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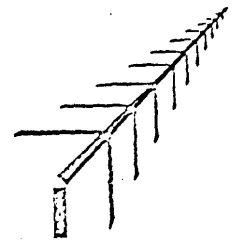

Influence of Forest and Rangeland Management on Anadromous Fish Habitat in Western North America

TIMBER HARVEST

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ABSTRACT

The water and land-system processes through which timber harvesting affects anadromous fish habitat in western North America are discussed. The effects of timber harvesting on the water balance that regulates streamflow are evaluated, as are direct influences of harvesting on slope stability, erosion, and the introduction of debris into stream channels. The effects of removal of riparian vegetation are included. Techniques presently available to resource managers for predicting these effects are documented.

KEYWORDS: Logging (–hydrology,.fish habitat, riparian vegetation, anadromous fish.

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INFLUENCE OF FOREST AND RANGELAND MANAGEMENT ON ANADROMOUS FISH HABITAT IN WESTERN NORTH AMERICA

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PREFACE

This is one of a series of publications on the influence of forest and rangeland management on anadromous fish habitat in western North America. This paper addresses the effects on fish habitat of timber harvest. Our intent is to provide managers and users of forests and rangelands with the most complete information available for estimating the consequences of various management alternatives.

In this series of papers, we will summarize published and unpublished reports and data as well as the observations of scientists and resource managers developed over years of experience in the West. These compilations will be valuable to resource managers in planning uses of forest and rangeland resources, and to scientists in planning future research.

Previous publications in this series include:

1. "Habitat requirements of anadromous salmonids," by D. W. Reiser and T. C. Bjornn.
2. "Impacts of natural events," by Douglas N. Swanston.
4. "Planning forest roads to protect salmonid habitat," by Carlton S. Yee and Terry D. Roelofs.
7. "Effects of livestock grazing," by William S. Platts.
8. "Effects of mining," by Susan B. Martin and William S. Platts.
11. "Processing mills and camps," by Donald C. Schmiege.

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INTRODUCTION

This discussion is confined to the effects of timber harvesting on stream ecosystems. Felling and yarding of trees cause changes to anadromous fish habitat in western North America through changes in water and land-system processes. The discussion provides answers to these questions:

- Which habitat elements are influenced by harvesting?
- What aspects of harvesting influence these habitat elements most and least?
- What predictive techniques are available to evaluate these effects?
- Which harvesting influences are particularly difficult to predict?

Although lakes and estuaries are vital for the life cycle of many anadromous salmonids, they are not considered here. Many of the effects of forest harvesting on stream systems, such as sedimentation and movement of organic debris, ultimately influence lakes or estuaries, but these effects are considerably removed from the direct influences of timber harvesting..

Stream habitat includes stream channels and the near-stream environment (flood channels, sloughs), organic and'inorganic material in beds and banks, and the water itself. Many studies of forest hydrology, however, do not directly address these habitat components but instead consider annual runoff, total sediment yield, and other influences from the top of the hillside down. The section on stream-habitat elements will attempt to invert this perspective and view harvesting impacts from the streamside up.

Although this review is intended for use by resource managers who are not trained in fishery ecology or forest hydrology, references are given to examples from the literature or from management practice for specific topics. Excellent reviews of the effects of forest harvesting on water and runoff (Gary 1979, National Council of the Paper Industry for Air and Stream Improvement 1979, Toews and Brownlee 1981) were source documents for much of the discussion.

The close relation of watershed (basin) properties to stream characteristics has been repeatedly emphasized (for example, Hynes 1975, Lotspeich 1980); through the alteration of the processes and structure of these relations, harvesting influences fish habitats. Figure 1 outlines a conceptual model tracing these linkages from ecosystem process and structure through stream habitat elements to fish.

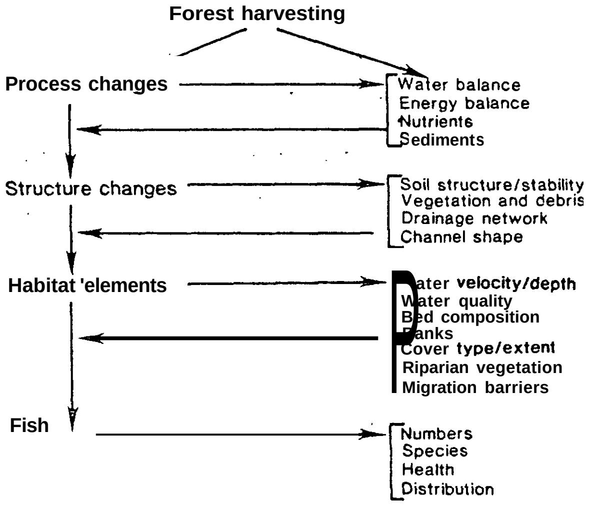


Figure 1--Relations of forest harvesting to fish.

In this model, the influences of forest harvesting are transmitted through changes in processes and structures in the watershed which in time modify the habitat elements identified by Reiser and Bjornn (1979) as important for anadromous salmonids.

In this model, although water plays a central role in causing or transmitting impacts of forest harvesting to fish habitat, many effects are transmitted directly without changing the hydrologic cycle. These include direct changes to channel configurations, the direct introduction of debris, and the removal of streamside vegetation.

Considerable overlap exists among these harvesting effects. These interactions only emphasize that the land-water ecosystem must be managed as an integrated whole for the maintenance of productive fish habitat.

STREAMFLOW

The word streamflow does not appear in figure 1, not because streamflow is irrelevant to fish, but rather because the meaning of the word depends on its use. Streamflow is defined as the amount of water flowing in a channel per unit of time. But the absolute amount at a given time (instantaneous discharge) or the aggregate amount over a year (annual runoff) mean nothing to fish habitat without reference to the corresponding water velocity, the area (or volume) of channel it covers, and--most important--the degree to which that flow departs from "normal" behavior for a given channel.

Streamflow is described in hydrographs of runoff versus time. Figure 2 illustrates a hypothetical composite of yearly hydrographs representing several streams in western North America. Absolute runoff amounts are not indicated because any given discharge can be a flood in a small channel or a low flow in a large river. For fish, increases or decreases in the number of channel-modifying flows (high water velocities) or low flows (causing dry channels) are the most important events.

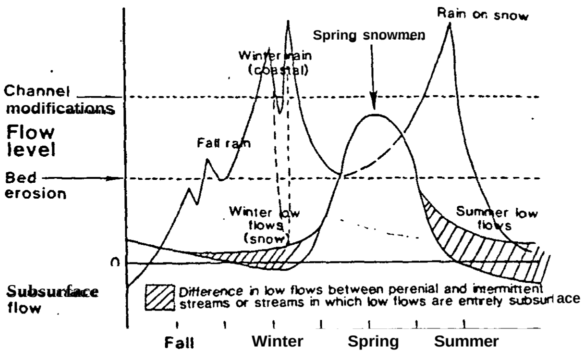


Figure 2--Examples of composite hydrographs through the year, comparing rain and snow events.

Streamflow in a natural system may be stable or unstable, depending on the size of the upstream basin and the number of storage elements, such as lakes, contained within it to buffer the effect of rain or snowmelt. The intensity of runoff also depends upon whether it is derived from rain (many winter storm peaks), from a melting snowpack, or both. Rain-on-snow events, either in low-elevation coastal forest (multiple winter snowmelt events) or in the Rocky Mountains (high-intensity spring rain on melting snowpacks), are not well understood. Swanston (1980) has discussed the range of natural runoff events that occur, and the section on forest harvesting and the water balance includes a discussion of harvesting effects on rain- or snow-dominated events. In general, harvesting affects low flows more than peak flows.

