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Chapter 6

Timber Harvesting, Silviculture, and Watershed Processes

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Waters in forested lands of western North America are major producers of anadromous salmon and trout. The size of the fishery resource is large, but it is diminishing as a result of human activities and currently is only a fraction of its original size. Western forested watersheds also produce an array of other natural resources, including a variety of wood products. Areas that produce both timber and salmonids coincide over much of western North America (Figure 6.1), and the increasing public demand for both of these resources creates frequent management conflicts. Under most circumstances, both timber and fish can be successfully managed in the same watershed if measures to protect water quality and fish habitat are carefully coordinated with timber management operations.

This chapter is confined to the effects of timber management activities on stream ecosystems, particularly streams with anadromous salmonids. Lakes and estuaries are also vital to the life cycle of many anadromous salmonids, but consideration of those realms is left to other authors (e.g., Tschaplinski 1988).

Timber management activities discussed in this chapter include felling and yarding of trees, site preparation by burning or scarification, fire hazard reduction, forest regeneration by planting or seeding, reduction of competition by brush removal and tree thinning before commercial harvest, and some effects of road building on the hydrologic and sediment systems discussed in the chapter. Other chapters of this book treat road building (Furniss et al. 1991) and forest chemicals (Norris et al. 1991) in detail.

Numerous models allow the standing crop of fish to be estimated from habitat variables. Fausch et al. (1988) reviewed 99 models of various types, and Hicks et al. (1991, this volume) summarize the response of salmonids to changes in habitat. The diverse habitat requirements of many salmonids are discussed in this volume by Bjornn and Reiser (1991). We will concentrate, therefore, on how timber management influences hydrologic and sediment transport processes and thereby affects the amount and quality of flowing water, gravel substrates, cover, and food supplies required by all salmonid species.

Relations between Timber Management and Salmonid Habitat

Because the several species and life phases of salmonids have diverse habitat requirements, streams that support them productively must sustain a varied complex of hydraulic and geomorphic conditions (Sullivan 1986) that are distrib-

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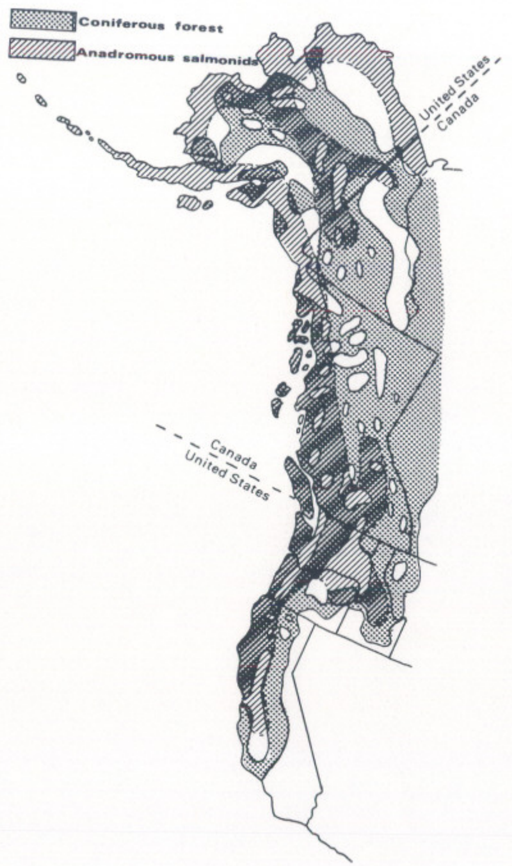

FIGURE 6.1.—Areas of timber and anadromous salmonid production in western North America.

uted along the stream continuum (Vannote et al. 1980). The close relation between watershed (basin) properties and stream characteristics has been repeatedly emphasized (Lotspeich 1980), and serves as a good approach for understanding how forest management influences fish habitat.

Figure 6.2 is a conceptual model of the linkages between timber management activities and fish. In this model, the influences of these activities are transmitted through changes in watershed processes and structures that, in turn, modify the habitat elements described by Bjornn and Reiser (1991). Hartman (1988) provided an excellent synthesis of these complex relationships for the watershed of

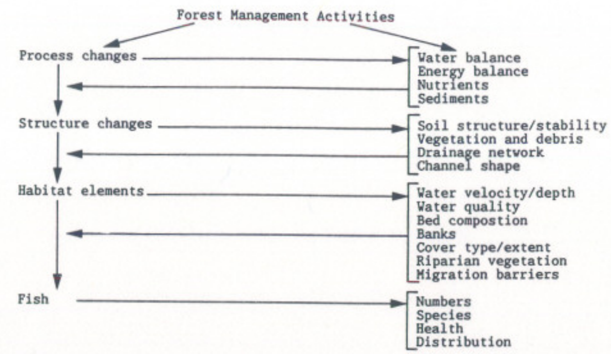

FIGURE 6.2.—Linkages between timber management activities and fish production.

Carnation Creek, British Columbia, and reemphasized the importance of understanding basic watershed processes.

Water plays a central role in watershed processes, but equally important are the sediments it moves and the structure imposed on stream channels by bedrock and the trees, roots, and logs of the riparian ecosystem. The land–water ecosystem must be managed through space and time as an integrated whole if productive fish habitat is to be maintained.

Importance of Small Streams

Salmonids occupy a wide variety of streams that range in size from tiny headwater tributaries to the mainstream Columbia River. Some species even migrate to, and spawn and rear for a while in, first-order streams that may become intermittent or dry in summer.

Most spawning and rearing in forested watersheds, however, takes place in second- to fourth-order streams; coho salmon and trout often are found further upstream than other salmonid species. Such small streams account for the majority of total aggregate stream length available to salmonids in most watersheds.

Even when small streams are not accessible to migrating fish because of barriers or steep gradients, they are vitally important to the quality of downstream habitats. The channels of these streams carry water, sediment, nutrients, and wood debris from upper portions of the watershed. The quality of downstream habitats is determined, in part, by how fast and at what time these organic and inorganic materials are transported.

Small streams are responsible for a high proportion of salmonid production in a basin, and they influence the quality of habitat in larger tributaries downstream. They also are the streams most easily altered by forest management activities. Small streams are intimately associated with their riparian zones and are highly responsive to alterations in riparian vegetation and the surrounding watershed.

