Chapter 14

Responses of Salmonids to Habitat Changes

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Streams in western North America provide spawning and rearing habitats for several species of salmon and trout that are of substantial economic importance in the region. Timber that grows on lands through which these streams flow is also economically important, and its harvest can substantially change habitat conditions and aquatic production in salmonid streams. Undisturbed forests, the streams that flow through them, and the salmonid communities in these streams have intrinsic scientific, genetic, and cultural values in addition to their economic importance. The complex relations between salmonids and their physical environment, and the changes in these relations brought about by timber harvest, have been investigated extensively (see the bibliography by Macdonald et al. 1988). However, in spite of considerable evidence of profound changes in channel morphology and in light, temperature, and flow regimes associated with timber harvests, much uncertainty exists about the responses of salmonids to these changes.

Responses of salmonid populations to changes in their freshwater environment brought about by forest-management activities are similar in many respects to those caused by other land-management activities such as mining (Nelson et al. 1991, this volume) and livestock grazing (Plates 1991, this volume). For example, fine sediment potentially has the same biological effect in streams whether it results from mining effluent, streambank erosion in grazed pasture lands, or road construction and clear-cut logging (Lloyd et al. 1987). The severity of its effect, however, depends on particle size and concentration, which in turn are related to sediment source. Changes in stream productivity caused by increased nutrient loading can similarly result from mining, livestock grazing, or forest management. Removal of riparian vegetation by any management activity changes the light and temperature regimes of a stream, leading to changes in primary and secondary production, in emergence times of salmonid fry, and in summer and winter survival of juvenile salmonids. There are also similarities between effects of natural catastrophic events, such as volcanic eruptions, and those of timber harvest (Sedell and Dahm 1984; Martin et al. 1986; Bisson et al. 1988). Despite substantial research by federal, state, and provincial agencies, universities, and the timber industry (Salo and Cundy 1987), effects of forest practices on salmonids are still not well known. Less information is available on effects of livestock grazing and mining on salmonids (Rinne 1988; Nelson et al. 1991). We

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have thus chosen to focus our evaluation on the effects of timber harvest. Many of our conclusions, however, should be applicable to habitat changes caused by any management activity.

We consider the effects of logging on salmonids and their freshwater habitats in several ways. We first describe the effects of logging and other aspects of forest management on isolated parts of salmonid life cycles. Then we discuss integrated effects of forest practices on stream-dwelling salmonid populations. We also attempt to elucidate patterns of regional variation in the response of fish populations and to evaluate management practices that best protect fish habitat.

Responses to Specific Components of Habitat Change

In this section we examine the evidence that specific types of environmental change associated with logging practices have influenced short-term survival and growth of salmon and trout. Categories of environmental change commonly attributed to timber harvest activities, and their generalized consequences for salmonids, are shown in Table 14.1. The data supporting the generalizations in Table 14.1 were drawn from a variety of studies; some studies were process-specific and some examined the integrated effects of logging within a drainage. Furthermore, some of the studies were short-term comparisons of logged and unlogged basins whereas others were longer-term comparisons of a particular basin before and after logging. Duration of postlogging assessments has varied from 1 year to over a decade. For some types of habitat change, short-term studies have been sufficient to determine the responses of salmonid populations. For other types of change (e.g., the rate of recruitment of large woody debris), short-term studies have been inadequate to evaluate population response, and multisite comparisons of specific habitat change have been weakened by confounding factors. We considered these limitations as we reviewed each of the possible types of habitat change associated with timber harvest.

TABLE 14.1.—Influences of timber harvest on physical characteristics of stream environments, potential changes in habitat quality, and resultant consequences for salmonid growth and survival.

Forest practice	Potential change in physical stream environment	Potential change in quality of salmonid habitat	Potential consequences for salmonid growth and survival
Timber harvest from streamside areas	Increased incident solar radiation	Increased stream temperature; higher light levels; increased autotrophic production	Reduced growth efficiency; increased susceptibility to disease; increased food production; changes in growth rate and age at smolting
	Decreased supply of large woody debris	Reduced cover; loss of pool habitat; reduced protection from peak flows; reduced storage of gravel and organic matter; loss of hydraulic complexity	Increased vulnerability to predation; lower winter survival; reduced carrying capacity; less spawning gravel; reduced food production; loss of species diversity

TABLE 14.1.—Continued.

Forest practice	Potential change in physical stream environment	Potential change in quality of salmonid habitat	Potential consequences for salmonid growth and survival
	Addition of logging slash (needles, bark, branches)	Short-term increase in dissolved oxygen demand; increased amount of fine particulate organic matter; increased cover	Reduced spawning success; short-term increase in food production; increased survival of juveniles
	Erosion of streambanks	Loss of cover along edge of channel; increased stream width, reduced depth	Increased vulnerability to predation; increased carrying capacity for age-0 fish, but reduced carrying capacity for age-1 and older fish
		Increased fine sediment in spawning gravels and food production areas	Reduced spawning success; reduced food supply
Timber harvest from hillslopes; forest roads	Altered streamflow regime	Short-term increase in streamflows during summer	Short-term increase in survival
		Increased severity of some peak flow events	Embryo mortality caused by bed-load movement
	Accelerated surface erosion and mass wasting	Increased fine sediment in stream gravels	Reduced spawning success; reduced food abundance; loss of winter hiding space
		Increased supply of coarse sediment	Increased or decreased rearing capacity
		Increased frequency of debris torrents; loss of instream cover in the torrent track; improved cover in some debris jams	Blockage to migrations; reduced survival in the torrent track; improved winter habitat in some torrent deposits
	Increased nutrient runoff	Elevated nutrient levels in streams	Increased food production
	Increased number of road crossings	Physical obstructions in stream channel; input of fine sediment from road surfaces	Restriction of upstream movement; reduced feeding efficiency
Scarification and slash burning (preparation of soil for reforestation)	Increased nutrient runoff	Short-term elevation of nutrient levels in streams	Temporary increase in food production
	Inputs of fine inorganic and organic matter	Increased fine sediment in spawning gravels and food production areas; short-term increase in dissolved oxygen demand	Reduced spawning success

Changes in Stream Temperature and Light Regime

Changes in stream temperature and light regime after logging can have both positive and negative consequences for salmonid production. As a result, the effects of changes in temperature and light on salmonids are difficult to predict. Removal of streamside vegetation allows more solar radiation to reach the stream surface, increasing water temperature and light available for photosynthesis (Brown and Krygier 1970). In small streams (first to third order), increased daily temperature fluctuations also result from opening the vegetative canopy (Meehan 1970; Beschta et al. 1987; Bisson et al. 1988). The interpretation of much of the early research on temperature changes induced by logging was that these alterations were predominantly harmful to salmonids (Lantz 1971). Recent evidence has suggested that, under certain conditions, temperature and light increases can be beneficial.

Beschta et al. (1987) summarized studies of stream temperature changes associated with canopy removal over small streams in Pacific coastal drainages. They found a latitudinal gradient in increase of daily maximum temperature in summer that ranged from only a few degrees Celsius in Alaska to more than 10°C in Oregon. In the first 5 years following the 1980 eruption of Mount St. Helens, Washington, which virtually devegetated the watersheds of many Toutle River tributaries, Martin et al. (1986) and Bisson et al. (1988) measured peak midsummer stream temperatures of 29.5°C and diel variations as great as 17.0°C.

Although large changes in thermal and light regimes after timber harvest have been observed during summer, winter temperatures do not appear to be strongly affected by canopy removal, although even minor changes can have important consequences for streams when water temperatures are low. In general, forest canopy removal results in increased winter temperatures in low-elevation coastal drainages (Beschta et al. 1987). In northern latitudes and at higher elevations, a reduction in winter stream temperatures may occur due to loss of insulation from the surrounding forest coupled with increased radiative cooling of the stream. Where winter temperatures are lowered, ice forms more rapidly and the possibility of winter freeze-up increases. Such conditions may reduce habitat quality if anchor ice formation is extensive or if ice jams occur and then release ice flows to scour the streambed (Needham and Jones 1959). In contrast, slight postlogging increases in late-winter water temperature were found in Carnation Creek, a coastal stream on Vancouver Island, British Columbia (Hartman et al. 1987; Holtby 1988b). These temperature increases led to accelerated development of coho salmon embryos in the gravel and earlier emergence of juveniles in the spring. Earlier emergence resulted in a prolonged growing season for the young salmon, but increased the risk of their downstream displacement during late-winter freshets. Many changes in salmonid growth and survival resulted from the stream temperature increases in this watershed (Figure 14.1).

Among the potential benefits of elevated light and temperature during summer are increased primary and secondary production, which may lead to greater availability of food for fish. Solar radiation is an important factor limiting algal growth in forested streams (Hansmann and Phinney 1973; Stockner and Shortreed 1978; Gregory 1980; Gregory et al. 1987). Shifts in periphyton composition in response to elevated temperatures have been observed in laboratory streams (Phinney and McIntire 1965; Bisson and Davis 1976). Typically, well-lit warm streams are dominated by filamentous green algae instead of the epilithic diatoms that predominate in heavily shaded streams. After logging, increases in filamentous green algae promote the abundance of grazer invertebrates as the stream shifts from allochthonous to autochthonous carbon sources. Streams in clear-cut drainages often produce more baetid mayflies, grazing caddisflies, and orthocladid midges than do streams in forested watersheds (Hawkins et al. 1982). These groups are often more likely to enter the drift and thus become potential food items for salmonids (Gregory et al. 1987). Wilzbach et al. (1986) found that cutthroat trout captured drifting prey more efficiently in open areas than in

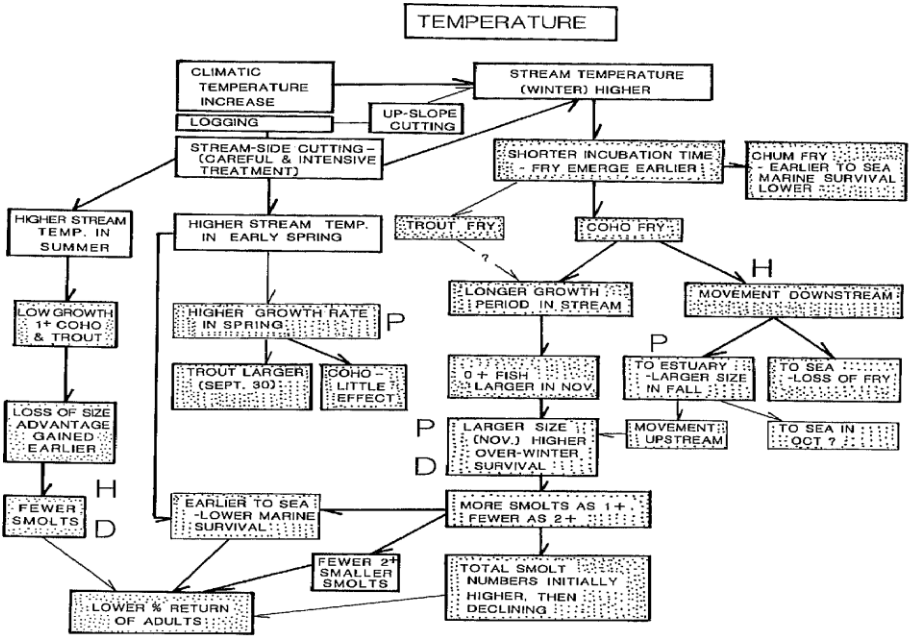

FIGURE 14.1.—Effects of logging on temperature-dependent processes at Carnation Creek, British Columbia, and the effects of temperature changes on fish populations. (From Hartman 1988.) The letter D, Fl, or P indicates the existence of an interaction with woody debris, stream hydrology, or production-related processes. Firmly established conclusions and cause-and-effect relations are indicated by heavy lines. Effects on fish are indicated by stippling.

adjacent old-growth forest, where light intensities were reduced by canopy shading. In some streams, increased food availability can mitigate those detrimental habitat changes associated with removal of riparian vegetation, including high summer temperatures (Bisson et al. 1988). The importance of autochthonous production to salmonid populations in clear-cut watersheds of the western USA has been suggested by several studies (Murphy and Hall 1981; Hawkins et al. 1983; Bisson and Sedell 1984; Bilby and Sisson 1987). In a whole-river enrichment study on Vancouver Island, British Columbia, stimulation of algal growth by inorganic nutrient addition resulted in greater benefits to salmonids than did stimulation of heterotrophic production through addition of cereal grains (Slaney et al. 1986; Perrin et al. 1987). Bilby and Bisson (1989) also found that summer production of juvenile coho salmon was more directly related to the amount of organic matter produced by autochthonous sources (algal photosynthesis) than to organic matter produced by allochthonous carbon sources (terrestrial litter inputs and fluvial transport), regardless of whether the stream flowed through a clear-cut or an old-growth forest. Potentially negative effects on salmonids of logging-related changes in summer temperature were reviewed by Beschta et al. (1987). These include temperature elevation beyond the range preferred for rearing, inhibition of upstream migration of adults, increased susceptibility to disease, reduced metabolic efficiency with which salmonids convert food intake to growth, and shifts of the competitive advantage of salmonid over nonsalmonid species. Of these five categories of effects, the last is least understood. Reeves et al. (1987) found that stream temperature influenced the outcome of competitive interactions between redside shiners and juvenile steelhead. The shiners were more active and competitively dominant at warm temperatures whereas steelhead were dominant at cool temperatures. The authors hypothesized that a long-term increase in stream temperature could allow redside shiners to displace steelhead from reaches where steelhead formerly enjoyed a competitive advantage. From the perspective of basin-wide temperature, the most important role of tributaries may be to provide cool water downstream. Positive effects of canopy removal in tributaries may be more than offset by reduced cooling influence in main-stem habitats.