Another important concept in the analysis of harvesting impacts on streamflow is the manner or route by which water travels from a forest site to a channel. Most of this route is underground in forested areas, with surface water normally appearing in "source areas" near main channels.

During periods of increased runoff, these source areas expand upslope (fig. 3), causing an increase in the first-order or headwater channel network and more rapid runoff (Betson 1964). Although these small channels may not contain fish throughout the year, they are easily influenced by forest harvesting: in addition to water, they transport sediment and debris to main channels. Changes in soil structure or in the shape of a hillside (for example, from forest roads, skid trails, or yarding) can increase or decrease the availability of these runoff source areas and hence increase or decrease peak flows.

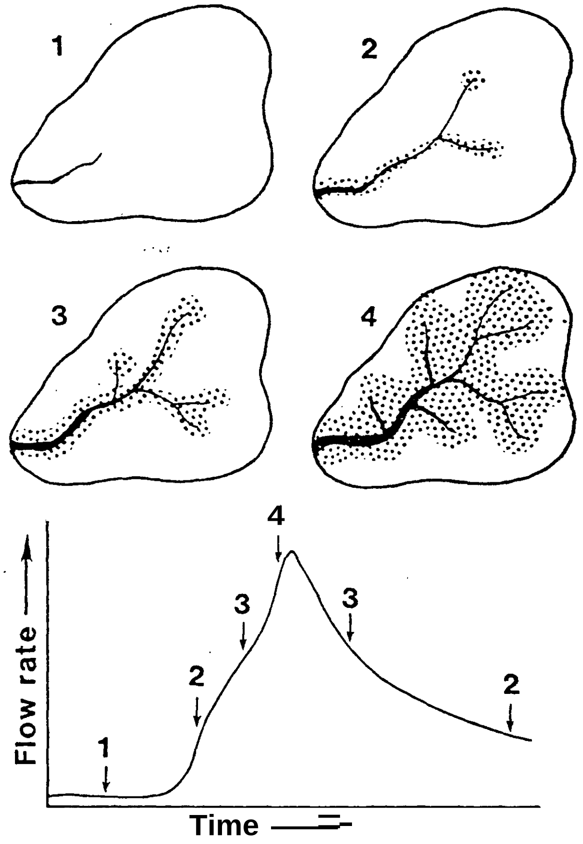


Figure 3--Expansion of channel networks during a runoff event (Harr 1976).

Some evidence suggests that road networks alone may cause accelerated peak flows in a small basin (Hsieh 1970), but quantitative predictions are not available. The imposition of road networks has the effect of increasing the density of the surface-drainage network in a basin, hence shortening the time required for water to reach the outlet of the stream. Little is known about the absolute magnitude of increased runoff caused by such changes in drainage densities.

The resource manager's task is difficult because of the large variability in natural streamflows, the number of hydrologic processes affected by forest harvesting, and the direct and indirect influence of streamflow on fish habitat. Harr (1980a) has said, "I do not believe we can predict changes in size or duration of these (channel-modifying) high flows at this time." Nevertheless, with some understanding of the water and energy balances, we can anticipate the type and direction of change in streamflow, and--with data (or experience) applicable to a given stream--whether those changes are likely to be small or large. In the following section, the various components of the water balance will be discussed with respect to their potential influence on streamflow.

FOREST HARVESTING AND THE WATER BALANCE

An understanding of the water balance and the hydrologic cycle is the basis for all watershed management prescriptions dealing with forest harvesting and runoff. The water-balance equation states that:

Inputs - losses ± storage = output,

where inputs include rain, snow, and fog drip; losses include evaporation from water, ground, and foliage, transpiration from plants, and deep seepage to ground-water tables; storage may be in surface depressions, the soil, in channels, or as snowpacks; and output is the stream runoff. Note that this water-balance equation deals only with amounts of water, not with the rates of movement, and it usually can be applied only on a yearly or monthly basis. To apply it to short intervals (days or hours) requires data on input and loss with a similar time resolution (Stephenson and Freeze 1974).

Less demanding empirical techniques using regional data have been used for generalized results, for example, changes in mean annual runoff (Isaacson 1977). Applying such empirical techniques outside the area where they were developed should be done with caution because of differences in processes and physical conditions (Hetherington 1978).

For a watershed, forest harvesting does not normally change the total amount of rain or snow entering a basin (Troendle 1980). The possible exception is in areas where forest foliage catches significant amounts of fog (Harr 1980b), which may be lost after harvesting. Harvesting may, however, substantially change the distribution of water and snow on the ground, the amount intercepted or evaporated by foliage, the rate of snowmelt or evaporation from snow, the amount that can be stored in the soil or transpired from the soil by vegetation, and the physical structure of the soil, which governs the rate and pathways of water movement to stream channels. Within this complexity of water-balance elements, harvesting effects can be roughly grouped into three major categories that form the basis for most runoff analyses:

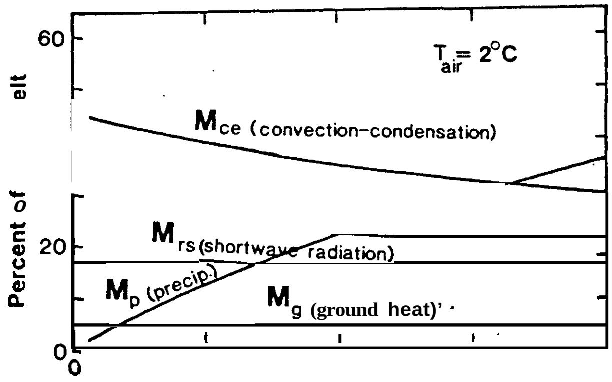
- Influences on snow distribution and melt rates.
- Influences on interception, evapotranspiration, and soil storage.
- Influences on soil structure affecting infiltration and water transmission rates.

Each of these must be considered in evaluating harvesting effects.

INFLUENCES ON SNOW DISTRIBUTION AND MELT RATES

Forest openings alter wind patterns, causing snow to be trapped in them. Small openings (up to eight tree heights) are more effective than large ones in trapping snow, although even in large openings more runoff will be generated than from forested terrain. Because the soil in forest openings is wetter (and hence is closer to its storage capacity), the melt water comes out faster and results in earlier (by as much as a month) and higher (by 1 to 3 times) peak flows. This effect is maximum when openings are from 2 to 6 times as wide as average tree heights, and has been demonstrated to persist for several decades, probably until mature crown-cover distributions and structure are restored (Swanson and Hillman 1977, Gary 1979, Troendle 1980).

For snow to melt, energy must be available. Although short-wave solar radiation dominates most melting, other factors can be important under a cloudy sky or during rain. Figure 4 summarizes the relative importance of different sources of energy during rainfall, and illustrates that convection-condensation energy dominates melting until rainfall is high (greater than 17 cm/day).



The importance of high-intensity rain-on-snow runoff has been demonstrated in flood-frequency analysis (Miles 1981). In coastal forests where winter rains are common over a variety of elevational zones, serious concern has been expressed, but few data have been collected about the influence of mid- to upper-elevation logging on winter peak flows.