Vegetative crown cover is often complete over first- through third-order streams. Because small streams depend largely on litter fall for organic energy input (Murphy and Meehan 1991, this volume), any manipulation of the canopy or streambank vegetation will influence the stream's energy supply. Likewise, road building or other activities that increase sediment supplies or modify local runoff may have greater effects on smaller streams than they would on larger systems.

Although larger streams generally have a greater capacity to buffer the effects of changes to the riparian zone, salmonid fry often preferentially inhabit the lower-velocity margins and back channels of such streams (Ptolemy 1986). Forest harvesting and other land-use impacts can accumulate over time to cause substantial changes in stream-edge environments, even along very large rivers (Sedell and Froggatt 1984).

Hydrologic Effects

Water defines fish habitat more than any other factor does. Hence, changes in the quantity, quality, or timing of streamflow caused by timber harvesting and silviculture are a primary focus for timber–fish interactions. The basic components of the hydrologic cycle—precipitation, infiltration, evaporation, transpiration, storage, and runoff—have been introduced by Swanston (1991) in this volume. Here we discuss how timber management activities influence those components and some of the consequent effects on salmonid habitats.

Regional Variations in Streamflow Response

Regional differences in runoff patterns, ranging from rain-dominated to snowmelt-dominated systems, are illustrated by Swanston (1991). Coastal watersheds with high-elevation ranges may have a mixture of runoff types with gradual transition zones; as one moves from south to north along the Pacific coast, the summer "dry" period becomes increasingly wet.

This regional variability makes it very difficult to generalize about the hydrologic effects of forest management, but can help resource managers to focus on those parts of the hydrologic cycle that will have the most influence on fish habitats in their areas. For example, in rain-dominated coastal systems, frequent high winter floods make the maintenance of side channels a primary habitat protection activity. In interior snow-dominated watersheds, by contrast, management practices to augment low late-summer rearing flows are encouraged.

Regional variation in streamflow behavior will also influence management practices related to sedimentation. In the interior basins, spring breakup and snowmelt are responsible for most of the movement of road and channel sediments, but, along the coast, frequent rains provide sufficient energy to transport material during many months of the year.

In general, forest management activities influence salmonid habitats when they alter the normal regional streamflow pattern at the extremes—that is, by increasing or decreasing the normal levels or occurrences of very high or very low flows. Management actions to manipulate these changes in beneficial directions may be possible, and are furthered by an understanding of how timber harvesting affects each component of the water balance.

Influences on the Water Balance

Timber management activities do not normally change the total amount of precipitation entering a watershed. A possible exception occurs in areas where fog drip from forest foliage adds substantially to water input but is lost when forest vegetation is removed (Harr 1982). Harvesting may, however, substantially alter the spatial distribution of water and snow on the ground, the amount intercepted or evaporated by foliage, the rate of snowmelt or evaporation from snow, the amount of water that can be stored in the soil or transpired from the soil by vegetation, and the physical structure of the soil that governs the rate and pathways by which water moves to stream channels. Within this complex of elements in the water balance, the effects of harvest and silviculture can be grouped into three major categories that form the basis for most runoff analyses: influences on snow accumulation and melt rates; influences on evapotranspiration and soil water; and influences on soil structure that affect infiltration and water transmission rates.

Snow accumulation and melt.—The forest canopy intercepts snowfall, redistributes snow, shades the snowpack, and lowers wind velocities. Harvesting affects these processes in various ways, depending on the temperature, precipitation, and wind patterns characteristic of a region.

In the colder, drier winter climate of the interior, intercepted snow is easily blown from the canopy. During prolonged windless periods, snow may sublimate and be lost from the snowpack.

In warmer, more moist climates of the transient-snow zones, snow is wetter and sticks longer in the forest canopy. Warm air (above 0°C) melts intercepted snow, causing it to reach the ground as meltwater or in wet clumps. Snowpacks under mature forest are thus variable in depth, discontinuous, and wetter than snowpacks in the open (Berris and Harr 1987). Under younger tree canopies, however, snow may be deep because tree branches are more flexible and bend downward, causing snow to slide off onto donut-shaped piles around individual boles (Berris 1984).

Forest openings alter wind patterns and trap snow. Small openings (up to eight tree heights in diameter) trap snow more effectively than large ones, although more snow will be available for melt even in large openings than in forested terrain. In the West Kootenays of British Columbia, snow accumulation in openings up to 42 tree heights in diameter was 37% greater than in the forest and melted 38% faster (Toews and Gluns 1986). Troendle and King (1985) found that peak snow water equivalent (depth of water that results when snow melts completely) averaged 9% higher, and peak snowmelt flows averaged 20% greater, after a forest was logged in small patches.

In dry interior climates, the rate at which snow melts from openings depends principally on energy from shortwave solar radiation (i.e., sunshine). Hence, the loss or creation of shade patterns can significantly affect the rate of melt and the timing of runoff peaks. During cloudy, rainy, and windy weather characteristic of winter storms on the Pacific coast, in contrast, sunshine is a minor heat source for melt compared to the convective transfer of sensible and latent heat from moist air to the snowpack. When rain falls on snow, the melt rate increases in proportion to the wind speed and the air temperature (U.S. Army Corps of Engineers 1956).

Forest harvesting that opens up stands to stronger winds can thus increase the melt rate. For example, Harr (1986) and Berris and Harr (1987) found that more heat was available to melt snow in a recent clear-cut than in an adjacent old-growth Douglas-fir stand during a rain storm of an intensity that recurs at roughly 2-year intervals. The greater amount of heat, coupled with 2–3 times more water in the snowpack, resulted in 22% more water (rain plus snowmelt) flowing from the clear-cut than from the forested plot. Likewise Golding (1987) documented a 13.5% increase in peak winter storm flows after only 19.2% of a coastal British Columbia watershed was clear-cut.