Decreased Supply of Large Woody Debris

Among the most important long-term effects of forest management on fish habitat in western North America have been changes in the distribution and abundance of large woody debris in streams. These changes have extended from small headwater streams to the estuaries of major rivers (Sedell and Luchessa 1982; Maser et al. 1988). Overall trends have included reduction in the frequency of pieces of large, stable debris in streams of all sizes; concentration of debris in large but infrequent accumulations; and loss of important sources of new woody material for stream channels (Bisson et al. 1987). As noted elsewhere in this volume (see Reeves et al. and Sedell et al.), these trends have been accelerated by stream channelization and by debris removal for navigation (Sedell and Luchessa 1982), for upstream fish migration (Narver 1971), and for reduction of property damage during floods (Rothacher and Glazebrook 1968). Large woody debris plays an important role in controlling stream channel morphology (Keller and Swanson 1979; Lisle 1986b; Sullivan et al. 1987), in

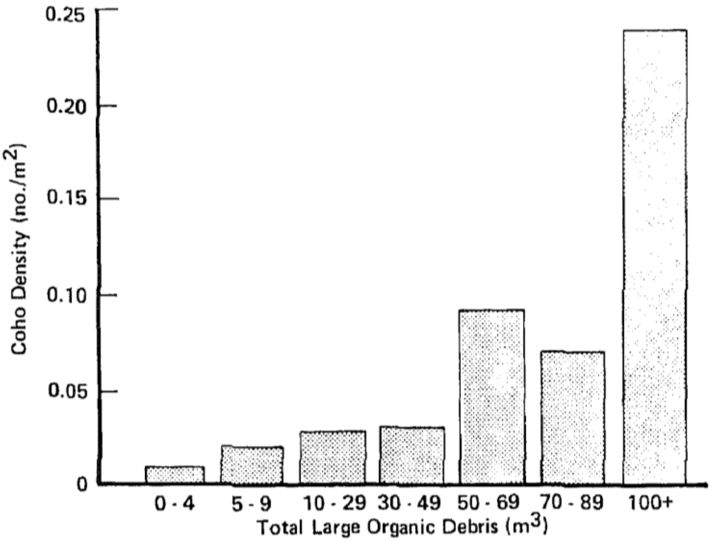

FIGURE 14.2,—Relationship between abundance of woody debris and density of juvenile coho salmon during winter in southeastern Alaska. (From Murphy et al. 1984a.)

regulating the storage and routing of sediment and particulate organic matter (Swanson et al. 1976; Swanson and Lienkaemper 1978; Naiman and Sedell 1979; Bilby 1981; Megahan 1982; Bilby and Ward 1989), and in creating and maintaining fish habitat (Bryant 1983; Lisle 1986a; Murphy et al. 1986; Bisson et al. 1987). The abundance of salmonids is often closely linked to the abundance of woody debris (Figure 14.2), particularly during winter (Bustard and Narver 19756; Tschaplinski and Hartman 1983; Murphy et al. 1986; Hartman and Brown 1987). Large woody debris creates a diversity of hydraulic gradients that increases microhabitat complexity (Forward 1984), which in turn supports the coexistence of multispecies salmonid communities (Figure 14.3). Prior to the development of extensive road networks, large streams and rivers were used to float logs downstream to mills. Widespread reaches of rivers were cleared of snags to permit navigation and to prevent logs from accumulating in large jams during transport (Sedell and Luchessa 1982; Sedell et al. 1991, this volume). Channel clearance accompanied timber harvest in the lower portions of river basins. As logging progressed upstream and the streams became too small to transport logs effectively, splash dams were built to store logs and water until sufficient head had accumulated to *allow* the logs to be sluiced *downstream to a* larger river. Splash dams were numerous in coastal watersheds (Wendler and Deschamps 1955; Sedell and Luchessa 1982). The long-term effect of channel clearance and splash damming was to remove vast quantities of woody debris from medium- and large-sized streams, a condition from which many rivers have apparently not recovered after 50 to 100 years (Sedell et al. 1991). Little is known *about the effects of snag removal* and splash *damming on saimonid populations,* partly because these practices are not frequently used today. It is likely, however,

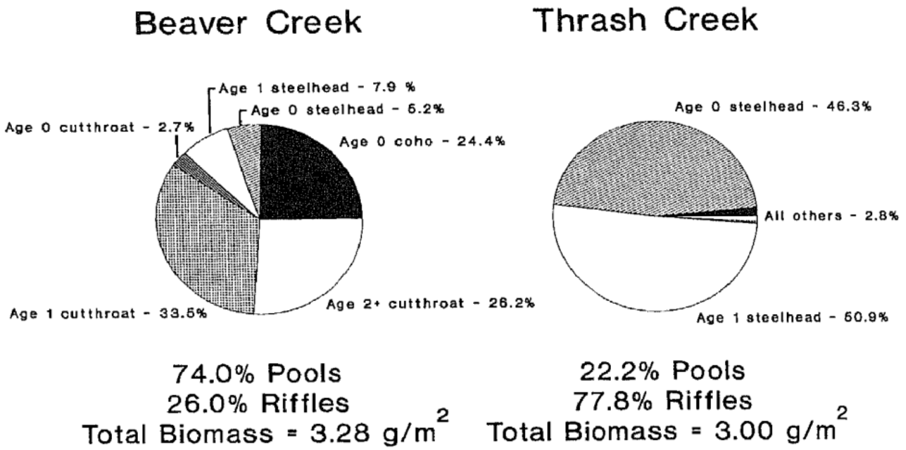

FIGURE 14.3.—Comparison of salmonid communities in two Washington streams with similar fish biomasses: Beaver Creek, a debris-rich stream in the Nisqually River system, and Thrash Creek, a debris-poor stream in the Chehalis River system. (P. A. Bisson, Weyerhaeuser Corporation, unpublished; reproduced in part from Sullivan et al. 1987.)

that species making extensive use of larger stream channels (e.g., chinook and chum salmon) were greatly affected. Beginning in the early 1970s, forest practice rules in some western states required removal of slash (limbs and tops) from streams immediately after timber harvest. In many cases, stream cleaning also removed large pieces of merchantable prelogging debris from the channel. Recent case studies have assessed the immediate effects of debris removal on salmonid populations. Almost without exception, removal of large woody debris has resulted in loss of important habitat features and a decline in salmonid population abundance (Bryant 1980; Toews and Moore 1982a; Lestelle and Cederholm 1984; Dolloff 1986; Elliott 1986). Debris removal caused a decline in channel stability and a corresponding reduction in the quality and quantity of pools and cover. Bisson and Sedell (1984) observed enlarged riffles and a reduction in the number of pools in cleaned stream channels in Washington. The increased frequency of riffles favored underyearling steelhead and cutthroat trout, which preferred riffle habitat, but caused a decrease in the relative proportions of coho salmon and older age classes of steelhead and cutthroat trout, which preferred pools. Removal of nearly all large trees from riparian zones during logging has also caused a long-term reduction in the recruitment of new large woody debris to stream channels, leading to a reduction in the quality of fish habitat. There may be a short-term increase in the debris load caused by entry of slash during harvesting and yarding, but this small unstable debris is often floated downstream within a few years, to be trapped in a few widely spaced debris jams (Bryant 1980). If the debris load of a channel is not replenished by large-scale inputs such as extensive blowdowns or debris avalanches, the second-growth riparian zone becomes the principal source of new woody debris. In young forest stands, inputs of debris large enough to be stable in streams with channel widths greater than about 15 m remain low for at least the first 60 years of riparian forest regrowth (Grette 1985; Long 1987). Many streams in second-growth forests have become progressively debris-impoverished following logging to the edge of the channel. Young riparian stands do not produce sufficient debris of the proper size and quality to replace material lost when channels are cleaned and large preharvest debris gradually decays (Sedell et al. 1984; Andrus et al. 1988). The effect on fish habitat has been a decrease in channel complexity, in number and volume of pools, in quality of cover, and in capacity of streams to store and process organic matter.

Some debris jams formed after logging or after a logging-related debris flow have blocked upstream fish migration. The improper design, construction, or maintenance of culverts on forest roads can also prevent or hinder upstream movements (Toews and Brownlee 1981; Furniss et al. 1991, this volume). To date, the relative importance of natural barriers, logging-related debris jams, and impassable culverts in limiting upstream movements of salmonids has not been assessed in any basin-wide survey. With the exception of dams on large rivers, we have little information on the extent to which fish-passage problems occurring in an entire drainage system have limited salmonid production.

Reduced Dissolved Oxygen Concentration

The introduction of fine logging slash, leaves, and needles into streams as a result of timber harvest can increase biochemical oxygen demand at critical times of low flows and high temperatures. In one small coastal Oregon drainage that was logged to the stream edge, dissolved oxygen concentrations of surface water decreased following timber harvest to below levels acceptable for salmonid survival and growth (Hall and Lantz 1969; Moring 1975a). Accumulation of fine organic matter from logging debris, in combination with increased stream temperature, was responsible for the decrease in dissolved oxygen. However, apart from short-lived effects in small streams in areas that naturally experience high summer insulation, there is no evidence of a major effect of logging on salmonids from low dissolved oxygen concentrations in surface water. Of more importance than the usually transient decreases in dissolved oxygen in surface water are postlogging reductions in intragravel oxygen levels. These reductions may be caused by increased oxygen demand from fine organic matter introduced into the gravel matrix or by reduced interchange of surface and intragravel water. Several field studies have demonstrated reductions in oxygen concentration in redds following logging (e.g., Ringler and Hall 1975). However, increased intragravel sediment, decreased permeability, and decreased velocity of intragravel water often coincide with reduced levels of dissolved oxygen. Hence, the importance of reduced oxygen levels as a primary cause of mortality of embryos and alevins in gravel is difficult to assess. It is rare for oxygen deprivation to directly kill many embryos and alevins in stream gravels after logging, but emergent juveniles that have incubated in oxygen-poor gravels may have reduced viability, and this may be an important factor in the regulation of salmonid populations. In an extensive review of the effects of intragravel oxygen on salmonid embryos and alevins, Chapman (1988) concluded that any reduction in dissolved oxygen below saturation may cause salmonids to be smaller than normal at emergence. Smaller juveniles are at a competitive disadvantage and likely have reduced fitness within the population (Mason 1969).

Altered Streamflow

The pattern of a stream's discharge affects the water depths and velocities that stream-dwelling salmonids will encounter the amount of habitat available at different times of the year, and, to some extent, stream temperatures. Changes in streamflow caused by timber harvest are discussed in detail by Chamberlin et al. (1991, this volume). The effect of timber harvest on streamflow varies with logging method, soil permeability, season, and climate. Vegetation influences streamflow by intercepting precipitation and transpiring water (Bosch and Hewlett 1982). Removal of timber reduces transpiration and interception, and summer low flows and early fall peak flows usually increase as a result (Harr et al. 1975; Harr 1983). Of particular concern in western North America are increased peak flows that result from rainfall on snow following clear-cut logging in the transient snow zone (Harr 1986). Streamflow does not always increase following logging. The presence of a well-developed coniferous forest can result in greater streamflows than occur after timber harvest. In coastal watersheds or at high elevations, fog drip can augment streamflow. This effect, caused by interception of wind-blown fog by tall trees, is most influential in summer (Harr 1982). In addition, increases in streamflow that result from timber harvest are generally short-lived within a timber harvest rotation; streamflow returns toward preharvest conditions as vegetation regrows (Harr 1983). Summer flows 10 years or more after logging may actually be lower than preharvest summer flows (Hicks et al., in press). The effects on salmonids of changes in streamflow have not been documented separately from other effects of logging. To what extent the ameliorating effect of short-term increases in summer flows may be counterbalanced by increased severity of floods in other seasons is not known. In large basins, timber harvest activities are usually dispersed in space and over time. The result is that logging in large basins causes proportionately smaller changes in streamflow than it does in small basins (Duncan 1986).