Wind also augments melting, by improving the efficiency of heat transfer. Where higher wind velocities are produced by harvesting in humid air, such as along the north Pacific coast, accelerated melts may be possible.[1] Because rates of melting are directly proportional to wind velocities, the increase in melt depends on the relative amount of wind increase caused by forest openings.

Whether increased flows from a forest site cause an increase or decrease in runoff from an entire basin depends on the distribution of openings in the basin--their aspect, elevation, and distance from stream channels. Enough is known about snow accumulation and melt that timber harvest can be scheduled to provide runoff that meets fishery management objectives, by ensuring that melt at different locations in a basin is synchronized or not (Anderson 1956, 1957; Leaf and Brink 1973). For example, fishery managers who wish to maintain desynchronized snowmelt to minimize peak flows should encourage earlier melting in those watershed locations that are producing the most melt water during "normal" peak-runoff periods. Conversely, if harvesting causes earlier melting in upper elevations and on north-aspect slopes, increases in peak runoffs may be expected from the synchronization of previously dispersed runoff source areas.

Quantitative management models to predict runoff amounts and timing have been successfully applied in the Western United States (Leaf and Brink 1973, Thomsen and Striffler 1980). Many data are required for their application, however, and the development of local empirical techniques may prove to be more practical for the resource manager (Isaacson 1977). Swanson and Hillman (1977) also demonstrated that quantitative results can be anticipated in snow-dominated basins. A comparison of responses given by four snow models is provided by Baker and Carder (1977).

The duration-of-flow increases from snow management summarized by Gary (1979) suggest that significant (15-60 percent) increases in snow accumulation may persist for several decades. The proper management of the resulting runoff, so as not to exceed channel stabilities, has the potential of providing both additional water for spring storage and also increased late-season flow when space for fish habitat may be limiting;

INTERCEPTION, EVAPOTRANSPIRATION, AND SOIL STORAGE

Tree cutting eliminates a substantial area of leaves and stems which would otherwise intercept rain or snow and allow it to be reevaporated when sufficient energy was available. Fewer tree roots likewise reduce the amount of water that would otherwise have been transpired from the soil and lost to runoff. The combined effect of these two factors causes soil-water contents (and hence ground-water tables) and runoff to be higher in cleared areas than under forest cover.

Table 1 illustrates examples of changes in annual runoff that have been documented after forest harvesting.

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[1] Personal communication, D. Toews, British Columbia Forest Service, Nelson, B.C., 1981.

Table 1--Examples of changes in annual runoff after timber harvest[1]

Location	Species	Treatment	Increase in water yield (first year)
			Percent
Coweeta, N.C.	Hardwoods	100% clearcut	40
Coweeta, N.C.	Hardwoods	35% selective	40
H. J. Andrews, Oreg.	Conifers	40% clearcut	[2]--
Wagon Wheel Gap, Colo.	Mixed	100% clearcut	22
Fool Creek, Colo.	Conifers	40% clearcut	30

[1] Hibbert (1967).

[2] Small increase in low flow.

These increases in runoff are largest during peak growing (transpiring) periods and small or nonexistent during winter or periods of heavy precipitation. Research suggests that increased soil-water content in harvested areas may cause early fall rains or initial snowmelt to produce more runoff than under forested conditions, although these will not normally be extreme events (Rothacher 1973) (see fig. 2).

From the perspective of increased or decreased fish-habitat area, changes in low flows have a greater relative impact than changes in high flows because small absolute increases in runoff may double or triple the normal minimum summer streamflow.

Increases in soil-water content and ground-water levels from forest harvesting have two indirect effects that may be more significant to fish habitat than increased runoff. High soil-water content lowers soil strength and has been demonstrated to be an important factor in increasing the rate of slope mass movements after harvesting (O'Loughlin 1972, Swanston 1974a). On the positive side, higher ground-water tables after harvesting may expand available habitat in flood-plain areas that might otherwise be inaccessible during summer low flows.[2]

Increased runoff because of elimination of interception or transpirational losses are greatest in soils with high densities of tree roots, and it persists until those soil volumes are reoccupied with new roots. Other plants (new undergrowth) may somewhat offset these losses, but the relative amounts depend on transpiration efficiency and root volumes. In snowpack zones, the combined effects of increased snow accumulation and higher soil-water content increase runoff for a longer period than in rain-dominated regions.

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[2] Unpublished Annual Report of the Carnation Creek Watershed Study. Can. Dep. Fish. and Oceans, Vancouver, B.C., 1980.

Predictive techniques for estimating increases in flow from evapotranspiration "savings" require estimating the amount of water transpired by the species being cut, deducting it from the water balance, and routing it to runoff. In general, the amount of water saved is proportional to the percentage of basal area cut in a basin (a 50-percent cut will cause half the increase of a 100-percent cut). Water increases from evapotranspiration savings cannot exceed the potential evapotranspiration controlled by climatic factors and will usually be a small fraction of that amount;

INFLUENCES ON SOIL STRUCTURE

Forest harvesting can have from negligible to severe impacts on soil surfaces and soil structure, either locally or over entire basins. Although most severe impacts leading to erosion, mass movements, and accelerated runoff are derived from road or skid.trail networks (Sidle 1979, Swanston 1979), the tree cutting itself reduces soil strength by eliminating root structures, and the yarding process may expose mineral soil to accelerated surface erosion.

When soil disturbance is severe and bare mineral soil is exposed, reductions in water infiltration rates may occur. In extreme disturbance, especially with fine-textured soils, water may run off the ground surface instead of entering the soil. Such surface-runoff water is not available to enter soil storage but instead causes rapid local runoff with possible reductions in later low flows.

Normal capacities for forest soil infiltration (maximums) are much greater than normal rainfall or snowmelt rates. Only when infiltration capacities are extensively reduced by compaction or sedimentation on surface layers does rapid surface runoff occur. A measure of the degree of impact is shown in figure 5, which illustrates the amount of mineral soil exposed by different harvesting techniques.

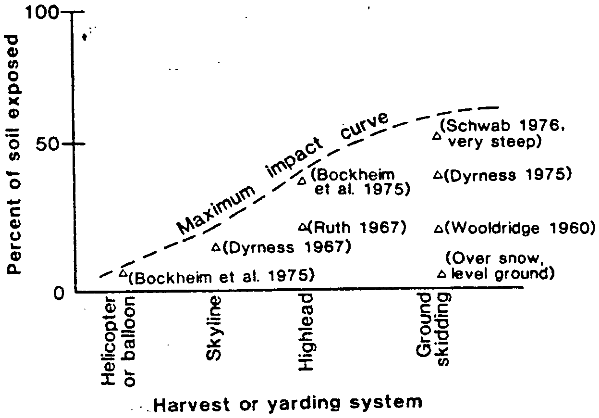

Figure 5--Amount of mineral soil exposed by alternative yarding techniques and terrains (Schwab 1976, Smith and Wass 1980).

In general, these impacts can be ranked on the basis of ground contact: none (helicopter); minimum (skyline, high-lead); and maximum (tractor skidder operations). On steep terrain, even high-lead yarding has been shown to cause high (30-60 percent) surface soil disturbance (Smith and Wass 1980), but on flatterrain or with a modest snow cover, tractor skidding may produce negligible disturbance. These findings suggest that the type of harvesting method is less important than whether or not it is appropriate to the local terrain.

