Fisheries Program) (Fig. 7).

Historical catch records (supplied by Quinault Indian Fisheries Program) show relatively high catches prior to 1960 (mean = 11,400, range = 5,366 to 17,096) and low catches between 1960 and 1972 (mean = 5,930, range = 3,090 to 9,322). If one assumes a consistent amount of effort over this period, then the number of fish returning to the Queets River has dropped by about half (Fig. 8).

It is our contention that the interception rate for these coastal stocks is too high. Data on fall coho runs in the Sol Duc River (an adjacent system), based on coded-wire-marked experimental groups, indicate a catch-to-escapement ratio of 15.9:l (31). That is, nearly sixteen fish are being harvested in the various fisheries before one escapes to spawn. It is probably not unrealistic to assume that Clear-water stocks are being harvested at or near the rate of Sol Duc stocks. A biologically sound C:E ratio for natural stocks is more like 5:l or less (WSDF, personal communication). This heavy harvest is caused by a combination of commercial and sport fisheries extending from California through coastal Canada. The greatest individual catches of coded-wire-marked fish reported on the Sol Duc, in order of decreasing magnitude, were: the Canadian troll and net (33.3 percent), the Washington ocean troll (27.8 percent), and the Quillayute River Indian gillnet fishery (21.7 percent), with the remaining 17.2 percent spread over six other harvest groups (Table 6). An example of a relatively new fishery is the Washington ocean sport charter boat (Neah Bay, La Push, Westport) fishery; this fishery was essentially nonexistent prior to 1955, but now the annual catch is over 500,000 fish. It has been estimated by Phinney and Miller (38) that this fishery is composed of approximately 12 percent Washington coastal stocks. The buildup of this fishery closely coincides with the decline in the Queets Tribal coho catches (Fig. 8). We do not mean to imply that the increase in the charter boat fishery alone is the cause of the decline of the Queets coho catches, we only mean to say that this is an example of a relatively recent significant increase in a fishery. The west coast Vancouver Island Canadian fishery has also become a significant fishery in recent years. This Canadian fishery has averaged over 1.3 million coho annually, and, according to Table 6, could be taking a significant number of Washington coastal stocks. We feel that in recent years there has been a dramatic increase in the total ocean interception of Washington coastal coho stocks, and this is probably the principal reason for the 50 percent reduction in return of coho to the Queets terminal area between 1960 and 1972. Since 1972 the