Whether increased water outflow from a logged site causes an increase or a decrease from the whole basin depends on where the site is with respect to other elevations, aspects, and distances from the channel mouth. Shallow snow in the transient-snow zones melts and runs off fairly quickly during rain storms, for example, but deeper snowpacks such as those in the Sierra Nevada may not translate melt into runoff changes as directly (Kattelmann 1987). In the snow zone, models such as those of Leaf and Brink (1973) and Kattelmann (1982) can help forest managers design logging plans that synchronize or desynchronize the runoff of snowmelt at different locations in a basin, and thereby contribute to fishery management objectives.

In the transient-snow zones of the Pacific coast, the effects of harvest on runoff are variable and not well documented, primarily because the montane relief and meteorology are themselves so variable. Still, plot studies on both small and large paired watersheds have shown increases in the size of peak flows after logging (Harr and McCorison 1979; Christner and Harr 1982; Harr 1983), suggesting that timber harvests can affect fish habitat in these areas as well.

Influences on evapotranspiration and soil water.—Clear-cutting, shelterwood cutting, or thinning eliminates or reduces a substantial area of leaves and stems that would otherwise intercept precipitation and allow it to be evaporated when sufficient energy was available. Likewise, fewer tree roots reduce the amount of water that would otherwise be extracted from the soil and hence be unavailable for streamflow. These two factors cause soil water content (and sometimes groundwater) and runoff to be higher in logged than in unlogged areas, and the effect increases as the percentage of stems removed increases. When stands are only thinned, the residual stand may increase its use of water (Hibbert 1967), so changes in streamflow following thinning are likely to be less than might be expected from counts of trees alone.

Table 6.1 shows some examples of changes in annual runoff that have been observed after timber harvesting. The increases have been largest (in absolute terms) during the growing season, when substantial precipitation also occurs. In western Oregon, the greatest portion of the annual increase occurred during the early part of the fall–winter rainy season, when rain rapidly filled the soil pores in cleared areas and then had to run off as surface flows (Rothacher 1971; Harr et al. 1979). Later in the rainy season, even soils under mature canopies became saturated, so runoff from logged and unlogged areas was roughly the same.

These generalizations apply to clear-cut areas that have not been further disturbed by roads, yarding, or burning, and that are not subject to major rain-on-snow events. Compounding effects of such physical disturbances are discussed in the next section.

TABLE 6.1.—Examples of changes in annual runoff after timber harvest. (From Hibbert 1967.)

Location	Species	Treatment	Increase in water yield in the first year (%)
Coweeta, North Carolina	Hardwoods	100% clear-cut	40
Coweeta, North Carolina	Hardwoods	35% selective	40
H. J. Andrews, Oregon	Conifers	40% clear-cut	[a]
Wagon Wheel Gap, Colorado	Mixed	100% clear-cut	22
Fool Creek, Colorado	Conifers	40% clear-cut	30

[a] Small increase in low flow.

Increased late-summer or fall runoffs can increase available fish habitat. They may also moderate the increases in stream temperature that result from removal of shade vegetation. Summer flows have doubled and tripled immediately after clear-cutting and broadcast burning of logging slash in small watersheds (Rothacher 1971; Harr et al. 1979), although increases were short-lived. Rapid regrowth of riparian vegetation may reduce summer streamflows below prelogging levels (Harr 1983).

Increases in soil water content and groundwater levels can indirectly affect fish habitat in other ways. On logged hill slopes, moist soil is vulnerable to mass movements (O'Loughlin 1972; Swanston 1974). On the other hand, higher groundwater levels after harvesting may expand the area of floodplain habitats accessible to fish, particularly during summer low-flow periods (Hetherington 1988).

Influences on soil structure.—The third group of influences that timber harvesting and silviculture can have on the water balance involves the entry of water into soil and its downslope movement to streams. Most undisturbed forest soils can accept water much faster than normal rates of rainfall or snowmelt (Dyrness 1969; Harr 1977), and virtually all water that reaches such soils enters them and follows subsurface routes to stream channels. Substantial surface runoff occurs only when storms are unusually heavy or rainy seasons are especially long, as noted above for western Oregon.

Forest management activities that disturb the soil such as road building, yarding, burning, or scarification can alter the pathways water takes to stream channels, and hence increase (or decrease) the volume of peak streamflows. Soil can be compacted by logging equipment (Greacen and Sands 1980) or by logs dragged over the ground during yarding and site preparation (Dyrness and Youngberg 1957). When surface soils are exposed, their pores can be clogged by fine sediment and their structure can be broken down by the energy of falling raindrops (Lull 1959). If the infiltration capacity of the soil is sufficiently reduced, water runs off over rather than through the soil. Higher peak flows and increased sediment transport result.

In general, yarding exposes the least amount of soil when it is done with balloons or helicopters, and the most when logs are skidded with tractors (Figure 6.3). In steep terrain, high-lead cable yarding has disturbed soils over

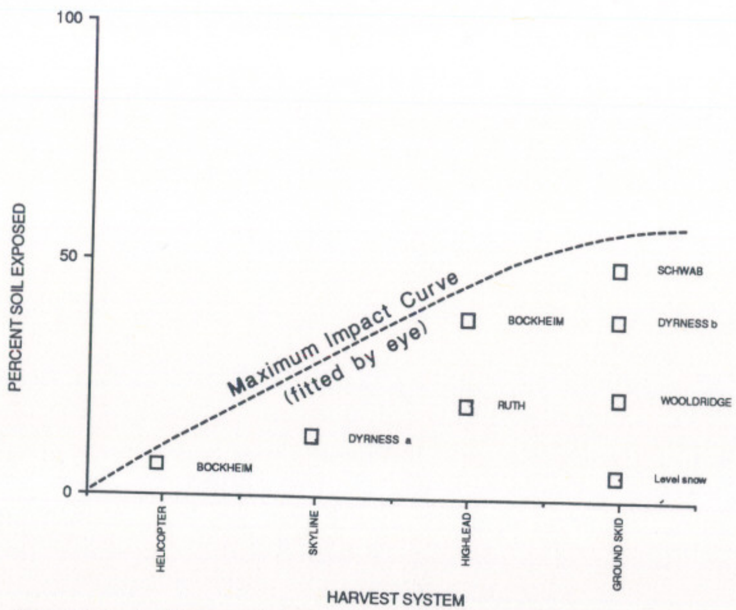

FIGURE 6.3.—Areal extent of mineral soil exposed by alternative yarding techniques. Squares represent empirical studies by the authors indicated and the well-known protection afforded soils by snow cover. Logs moved by helicopter and skyline cables do not touch the ground during transportation. In high-lead yarding, one end of a log is suspended from an overhead cable and the other end drags along the ground. Ground-skidded logs are dragged full length over the terrain. References: Bockheim = Bockheim et al. (1975); Dyrness a = Dyrness (1967b); Dyrness b = Dyrness (1965); Ruth = Ruth (1967); Schwab = Schwab (1976); Wooldridge = Wooldridge (1960).