Increased Fine Sediment

Fine sediment can enter streams during and after timber harvest as a result of road construction, timber harvest, and yarding activities (Everest et al. 1987a). Mass soil movements following road construction and timber harvest produce fine sediment, but the amount of fine sediment washing from the unpaved surfaces of actively used logging roads can equal that produced by landslides (Reid and Dunne 1984). Fine sediment that settles in streams or moves in suspension can reduce salmonid viability. Determination of the effects that deposited fine sediments have on salmonids is complicated by the variability in responses among salmonid species and by the adaptability of salmonids to ambient sediment levels (Everest et al. 1987a). Fine sediment deposited in spawning gravel can reduce interstitial water flow, leading to depressed dissolved oxygen concentrations, and can physically trap emerging fry in the gravel (Koski 1966; Meehan and Swanston 1977; Everest et al. 1987a). Survival of coho salmon in natural and simulated redds is related to the proportion of fine particles in the gravel (Figure 14.4).

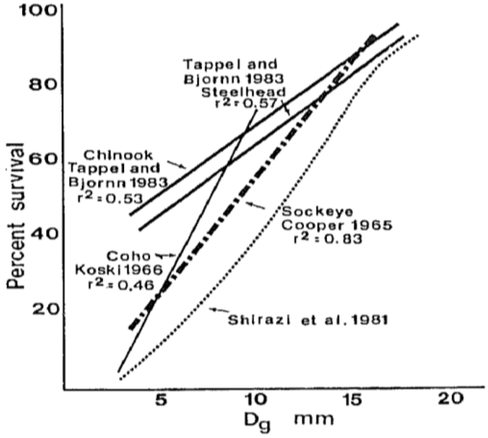

FIGURE 14.4.—Survival to emergence in relation to geometric mean particle size (D_g) for natural coho salmon redds (Koski 1966), and for other salmonids in laboratory gravels (Cooper 1965; Tappel and Bjornn 1983). The composite model of Shirazi et al. (1981) is plotted in the same D_g range (3-17 mm). (Entire figure from Chapman 1988.)

Salmonid survival apparently was affected when timber harvest increased the amount of fine sediment in spawning gravels of some Alaska streams (Smedley 1968; Smedley et al. 1970); in some cases, however, the amount of sediment in gravels returned to prelogging conditions within 5 years (McNeil and Ahnell 1964; Sheridan and McNeil 1968; Sheridan et al. 1984). Studies in coastal drainages of the Olympic Peninsula, Washington, have addressed the effects on spawning success of sediment from landslides and logging road surfaces (Cederholm and Salo 1979; Cederholm et al. 1981; Cederholm et al. 1982; Cederholm and Reid 1987). The concentration of intragravel fine sediment in spawning riffles was positively correlated with mass soil movements and the extent of roading within watersheds. The effects of sedimentation on salmonid spawning success were estimated by monitoring the survival of embryos and alevins in natural redds (Tagart 1976) and in experimental redds containing a mixture of gravel meant to simulate conditions in Clearwater River tributaries. Based on these studies, Cederholm et al. (1981) believed that accelerated erosion caused by landslides and logging roads led to a significant reduction in emergence of coho salmon fry. Coupled with high rates of ocean harvest and resultant low spawner densities, the reduced survival to emergence was thought to have resulted in lower smolt yields from the Clearwater River basin. Studies in British Columbia (Scrivener and Brownlee 1989), Oregon (Hall et al. 1987), and Idaho (Stowell et al. 1983) have also shown declines in survival to emergence or in salmonid abundance associated with sediment increases after logging. Some studies showed temporary increases in sedimentation related to logging, although subsequent effects on salmonids have been difficult to document. Female salmon clean gravel as they construct redds, which may be one reason that effects of fine sediment in gravel are often less than predicted (Everest et al. 1987a). Chapman (1988) reviewed the laboratory evidence for the effect of fine sediment on salmonid reproduction. He found that laboratory studies had generally failed to reproduce conditions in the egg pocket of the redd and therefore did not yield accurate predictions of survival in natural streams. He concluded, however, that increases of fine sediment did reduce survival to emergence.

In addition to directly affecting salmonid survival, fine sediment in deposits or in suspension can reduce primary production and invertebrate abundance and thus can affect the availability of food within a stream (Cordone and Kelley 1961; Lloyd et al. 1987). In northern California, diversity of invertebrates was lower in streams passing through clear-cut areas with no buffers or only narrow buffers than it was in streams in unlogged watersheds. However, the densities of invertebrates were higher in the clear-cut areas or not significantly different from those in unlogged watersheds (Newbold et al. 1980; Erman and Mahoney 1983). The effect on fish production of this change in invertebrate community structure was not investigated. The detrimental effects of large amounts of fine sediment are generally accepted, but precise thresholds of fine sediment concentrations that result in damage to benthic invertebrates are difficult to establish (Chapman and McLeod 1987). Increases in suspended sediment can affect salmonids in several ways. Suspended sediment can alter behavior and feeding efficiency. Fish may avoid high concentrations of suspended sediment (Bisson and Bilby 1982; Sigler et al. 1984); at lower concentrations, fish may cease feeding (Noggle 1978; Sigler et al. 1984) and their social behavior may be disrupted (Berg and Northcote 1985). In nearly all cases, suspended sediment concentrations resulting from timber harvest are not sufficient to cause significant abrasion of the skin or gills of salmonids (Everest et al. 1987a; Bjornn and Reiser 1991, this volume), although temporary spikes of suspended sediment from landslides may approach lethal thresholds.

increased Coarse Sediment

Channel morphology changes when timber harvesting increases the rate at which coarse sediment is delivered to streams. Increased frequencies of landslides and other mass wasting events can cause channels to aggrade where the gradient and other aspects of valley topography permit gravel deposition. Stream reaches that are aggraded with coarse sediments typically become wider, shallower, and more prone to lateral movement and bank erosion (Sullivan et al. 1987). More water passes through deposited gravels, reducing surface flow. Total riffle area increases but pool area decreases, and other types of habitat may be lost (Everest et al. 1987a). Habitat alteration caused by debris torrents has been well documented in the Queen Charlotte Islands, British Columbia. In stream sections affected by debris torrents, average pool depth was reduced by 20-24%, and pool area was reduced by 38-45%. Cover associated with large woody debris was reduced by 57%, and undercut bank cover was reduced by 76%. Riffle area increased by 47-57%, and stream channel width increased by 48-77% (Tripp and Poulin 1986b). The amount of landsliding was directly related to the proportion of the basin area logged (Tripp and Poulin 1986b). The effect of logging was to increase landsliding frequency by 34 times in this geologically unstable terrain (Rood 1984). The frequency of debris torrents increased by about 40 times in logged areas compared to unlogged areas, and increased by 76 times in roaded areas compared to unlogged areas without roads (Rood 1984). A combination of logging and landsliding reduced the salmonid cover attributable to large woody debris by 58%. Reaches with landsliding had reduced width:depth ratios and less surface flow (Tripp and Poulin 1986b). In erosion-prone areas of the Oregon Coast Range, logging roads caused rates of debris avalanche erosion that were 26-350 times greater than in adjacent forested areas. Rates were 2.2-22 times greater in clear-cut areas than in unharvested forest. When these rates were adjusted for the smaller area that was occupied by roads compared to that in clear-cuts, forest roads accounted for 77% of the total accelerated debris avalanche erosion (Swanson et al. 1981). In one stream in this area with little cover from boulders or large woody debris, debris torrents added new structure to the channel, temporarily enhancing the abundance of coho salmon (Everest and Meehan 1981a).

Altered Nutrient Supply

Stream concentrations of plant nutrients and other dissolved ions increase for a few years following logging (Brown et al. 1973; Scrivener 1982, 1988b). When accompanied by increased light, these nutrient additions often result in increased algal growth (Gregory et al. 1987). However, the effects of nutrient increases on invertebrate and salmonid populations have not been thoroughly studied. Bisson et al. (1976) studied the effects of adding nitrate-nitrogen to model stream channels in southwestern Washington. They observed a temporary increase in the biomass of benthic invertebrates and in the production of stocked rainbow trout. After 2 years of continuous nutrient additions, however, no significant differences were found in either invertebrate biomass or trout production between enriched and unenriched streams. Slaney et al. (1986) added both nitrogen and phosphorus to the Keogh River on the east coast of Vancouver Island, British Columbia, after which steelhead grew faster and smolted when younger but larger. Steelhead smolt output also increased to as much as twice the preenrichment level (P. A. Slaney, Fisheries Branch, British Columbia Ministry of the Environment, personal communication), but it is not yet clear if the size of the returning adult run has increased. Studies indicate that nutrient increases (mostly nitrate) are limited to the first decade after logging; that primary production is stimulated in the presence of increased light and nutrient concentrations; that watersheds dominated by volcanic rock are more likely to show enhanced autotrophic production after logging than watersheds dominated by sedimentary or metamorphic rock; that herbivorous invertebrates will most likely benefit from increased algal growth; and that salmonid production may or may not be enhanced during periods of increased nutrient concentration (Gregory et al. 1987).

Responses of Salmonid Populations to Forest Management

Thus far we have reviewed evidence that the growth or survival of salmonids at various life stages changes in response to changes in individual components of the habitat. It is also important to know the combined effect on salmonid populations of all the changes that occur in the course of normal forest management. In this section, we review results of several long- and short-term studies designed to measure response of salmonid populations to timber harvest. We have included

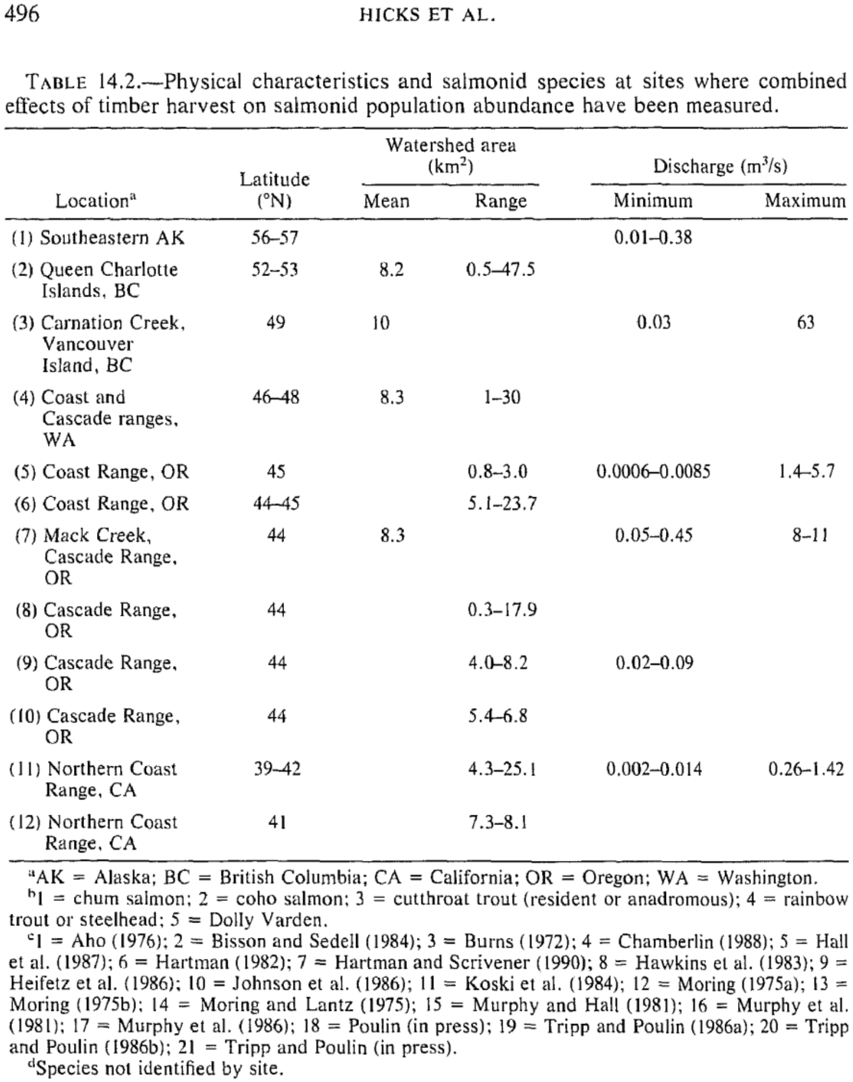

TABLE 14.2.—Physical characteristics and salmonid species at sites where combined effects of timber harvest on salmonid population abundance have been measured.