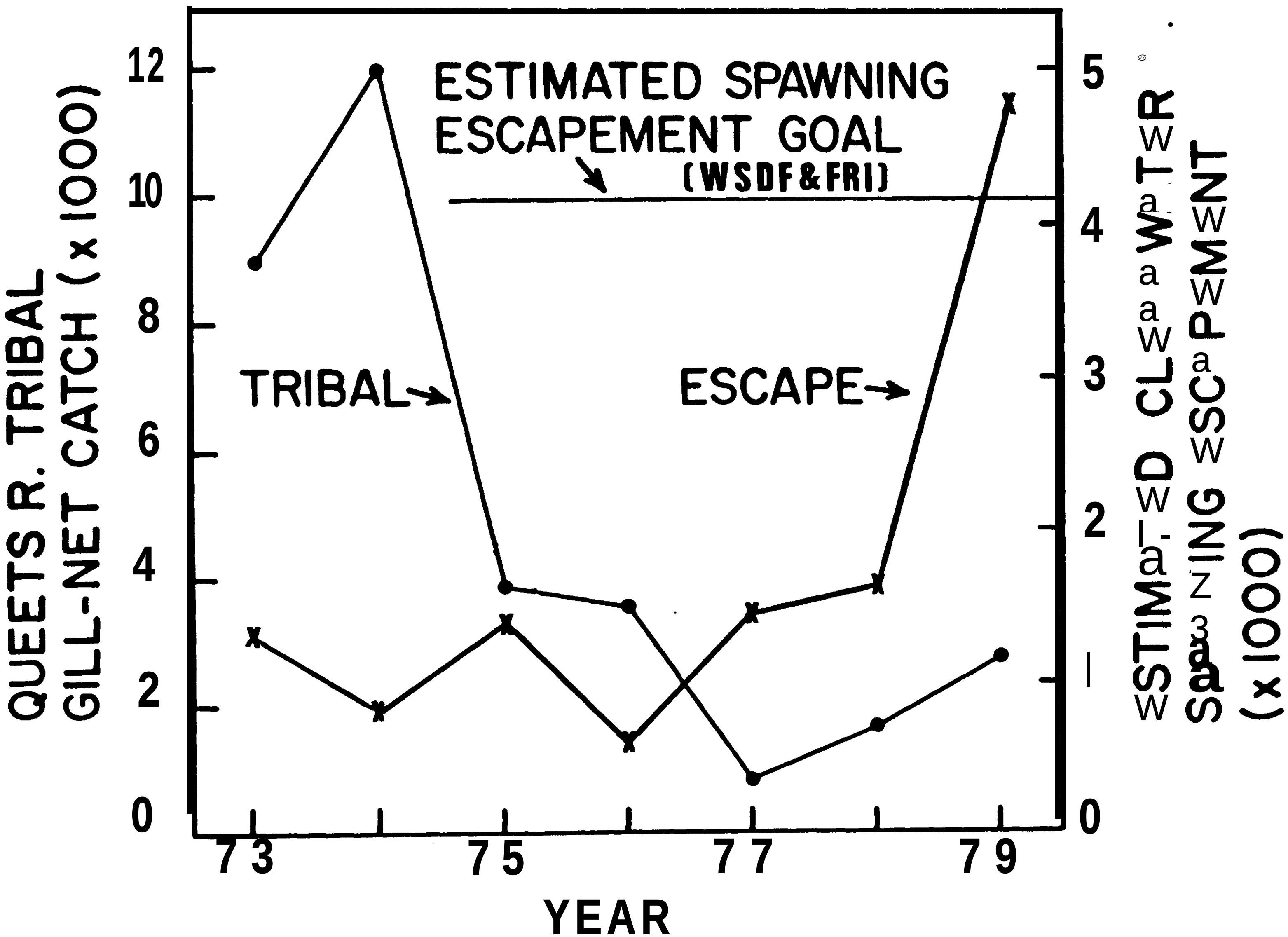


Fig. 7. Annual Queets River Tribal gill-net catch and Clearwater River escapement of coho salmon (1973-1979).