30–60% of the logged areas (Smith and Wass 1980); on flat terrain or over snow cover, however, even tractor skidding may cause negligible disturbances (Bockheim et al. 1975; Klock 1975). These findings indicate that soil disturbance will be minimized when the harvesting system is well matched to particular site characteristics.

Internal changes in soil structure also take place after logging, as tree roots die, sediment fills soil pores, and compaction occurs. The role of large subsurface pathways in the rapid transmission of water has been shown by Cheng et al. (1975), de Vries and Chow (1978), and Hetherington (1988). The collapse or blockage of these "macropores" forces water to flow over the surface, which may accelerate erosion.

Roads and landings have relatively impermeable surfaces, and water runs off them rapidly. Ditches along roads not only collect surface runoff, they can intercept subsurface flow and bring it onto the surface (Megahan 1972). The effects of roads alone on basin hydrology have not received much study, but there

is some evidence that roads can accelerate storm runoff and cause higher peak flows in small basins (Harr et al. 1975, 1979; Harr 1979).

Soil properties on upper slopes are remote from the concerns of most managers of fish habitat. Nevertheless, soil disturbances there usually speed up water movement; if disturbances are extensive, the size of peak flows will increase. Only the maintenance of intact surface and subsurface soil structure can assure "normal" hydrologic behavior. Stream and upland managers, loggers, forest hydrologists, soil scientists, and terrain specialists should consult broadly with one another to avoid introducing long-lasting and undesirable hydrologic changes when trees are harvested anywhere in a watershed.

Summary of water balance influences.—Timber management activities can affect streamflow by altering the water balance or by affecting the rate at which water moves from hillsides to stream channels. The more severe an alteration of the hydrologic cycle is, the greater the effect on streamflows, and hence on fish habitats, will be.

Changes in flow condition depend on many factors. The expected effects of soil disturbance on flow dynamics are illustrated in Figure 6.4. Another aid for analyzing the net effect of timber harvesting is the "water resources evaluation of non-point silvicultural sources" (WRENSS: U.S. Forest Service 1980a). Discussions by Isaacson (1977) and Toews and Gluns (1986) also are helpful in this regard.

Beyond the semiquantitative modeling techniques that must be calibrated to the characteristics of a specific watershed, the following broad generalizations usually apply.

- Harvesting activities such as roadbuilding, falling, yarding, and burning can affect watershed hydrology and streamflow much more than can other management activities such as planting and thinning.
- Clear-cutting causes increased snow deposition in the openings and advances the timing and rate of snowmelt. The effect lasts several decades until stand aerodynamics approach those of the surrounding forest. Snowmelt can be accelerated by the large wind-borne energy inputs of warm rain falling on snow.
- Harvested areas contain wetter soils than unlogged areas during periods of evapotranspiration and hence higher groundwater levels and more potential late-summer runoff. The effect lasts 3–5 years until new root systems occupy the soil.
- Road systems, skid trails, and landings accelerate slope runoff, concentrate drainage below them, and can increase soil water content.
- Hydrologic models such as WRENSS help predict the net effect of a harvesting pattern and sequence on runoff, but each basin must be analyzed to ensure that the most important hydrologic processes are understood.

Influences on Water Quality

The principal water quality variables that may be influenced by timber harvesting are temperature, suspended sediment, dissolved oxygen, and nutrients. Elsewhere in this volume, forest chemicals are discussed by Norris et al. (1991), the important role of the riparian zone in controlling energy inputs (temperature

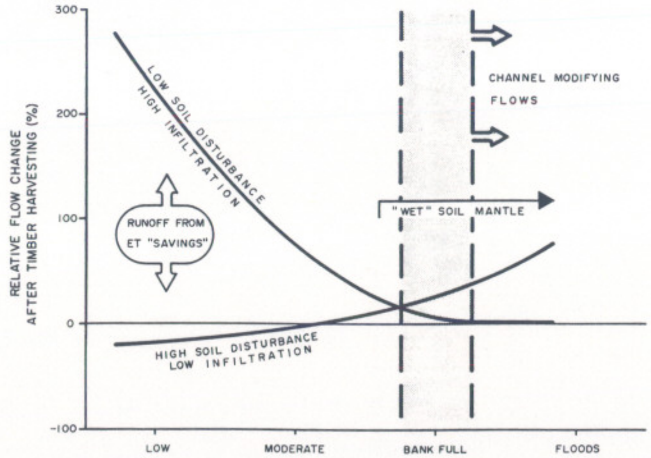

FIGURE 6.4.—Alterations in relative flow after forest harvesting as functions of flow condition when soil disturbances have been small or large. When flow is low, as it may be in late summer, and timber clearance has caused only slight disturbance to the soils, precipitation falling on the soil will infiltrate normally but less will be lost to evapotranspiration (ET) than previously, leaving more water for a sustained augmentation of flow. If soils have been compacted and otherwise disturbed, little rainfall will infiltrate and recharge soil water; most will run off on the surface, causing a transitory peak in flow, and sustained flow will not benefit from an ET "savings." At higher flows, which reflect wetter soil mantles in the watershed, the ET savings become a smaller proportion of the total water budget, so clear-cutting has less relative effect on flow when soil structure remains intact; compacted soils, however, deliver increasing amounts of surface runoff.

and nutrients) is treated by Murphy and Meehan (1991), and the interaction between water quality and fish response is covered by Hicks et al. (1991).