Location[a]	Latitude (°N)	Watershed area (km^2)		Discharge (m^3/s)	
		Mean	Range	Minimum	Maximum
(1) Southeastern AK	56–57			0.01–0.38	
(2) Queen Charlotte Islands, BC	52–53	8.2	0.5–47.5		
(3) Carnation Creek, Vancouver Island, BC	49	10		0.03	63
(4) Coast and Cascade ranges, WA	46–48	8.3	1–30		
(5) Coast Range, OR	45		0.8–3.0	0.0006–0.0085	1.4–5.7
(6) Coast Range, OR	44–45		5.1–23.7		
(7) Mack Creek, Cascade Range, OR	44	8.3		0.05–0.45	8–11
(8) Cascade Range, OR	44		0.3–17.9		
(9) Cascade Range, OR	44		4.0–8.2	0.02–0.09	
(10) Cascade Range, OR	44		5.4–6.8		
(11) Northern Coast Range, CA	39–42		4.3–25.1	0.002–0.014	0.26–1.42
(12) Northern Coast Range, CA	41		7.3–8.1		

[a] AK = Alaska; BC = British Columbia; CA = California; OR = Oregon; WA = Washington.

[b] 1 = chum salmon; 2 = coho salmon; 3 = cutthroat trout (resident or anadromous); 4 = rainbow trout or steelhead; 5 = Dolly Varden.

[c] 1 = Aho (1976); 2 = Bisson and Sedell (1984); 3 = Burns (1972); 4 = Chamberlin (1988); 5 = Hall et al. (1987); 6 = Hartman (1982); 7 = Hartman and Scrivener (1990); 8 = Hawkins et al. (1983); 9 = Heifetz et al. (1986); 10 = Johnson et al. (1986); 11 = Koski et al. (1984); 12 = Moring (1975a); 13 = Moring (1975b); 14 = Moring and Lantz (1975); 15 = Murphy and Hall (1981); 16 = Murphy et al. (1981); 17 = Murphy et al. (1986); 18 = Poulin (in press); 19 = Tripp and Poulin (1986a); 20 = Tripp and Poulin (1986b); 21 = Tripp and Poulin (in press).

[d] Species not identified by site.

studies in which quantitative estimates have been made of the abundance of salmonids and their habitats. In conjunction with our evaluation, we recommend management practices that protect fish populations and their habitats from harmful effects. The studies that meet our criteria, their locations, and descriptions of the watersheds involved are listed in Table 14.2. We excluded studies limited to specific parts of salmonid life history, such as studies of embryo survival in gravel infiltrated by fine sediment.

Role of Streamside Management Zones

One of the major developments in forest management in relation to fisheries over the past 25 years has been increased protection of streamside vegetation

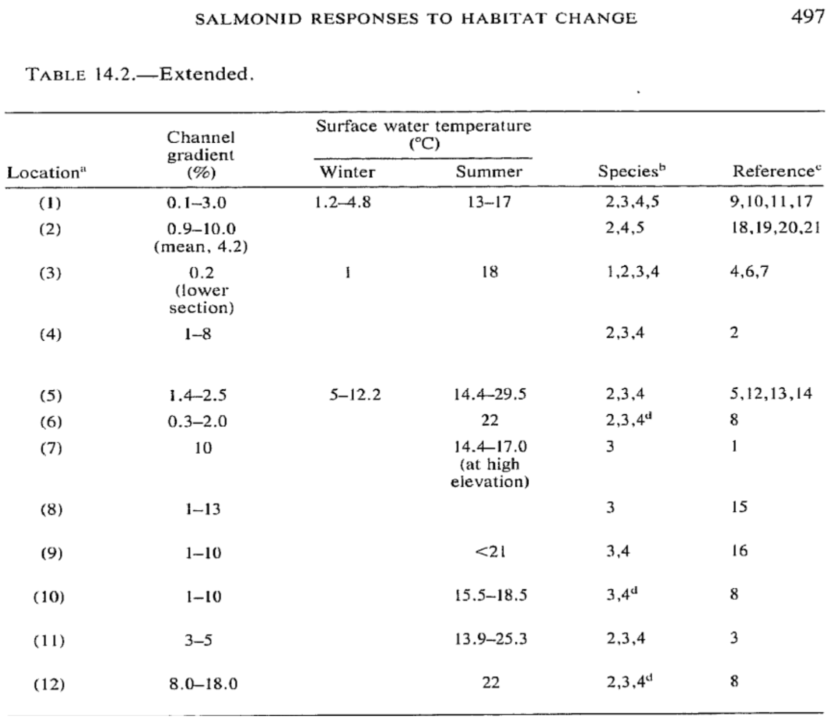

TABLE 14.2.—Extended.

Location[a]	Channel gradient (%)	Surface water temperature (°C)		Species[b]	Reference[c]
		Winter	Summer		
(1)	0.1–3.0	1.2–4.8	13–17	2,3,4,5	9,10,11,17
(2)	0.9–10.0 (mean, 4.2)			2,4,5	18,19,20,21
(3)	0.2 (lower section)	1	18	1,2,3,4	4,6,7
(4)	1–8			2,3,4	2
(5)	1.4–2.5	5–12.2	14.4–29.5	2,3,4	5,12,13,14
(6)	0.3–2.0		22	2,3,4[d]	8
(7)	10		14.4–17.0 (at high elevation)	3	1
(8)	1–13			3	15
(9)	1–10		<21	3,4	16
(10)	1–10		15.5–18.5	3,4[d]	8
(11)	3–5		13.9–25.3	2,3,4	3
(12)	8.0–18.0		22	2,3,4[d]	8

during timber harvest. The gradual development of streamside management concepts has come about partly because of the studies we review and partly because more has been learned about the ecological structure and function of riparian zones (Swanson et al. I 982a; Gregory et al. in press). The importance of streamside management as a tool to protect fishery values has been demonstrated in several studies that have compared fish habitat and salmonid populations in streams that were and were not given riparian protection during timber harvests. The evidence shows that streamside management zones minimize damage to habitat and effectively maintain the integrity of fish populations. This evidence is generally consistent over a wide span of time and space.

Alsea Watershed.—In the Alsea Watershed Study on the Oregon coast, fish populations and stream habitats were much less altered in a watershed that was patch-cut with intact streamside zones than in one that was completely clear-cut to both streambanks (Hall and Lantz 1969; Moring and Lantz 1975; Hall et al. 1987). This long-term evaluation of the influence of timber harvest on streams and their salmonid populations was established in 1958. It extended for 15 years and compared an unlogged control watershed with one that was completely clear-cut and another that was patch-cut with buffer zones left along the main channel.

Changes in physical habitat were extreme in the clear-cut basin. Only minor changes occurred in the patch-cut basin. Among the changes in the clear-cut stream was a large increase in summer stream temperature (Brown and Krygier 1970). A substantial reduction in dissolved oxygen occurred in surface water during the summer of logging, owing to accumulation of fine debris in the stream channel (Hall and Lantz 1969). During the first winter after logging, suspended sediment in the clear-cut stream increased about fivefold above the prelogging concentrations (Beschta 1978). Suspended sediment levels returned nearly to normal by the end of the 7-year postlogging phase of the study. There were increases in concentration and changes in vertical distribution of fine sediment in spawning gravels in the clear-cut watershed (Moring 1975a; Ringler and Hall 1988). As a consequence, gravel permeability in the clear-cut stream was substantially reduced below that in the patch-cut stream (Moring 1982). There were two episodes of short-term increase in suspended sediment in the patch-cut watershed caused by debris avalanches associated with roads, but these increases persisted for only 1 year. The avalanches occurred high in the watershed and formed settling basins that trapped most of the material from the hillslope. Thus they did not influence channel structure in the lower reaches inhabited by anadromous salmonids.

The two dominant salmonid species, coho salmon and cutthroat trout, responded differently to these habitat changes. Response of the coho salmon populations was difficult to assess. Smolt production in all three watersheds decreased after logging, as measured by the size of the normal smolt migration from February through May. However, owing to a progressive decline in numbers of smolts produced in the control watershed over the period of the study, and to substantial year-to-year variation in smolt abundance, the significance of the reductions was uncertain. The only change in abundance or behavior of smolt-sized coho salmon that could be attributed to timber harvest was a substantially earlier migration from the clear-cut watershed for the first 4 years after logging. A high proportion (average, 41%) of the total numbers of smolt-sized salmon migrated from November through January in those 4 years. The fate of these early downstream migrants could not be determined, but they were presumed to have suffered above-average mortality.

Another source of salmon production in these watersheds was affected by logging. Numbers of *migrant fry* that *left* headwater *streams soon after emergence* from the gravel declined to less than half the prelogging value in the clear-cut watershed (Hall et al. 1987) but changed little in the other two basins (Figure 14.5). The most likely cause of this reduced migration was the impaired gravel permeability, which could have substantially lowered survival from egg deposition to emergence (Hall et al. 1987). Cutthroat trout resident in the clear-cut basin during late summer decreased to about one-third of their prelogging abundance immediately following logging (Figure 14.6). Their numbers remained near that low level for the entire postlogging study period (Moring and Lantz 1975). Abundance of cutthroat trout did not change in the patch-cut or control streams.

By its completion in 1973, the Alsea Watershed Study had established the value of riparian zone protection during logging as a means of maintaining productive

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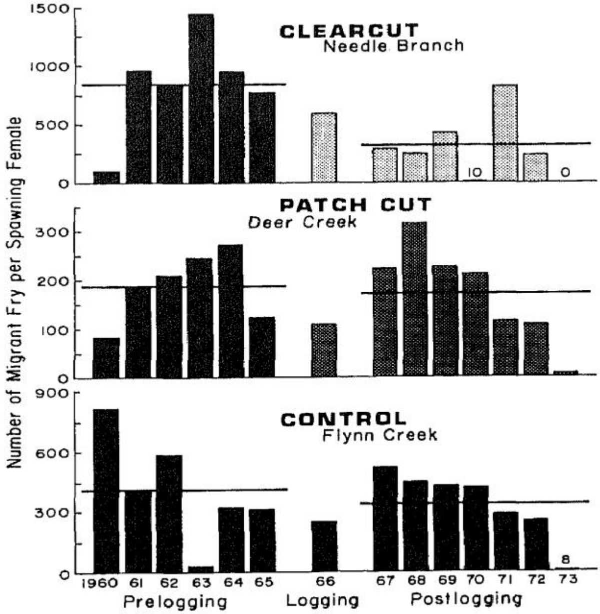

FIGURE 14.5.—Numbers of migrant coho salmon fry standardized by the number of spawning females that produced them in each stream of the Alsea Watershed Study, Oregon Coast Range. Horizontal lines are means of pre- and postlogging periods. (From Hall et al. 1987.)

fish habitat. Management practices and forest practice rules gradually began to incorporate greater protection for streamsides zones.

Carnation Creek.—The value of protecting the streamside zone was also demonstrated in the most comprehensive study of its kind to date, at Carnation Creek, British Columbia (see Poulin and Scrivener 1988 for an annotated bibliography). The watershed, on the west coast of Vancouver Island, has a cool, maritime climate. The study began in 1970 with a 5-year prelogging phase; it continued through a 6-year logging phase and a 5-year postlogging evaluation. Some monitoring continues, although the major research effort has been completed.