Table 2--Surface and subsurface water velocities

Location	Flow velocities
Surface channels	10 - 300 cm/s
"Macro" pores	1/10 - 150+ cm/h
Soil matrix	0.1 - 10 cm/h

[1] Rates of outflow from root channels of 10-100 centimeters per second have been measured (personal communication, E. D. Hetherington, Dep. Fish. and Environ., Can. For. Serv., 506 W. Burnside Rd., Victoria, B.C., 1981).

Internal changes in soil structure may also occur from compaction, the death of tree roots, or sedimentation. When large voids and root channels are closed off or no longer connect to the soil surface, water is forced to travel more slowly into and through the soil matrix rather than rapidly through large channels. Cheng et al. (1975) and DeVries and Chow (1978) illustrated these pathways and suggested that reductions in peak flows and higher soil-water content may result from the slower movement of water through the soil matrix.

Table 2 illustrates the relative flow velocities found through the runoff process.

Other effects of such changes in soil structure are to raise groundwater levels,[3] increase the amount of soil-water storage, and increase the amount of surface (as opposed to subsurface) runoff.

To the manager concerned with fish habitat, changes in upper slope hydraulic conductivities are remote. Usually, however, disturbance to soil structure will cause some reduction in water runoff times and some increases in flow peaks. The amount of these changes may be small and difficult to predict, but only the maintenance of intact surface and subsurface soil structures can assure "normal" hydrologic watershed behavior. Basins with soil structure dependent on organic material and roots of mature or old-growth forest must be examined and managed for all components of the water balance to avoid introducing long-lasting hydrologic changes.

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[3] See footnote 1, table 2.

DIRECT IMPACTS OF FOREST HARVESTING

In addition to processes affecting runoff, forest harvesting activities directly influence fish habitat in four major areas:

- Acceleration of erosion and mass-movement processes.
- Introduction and removal of organic debris.
- Alteration of channel shape.
- Removal of streamside vegetation.

Some of the consequences of these activities can be anticipated and they need not be deleterious. Indeed, with adequate knowledge of the characteristics of particular streams, enhancement of some habitats is possible.

EROSION AND MASS MOVEMENT

The relation of harvesting methods to exposed mineral soil (fig. 5) suggests that surface erosion from felling and yarding is largely a function of the design of specific harvesting operations. High soil loss results from inappropriate choice of harvesting technique because soil loss also represents a loss of forest-site capability. The classic study of Reinhart et al. (1963) illustrates the correlation between logging design and subsequent sediment loss (table 3).

Table 3--Maximum turbidity and frequency distribution of samples for five West Virginia watersheds, December 1957 to April 1960[1]

Treatment	Maximum turbidity measured	Frequency distribution of samples by turbidity unit[2] classes				Total
		0-10	11-99	100-999	1000+	
	Turbidity units	Number of samples				
Commercial clearcut	56,000	126	40	24	13	203
Diameter limit	5,200	171	17	8	7	203
Extensive selection	210	195	8	0	0	203
Intensive selection	25	201	2	0	0	203
Control	15	202	1	0	0	203

[1] Reinhart et al. (1963), p. 20.

[2] Roughly parts of soil per million parts of water.

Unfortunately, no general techniques and few empirical studies (Rickert et al. 1978) are available for predicting either the increase in concentration of suspended sediments in stream water or the total volume of sediments likely to be added to a stream as a consequence of hillslope erosion processes. Application of the Universal Soil Loss Equation has been discussed in depth by the National Council of the Paper Industry for Air and Stream Improvement (1979) but currently seems to be inapplicable to forest sites. Where extensive data on sediment are available, multivariate techniques (Anderson 1957) have identified the contributions of sediment to streams by various land-use activities. Anderson (1967) provided an extensive review of the subject, but the prudent manager can only operate on the principle of minimizing exposed soil (fig. 5).

That removing tree cover on steep slopes reduces slope stability has been well established (Swanston 1974b). When slopes are near the limit of their safety factor, harvesting may accelerate the rate of mass movements, especially in response to large storms, earthquakes, or other major events. Yet the actual increase in number or rate of mass movements is difficult to predict, and their influence on fish habitat is a function of proximity to the active channel or to sediment-transport mechanisms. Usually in severe channel sedimentation, both slope failure and subsequent surface erosion act together to produce relatively long-lasting effects.

Land managers seeking to avoid accelerated rates of mass movement must identify and avoid slopes at or near stability thresholds, maintain vigorous root networks, and avoid increasing soil-water content. My discussion and guidelines, such as Swanston (1976), suggest that precluding timber harvesting completely in some areas may be necessary to avoid problems with slope stability. This is especially important when the unstable slope leads directly into a stream channel.

Recovery of slopes from accelerated mass movements requires that vegetation be reestablished. Effects may persist for decades, however, as introduced sediment works its way downstream. "Memory," or time lag for a channel to transmit material downstream, may extend for several decades.[4/]

The negative effects of fine sediments on stream gravels are well documented (Reiser and Bjornn 1979). Less well understood are the dynamics of sediment sorting and transport in streams. During high flows, some sediment is picked up and exported, while new gravel is deposited from upstream. Clearly, some erosion of stream banks and beds is necessary to replace lost gravel, but techniques to estimate exactly how much new sediment is necessary to maintain gravel in the streambed are lacking.

Studies in the Pacific Northwest indicate that even in fairly stable watersheds, increases in surface fines can occur from accelerated bank erosion (Toews and Brownlee 1981). This suggests that maintenance of the stream channel as well as hillslope integrity must be included in the design of forest harvesting.

INTRODUCTION AND REMOVAL OF ORGANIC DEBRIS

Numerous recent studies have identified the important role of large organic debris in controlling sediment transport, providing habitat for aquatic organisms, and dissipating hydraulic energy in small- to moderate-sized stream channels (Swanson and Lienkaemper 1978, Keller and Swanson 1979, Bryant 1980). Tree cutting adjacent to streams has the potential for introducing large amounts of debris; on steep slopes, residual debris can be transported to main channels years later as catastrophic debris torrents. At Carnation Creek., on the West Coast of Vancouver Island, British Columbia, debris movement increased by 3 times after streamside areas were logged (see footnote 1) and average debris size was reduced fourfold.

Although stable debris contributes to channel stability and habitat variability, excessive amounts impede fish movement and may reduce dissolved oxygen levels if fine organics accumulate on stream bottoms (Hall and Lantz 1969). Of considerable concern in the Pacific Northwest is the unknown effect of the conversion of large-diameter old-growth forest to small-diameter second-growth. The reduction in size of normal large organic debris in coastal streams may increase rates of sediment transport and result permanently in streambeds that are less stable and less productive over large regions.

[4/] Manuscript in preparation, "Sediment routing and channel changes in an aggrading stream in the Puget Lowland, Washington," by M. A. Madej. In: Proceedings of the Workshop on Sediment Budgets and Routing in Forested Drainage Basins, Oreg. State Univ., Corvallis, May 30-June 1, 1979.

Debris accumulations also impede fishing access and generally reduce recreational opportunities in a river. Direct debris management as a part of harvesting design offers potential for avoiding adverse impacts or for enhancing some stream environments. Numerous local guidelines exist for directing tree felling and yarding, avoiding slash buildups in gullies, and removing unwanted debris from active channels. All such measures depend on practitioners' understanding of the positive, as well as the negative, role of debris in the channel environment (Toews and Brownlee 1981).