Temperature.—Solar energy is the largest component of energy available to warm stream water in summer. When streamside vegetation is removed, summer water temperatures usually increase in direct proportion to the increase in sunlight that reaches the water surface. Water has a high heat capacity, so a stream's volume, depth, and turbulence affect the actual temperature at any point in the water column. Forest harvesting can cause mean monthly maximum stream temperatures to increase as much as 8°C and mean annual maxima to rise 15°C (Brown and Krygier 1970), but specific stream and watershed conditions cause wide variation in the processes affecting temperature increases (see Beschta et al. 1987 for a comprehensive review).

Figure 6.5 suggests that smaller streams have a greater potential for increases in temperature from streamside harvesting than do larger streams, because a greater proportion of their surface areas will be newly exposed to the sun. However, they may be shaded by smaller trees or deciduous vegetation. Planned openings along

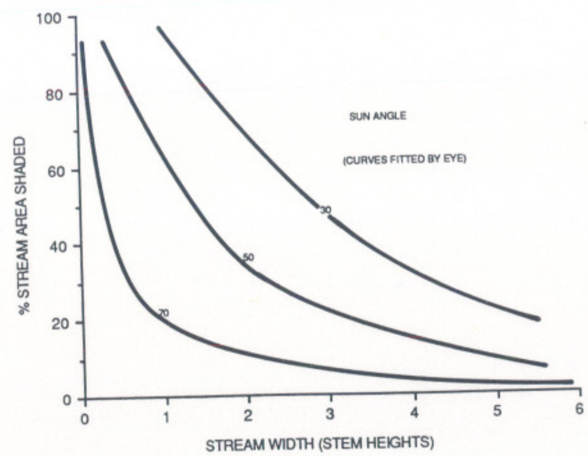

FIGURE 6.5.—Percentage of stream area shaded as functions of stream width and latitude or season. Stream width is indicated as multiples of the height of the prevailing riparian vegetation. Latitude or season is indexed by the noon angle of the sun above the horizontal.

cold coastal streams might enhance fish productivity if other habitat requirements were maintained. In this as in other habitat manipulations, however, caution is required because modest changes in water temperature can change the time required for salmonid eggs to develop and hatch (Holtby 1988a). In northern areas, removal of over-stream coniferous vegetation may lower winter stream temperatures because a net outward energy flow may result, causing slower egg development, deeper surface ice, and bottom-ice formation on gravels. Further, if logging leads to a higher groundwater table in the valley bottom, this will influence the thermal regime of flows in winter (Hetherington 1988)—or, indeed, in any season. Only a careful analysis of the energy balance, including groundwater influences, can indicate the likely direction and magnitude of changes in water temperature that forest harvesting will cause. Techniques are available for predicting changes in a stream's heat budget and consequent changes in water temperature (e.g., Brown 1980; Beschta et al. 1987).

Suspended sediment.—Forest harvesting and silviculture can influence suspended sediment concentrations in a variety of ways, all related to the erosion and sedimentation processes discussed earlier. Most streams carry some sediment, and the amount varies seasonally, but we are most concerned with forest management activities that substantially change the magnitude, timing, or duration of sediment transport and overwhelm the ability of salmonids to cope with or avoid the resulting stress.

Poorly designed roads and skid-trail systems are persistent sources of sediment, but so are open slopes whose soils have been exposed by yarding activities, mass movements, scarification, or intense fire. In cold climates, removal of insulating vegetation promotes formation of ice lenses in and frost heaving of soils, facilitating soil movement during spring thaws (Slaney et al. 1977).

Few studies have identified the component of suspended stream sediments originating from harvesting activity alone (without road influence). Some have illustrated that careful, well-planned logging can take place without appreciable sediment production (Packer 1967), whereas others have documented very high sediment levels (Reinhart et al. 1963) as a result of unplanned activity. Furniss et al. (1991) discuss in more detail the very important role that roads have in sediment production.

We cannot overemphasize the importance of maintaining the integrity of the riparian zone during harvest operations. In addition to disturbing surface soil, activities near the stream bank may destabilize channel margins, releasing sands that settle in and clog the streambed gravels (Scrivener 1988a).

Dissolved oxygen.—Concentrations of dissolved oxygen in intergravel spaces may be reduced if fine organic debris accumulates on and in the streambed. The high chemical and biological oxygen demands of such debris and the bacteria on it may persist for long periods until the bottom material is removed by high flows. Logging and skidding near or across small streams obscured by snow are particularly likely to contribute fine organic debris to watercourses during spring runoffs.

Clogging of surface gravels by fine inorganic sediments can restrict intergravel flow enough to lower dissolved oxygen concentrations. This problem usually occurs only when large or persistent volumes of sediment emanate from active road systems, mass soil movements, bank slumps, or destabilized upstream channels (Scrivener and Brownlee 1989).

During extremely low flows, dissolved oxygen concentrations decline in streams (Bustard 1986). Turbulent exchange of gases with the air decreases. Fish and other respiring organisms—including those associated with organic debris—become concentrated in a few channels and in pools that are nearly or completely isolated. If channels are aggraded and pools shallow, the reservoir of dissolved oxygen is small. In summer, high temperatures both accelerate respiration and lower the solubility of oxygen. In winter, ice cover may prevent diffusion of oxygen from air to water. Harvest activities that impose large oxygen demands on streams exacerbate the normal stresses that low flows place on fish.

Nutrients.—Concentrations of inorganic nutrients (e.g., N, P, K, Ca) in streams may increase after logging, but usually by moderate amounts and for short periods (Fredriksen 1971; Scrivener 1982). Likewise, 5- to 10-fold increases in nutrient releases after slash burning have shown rapid returns to earlier levels. The mobilization of nutrients is tempered by their adsorption onto soil particles and by their uptake by microorganisms that decompose stream detritus (Murphy and Meehan 1991).

Streams in which algal production is limited by a particular nutrient (e.g., phosphorus) may have major algal blooms in response to minor increases of that nutrient, if temperature and flow conditions permit. These blooms can harm salmonid production if their remnants settle into interstitial gravel space. For this reason, forest fertilizers, like pesticides, should not be applied within buffer strips along streams.