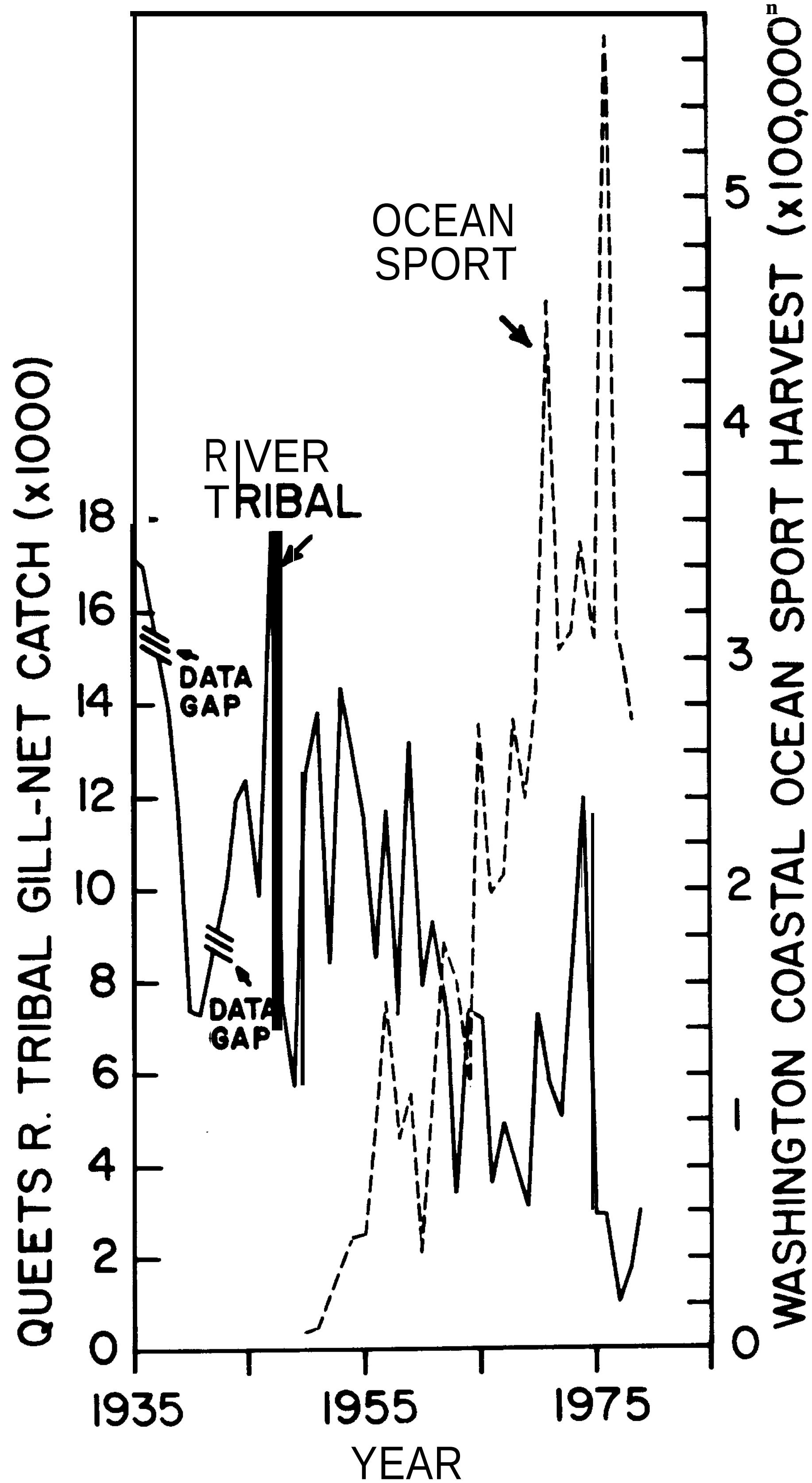


Fig. 8. Annual Queets River Tribal gill-net catch and Washington coastal ocean sport catch (1935-1979).

Table 6

Estimated catch distribution for three groups of 1971 brood coho
released from Soleduck Hatchery
(from Wood and Mosley, 1978)

Fishery	Summer run coho		Hybrid coho		Fall run coho		Total	
	Number caught	% of Total catch	Number caught	% of Total catch	Number caught	% of Total catch	Number caught	% of Total catch
Washington ocean troll	2,446	36.7	2,206	28.7	7,419	25.5	12,071	27.8
Washington ocean sport	807	12.1	548	7.1	1,760	6.0	3,115	7.1
Puget Sound sport	18	0.3	13	0.2	23	0.1	54	0.1
Fresh water sport	49	0.7	15	0.2	39	0.1	99	0.2
Quileute Indian gill net	848	12.7	1,744	22.7	6,853	23.5	9,445	21.7
California ocean troll	57	0.9	19	0.2	155	0.5	231	0.5
Oregon ocean troll	587	8.8	768	10.0	2,481	8.5	3,836	8.8
Oregon ocean sport	18	0.3	6	0.1	124	0.4	148	0.3
Canadian troll and net*	1,842	27.7	2,351	30.7	10,271	35.3	14,470	33.3
Total catch	6,668		7,676		29,125		43,469	
Soleduck Hatchery Returns	1,080		520		1,829		3,429	
Total recovery	7,748		8,196		30,954		46,898	
Catch:Escapement ratio	6.2:1		14.8:1		15.9:1			
Hatchery return rate (%)	1.9		0.9		0.83			

*Canadian recoveries subject to slight changes pending final editing.