The study design involved three streamside harvest treatments, each applied to a different part of the same main-stem channel. In the lowest part of the basin, an unlogged buffer strip, varying in width from 1 to 70 m, was left along the stream. The next section upstream received a "careful treatment," in which all streamside trees were felled but were not yarded into or across the stream. Farthest

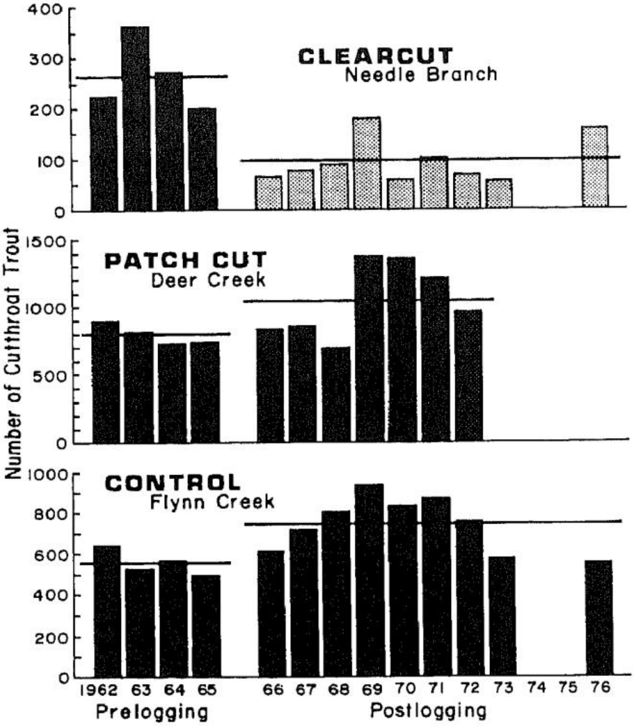

FIGURE 14.6.—Late-summer population estimates of juvenile cutthroat trout in the three streams of the Alsea Watershed Study, Oregon Coast Range. Horizontal lines are means of pre- and postlogging periods. (From Hall et al. 1987.)

up stream, in an "intensive-treatment" section, timber was felled into the stream and yarded from it (Hartman and Scrivener 1990). It was difficult to assess the effects of these treatments on salmonid populations because timber was harvested progressively and a variety of treatments was applied to the same channel. In several instances, downstream transport of material derived from a more severe upstream treatment influenced physical processes, habitat quality, and fish populations in the lower sections where treatment had been more conservative. Nonetheless, much useful information and several management recommendations have come from the study (e.g., Toews and Brownlee 1981; Hartman 1988). Several physical changes in the stream were related to the intensity of streamside treatment. Owing to removal of streamside vegetation from a substantial length of the main channel and of its tributaries, stream temperature increased in all months, the mean increase ranging from 0.7°C in December to 3.2°C in August. In contrast to other Pacific coast streams, in which autotrophic production increased notably when the canopy was opened, periphyton abundance in Carnation Creek was low before logging and did not increase after logging

(Shortreed and Stockner 1983). The failure of primary production to respond to increased light levels was attributed to a low level of phosphorus. The volume and stability of large woody debris decreased in the two sections without a buffer strip, but did not change consistently in the section with a buffer strip. Streambank erosion and stream widening were significantly greater upstream from the buffered section than within it; stream width increased nearly 2 m in the careful-treatment section between 1979 and 1985 but only about 0.1 m in the protected reach (Hartman and Scrivener 1990). Bank erosion and scour and redeposition of stream substrates were the primary causes of an increase in fine sediment in spawning gravels. The major source of fine sediment appeared to be the two sections without a buffer strip, especially an area affected by a debris torrent (Hartman and Scrivener 1990). The fraction of the bed composed of small gravel and sand increased from about 29% before logging to about 38% in 1985-1986 (5 years after the end of logging), an increase of about 30% above baseline (Scrivener and Brownlee 1989). Levels of suspended sediment were low and variable, and did not appear to increase significantly after logging.

Increased fine sediment in spawning gravel was accompanied by a reduction in estimated survival of chum salmon to emergence, from 22% before logging to 12% after (Scrivener and Brownlee 1989). Holtby and Scrivener (1989) predicted that this increased mortality, combined with an earlier migration of emergent fry to the estuary in response to increased stream temperature, would adversely affect future numbers of adult chum salmon returning to spawn. Adult returns were estimated to have been reduced by 25% as a result of logging, and year-to-year variation in abundance increased.

The number of steelhead smolts leaving Carnation Creek declined dramatically following the start of logging (Figure 14.7A), possibly because of reduced winter habitat for age-1 fish. Comparison of steelhead smolt production and adult numbers in Carnation Creek with numbers in adjacent rivers suggests that the changes were not part of a coast-wide trend, but rather the result of logging-related changes (Hartman and Scrivener 1990). Cutthroat trout smolts did not change in abundance following logging (Figure 14.7A). The size of smolts of both cutthroat trout and steelhead fluctuated substantially over the period of the study, but showed no clear change as a result of logging (Figure 14.7B). Coho salmon in Carnation Creek, like chum salmon, experienced a reduction in estimated survival to emergence as a result of increased fine sediment in spawning gravel caused by logging (Scrivener and Brownlee 1989). Average survival of coho salmon was 29% before logging but 16% after logging. The extended consequences of increased early mortality were difficult to interpret, however, because subsequent survival to spawning was influenced by other logging-related changes in the watershed as well as by climatic, biological, and fishery dynamics during the oceanic phase of the life cycle. Higher stream temperatures after logging caused juvenile coho salmon to emerge earlier and to grow faster during their first summer, resulting in larger sizes of both age-1 and age-2 smolts (Figure 14.8B). Winter survival from age 0 to age 1 in the main channel should have been reduced by decreases in the amount and stability of large woody debris (Tschaplinski and Hartman 1983). Because age-0 fish were larger in autumn, however, and because they made extensive use of a well-developed floodplain rearing area during winter, overwinter survival actually increased and a larger proportion of smolts went to

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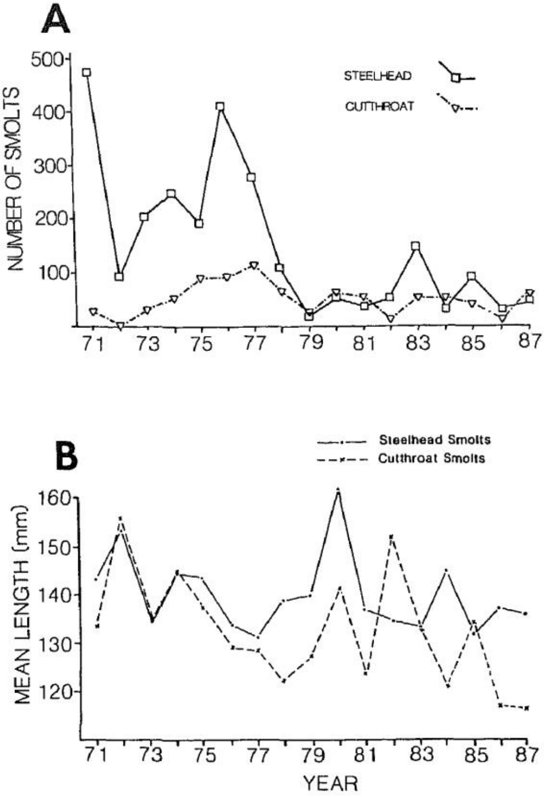

FIGURE 14.7.—Numbers (A) and size (B) of steelhead and cutthroat trout smolts leaving Carnation Creek from 1971 to 1987. Logging occurred between 1975 and 1981. (From Hartman and Scrivener 1990.)

sea at age 1 than was the case prior to logging. Consequently, total numbers of emigrants increased (Figure 14.8A). Nevertheless, the survival of smolts at sea probably declined because their spring migration took place an average of 2 weeks earlier than it did before logging (Holtby 1988b). The net result of logging was estimated to be a 6% reduction in returns of adult coho salmon and greater year-to-year variation in the number of returning spawners (Holtby and Scrivener 1989).

Changes in abundance of fish populations in Carnation Creek have been difficult to attribute to specific streamside treatments because there was only a single fish trap at the outlet of the watershed, and most of the assessment was based on overall changes in populations of the entire basin. In addition, there was no unlogged control watershed. These limitations were largely overcome by means of

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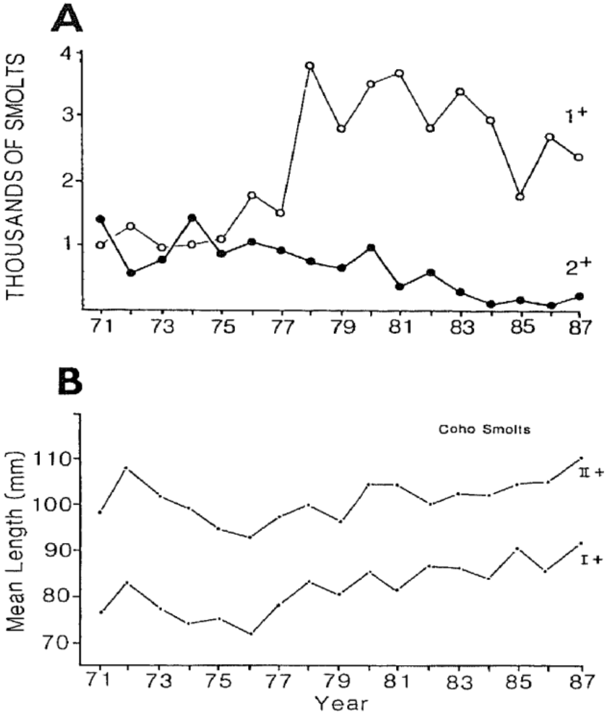

FIGURE 14.8.—Numbers (A) and size (B) of age-1 and age-2 coho salmon smolts migrating from Carnation Creek from 1971 to 1987. Logging occurred between 1975 and 1981. (From Hartman and Scrivener 1990.)

an elaborate series of linked regression models that accounted for the effects of logging, climate, and fishing (Holtby 1988b; Holtby and Scrivener 1989). This integrated approach to understanding the effects of logging on a salmonid population identified five distinct changes in the life history of coho salmon that were related to year-round temperature increases. These changes were (I) accelerated embryo development and earlier alevin emergence; (2) larger size at the end of summer, resulting from increased length of the growing season; (3) greater overwinter survival due to larger size; (4) more and larger age-1 coho salmon smolts and fewer age-2 smolts; and (5) earlier seaward migration of smolts in the spring. This analysis, which considered all life-history phases, illustrates the detail needed to understand the complex effects on salmonids of logging-related changes in streams. These efforts stand out as the most comprehensive attempt to place logging impacts within the context of the entire life cycle of an anadromous salmonid population.

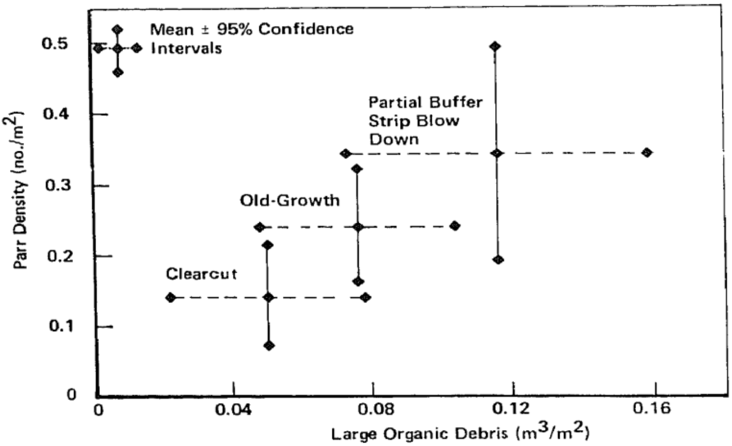

FIGURE 14.9.—Relationship between abundance of woody debris and density of coho salmon parr during winter in southeastern Alaska. Buffer-strip sites had experienced partial windthrow and had more debris than did old-growth sites. (From Murphy et al. 1984a.)

Southeastern Alaska.—Streamside management zones were shown to be effective in maintaining habitat and salmonid populations in a postlogging study of 18 streams in southeastern Alaska. Responses of coho salmon, Dolly Varden, and cutthroat trout populations to two treatments—clear-cutting to the stream edge (1-12 years previously) and clear-cutting with a buffer zone (3-10 years previously)—were assessed for 1 year (Murphy et al. 1986). Some buffer strips had experienced windthrow or had been selectively logged. In summer, coho salmon fry were more abundant in clear-cut and buffered reaches with partially open canopies than in old-growth reaches, apparently because increased primary production led to increased food availability. In winter, parr densities were positively correlated with the amounts of large woody debris present in streams (Figure 14.9). Juvenile salmonids depended on pools with cover created by large woody debris and on the protection provided by undercut banks (Heifetz et al. 1986). As a result, parr were less abundant in clear-cut reaches, where most of the large debris had been removed, than they were in old-growth and buffered reaches, where debris remained. Thus the increased abundance of coho salmon during their first summer was believed to have been more than offset by declines associated with loss of winter habitat (Koski et al. 1984). The net result was lower abundances of parr in, and lower predicted smolt outputs from, clear-cut reaches compared with sites with buffer strips or in old-growth forest (Murphy et al. 1986). Steelhead fry and parr responded like coho salmon (Johnson et al. 1986).