Effects of Harvests on Erosion and Sedimentation

Forest harvest activities can influence both upland erosional processes and the way that forest streams process sediment in their channels. The degree of influence varies with geology, climate, vegetation, dominant geomorphic processes, and land uses (H. W. Anderson 1971). The episodic climatic history of western basins over hundreds or thousands of years also makes time an important consideration in the analysis of forestry practices (Benda et al. 1987).

Sediments entering stream channels can affect channel shape and form, stream substrates, the structure of fish habitats, and the structure and abundance of fish populations. In the following discussion, we assume that the goal of forest managers is to maintain streams in their "normal" configurations by minimizing changes in the amount of sediment entering and passing through the systems. Although natural stream processes vary substantially from year to year, and streams change inexorably with time, stream reaches retain characteristic properties over much longer times than those encompassed by forest management cycles. It is against those basic properties that the effects of harvest practices are measured.

Changes in Erosional Processes

Swanston (1991) discusses in this volume how sediment originates either from surface erosion of exposed mineral soil or from mass movements such as landslides, debris torrents, slumps, and earthflows. Furniss et al. (1991) add to the discussion of road-related sediment production.

Surface erosion.—The potential for surface erosion is directly related to the amount of bare compacted soil exposed to rainfall and runoff. Hence, road surfaces, landings, skid trails, ditches, and disturbed clear-cut areas can contribute large quantities of fine sediments to stream channels. Not all hillside sediment reaches the stream channel, but roads and ditches form important pathways. For example, gravel-surfaced logging roads increased sediment production by 40% when they were heavily used by logging trucks (Reid and Dunne 1984). In the Clearwater River basin of Washington, the amount of material less than 2 mm in diameter that washed off roads equalled the amount produced by landslides and has contributed to poor gravel quality for spawning coho salmon.

The quality of management planning strongly influences sediment production from forest-harvesting activity, as illustrated by the classic study of Reinhart et al. (1963) on the Fernow Experimental Watershed, West Virginia. Sediment production varied over 3 orders of magnitude according to the degree of planning and care with which the skidder logging was conducted.

As a general rule, surface erosion results from the exposure of mineral soil, and, as we discussed under soil structure above, it is minimized by the use of yarding systems that are well matched to the terrain and soil types. Packer (1967) reviewed several additional examples and concluded that the best erosion control practices are to avoid operations in very wet seasons, to maintain vegetative buffer zones below open slopes, to skid over snow, and to ensure prompt revegetation.

Silvicultural activities that require scarifying the ground or burning can increase sediment production if buffer strips are not left between treated areas and stream channels. Even when burns do not expose mineral soil, a water-repellent layer can form and reduce the ability of water to infiltrate into the soil (Krammes and DeBano 1965; Bockheim et al. 1973), increasing the runoff available for surface erosion.

An indirect effect of burning is loss of the insulating layer of organic matter. In northern latitudes where soils freeze or permafrost occurs, modifying the freeze–thaw relationship can have serious and long-lasting effects on soil structure and sediment production.

Mass movements.—Mass movement of soil is the predominant erosional process in steep high-rainfall forest lands of Oregon, Washington, British Columbia, and Alaska. The frequency of mass erosion events in forested watersheds is strongly linked to the type and intensity of land treatment in the basin (Rood 1984). Although most mass movements are associated with roads and their drainage systems, many originate on open slopes after logging has raised soil water tables and decreased root strengths (O'Loughlin 1972).

The increase in mass soil movement due to clear-cutting varies widely, ranging from 2–4 times in Oregon and Washington (Ice 1985), to 31 times in the Queen Charlotte Islands of British Columbia (Rood 1984). An increase of up to 6.6 times found by Howes (1987) in the southern Coast Mountains of British Columbia is probably closer to the norm. Although this is much lower than the increases associated with roads, the greater total area of clear-cuts may balance the net result on a weighted-area basis (Swanson and Dyrness 1975).

Much can be done to identify slopes susceptible to mass movements through the use of aerial photography and engineering analyses (Swanson et al. 1987). Howes (1987) developed a procedure—based on terrain mapping and slide occurrence—for quantitatively predicting landslide susceptibility after harvesting. It is usually impossible to harvest unstable hillsides without increasing mass movements, however, except perhaps when careful selective logging with helicopter yarding can be done.

When soils are mass-wasted into stream channels, their effects on salmonid habitats depend on the sediment-processing capability of the stream. They might be beneficial if they bring stable rubble and woody debris complexes to "sediment-poor" channels (Everest and Meehan 1981b). Many mass movements bring soil to higher-gradient reaches, however, and the sediment is carried downstream to a deposition zone where it severely impairs the stream's ability to support fish rearing and spawning.

Remedial measures are available to correct surface erosion problems, but they are costly and far from perfect. Correcting the effects of accelerated mass movements may require tens or hundreds of years, because it involves replacement of stable root systems and the creation of new soil. Measures to accelerate revegetation in severely disturbed areas should include planting deciduous trees, shrubs, and grasses; hydroseeding; and mechanically stabilizing gully systems (Megahan 1974; Heede 1976; Swanston 1976; Carr 1985).

Changes in Sediment Processing by Forest Streams

Sediment transport in forest streams involves the detachment and entrainment of sediment particles, their transport, and their deposition. The process repeats whenever flow velocities are high enough to move the stream's available material.

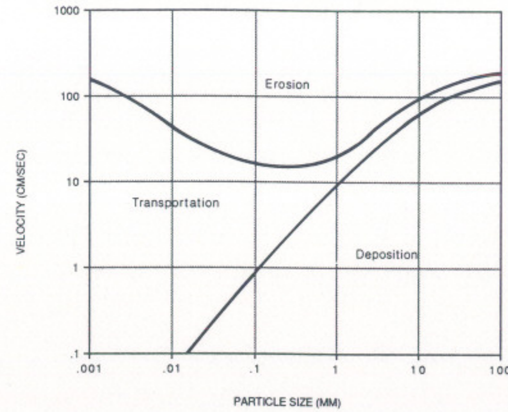

FIGURE 6.6.—Effects of water velocity on sediment particle sizes that are eroded, transported, and deposited in streams. The upper curve indicates the minimum velocities that erode particles of various sizes. Particles of 0.1–1 mm in diameter are the easiest to erode; smaller particles pack more tightly and are bonded by molecular forces, and the mass of larger ones makes them harder to move. The lower curve indicates the minimum velocities that keep particles moving once they already are in motion.