Queets Tribal catch has fluctuated between a high of 12,000 in 1974 and a low of 875 in 1977, when Queets Tribal fishery restrictions were imposed by the Department of Fisheries for the first time. Since 1977 the Washington State Department of Fisheries (Bill Wood, personal communication) has attempted to bring about reductions in the Queets Tribal catch through season restrictions to allow for escapements to seed the system. Also, over the past two years some progress has been made in reducing the ocean sport and commercial harvest along the Washington coast. In the 1979 spawning season the escapement of coho salmon reached the State Fisheries escapement goal for the first time since 1972, and the outlook is good for this year.

Spawning Gravel Sedimentation

The results of this study indicate that logging roads are a significant source of fine sediment which is becoming deposited in some downstream spawning gravels. Whether from landslides or from road surface erosion, a significant amount of fine sediment is accumulating in spawning gravels of tributary basins experiencing heavy road use. Increase in the amount of fine sediments over natural levels results in a significant decrease in coho salmon survival to emergence. Therefore, proportionately greater numbers of adults are needed to seed the system. It appears that if less than 2.5 percent of a basin's area is road, then the sediment levels remain near natural; however, when the road area exceeds 2.5 percent, the proportion of fines in spawning gravels begins consistently to exceed natural levels. In the basins of some tributaries such as Miller and Christmas Creeks, roads account for between 5 and 6 percent of the total area; these streams also have some of the highest levels of fines in their spawning gravels, with measured percentages of fines consistently between 15 and 20 percent compared with 10 percent in natural areas. Based on a 2 percent reduction in survival to emergence for each 1 percent increase in the percent fines over natural levels (Fig. 4), these populations are near a critical level of survival beyond which recovery will be difficult. There are other tributaries like Stequaleho Creek and Solleks River where high discharge, steep gradient, and minimal organic debris accumulations have resulted in high sediment flushing rates. The gravel composition at main river gravel sampling locations, but for one exception, are close to natural levels (19).

We feel that a large amount of the sediment that we are measuring in the spawning gravels today has come from the older roads, those built before 1972. Many of the older roads were constructed using sidecast methods in steep country which often resulted in landslides. Also, many of the cross drains on these old roads are poorly protected from gully erosion, often resulting in undercutting of fills and eventual slumping. Many of the old fills contain large amounts of buried decaying trees and slash and are likely to fail in the future. Current methods of road construction and erosion prevention have vastly reduced erosion problems.

Probably the most rewarding part of our work has been the eagerness of the DNR to develop new and innovative methods of road construction and erosion prevention. Some of the techniques are:

1) Reducing road construction by using logging techniques that allow long yarding distances.

2) Using longline logging techniques with suspension over streams.

3) Jacking and pulling trees to prevent them from entering stream courses.

4) End-hauling material to safe waste areas and eliminating sidecast in steep country (slopes over 40 percent).

5) Placing flumes and energy dissipators on all critical cross-drainages to prevent erosion of fills and steep slopes.

6) Grass-seeding steep cut and fill areas to stabilize soil and reduce sediment loss.

7) Cleaning out all class 4 or larger streams concurrently with logging, while avoiding removal of older, naturally deposited debris.

8) Building a blacktop road system of mainlines and secondary roads, thus nearly eliminating sediment loss from these segments during periods of heavy rainfall.

9) Instituting an aggressive culvert patrol covering all roads in the system during periods of heavy rainfall, resulting in immediate care of landslides and culvert or bridge failures.

10) Building sediment traps below landslides to intercept silt before it enters streams.

11) Putting old roads "to bed" (closing them off and water-barring them) to prevent surface erosion.

12) Using balloon and helicopter logging techniques in some areas of difficult access.