Northern California.—Logging in the north Coast Range of California was compatible with natural production of anadromous fish when adequate attention was given to stream protection (Burns 1972). Four streams were studied for one summer before, during, and after logging (3 years total). The two streams in watersheds that were carefully logged with protection of streamside vegetation showed minimal changes in habitat characteristics and in salmonid populations.

Cascade Mountains.—In some locations, lack of a streamside management zone has not appeared to be detrimental to production of salmonids in the years immediately following logging. Frequently, short-term production has even been enhanced by removal of all streamside vegetation. This was particularly true for small clear-cuts along high-gradient stream reaches where sediment and temperature changes were minimal (Gregory et al. 1987). A trend towards short-term enhancement of cutthroat trout populations in streams in the western Cascades of Oregon and Washington was shown by initial comparisons of logged and unlogged streams (Aho 1976; Hall et al. 1978; Murphy and Hall 1981; Bisson and Sedell 1984). Comparisons of 24 stream reaches in the Oregon Cascades showed that biomass of cutthroat trout was highest in clear-cut, intermediate in old-growth, and lowest in second-growth forests (Murphy and Hall 1981). The different responses of trout to logging in the Cascades and in the Oregon Coast Range (Alsea Watershed Study) led to further attempts to determine the underlying mechanisms. Paired logged and unlogged sites were compared in the Oregon Cascades and in the Oregon and California Coast Ranges (Murphy et al. 1981; Hawkins et al. 1983). The results of these studies, which included both high- and low-gradient streams, were generally consistent with the earlier work in the Cascades. Trout populations were higher in most of the recently logged sites than in the shaded forest sites.

Increased food abundance seemed to be the primary basis for increased growth and biomass of the trout populations in these streams. Opening of the canopy allowed greater primary production, which led to greater abundances of invertebrates in both the benthos and the drift (Hawkins et al. 1982; Wilzbach et al. 1986). In addition, trout were able to forage more effectively in the open sites; efficiency of prey capture was directly related to the amount of sunlight reaching the stream surface (Wilzbach et al. 1986). The conclusion from most of these studies was that greater food availability compensated for any negative effects of increased sedimentation and other habitat changes, at least in the first 10-15 years after logging. There were some indications that the return of heavy shade to the streams after 15 years was associated with a decrease in trout abundance to levels below those found in old-growth forests. This could be a particular problem in low-gradient sites, where sediment accumulation is greatest (Murphy and Hall 1981; Murphy et al. 1981). Timber harvesting along streams where streamside management zones are not provided, particularly when accompanied by removal of large woody debris from the channel and banks, often leads to substantial modification of channel structure (Sullivan et al. 1987). Such alterations may lead to changes in the relative abundance and age structure of salmonid species in these streams. Shifts in species and age composition were noted when populations of cutthroat trout, steelhead, and coho salmon were compared at 25 logged and unlogged sites in southwestern Washington (Bisson and Sedell 1984). The 12 logged sites had been clear-cut from 1 to 11 years prior to the survey. No protection had been provided in the streamside zones of the logged watersheds, and woody debris had been removed from the channels. Habitat changes associated with timber harvest and debris removal included decreases in pool area and volume and increases in riffle length. Where paired comparisons could be made in the same drainage basin, the biomass of all salmonids combined averaged 1.5 times greater in logged than in unlogged sites (Bisson and Sedell 1984). In most logged streams, the proportion of age-0 steelhead and age-0 cutthroat trout increased, but the proportion of age-0 coho salmon and age-1 and age-2 cutthroat trout decreased.

Bilby and Bisson (1987) studied the factors controlling the summer residency and production of age-0 hatchery-raised coho salmon in the upper Deschutes River, Washington, a relatively cool area at 1,200 m elevation. These fish were stocked at high density (up to 6/m^2) in paired old-growth and clear-cut watersheds. Production in the clear-cut watershed ranged from 1.2 to 2.6 times greater than production in the old-growth watershed over 2 years. Proportionately more fish remained in the old-growth site, which possessed better physical rearing habitat than did the clear-cut site. However, summer mortality in the old-growth site was significantly greater than in the clear-cut site, and growth rates were lower in the old-growth site. The number of coho salmon remaining in the two streams at the end of summer was not significantly different, but fish in the clear-cut site weighed about 20% more than fish in the old-growth site. Bilby and Bisson (1987) concluded that summer production was most strongly influenced by trophic conditions (the clear-cut site having more available food), whereas volitional residency was most strongly influenced by habitat quality (the old-growth site having better rearing habitats).

Benefits of streamside management zones.—The benefits of opening the canopy when timber is harvested to the stream edge may be offset by reduced diversity of fish species or increased annual variation in production. In the long term (over the length of a timber harvest rotation), most evidence indicates that careful streamside treatment is a better strategy than clear-cutting to the stream edge. Originally, the primary purpose of streamside management zones was control of stream temperatures. Recent timber harvest policies and forest practice rules have acknowledged the additional role of such zones in protecting channel stability and in providing future sources of large woody debris. We now recognize many more functions of the riparian zone (Gregory et al., in press). Future management efforts need to be directed toward prescription of the appropriate sizes and densities of trees in streamside management zones so that these zones accomplish all desired functions (Steinblums et al. 1984; Bisson et al. 1987).

In summary, intact streamside management zones have the following benefits:

- maintenance of stable streambanks, with overhanging cover and undercut banks.
- protection for stable large wood in the channel.
- provision for a continuing source of large wood for the future.
- maintenance of stable streambed and stream channel, minimizing increased sedimentation.
- prevention of substantial modification of stream temperature.

Effects of Roads and Hillslope Timber Harvest

Valuable as it may be, protection of streamside zones alone is not necessarily sufficient to insure maintenance of productive stream ecosystems in watersheds where timber is harvested. Particularly in steep terrain, debris avalanches and related mass movements of soil, timber, and debris from hillslopes may adversely affect salmonid habitats. Increased frequency of debris torrents resulting from road building and logging has been implicated as a major cause of degradation of fish habitat in some areas with steep slopes, unstable soils, and predisposing climate.

One series of studies has documented the effect of landslides on salmonids and their habitats in small streams on the Queen Charlotte Islands, British Columbia. Salmonid habitats were surveyed in 44 streams with known logging histories (Tripp and Poulin 1986b). Stream reaches studied included those in logged basins with debris torrents, those in logged basins without debris torrents, and those in unlogged basins without torrents. Methods of stream rehabilitation, effects of different cutting patterns, and alternative harvest methods 'to reduce mass soil movement were studied.

As part of the same study, salmonid abundance was investigated in 29 streams, and smolt migration was assessed in seven of these (Tripp and Poulin 1986b). Densities of juvenile coho salmon in late summer were almost as high in streams affected by debris torrents as they were in logged streams without torrents. The amount of cover present in summer was similar in both groups of streams but the type of cover differed greatly between groups. The cover in streams unaffected by debris torrents was predominantly rootwads, small and large woody debris, undercut banks, and deep water. In streams affected by debris torrents, cover was formed by rocks, boulders, and associated turbulence at the water surface.

Winter survival following logging was substantially lower in streams with debris torrents than in those without torrents, and was related to the type of cover in the two groups of streams. Winter cover was less abundant and less diverse, and pieces of large woody debris were less numerous, in streams affected by debris torrents than in unaffected streams. The amount of pool habitat regarded as good for overwintering juvenile salmonids, especially coho salmon, was reduced by an average of 79% in affected streams compared to unaffected ones, and the amount of cover suitable for overwintering was reduced by 75%. Correspondingly in these logged areas, overwinter survival of coho salmon averaged 1.8% in stream reaches affected by debris torrents compared to 24.5% in unaffected streams. Smolt yield averaged 0.02 fish per lineal meter in affected streams but 0.24 fish/m in unaffected streams, a 12-fold difference. Smolt yield from streams in unlogged areas unaffected by torrents was not measured, but was estimated to be 1.1-1.4 fish/m based on results from a stream in which habitat had been improved with channel structures (Tripp and Poulin, in press). Among western North American streams that flow through unlogged forests and have less than 10 km of their lengths accessible to anadromous salmonids, the average smolt yield is 1.4/m (Marshall and Britton 1980; Holtby and Hartman 1982).

Channel morphology in Queen Charlotte Island streams was profoundly influenced by logging-associated debris torrents. We can speculate on the species-specific effects of changes in stream reaches affected by debris torrents. Reduced average pool depth and area, reduced cover, and increased riffle area and channel width (Tripp and Poulin 1986b) would decrease habitat suitability for pool-dwelling species such as coho salmon. Comparison of hydraulic conditions in two Queen Charlotte Island streams, one in a logged and the other in an unlogged area, led Hogan and Church (1989) to conclude that there indeed was a decrease in rearing area for coho salmon at higher discharges in the logged area. Habitat suitability for species such as juvenile steelhead, which can occupy shallow-water habitats (Everest and Chapman 1972; Hicks 1990), might increase following logging. However, surface water flow decreased after mass wasting, owing to percolation through gravel in riffles and side channels (Tripp and Poulin 1986b), reducing the quality of these channel units as fish habitat. Riffle habitat quality was similarly reduced in Carnation Creek following logging (G. Hartman, Canada Department of Fisheries and Oceans, personal communication). The dramatically increased occurrence of mass wasting in logged basins, and especially in logged and roaded basins, indicates that channel widening, reduced area and quality of pools, and reduced surface flow might be a widespread result of logging in similar geoclimatic regions. Timber harvest and road construction on unstable slopes, combined with several years of above-average rainfall, damaged spawning areas in the South Fork Salmon River, Idaho (Platts and Megahan 1975). Fine gravel and sand (<4.7 mm) from weathered granite entered stream channels as a result of accelerated surface erosion and landslides, increasing river bedload by 3.5 times and practically destroying the spawning potential of the main river. A moratorium was placed *on logging and road construction on National Forest lands in the watershed* in 1965, vegetation was planted, and roads were stabilized, after which surface and landslide erosion declined dramatically. The proportion of fine sediments in spawning areas decreased progressively in four monitored areas from a range of 45 to more than 80% in 1966 to 12-26% in 1974, and the particle-size distribution returned to near optimum for spawning of chinook salmon (Platts and Megahan 1975). The response of fish runs to improved spawning conditions was difficult to evaluate owing to problems of fish passage at numerous downstream hydroelectric dams in the Snake and Columbia river basins. In this section, we have identified logging-induced changes in the rate of erosional processes as potentially damaging to salmonid populations. These harmful changes can be ameliorated by reduced road building and by careful design, placement, and construction of the forest roads that are built (Furniss et al. 1991). Lands especially susceptible to erosion should be excluded from logging. Exclusion of headwall areas from timber harvest, because of their high risk of landslides, has been used experimentally in the Oregon Coast Range (Swanson and Roach 1987).

Geoclimatic Trends in Salmonid Response

Geology, geomorphology, and climate control hillslope angles, soil depth, and resistance of bedrock to weathering. However, at the time scales considered in most studies of logging effects on salmonid populations (1-15 years), the geomorphic surface of a basin controls erosion rates (Gregory et al., in press).

Geomorphology and Geology

Hillslope angles, soil depth, and resistance of bedrock to weathering determine the *susceptibility of* hilislopes *to* failure, the geomorphic structure and stability of stream channels, and the hydrologic and nutrient regimes. In the Queen Charlotte

Islands, steep slopes, high rainfall, and erosive soils were responsible for the increased mass wasting that followed logging and damaged salmonid populations (Gimbarzevsky 1988; Poulin, in press).

The geomorphic configuration of a stream and its valley can influence salmonid population dynamics (Sullivan et al. 1987). Many of the juvenile coho salmon in Carnation Creek overwintered in the floodplain of the lower stream, which contained a network of sloughs, beaver ponds, and abandoned meander channels (Tschaplinski and Hartman 1983; Brown 1987). Winter survival and growth of coho salmon in these slack-water areas far exceeded those of coho salmon overwintering in the main stem (T. G. Brown 1985).