ALTERING CHANNEL SHAPE

The breakdown and destruction of streambanks by felling and yarding are among the most persistent of direct impacts of harvesting, and they are the most difficult to avoid when streamside felling or skidding and cross-stream yarding occur. With the exception of helicopter, skyline, or other high-deflection systems, near-stream yarding may reduce bank stabililty and increase stream widths (Narver 1972) as well as eliminate bank cover. Contributing factors include steep slopes, high soil-water content, leaning trees, bank soils with low cohesion, and lateral channel instability. Although measures for protecting the streambank environment are available (Lantz 1971, Moore 1978), avoidance is frequently the only alternative to extensive bank destruction.

The homogenization of stream-channel configurations from harvesting activities is a particularly long-lasting threat to fish habitat. The role that cover plays in all models of fish production (Binns and Eiserman 1979) suggests that a varied stream-channel morphology, stable in-stream debris, and a variety of substrate sizes are necessary for good fish production. Recovery from the loss of these components of channel habitat, if at all possible, may require several decades.

Although near-stream logging can cause severe problems, it also offers the opportunity for habitat enhancement. Many coastal streams experience severe winter freshets, during which high mortality of overwintering salmonid fry (and adults) may occur (Bustard 1973). Survival under these high-velocity conditions requires access to low-velocity backwater or pond areas. Such refuges can be easily created as part of the logging plan in flood-plain areas.

REMOVING STREAMSIDE VEGETATION

Streamside vegetation is instrumental in stabilizing banks, controlling organic debris, and providing cover (Meehan et al. 1977). On small- to medium-sized streams (first- to fifth-order), streamside vegetation also yields fine particulate organic matter into the aquatic food chain (Naiman and Sedell 1979) and controls water temperature through shading (Meehan 1970). The separate effects of shade on water temperature (Brown 1969) and on limiting food production have been well documented. The work of Stockner and Shortreed (1978) also suggests that the deliberate opening of small, cold streams could significantly enhance their productivity through the moderate increase of water temperatures and the acceleration of photosynthetic activity.

Stream temperatures must, of course, remain within fairly well-defined limits (Reiser and Bjornn 1979), and procedures exist for determining the amount of shade required for maintaining them (Brown 1970). For small streams, the shade and nutrient requirements can often be met with noncommercial or shrub vegetation. In any streamside harvesting, however, the requirements of bank stability and debris control must be considered along with those of shade and nutrients.

The value of maintaining streamside vegetation as a buffer strip has been well documented (Streeby 1970), and guidelines for determining required widths are available (Packer and Christensen 1964). Buffer strips are not a panacea for sediment control, however, because persistent sediment sources will quickly overwhelm the absorptive capacity of the forest floor when surface pores are clogged by fine sediments. Buffer strips must also be designed for wind firmness and are most approprigte for keeping debris from channels and for preventing direct effects on the banks.

ELEMENTS OF STREAM HABITAT: A SUMMARY OF HARVESTING IMPACTS

The preceding discussion focused on watershed and streamside processes affected by tree cutting and yarding. What are these harvesting effects on the elements of stream habitat identified by Reiser and Bjornn (1979) (fig. 1)?

Although considerable overlap in importance exists among habitat elements, the stream manager must usually identify specific factors limiting production of a given stream or fish species. For example, a stream supporting resident salmonids would have a high cover requirement, but a stream supporting pink (Oncorhynchus gorbuscha (Walbaum)) or chum (O. keta (Walbaum)) salmon would be limited primarily by the quality and quantity of its spawning gravel. Rivers with the most stable diversity throughout their length offer the maximum opportunity for a variety of fish habitats.

For each habitat element, clues for predictive or evaluative techniques will be suggested, and a direction or range of expected positive or negative alterations will be indicated. Few of these, however, can be applied to particular streams without accurate site-specific information about the watershed, stream, and fish populations, and the specific forest harvesting procedures proposed. These techniques do not normally allow quantitative predictions, but rather indicate critical factors that aquatic resource managers must consider in the planning and assessment of forest harvesting operations.

WATER DEPTH AND VELOCITY

Increases in water depths and velocities occur when runoff increases. Because water velocities high enough to scour streambeds or modify channels occur during nearly bank-full or higher flows, does forest harvesting alone increase flows significantly in this high-flow range? Evidence suggests that increased runoff from evapotranspiration and interception losses alone does not increase high flows sufficiently to be of concern (see fig. 2, Megahan 1979). Much greater flow increases, however, may be caused by synchronization of snowmelt in intensively harvested small basins or in conjunction with rain-on-snow events. Again, no direct data demonstrates that these have caused destructive instantaneous peak flows (Harr 1980a), but considerable circumstantial evidence suggests that harvesting in coastal British Columbia may have contributed to deteriorating aquatic habitats in a region where rain-on-snow events are common.

These somewhat conservative conclusions must be placed in the context of the expected size and location of harvesting areas. If an entire south-aspect basin, for example, were to be harvested, destructive runoff increases might be expected. Also, little is known about the long-term effects on channel geomorphology of relatively modest changes in stream regime. Increased return frequencies of moderate runoff events may play an important role in redistributing bed material downstream. If these events, which normally occur every year or two, become prevalent several times a year in response to mid- or upper-elevation rain-on-snow events, long-lasting changes in channel morphology and bed composition may result. Low flows, on the other hand, have been consistently shown to increase after harvesting, as long as soil infiltration properties are maintained and basin water inputs do not decrease. Figure 6 suggests a relation of relative flow to the amount of increase expected from forest harvesting.

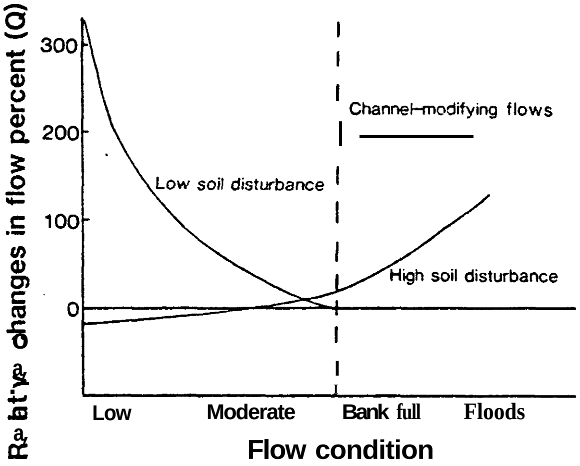


Figure 6— Alterations in relative flow after forest harvesting as a function of soil disturbance and flow.

These results may be reversed, as suggested in the lower curve, if soil disturbance is extensive enough to cause surface runoff in watersheds that formerly had high infiltration capacities.

Decreased low summer flows have also been documented in a watershed where water inputs from fog drip were eliminated by timber harvest (Harr 1980b). To resolve such questions, a water balance must be estimated for the basin of concern.