Cumulative Effects

What long-term effect the sediments resulting from logging roads will have on the Clearwater River coho stocks is difficult to predict; however, we feel the adverse effects would be insignificant if the coho salmon spawning populations were large enough to fully seed (supply adequate recruitment for) the streams.

Populations respond to different kinds of stress either by use of phenotypic characteristics or by flexibility in genetic composition. Long-term changes, such as variation climate or salinity or isolation by the formation and ageing of lakes, are adapted to by natural selection.

Resilience [1] mechanisms such as fecundity, physiological tolerance to acute but temporary changes in environment., and flexibility in behavior, as in opportunistic feeding habits, allow populations to tolerate short-term perturbations.

In this study we have mainly been concerned with the relatively short-term changes associated with spawning gravel sedimentation. We must remember that floods, landslide-caused sedimentation, deposition of organic debris into streams, and scouring of the substrates of streams occur naturally and with varying frequencies during the life spans of aquatic organisms. When these processes are accelerated through land use practices, cumulative effects can occur and they can be either additive or multiplicative (synergistic is a term frequently used for certain multiplicative events) and as a result the resilience mechanisms are stressed. Man has introduced another major impact on populations of salmon by harvesting them. The combination of over-harvesting and exposure to impacts from logging sedimentation can produce cumulative effects on the salmonid life cycle; in extreme cases stocks may be depressed to the point of extinction. The simple spawner-recruit curves of Ricker (39) are commonly used to determine "allowable harvest"; but the principle of harvesting the surplus applies to stresses other than fishing in that the surplus (harvestable portion) at times of stress must be used as the area of (stock) resilience.

The spawner-recruit curve with "normal" regulators (Fig. 9) shows the amount harvestable, or the resilient portion of the population curve, and defines the optimum number of spawners necessary for maximum harvest (or in this case maximum resilience). This curve is an example of compensatory survival. However, once the population is depressed below a certain level the compensatory mechanisms break down and depensatory mechanisms take over: for example, the number of recruits taken by predators may be a constant, resulting in a greater percentage of the population being removed at the lower levels. This may depress the salmonid population level below the level of replacement on the spawner-recruit curve (Fig. 10). There are many examples in the literature of populations driven to extinction by a combination of over-harvest and changes in environment (Salo and Stober 1977, Salo 1974) (43,44).

A hypothetical example of how a stock could be driven to extinction due to cumulative effects of natural and man-caused mortalities in the life-cycle is shown in Table 7. The possible impacts on a coho salmon population are shown in five different cases, and it is evident that when logging-caused sedimentation operated independently of a commercial

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[1] Resilience implies the ability to recover to a more or less equilibrium state. Boesch, D. F., and R. Rosenberg. 1978. Response to stress in marine benthic communities. In Symposium on "Ecology of Stress", Second International Congress of Ecology Jerusalem, Sept. 1978. Contribution No. 963, Virginia Institute of Marine Science.