Geology has also been used to explain local differences in stream channel morphology and salmonid populations (Sullivan et al. 1987). In the Oregon Coast Range, cutthroat trout and steelhead predominated in watersheds underlain by basalt, whereas coho salmon predominated in streams cut through sandstone (Hicks 1990). Streams in sandstone valleys had lower gradients and a greater proportion of their lengths consisted of pools compared with streams of the same size in basalt areas, which were dominated by riffles. Boulders can create stable stream structure and diverse habitat in the absence of large woody debris, and boulder-rich streams can continue to support good populations of salmonids if debris is lost (Osborn 1981; Hicks 1990). Complex geologic factors such as resistance of bedrock, amount of fracturing, and distance from source control the size distribution of substrate elements (e.g., Hack 1957; Dietrich and Dunne 1978), which partly determines channel geometry and habitat quality (Hicks 1990). Differences in watershed geology influence nutrient availability, and these differences have helped explain some of the responses of fish populations to logging. In southeastern Alaska, periphyton, benthos, and coho salmon fry were abundant in both old-growth and clear-cut portions of watersheds rich in limestone. Little periphyton and few coho salmon were found in logged reaches in watersheds dominated by igneous rock (Murphy et al. 1986). Other studies also have related nutrient concentrations and biological productivity to watershed geology (Thut and Haydn 1971; Swanston et al. 1977; Gregory et al. 1987). Nitrogen is often the primary limiting nutrient in watersheds dominated by volcanic parent material, whereas streams draining glacial deposits or granitic bedrock are more often phosphorus-limited.

Geography and Climate

Studies of logging effects show some influences of latitude and climate. Mean annual precipitation, surface water temperature, and snowfall vary with latitude, altitude, and distance from the coast (Geraghty et al. 1973). As maximum surface water temperatures increase from north to south, thermal loading as a result of clear-cutting increases (Brown 1969, 1970; Beschta 1984). This effect is superimposed on higher ambient surface water temperatures in more southern and inland areas (Beschta et al. 1987). We speculate that seasonally related effects of logging on salmonid production are more severe in the southern portions of the species' ranges than in the north. Summer streamflows are lower in the south than in the north. Higher water temperatures and lower surface flows associated with logging, combined with higher ambient summer temperatures, may reduce food and space resources, which will intensify competition (Allen 1969) and limit survival of salmonids in summer.

Large woody debris mediates winter survival of salmonids throughout western North America, but the mechanism appears to differ between the northern and southern portions of their ranges. Protection from the high velocities of winter peak flows is the main role of woody debris in areas with winter floods (Chamberlin et al. 1991). In the north, where winter is a period of low flow, the maintenance of pool depth by scour around woody debris is important in preventing stream freezing.

Our attempt to evaluate trends in response of populations from west to east, from the Cascades to the Rocky Mountains and eastward, was hampered by a lack of data. There have been several coordinated studies, including those of the Slim–Tumuch watershed in British Columbia, the Tri-Creeks system in Alberta, and the Nashwaak basin in New Brunswick (Macdonald et al. 1988), and several isolated investigations (e.g., Platts and Megahan 1975; Welch et al. 1977; Grant et al. 1986; Lanka et al. 1987), but little has been published on the response of salmonid populations to timber harvest in these more easterly areas. Climate also influences the occurrence and rate of mass wasting, which is the predominant means by which large amounts of soil, rock, and organic material are delivered to streams (Everest et al. 1987a). Antecedent weather conditions and storm intensity were more important than geology in determining the susceptibility of different bedrock types to erosion in the Queen Charlotte Islands (Poulin, in press). Bedrock type, however, influenced the slope of valley walls, which in turn influenced the extent of mass wasting (Gimbarzevsky 1983, 1988). The effects of mass wasting on winter fish survival in logged streams affected by debris torrents were thought to be so severe that too few adults might return to sustain a population of coho salmon in the future (Tripp and Poulin 1986b). Geomorphologic and geologic variables have been used successfully to explain salmonid abundance in logging-related studies (Ziemer 1973; Swanston et al. 1977; Heller et al. 1983; Lanka et al. 1987). However, no two studies have identified the same set of variables as being important. This shows that we have some understanding of the link between geology, geomorphology, and fish abundance that can be useful locally to predict the effects of timber harvest, but that we still have no models that apply over a wide area.

Limits of Present Knowledge

Uncertainties remain about the effects of forest practices on salmonid populations, demonstrating the limits of our present knowledge. Nevertheless, there appear to be some unifying links among studies of the integrated salmonid response to logging. An increase in solar radiation reaching a stream after removal of streamside vegetation usually enhances production of algae and invertebrates. The net effect is often greater salmonid production within the first 20 years after timber harvest. At least some of the benefit of increased summer production can be lost by reduced winter survival. Reduction in winter survival can result from loss of habitat structure caused by reduced amounts and stability of large woody debris and by increased amounts of coarse sediment. Differing habitat requirements of salmonid species such as coho salmon and steelhead (Hartman 1965) result in varied responses to logging-related changes in channel morphology (Reeves and Everest, in press). Reductions in habitat complexity and pool depth truncate the diversity of species and age-classes, favoring single species and age-classes. Increases in riffle area increase the suitability of habitat for steelhead, if streamflows are sufficient to maintain adequate water depth.

Incongruous Time Scales

In our opinion, one explanation for the incomplete state of knowledge lies in the very different time scales characteristic of management practices, natural processes, and evaluative studies. The period of a single rotation in timber harvest in western North America is 45-100 years. The natural processes that influence stream productivity and that may mitigate changes caused by timber harvest operate over a variety of time scales ranging from months to centuries. Yet almost all of the studies evaluating the effects of forest management on stream habitat and salmonid populations have encompassed less than 5 years. Nearly all have concentrated on changes immediately following timber harvest. Of the few studies at the population level carried out to date, only the Carnation Creek and the Alsea Watershed studies extended for 15 years or more, and even that length of time is inadequate for full evaluation of logging effects. Some population studies (e.g., Murphy and Hall 1981) dealt with streams whose watersheds had been logged as many as 30-40 years earlier, but none of the studies was capable of monitoring the effects of environmental disturbance over the length of a rotation. The need for long-term evaluation is further illustrated by observations from the Carnation Creek study. Had the study terminated in the first few years after logging, the eventual impact on the coho salmon population would not have been detected (Hartman et al. 1987). Studies of salmonid populations in Great Britain (Egglishaw and Shackley 1985; Elliott 1985) also show the need for long-term research. These studies monitored anadromous salmonid populations in watersheds that had not experienced recent disturbance, yet Elliott (1985) noted that even 18 years of data on population abundance, streamfiow, and water quality had failed to provide a clear indication of the environmental factors that limit production. Short-term studies cause a biased perspective of habitat change. Some change that is most apparent persists for only a few years. Undue concern may be raised over a condition that is transient in the time scale of forest succession. Increased levels of suspended and deposited sediment could be considered an example of this sort (Everest et al. 1987a). In contrast, some effects that are beneficial or neutral in the short term can be followed by negative effects over the longer term. The short-term increase in productivity that accompanies higher light levels after canopy removal from some streams is an example. As the canopy closes during forest succession, the overall production of salmonids may drop below that of unlogged watersheds and remain there for many years (Gregory et al. 1987). Speed of canopy closure following removal of streamside vegetation depends on the local environment. Return of insolation at the stream surface to preharvest or lower levels as streamside vegetation regrows may be rapid in some locations such as the Oregon Coast Range, but the canopy may remain open for many years in an environment where plant growth is slow (Summers 1983).

A decrease in the supply of large woody debris is another change in habitat that may not occur for many years. Recent studies in Oregon have indicated that many existing stable pieces of large woody debris entered streams years ago. Heimann (1988) found that in watersheds logged without a buffer strip, preharvest debris continued to be the predominant wood in streams 140 years after timber harvest, but the total amounts of debris were only about 30% of preharvest levels. Unless adequate provision is made to supply streams with large pieces of wood into the future, the quality of fish habitat may decline severely. Decomposition times of some tree species are so long (e.g., >100 years for western redcedar: Swanson ct al. 1976) that there may be a lag time of many years before the shortfall is apparent. Two problems confound the clear separation of logging effects from those caused by other environmental changes and by fishery management activities. The first problem is that most studies of logging effects have used present-day habitats and fish populations as the baseline for comparison with postlogging conditions. As a consequence, logging-related reductions of salmonid populations that may have occurred over the past 100 years or more have gone undetected. In many areas, present-day levels of wild salmonid stocks are only small fractions of historical abundances. There has been little study of long-term (100 years or more) change in habitat of the sort undertaken by Sedell and Luchessa (1982) and Sedell and Froggatt (1984). Among the causes of habitat loss have been channel scour during log drives, removal of debris to improve navigation, logging of riparian conifers, and salvage of large wood from stream channels. The second problem is that the effects of logging are difficult to separate from the effects of other activities, such as power generation, irrigation, grazing practices, and fishery management (Pella and Myren 1974). Overfishing and loss of productive spawning and rearing habitat (e.g., Chapman 1986) have occurred concurrently with logging. In particular, excessive ocean harvests, especially of coho and chinook salmon, have often resulted in inadequate returns of wild fish to spawn. The low level of spawning has complicated assessment of the natural productive potential of streams (Cederholm et al. 1981). These conditions combined have made it extremely difficult to separate logging effects on fish populations from the effects of other natural and cultural influences within the time scales of evaluative studies.

Climatic Variation

A further difficulty in tracking logging-related habitat disturbances over time is introduced by long-term fluctuations in climate or the effect of a single event of very large magnitude. Large floods occurring periodically have disproportionate influences on channel morphology. Unusually severe storms occurred in the northwestern USA in 1949, 1955, 1964, and 1972. These intense storms caused high discharges, bed-load movements, landslides and associated debris torrents, and erosion of streambanks and floodplain terraces, all of which resulted in substantial, widespread changes in stream habitats. To some extent, timber harvest has intensified the effects of such floods on stream habitats (Anderson et al. 1976), and evidence of the resulting channel changes may persist for decades or more (Swanson et al. 1987). Frissell and Hirai (1989) described a complex interaction between land-management practices and long-term changes in the timing of storms that appears to have contributed to reductions in spawning success of chinook salmon in coastal streams of southern Oregon. Less apparent physically, but perhaps no less important biologically, are severe droughts such as those that occurred in the 1930s. Another unusual climatic event that can exert a strong influence on population abundance is an oceanic El Nino (Bottom et al. 1986; Johnson 1988).

In the evaluation of logging-related habitat changes and their effects on fish populations, disturbance regimes imposed by management should be compared to natural disturbances in both frequency and amplitude. Salmonid populations in western North America have evolved in a landscape where they experienced severe environmental stresses, including forest fires, floods, mass soil and ice movements, debris torrents, glaciation, and volcanism. Through evolutionary processes, salmonids have developed life history strategies enabling them to withstand considerable environmental variation and unpredictability. Salmon and trout accomodate exploitation and other stresses, at least in the short-term, through compensatory responses at one or more life stages. However, some effects of timber harvest may be more severe than similar natural perturbations, resulting in mortality beyond the range of compensation. For example, the abundance of large woody debris has been more substantially reduced by logging and associated salvage and stream-cleaning activities than by wildfire or volcanism (Sedell and Dahm 1984).

A major consequence of all these sources of variability in the natural environment is the large natural variation—both temporal and spatial—in the abundance of salmonids (Burns 1971; Lichatowich and Cramer 1979; Hall and Knight 1981; Cederholm et al. 1981; Platts and McHenry 1988). This variation is often large enough to obscure changes caused by timber harvest or other land management activities (Pella and Myren 1974; Platts and Nelson 1988).

Spatial Scales

Incongruence of spatial scale, as well as of temporal scale, has hindered interpretation of many studies. Bisson (in press) compared typical variations in western Washington salmonid populations in space and time on the basis of both standing stocks and smolt yields. He concluded that the smaller the scale, the greater the variability among sites. That is, differences in population abundance and smolt production tended to be greatest among limited stream reaches, whereas differences in smolt yield for whole basins tended to be proportionately smaller. Because most studies of timber harvest have focused on stream reaches or small watersheds, they have taken place at a spatial scale often characterized by relatively great variability, thus making logging-related changes more difficult to separate from natural variation.

Focus on individual stream reaches has also limited the accuracy of many studies. The study designs used have underestimated sampling error and have not addressed the comparative importance of different parts of a basin (Hankin 1984, 1986). Reach analysis does not effectively assess cumulative effects that may accrue from a multitude of small disturbances within a large watershed, or downstream changes that result from a single type of disturbance repeated over time. The criticism applies most strongly to short-term postharvest evaluations, but the limitation also occurs in watershed-level studies.