Figure 7 suggests a relation of increased flow velocities to some effects on fish and aquatic habitat that, in combination with figure 6, provides a means of estimating which flow-velocity changes are likely to be significant. In all analyses of this sort, the water-velocity distribution in the channel resulting from increased discharge must be estimated. Quantitative techniques are illustrated by the hydraulic simulations of the U.S. Fish and Wildlife Service (Bovee and Milhous 1978) that require site-specific data for the stream reach at alternative flow levels. Of equal importance in assessing the effects of increased or decreased flows is the accessibility of microhabitats (sloughs, bed material, debris) that provide low-velocity refuge areas in or adjacent to the stream channel. Water depths and velocities are also influenced by channel form, especially in the low-flow range. Increases in sediment supply or sediment transport rates may cause channel aggradation, and direct disturbance of streambanks may cause bank recession and channel widening (Narver 1972). Either process will lower relative water levels and may cause low flows to become entirely subsurface.

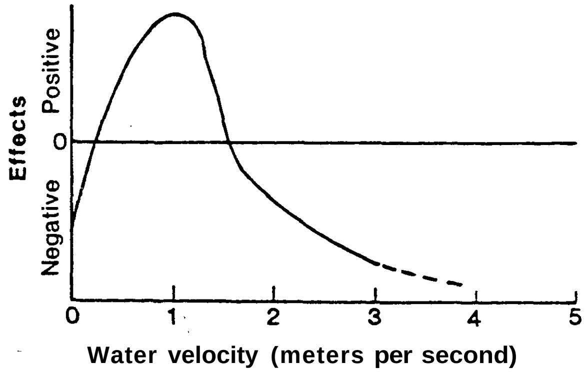


Figure. 7--The effect of increased water velocities. Shape and location of curve is a function of fish species, age, and condition (for example, see Bovee 1978).

The evaluation of consequences to fish habitat of changes in water velocities and depths (resulting from increased or decreased flows) has been considerably advanced by the Incremental Flow Methodology developed by the U.S. Fish and Wildlife Service (Bovee and Cochnauer 1977). This methodology provides a means of linking alternative flows to the resultant changes in available fish habitat.

The method predicts the amount of habitat area available at various flow levels and the relative value of those habitats to fish, based on depth and velocity curves for each species (curves of the relative frequency of use). Examples of these curves are given in figure 8.

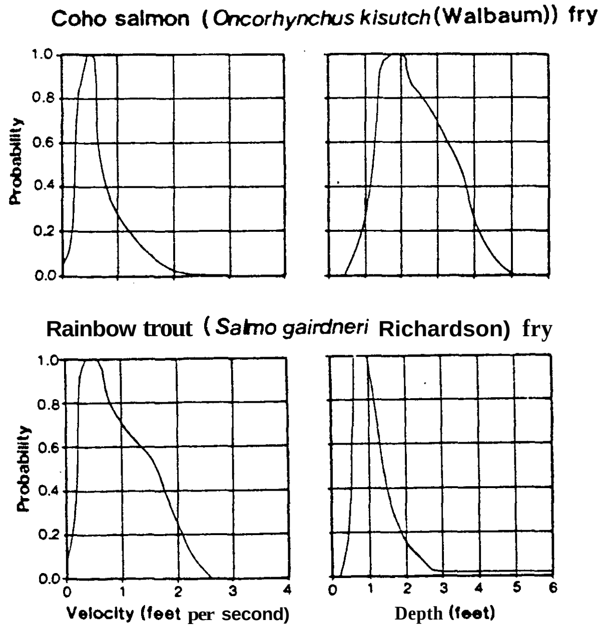


Figure 8--Probability-of-use curves (Bovee 1978).

WATER QUALITY

The principal water-quality parameters of anadromous fish habitat that may be influenced by felling and yarding are temperature, suspended sediment, dissolved oxygen, and nutrients.

TEMPERATURE

Removal of streamside vegetation usually increases summer water temperatures in direct proportion to the amount of increased sunlight on the water surface. Predictive energy-balance techniques, such as those of Brown (1970), may be used to manage water temperatures for optimun stream conditions, but must depend on the other consequences of streamside harvesting operations. Brown's equation requires information about discharge, the surface area of the stream, and the amount of incident solar radiation. Air and ground temperatures exert minor influences on stream .temperature, but influxes of tributary or ground water may raise or lower water temperatures substantially.

Figure 9 suggests that smaller streams have greater increases in water temperature than larger streams, but that they may be shaded by smaller trees or streamside deciduous vegetation. The management of water temperatures of small streams through selective streamside openings may enhance productivity in some locations.

Lowered water temperature during winter may also result from removing plant cover in northern areas, causing reductions in rates of egg development and increased icing. Small or low-gradient streams in northern locations should, therefore, be analyzed for potential decreases as well as increases in water temperature because either result is possible. Only a detailed energy balance will indicate the likely direction and magnitude of changes in water temperature.

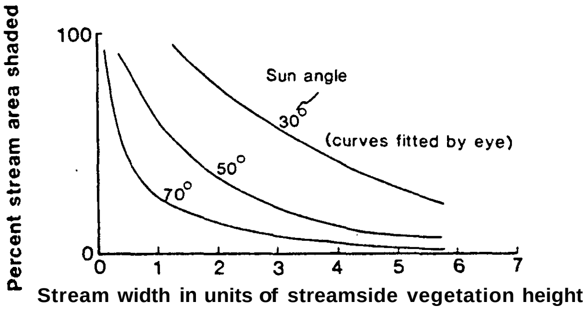
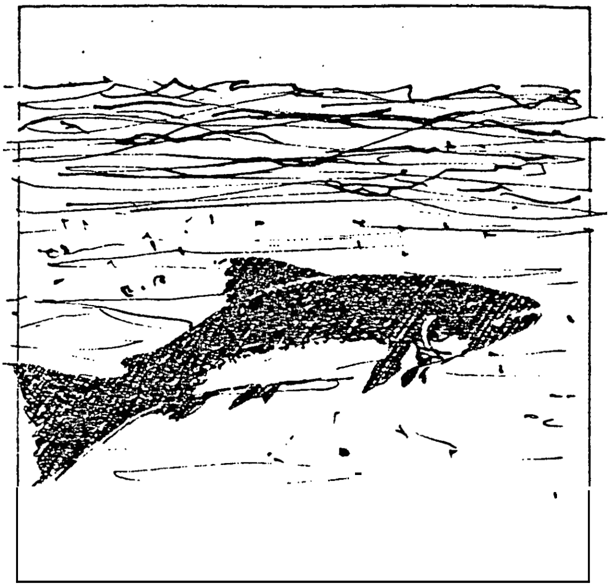


Figure 9--Percentage of stream area shaded as a function of stream width and height of streamside vegetation.



SUSPENDED SEDIMENT

Concentrations of suspended sediment are increased as a result of accelerated surface erosion or slope mass movements. Surface erosion (from exposure of mineral soil) may not be detrimental to aquatic habitat if harvesting methods are suited to slope and soils, but accelerated mass movements may be inevitable when trees are removed from slopes already near their threshold of stability. Usually, the amount of soil loss is more closely related to how and when harvesting is conducted than whether or not trees are cut. Remedial measures are available to correct surface-erosion problems, but the effects of accelerated mass movements may persist for tens or hundreds of years when slope stabilities require mature-forest root systems.

Increases in concentrations of suspended sediment are most injurious to fish habitat when the sediment source persists over a long period. Examples of persistent sediment problems include bank scour from increased volumes of debris, the accelerated development of ice lenses in soils no longer insulated by vegetation, and the headward erosion of new gully systems after landslides.