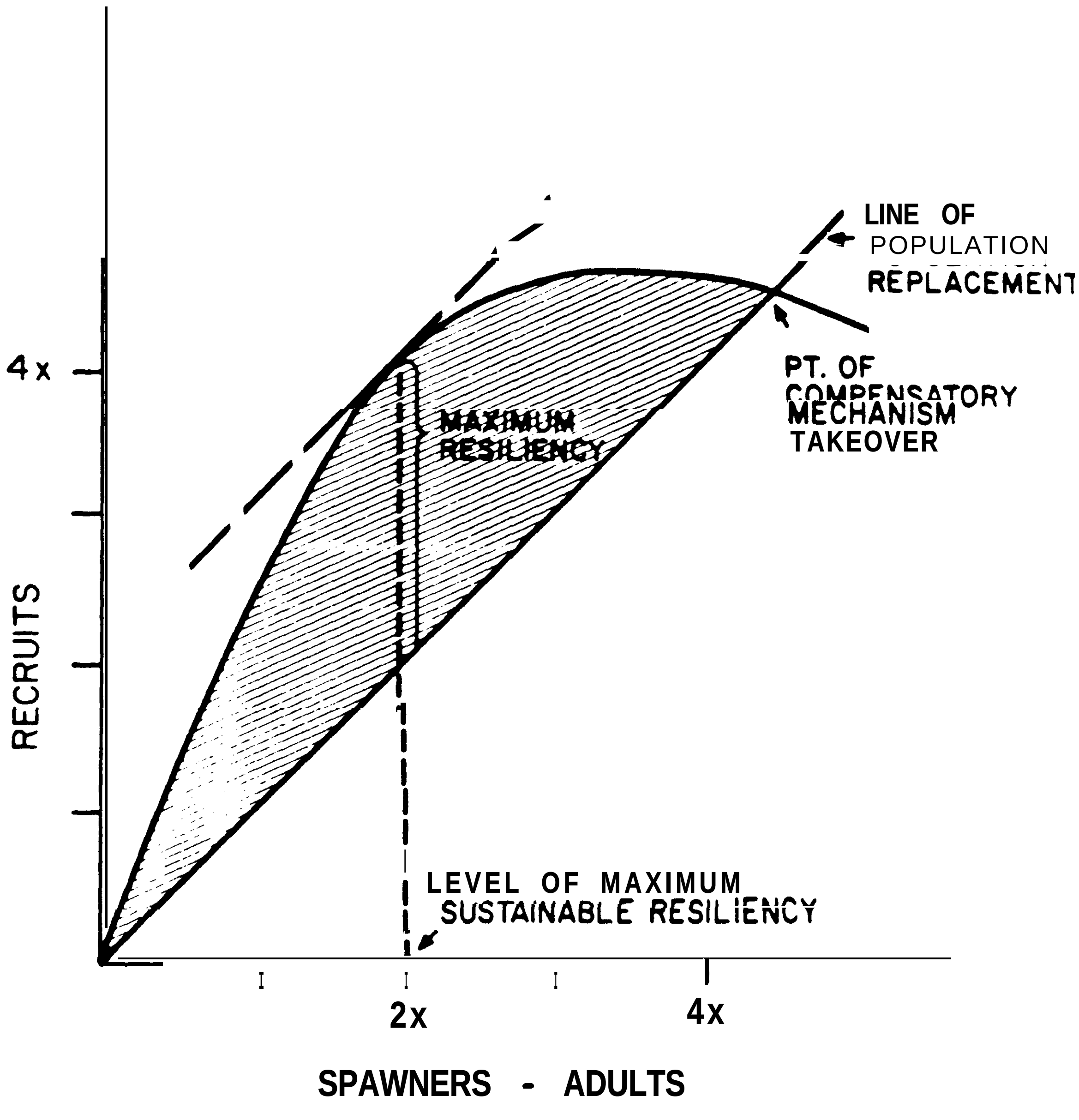

Fig. 9. Spawner-recruit curve with "normal" regulators (stresses).