Forest harvesting directly affects these processes when it increases (or decreases) the supply of sediment, when it alters the peak flow or the frequency of high flows, and when it changes the structure of the channel by removing the supply of large woody debris that forms sediment storage sites (Megahan 1982). Bank erosion and lateral channel migration also contribute sediments if protective vegetation and living root systems are removed (Scrivener 1988a).

When additional fine sediments are placed in transport, the intrusion or infiltration of some of the particles into relatively clean or porous surface layers of streambed gravels occurs (Beschta and Jackson 1979). If the source persists, increased amounts may settle deeper into the streambed (Scrivener 1988a) and have longer-lasting effects on egg and fry survival (Hartman et al. 1987).

If the resupply of small sediments from upstream sources is reduced, such as below a debris jam, the gravels become more coarse. In the case of drastic losses of sediment supply, such as below a dam or road sediment trap, downcutting of the channel can occur (Church and Kellerhals 1978).

In streams with gravel beds, most bedload transport takes place during the few "channel-modifying" flow days of each year (see Figure 6.6). Analyses of the hydrologic effects of harvesting on sediment movement and channel change in these streams must focus on whether or not the frequency of such flows will be increased or decreased by the proposed harvest pattern.

Effects of Harvests on Channel Forms and Geomorphic Processes

The fluvial environment is part of a larger watershed ecosystem that includes the floodplain, living vegetation and root systems, and organic debris in and adjacent to the channel. Fish habitats result from a complex interaction among water, sediment, and channel structure. Forest management can affect all of these components, as well as the hydrologic and sediment transport processes discussed above.

Integrating Hydrology, Sediment, and Channel Structure

To anticipate the effects of forest management on fish habitats, one must project changes in the hydrologic and sediment processes against the structural framework of the channel. No single technique exists for this very complex task, although component models have been attempted (e.g., Simons et al. 1982; Sullivan et al. 1987). Descriptive studies, such as the Carnation Creek watershed study in British Columbia (Hartman et al. 1987; C. D. Harris 1988), have shown the results of integrated changes, but quantitative prediction remains difficult because of wide variability in forest streams and a general lack of data. Nevertheless, some important interactions among geomorphic processes are understood, and at least the qualitative magnitude and direction of harvesting effects can be anticipated. For example, streams in which structural elements such as embedded logs have been removed have lost stored sediment to downstream reaches and have generally degraded. When there are fewer "steps" in the stream's profile, more energy is released to move sediment, resulting in a simpler, higher-gradient channel with poorer salmonid habitat. Bisson et al. (1987) extensively reviewed the hydrologic role of large woody debris in channels.

Channel environments are very broadly of two types: alluvial channels, whose form is controlled by a balance between flow regime and the sediments of the valley bottom; and bedrock-controlled channels, whose form is dictated by external structure (bedrock). In both types of channel, large woody debris and tree roots can be secondary controlling structures.

Forest harvesting can affect alluvial systems by weakening channel banks, removing the source of large woody debris, altering the frequency of channel-modifying flows, and changing sediment supply. Unlike bedrock-controlled channels, the alluvial system must change its form in response to geomorphic changes until a new balance between aggradation and degradation has been achieved (Leopold et al. 1964). In alluvial channels, both the removal of bank vegetation and increased sediment supply cause channels to become wider and shallower with fewer pools and more riffles.

Channels with more structural control, such as bedrock in the streambed or banks, large tree root systems in the banks, or armor layers (large rocks), are more stable with respect to fluctuations in flow and sediment supply, and maintain narrower and deeper channels. Even very stable channels can be radically modified, however, by the catastrophic effect of debris torrents.

Off-channel fish habitats in the floodplain such as side and flood channels, ponds, and swamps also can be strongly influenced by forest harvesting. Even in large rivers such as the Willamette River in Oregon, the loss of debris jams and related multiple floodplain channels has vastly reduced channel and shoreline area (Sedell and Froggatt 1984; Figure 6.7).

A special case of side channels occurs in glacial systems, where the clear-water sections fed by groundwater or valley-wall runoff provide the only nonturbid

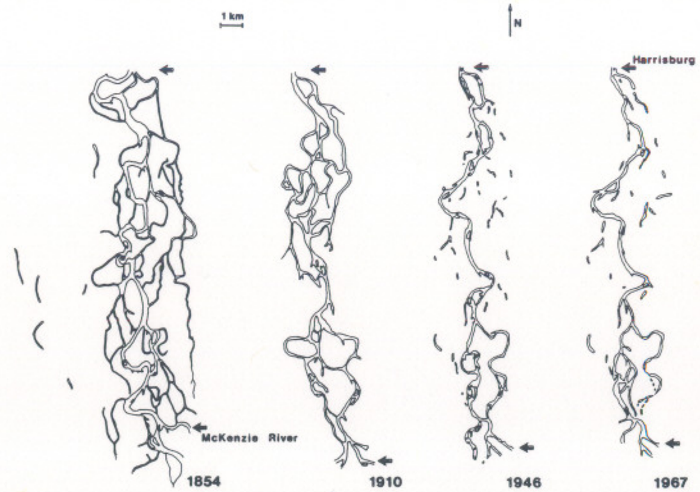

FIGURE 6.7.—Changes in the Willamette River channel, 1854–1967. Arrows show the locations of Harrisburg (top) and the McKenzie River tributary (bottom) in each panel.

habitat in the reach. These habitats are extensively used by rearing chinook salmon fry, and may be important for other species.

Geomorphic processes act over both time and space. If watershed erosion increases, for example, the "new" sediments may persist for long periods as they move through the system under the influence of different streamflows and form alluvial fans, bars, low terraces, sediment wedges behind stable woody debris, or even the streambank or floodplain itself (Hogan 1986). Hence, modifications to a stream system introduced in the early road-building phases of forest harvesting may have to be dealt with decades later when planning begins for the harvest of second-growth timber.