The majority of severe sediment problems, however, are related to road sy'stems, especially when the roads cross stream channels (Yee and Roelofs 1980). Control of drainage water is mandatory to avoid these problems. When yarding includes extensive ground skidding, careful location of skid trails and buffers of vegetation between skid trails and streambanks are necessary to minimize sediment accrual in stream channels.

Reduction in sedimentation from exposed soil in logged areas is normally accomplished through revegetation. Measures to accelerate revegetation in severely disturbed areas should include planting deciduous trees, shrubs, and grasses: hydroseeding; and mechanically stabilizing gully systems (Heede 1976, Swanston 1976).

CONCENTRATIONS OF DISSOLVED OXYGEN

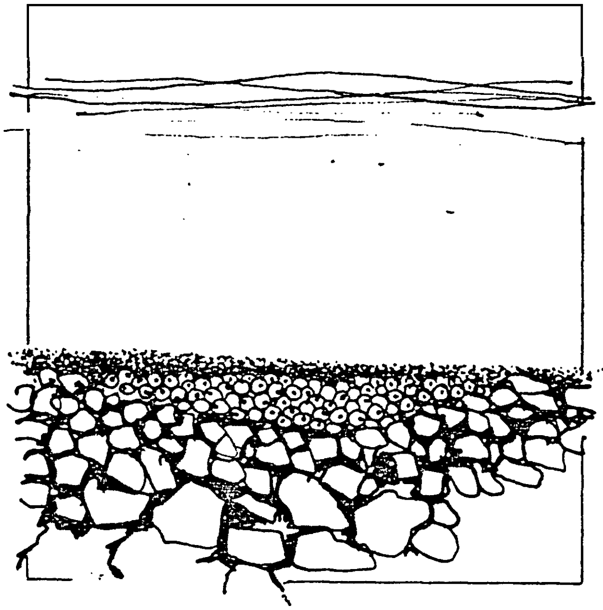
Concentrations of dissolved oxygen may be reduced in intergravel spaces if fine organic debris accumulates on and in streambeds. The effects of high biological oxygen demands may persist for long periods, until bottom material is removed and intergravel water is replaced. Logging and skidding near or across small streams covered by snow are particularly likely to result in fine-debris accumulation because operators may be unaware of stream locations.

Sometimes the complete clogging of surface gravels by fine sediments can also restrict intergravel flow sufficiently to lower dissolved oxygen concentrations, but such large volumes of sediment are more usually associated with road construction, slides, and bank scour than with upslope tree cutting and yarding. Major runoff events may introduce new fine sediments that persist until complete flushing has taken place (that is, until the next major storm).

NUTRIENTS

Nutrient concentrations in streams after logging may be increased, but usually by moderate amounts and for short periods. Both nutrients (Fredriksen 1971) and dissolved organic carbon are taken-up by both soil and stream micro-organisms (Hynes 1975), suggesting that dissolved material released solely by tree cutting is not likely to be a persistent problem in streams. This fairly sweeping generalization must be tempered by a realization that little is known about the microbiological processes of organic matter and nutrient transport from a forest to the stream. In severely degraded basins with extensive erosion and delayed revegetation, longer lasting alterations to water quality may occur.

For example, short-term increases of as much as 5-10 times in nitrate concentrations have been demonstrated in west coast streams after timber cutting and slash burning,[5] but these amounts were not deleterious. The normal relation of higher streamflows to decreased ion concentrations is apparently reversed only in the first few fall runoff events when ions stored on soil or organic matter are flushed out. Streams that are limited in a particular nutrient (for example, phosphate) may, however, experience major increases in algal production in response to minor nutrient increases if temperature and flow conditions permit. Such blooms may be harmful to anadromous fish production by filling interstitial spaces in the gravel.



STREAMBED MATERIAL

The two streambed parameters of most concern to anadromous salmonids are particle-size composition and mobility (amount of scour). Both embryos and fry require accessible intergravel voids and adequate water circulation, and adult salmonids benefit from low-velocity zones between and behind larger cobble's and boulders. Highly mobile bottom substrate does not support food organisms and may cause egg loss during high flows.

The consequences of forest harvesting associated with increased sediment production have been discussed above (surface erosion and mass movement1, and--in combination with factors affecting flow velocities--they provide the basis for analyzing harvesting impacts on .streambeds.

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[5] Personal communication, J. C. Scrivener, Can. Dep. Fish. and Oceans, Nanaimo, B.C., 1981.

Streambeds with water velocities sufficiently high to transport bed material benefit from some cleaning. Unfortunately, predictive models relating sediment loadings and streamwater velocities to resultant streambed particle-size composition do not exist, making flushing-capability models largely a matter of local empirical observations. Clearly, low-gradient streams are more vulnerable to irreversible clogging than high-gradient streams, and any long-term (persistent) increase in sediment source areas causes a decrease in the equilibrium composition of the streambed.

Figure 10 illustrates the velocity required to initiate and suspend various sizes of material in flowing water.

Figure 10 shows that bed material in the fine-sand range is the most susceptible to erosion (scour). Hence, disturbed soils with high contents of silt and fine sand (.06-.8 mm) offer the most potential for degrading streambeds.

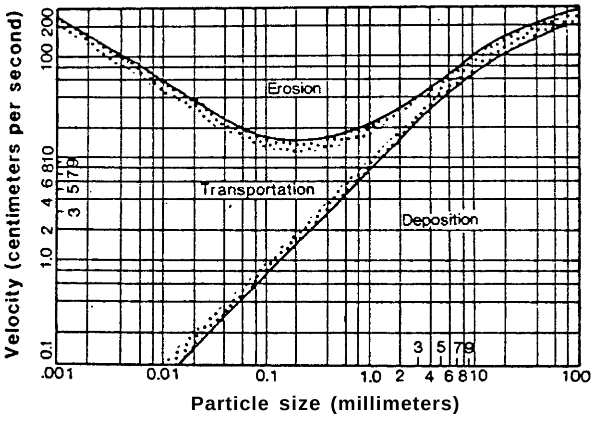

Figure 10--The effect of velocity on particle size in erosion, transportation, and deposition (Ruhe 1975).

Assessments of sedimentation impacts on streambeds, as well as on aquatic organisms, should include both duration and concentration of sediment loading. A measure, such as milligrams per liter-days, has been used to correlate with egg-to-fry survival rates (Slaney et al. 1977). Figure 11 illustrates the type of relation found.

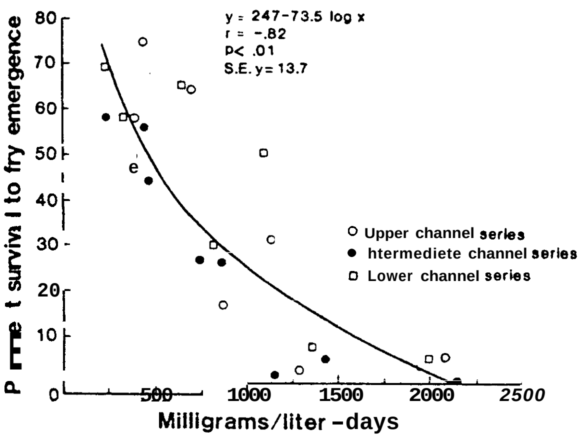

Figure 11--Relation of duration of suspended sediment to survival of rainbow trout from eggs to emergent fry (Slaney et al. 1977).