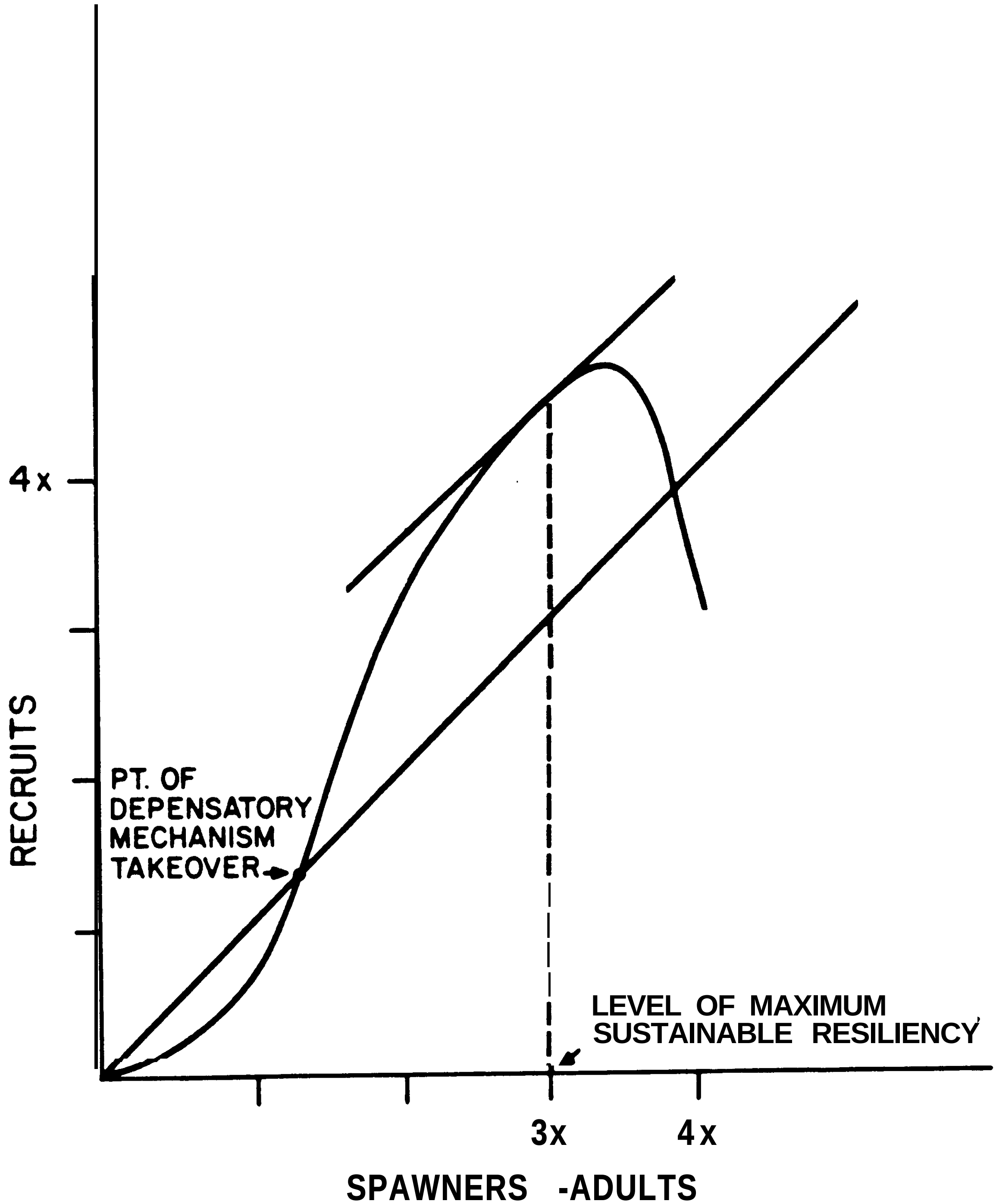

Fig. 10. Spawner-recruit curve with cumulative stresses.

Table 7

A hypothetical life history of a coho salmon based on five scenarios of natural mortality combined with the effects of logging on survival to emergence and heavy fishery harvest