There may be problems of scale in extrapolating work in relatively small basins to larger watersheds. For instance, debris torrents that remove channel structure from steep, lower-order drainages can add structure to higher-order, lower-gradient reaches downstream (Benda 19856). In addition, larger main-stem reaches have been shown to rear proportionately more fish on a basin-wide scale than the combined lower-order tributaries, despite high fish densities in headwater streams (Dambacher, in press; J. R. Sedell, U.S. Forest Service, unpublished). Though main-stem production in some systems is now low, its historic role may have been greater before channel complexity was lost (Sedell and Froggatt 1984). There are several reasons why studies have been concentrated in small basins. First, isolation of the effects of timber harvest from other activities requires working within watershed boundaries where logging is the only management influence. The mosaic of patterns of land use and other influences found in large basins therefore usually limits the size of study basins to small watersheds. Logging of large basins also occurs over too long a period to allow evaluation of its effects, because only a small proportion of the watershed area is normally harvested at any one time. Secondly, small streams have often been selected for study because they could be sampled easily, rather than because of their significance to total basin production. This is particularly true for the siting of facilities for counting salmonid smolts and adults. Maintaining effective fish traps during high streamflows is a major constraint on the size of stream that can be effectively monitored. Recent development of small, portable, floating smolt traps (McLemore et al. 1989) should provide the ability to monitor much larger systems than has been possible in the past.

Suggestions for Future Studies

We suggest three principal approaches for evaluation of the influences of logging on salmonids: (1) substitution of space for time by extensive evaluation of many watersheds in a short period, (2) long-term studies before and after logging, and (3) innovations in design that could improve data collection efficiency or strengthen the inferences drawn from data. In earlier analyses, Hall et al. (1978) and Hall and Knight (1981) suggested that studies of the effects of logging could be grouped in a two-way classification. The basis for grouping is (1) whether the studies are before-and-after comparisons or posttreatment evaluations of timber harvest, and (2) whether detailed studies are carried out on one or few streams (intensive) or shorter surveys are conducted on many streams (extensive). This classification results in four categories, the advantages and disadvantages of which are listed in Table 14.3. There is no single optimum study design, but Hall and Knight (1981) favored the extensive posttreatment survey, especially when it is combined with carefully designed process-oriented studies. Given the substantial work done since that time, and a recent further evaluation of study design (Grant et al. 1986), we have reviewed those conclusions. Extensive posttreatment analysis, especially when coupled with pairing of treatment and control streams or watersheds, is an attractive and relatively inexpensive method of analysis. In certain circumstances, it appears to have been effective (e.g., Murphy and Hall 1981; Bisson and Sedell 1984; Murphy et al.

TABLE 14.3.—Summary of advantages and disadvantages of the four major approaches to watershed stream analysis. (From Hall and Knight 1981.)

Advantages	Disadvantages
(A) Intensive before-after (5–7 years before treatment, 5–7 years after)	
Possible to assess year-to-year variation and place size of effects in context of that variation Can assess short-term rate of recovery (about 5 years) No assumptions required about initial conditions Possible to monitor effects over whole watersheds (provided substantial investment in facilities such as flow and sediment sampling weirs, fish traps) Long time frame provides format for extensive process studies	No replication; results must be viewed as a case study Results not necessarily applicable elsewhere (areas of different soils, geology, fish species, etc.) Results influenced by changes in weather Final results and management recommendations require exceptionally long time to complete—15 years or more after initial planning stage Difficult to maintain intensity of investigation and continuity of investigators over such a long period Considerable coordination required; must rely on outside agencies or firms to complete logging as scheduled
(B) Extensive before–after (1–2 years before treatment, 1–2 years after)	
Provides broader geographical perspective than (A) Larger number of streams lessens danger of bias by extreme case Increased generality of results allows some extrapolation to other areas Relatively short time to achieve results (3–4 years from planning stage)	Little opportunity to observe year-to-year variation Able to assess only immediate results, which may not be representative of longer time sequence Treatment influenced by unusual weather Must rely on coordinated efforts (see A above)
(C) Intensive posttreatment (one watershed, paired sites; several years after treatment)	
Shorter time for results than (A) Moderate ability to assess year-to-year variation Provides opportunity for moderate level of effort on process studies	Provides no separate control stream; requires assumption that upstream control reach was similar to treated area prior to treatment "Control" most logically must be located upstream of treatment; strong downstream trend in any variable would confound analysis Provides no spatial perspective; results of limited application elsewhere
(D) Extensive posttreatment (e.g., 10–30 watersheds); all observations made in 1–2 years (time after treatment variable)	
Wide spatial perspective allows extrapolation to other areas Long temporal perspective is possible; recovery can be assessed for as many years as past logging has occurred Provides ability to assess interaction of physical setting and treatment effects (e.g., effects of sediment input at different stream gradients) Requires least time of the four designs to complete (as little as 2 years) Probably most economical of the four approaches per unit of information	No data available on pretreatment conditions, forcing assumption that control and treatment sites were the same before treatment Control predominantly upstream Total cost and sampling effort concentrated in short period; requires extensive planning Not as effective as (A) in assessing whole watershed effects Harvest methods used in early logging may not be comparable to those used later

1986). In a test of this study design in some streams in eastern Canada, Grant et al. (1986) concluded that the basic structure of the design was valid, although they detected no clear changes in salmonid biomass in response to timber harvest. However, comparison of paired sites close together along the same stream channel is less appropriate for assessing the effects of whole watershed disturbances than for assessing the effects of localized disturbances. Further consideration has led us to conclude that stream-reach comparisons, a feature of most extensive survey designs, should be broadened to a larger watershed perspective. Recent development of basin-wide sampling designs for both habitat characteristics and fish populations (Hankin and Reeves 1988) should allow more effective assessment of habitat changes in entire basins.

Some studies, particularly earlier ones, did not examine certain key habitat variables that we now know to be important. Recent advances in the classification and quantitative description of stream habitats (Bisson et al. 1982; Frissell et al. 1986; Grant 1986; Sullivan et al. 1987), along with recognition of the important role of large woody debris (Sedell et al. 1984, 1988), have improved our ability to describe deleterious changes in habitat quality. Nonetheless, our present understanding seems inadequate to predict changes in fish populations by analysis of habitat changes alone. Understanding often seems inhibited by a tendency to focus on a limited subset of habitat variables, such that insufficient consideration is given to potential limiting factors (Everest and Sedell 1984; Chapman and McLeod 1987; Everest et al. 1987a; Bisson, in press).

Research effort has not been applied equally to all species. There has been a strong bias towards studies of coho salmon, cutthroat trout, and steelhead (Table 14.2). Chinook salmon in particular have been much less studied relative to their distribution and abundance, probably because most studies have focused on small watersheds. There has been some emphasis on pink and chum salmon in Alaska and British Columbia, but little of the work has been focused on responses at the population level.

We suggest that more emphasis is needed on long-term analysis of logging impacts. This recommendation is based on several related observations. The successful and insightful analyses that have come from the Carnation Creek study could not have resulted from a shorter-term study. The evaluation of long-term ecological studies by Strayer et al. (1986) highlighted the advantages and contributions of such studies and provided a good perspective on the value of extended monitoring. Increased support from the U.S. National Science Foundation for research on long-term ecological reserves reflects a recognition by the scientific community of the value of such work. Finally, analysis of long-term trends in habitat condition (Sedell and Luchessa 1982; Sedell and Froggatt 1984) has convinced us that gaining an accurate perspective on change in habitat may require a very long time.

One innovative study design was suggested by an historical analysis of habitat condition prior to large-scale timber harvest and salvage of downed timber in the

Breitenbush River in western Oregon (J. R. Sedell, U.S. Forest Service, unpublished). The original data forms from a survey of the river system conducted in 1937 by the U.S. Bureau of Fisheries were recovered. The survey was repeated in 1986 and showed a loss of more than 70% of pool habitat over the past 50 years. The river had changed to a single channel without debris jams and did not match its earlier description as "a mass of channels criss-crossed with downed logs and debris." The early surveys did not include quantitative assessment of fish populations, however. In a related attempt to evaluate the cumulative effects of timber harvest on channel structure, Grant (1988) used aerial photographs spanning the years from 1959 to 1979 to discern increases in stream channel width in the same reach of the Breitenbush River. Lyons and Beschta (1983) also used analysis of aerial photographs to measure changes in channel width in the Willamette River drainage in the Oregon Cascade Range over the same time period. They found major increases in channel width associated with timber harvest and road building. If it were possible to couple such analyses with models relating habitat quality to population abundance (see Fausch et al. 1988), a much clearer picture of the long-term effects of logging might emerge. We suspect that there are many such early surveys containing valuable information that have since been misplaced, forgotten, or otherwise ignored. If properly interpreted, these archived surveys could be used to provide a valuable baseline against which present-day conditions could be compared.

One conclusion that cannot be avoided from the studies relating salmonid populations to timber harvest activities is that fish habitats have been simplified over time and that this process of simplification continues. In this respect, agriculture, mining, grazing, and urbanization have the same net negative effects on habitat diversity and population abundances of major fish groups. The phenomenon is world-wide and is well documented for agricultural lands (Karr et al. 1983) and urbanized areas (Leidy 1984; Leidy and Fiedler 1985). Habitat degradation by simplification is one of the most important limits on the diversity of fish communities (Karr and Schlosser 1978). Highly diverse fish communities have been documented in association with stable channels, instream cover from boulders, living streamside trees, and downed trees in channels (Karr and Schlosser 1978; Welcomme 1985). Our understanding of the changes in stream habitat and salmonid populations brought about by timber harvest has improved, but our knowledge remains limited. Certain changes in stream habitats caused by logging—increased temperature and fine sediment, for example—appear to be less detrimental and more transient than originally perceived. Others—such as loss of large woody debris and changes in channel morphology and stability—were not forseen as problems earlier but have contributed to significant habitat degradation in the long term. We are concerned that logging impacts will become more severe as timber harvest moves to progressively less stable landforms and as the area of managed forest increases. As timber is harvested from the accessible and gentle terrain, logging occurs on steeper and less stable slopes, as it has in the Queen Charlotte Islands, for example. The results there and from other areas of steep terrain in western North America argue for intensified efforts to develop hazard-assessment techniques that will predict the potential disturbances to fish habitat from mass erosion and debris torrents. Some progress in this direction has been made (Benda 1985b; Swanson et al. 1987).

There is still much to learn before we can predict with confidence the effects of a particular logging operation on salmon and trout populations or prescribe management activities that will provide optimum habitat protection. However, a much wider array of analytical tools is now available. Several useful management guidelines and procedures for translating research findings into management practices have recently been produced (e.g., Toews and Brownlee 1981; Bryant 1983; E. R. Brown 1985; B.C. Ministry of Forests et al. 1988; Hartman 1988; Bilby and Wasserman 1989).

Finally, we emphasize that our review of 30 or more years of research on forestry and fisheries interactions has yielded several general principles that should be considered when logging operations are planned and implemented. Some of the most important of these follow.

- Protection of streamside zones by leaving streamside vegetation intact will help maintain the integrity of channels and preserve important terrestrial–aquatic interactions.
- Productivity of streams for salmonid populations tends to be enhanced under conditions of moderate temperatures, low to moderate sediment levels, high light levels, adequate nutrients, an abundance of cover, and a diversity of habitat and substrate types.
- Productive floodplain and side-channel habitats should be protected.
- Streams should be protected against frequent and extreme episodes of bed-load movement or sediment deposition through careful streamside management and through proper planning and engineering of roads and timber harvest systems.
- Management of streamside zones should include provisions for long-term recruitment of large woody debris into stream channels and for protection of existing stable large woody debris.
- The geology, geomorphology, and climate of a watershed mediate the response of fish populations to timber harvest. Site-specific management recommendations must consider regional landforms and climatic variation.

No single research approach will provide all the answers to the many complex questions that remain. We advocate a combination of short-term extensive studies over broad geographic regions and long-term intensive studies that emphasize critical terrestrial–aquatic interactions at the watershed scale. We further suggest that future long-term studies involve both biologists and foresters at the planning stage so that various logging treatments can be experimentally evaluated in a sound scientific manner. This process will also help to reduce the perceived conflict between forest and fishery management that has all too often hindered progress. We note that two of the most successful research efforts, the Alsea Watershed Study in Oregon and the Carnation Creek study in British Columbia, used such an approach. Coordinated experiments that are thoughtfully designed can speed solution of many of the remaining problems, resulting in our improved ability to intelligently manage all the resources of forested watersheds.