STREAMBANKS

Of all stream-habitat parameters, streambanks are the most susceptible to direct influence from logging activity. Streambanks (and stream margins) offer lower water velocities than main-stream currents. Undercut banks, overhanging root complexes, vegetation, and stable debris provide shade and protection from predators. Root networks contribute to streambank stability and minimize bank erosion during high flows. The maintenance of streambank structure must be included in the design of felling and yarding operations for any reasonable chance of success.

Harvesting operations that potentially cause damage to banks include felling across streams, yarding through or across streams, machine operation near streams, and the removal of vegetation which has roots that strengthen soil structure. Water-table increases in riparian zones also contribute to the weakening of streambank structure.

Techniques to assess the relative stability of streambanks to water erosion or mechanical disturbance have been developed (Pfankuch 1975), using ranking of slope, vegetation, and bank materials. The ranking classes must be calibrated to local stream conditions, however, and require considerable judgment for application. The most difficult problems of streambank protection are in small hillside streams within proposed timber harvest openings, across which logs must be yarded. Only snow or good deflection (cable systems) will protect such channels.

The protection of streambanks on channels without anadromous salmonid populations may be equally important. The management objective in such streams is to avoid creating new and persistent sediment sources, and to avoid introducing debris that can clog channels and induce catastrophic debris flows (sluice-outs) with their resulting downstream impacts.

Both streambanks and channels may accumulate the effects of forest harvesting over long periods. Unpublished data from the central interior of British Columbia suggest that the cumulative effects of debris-induced channel scour and erosion from collapsing skid-trail cuts have progressively deteriorated the in-channel cover quality of streams that initially showed few impacts. Little documentation exists, however, for analyzing long-term impacts on channel geomorphology.

COVER

The term "cover" refers to all elements of fish microhabitat that provide protection from potential predators, create lower water velocities, and enhance feeding opportunities. Cover requirements vary according to fish species and life stage.

Changes in large substrate (cobbles, boulders) from forest harvesting are unlikely, but incremental filling of intergravel interstices can result from persistent sediment sources. Other cover modifications that are of major concern are caused directly by harvesting, in streamside zones--including bank degradation, debris introduction, and the removal of low, overhanging streamside vegetation.

The overzealous cleanup of logging debris from stream channels can cause major habitat losses. Channels from which imbedded logs or root wads have been removed retain less gravel and have less diversity in pool and riffle morphology (USDI Fish and Wildlife Service 1980). Maintaining in-stream cover and streambed diversity usually requires that stream clearance be done by hand if harvesting operations have introduced excessive organic debris to the channel.

Manipulation of cover during harvesting should be considered in streams with habitat deficiencies. The introduction of appropriate large boulders, creation of accessible side channels, inducement of scour pools, and removal of barriers are all possible if biologists, foresters, and engineers cooperate in the design of logging operations.[6]

In general, forest harvesting reduces cover diversity in streams. This trend seems to be closely related to the reduction in debris size caused by harvesting larger, old-growth trees. Management of stream morphology is necessary to offset smaller stem sizes resulting from second-growth forestry.

RIPARIAN VEGETATION

The role of riparian vegetation in stabilizing banks, providing shade, as a source of organic matter and insects, and as a buffer against sediment and debris transport into streams has been mentioned. Riparian vegetation that overhangs water surfaces (less than 1 m) is particularly valuable as cover.

Riparian vegetation can be protected from the direct impacts of logging by directional felling, high-deflection yarding, maintenance of some deciduous species, and the use of fire; most important, however, is to assure that equipment is not operated near streambanks.

Some plant species, such as alder, have been shown to provide considerably higher food values to the stream ecosystem than conifers. The maintenance of alder near streambanks should be incorporated into the forest-management plan whenever possible. To protect regenerating conifers, alder of seed-bearing age must be suppressed.

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[6] Unpublished manuscript report, "Effects of the proposed Coquihalla highway on the fluvial environment and associated fisheries resource," by M. J. Miles, E. A. Hardin, T. Rollerson, and R. Kellerhals. Ministry of Transportation and Highways, Victoria, B.C., 1979.

MIGRATION BARRIERS

The creation or elimination of migration barriers is more often associated with engineering projects than with timber cutting and yarding. Debris jams and the results of debris torrents are obvious exceptions, but numerous other forms of barriers can also be created. Hillside debris is a common cause of culvert blockage, particularly when it accumulates over high-flow periods. Sediment deposition behind stream debris can also create an obstruction to migrating fish.

Other forms of migration barriers that may be indirectly associated with harvesting include the dewatering of channels in summer (through sediment deposition), increases in flow velocity and the elimination or reduction of resting pools (by debris removal and channel straightening), the creation of toxic or low-oxygen zones when large amounts of fine organic debris are deposited in low-gradient streams, and the creation of heat barriers in large open areas. All of these can be avoided if they are addressed in harvest planning, and natural barriers may be corrected when suitable equipment is available.

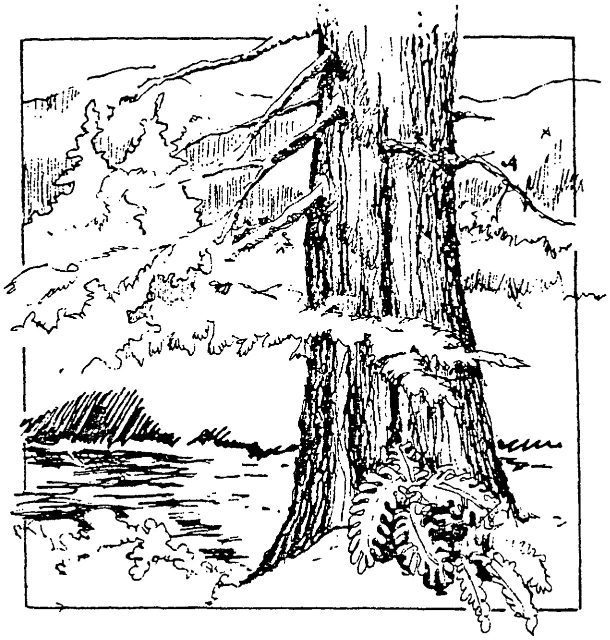
CONCLUSIONS

I have emphasized the diversity of processes and management options that lead to consequences in a stream ecosystem. Generalizations that apply to all interactions between logging and streams suggest that these steps are necessary to avoid deleterious impacts on anadromous fish habitats:

- The tolerance and habitat factors limiting production for the species present in a system must be determined (Reiser and Bjornn 1979).
- The natural variability in streamflow, temperature, sediment regime, debris, and riparian vegetation must be evaluated (Swanston 1979).
- The stability and probable hydrologic response of a watershed to alternative harvesting systems must be assessed (Harr 1980a).
- Harvesting methods and timing should be designed to minimize deleterious effects and to enhance stream habitat, if possible (Narver 1972, Bustard 1973, Moore 1978, Toews and Brownlee 1981).
- All activities that could cause mechanical disruptions of streambanks or the removal of riparian vegetation should be avoided.

Three generalizations on effects of forest harvesting are:

- Water-quantity problems (or benefits) are directly related to how much is harvested in a basin.
- Problems with water quality (especially sediment production) may arise from small but critically sensitive zones in the watershed as a consequence of how harvesting is conducted.
- Direct influences to stream habitat are usually a consequence of harvesting in the streamside zone and can be minimized by buffer strips or by careful logging design and execution.



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