LIFEHISTORY STAGE	(A) COMPLETELY NATURAL	(B) LOGGING INFLUENCES ALONE	(C) FISHERY INFLUENCES ALONE	(D) LOGGING AND FISHERY INFLUENCES TOGETHER	(E) AN OPTIMUM ECONOMIC AND BIOLOGICAL APPROACH
Amount of eggs deposited to seed to carrying capacity	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
	35% [1]	15% [2]	35%	15%	30% [3]
Emergent fry	350,000	150,000	350,000	150,000	300,000
	25% [4]	25%	25%	25%	25%
Parr at summer low-flow	87,500	37,500	87,500	37,500	75,000
	35% [5]	35%	35%	35%	35%
Seaward migrants (smolts)	30,600	13,100	30,600	13,100	26,200
	10% [6]	10%	10%	10%	10%
Total adult ocean survivors	3,000	1,300	3,000	1,300	2,600
	–	–	10% [7]	10%	50% [8]
Total adult fishery survivors	3,000	1,300	300	130	1,300
Escapement of both sexes	3,000	1,300	300	130	1,300
Escapement of females [9]	1,000	430	100	40	430
Eggs deposited to seed the next generation [10]	3,000,000	1,300,000	300,000	120,000	1,300,000
Amount of deposited eggs needed to reach carrying capacity	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
Excess or deficit of eggs for next generation	+2,000,000 (excess)	+300,000 (excess)	-700,000 (deficit)	-880,000 (deficit)	+300,000 (excess)

1/ Estimated from natural spawning gravel composition data (Cederholm and Salo 1979)

2/ Estimated from heavily logging-road-impacted spawning gravel data (Cederholm and Salo 1979)

3/ Estimated from moderately logging-road-impacted spawning gravel data (Cederholm and Salo 1979)

4/ Estimated using information in Au 1972, Edie (in prep.)

5/ Estimated using information in Bustard 1973, Edie (in prep.), Peterson 1980

6/ Estimated by Bill Wood (WSDF), harvest manager for Washington north coastal rivers

7/ Estimated using information in Wood and Mosley 1978

8/ Based on a 1 : 1 catch-to-escapement ratio

9/ Based on a 2 : 1 male-to-female sex ratio

10/ Based on a mean fecundity of 3,000 eggs per female fishery, the two effects are not as significant as they are when they occur concurrently. In Table 7, case A represents a coho salmon life history under completely natural conditions where a substantial excess (+2,000,000) of deposited eggs is available after a completed generation. Case B represents a life history when only the effects of logging-road-caused spawning bed sedimentation are imposed on the pre-emergent stage of the salmon's life history. In this case fewer smolts are produced, but there is still an excess of eggs(+300,000) at the end of the complete life cycle. Case C represents the same life cycle with only the effects of the various commercial and sport fisheries imposed on the adult stage of the coho life history. However, in this case, the high mortality of adults due to the 9:l catch-to-escapement ratio has resulted in a deficit of eggs (-700,000) in the next generation, resulting in a severely under-seeded condition. Case D is the situation that has existed in the Clearwater River system, where the effects of logging on the freshwater stages and the effects of the fishery on the saltwater stages are imposed over the natural mortality rates of the coho salmon. This latter case results in an extreme deficit of eggs (-880,000) at the end of one life cycle. This results in a severely lowered recruitment potential. This is a simplified example of the cumulative effects of two different man-caused influences superimposed on the natural mortality rates of coho salmon. When the logging road sediment influence is treated independently it is not a severe enough effect to reduce the escapement beyond what is necessary for the required egg deposition; but, when the logging and fishery influences are operating concurrently, they can lower the escapement significantly. Case D could eventually result in a stock of coho salmon being driven to the point at which depensatory mechanisms take over. Case E may be a compromise where some logging impact is allowed and some fishery is allowed, but together they do not have enough impact to cause an underseeded condition.

CONCLUSIONS

Increased intragravel sedimentation caused by logging-related sediment production and lowered spawning escapement of coho salmon due to heavy coastal fishery harvest have contributed to a generally underseeded coho salmon population in the Clearwater River system. In other words, the number of spawners comprising the escapement is below the optimum defined by the Ricker type spawner-recruit curves. Thus the population has become vulnerable to perturbation. Logging roads have been demonstrated to be an important source for fine sediments which enter spawning gravels, and in some tributaries the existing high levels of sediment are lowering the success of spawning and recruitment. The reduced escapement in combination with the lowered intragravel survival has resulted in stresses on these coho populations which could drive some sub-stocks to extinction. Therefore, we recommend that the fishing intensity and the production of logging road sediments be reduced.

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