The interactions of hydraulic force, sediment, and channel structure result in geomorphic forms and features that, to a salmonid, are its habitat. We can interpret the hydraulic geometry of stream channels within the framework of fish habitat preferences (Sullivan 1986), and it is useful to focus on these habitat elements as a means of clarifying forest management influences on streams.

Channel Forms and Fish Habitat

Biologists describe stream habitats in terms such as pools, riffles, spawning gravel, obstructions, and side channels, and many classifications are available (e.g., Bisson et al. 1982; Helm 1985). These terms are also geomorphic entities, derived from the processes described above, and they are selectively influenced by different harvesting activities. We will briefly discuss these five habitat elements in the context of the geomorphic processes that control them.

Pools.—Pools are the result of local scour or impoundment induced by structural controls in the channel or streambank. Pools are areas of high water velocity during peak flows, but at low flow their depth creates a depositional environment for fine sediment. Hence, if timber harvesting increases the supply of fine sediments, these sediments settle preferentially in pools, which become less useful to fish. Similarly, if the structural element causing the pool to exist (such as a log or tree root) is removed, the pool will disappear after the next flood flow. Pools are thus very susceptible to falling and yarding operations that influence the availability of large woody debris in or near the channel margins.

Riffles.—Riffles are bars (sediment deposits) with water flowing over them. Because riffles represent the first material deposited after high flows, they usually contain larger particles (gravel, cobbles, and boulders) than are found elsewhere in the stream. Aggrading streams have more depositional areas, and hence have more riffles. Riffles are food-producing areas, but offer few habitats to small fish. Harvesting activities that increase sediment supplies increase the extent and number of riffles. Removal of instream woody structure steepens the stream gradient and hence increases the average size of particles in the substrate.

Spawning gravel.—Spawning gravel is the sorted product of bed scour and redeposition from which sand and finer material has been removed and transported downstream. The maintenance of good spawning gravel requires that the stream's normal sediment supply contain relatively low amounts of fine material, and that flows be sufficiently high to "sort" out the fines that do accumulate. These conditions are often associated with the hydraulic transition zones between pools and riffles; the more transition zones, the more spawning gravels there will be. Hence, harvesting activities that maximize the number of pool-forming structural elements and minimize the influx of fine sediments will favor the maintenance of spawning gravel.

Obstructions.—Obstructions, or barriers to fish migration, are more often associated with road engineering than with timber harvest alone. Culverts or bridges, for example, can cause water velocities to be greater than the swimming ability of small fish (Dane 1978a; Bjornn and Reiser 1991). Excessive debris accumulation, if plugged by sediment, can also block fish passage. Channel aggradation worsens the problem at low flows because water may move entirely below the surface, preventing fish from passing the affected reach. Natural barriers often reflect regional geologic history—resistant rock strata, volcanic intrusions, faults, former sea levels—and may control the distribution of anadromous species over a broad region.

Side channels.—Side channels occur in the stream's margin, or where water is forced out of the channel into the floodplain. Side channels are alternative channel locations, and will remain stable only if their structural controls (usually tree root systems) remain intact. They are vulnerable to timber harvesting in the riparian zone unless harvesting is done with the greatest of care, and they can easily be isolated by dyking or dredging for flood protection, or by road construction without adequate culverts. Side channels have a direct hydrologic relationship to runoff from the valley walls and to the valley groundwater table, and hence may be influenced by many forest management activities.

Summary of Harvesting Influences on Channels

Four major timber management effects can modify a stream's geomorphic process and forms.

- Substantial increases in peak flows or the frequency of channel-modifying flows from increased snowmelt or rain-on-snow events can increase bed scour or accelerate bank erosion. Quantitative assessments of channel stability (Pfankuch 1975) and an analysis of flows at which normal channel changes begin will help determine whether flow increases may be important.
- Substantial increases in sediment supply from mass movements or surface erosion, bank destabilization, or instream storage losses can cause aggradation, pool filling, and a reduction in gravel quality (Madej 1982). Assessments of initial habitat condition (Binns and Eiserman 1979; Bisson et al. 1982; de Leeuw 1982) and estimates of the natural variability in sediment regime (Swanson et al. 1982b) will assist in determining whether sediment-supply increases will be meaningful.
- Streambank destabilization from vegetation removal, physical breakdown, or channel aggradation adds to sediment supply and generally results in a loss of the channel structures that confine flow and promote the habitat diversity required by fish populations (Forward [Harris] 1984; Scrivener 1988a).
- Loss of stable instream woody debris by direct removal, debris torrents, or gradual attrition as streamside forests are converted to managed stands of smaller trees will contribute to loss of sediment storage sites, fewer and shallower scour pools, and less effective cover for rearing fish.

Cumulative Effects of Forest Harvesting

In earlier sections, we described how hydrologic, sediment, and channel processes can be changed by timber-harvesting activities, and hence can affect salmonid habitats. These processes operate over varying time scales, ranging from a few hours for coastal streamflow response to decades or centuries for geomorphic channel change and hill-slope evolution. They are also distributed spatially over the landscape, progressively influencing more land area as timber management extends within watersheds and across regions. The consideration of how harvesting influences the landscape and fish habitats through space and time is the subject of this section.

Identifying Cumulative Effects

Observing and identifying cumulative effects of timber management on biophysical processes or fish habitats are difficult, not only because of technical complexity but also because few research efforts have been sustained or focused over the necessary time periods. Nevertheless, some studies now help demonstrate cumulative effects of logging on streams, beginning with the Wagon Wheel Gap (Colorado) snow accumulation and melt experiment, started in 1910 (Holscher 1967), and carrying through to the Carnation Creek watershed study (Hartman 1988), which began in 1972.

In addition to long-term watershed studies, several specific research techniques exist to provide information about cumulative effects. These include time-series analysis of historical aerial photography, tree ring and similar vegetative dating techniques, and standard geologic techniques applied to recent sediment deposits. Systematic review of historical media and file reports has helped define management treatments and effects on Pacific Northwest river systems (Sedell and Froggatt 1984).

Finally, synoptic survey designs such as those of the Fish/Forestry Interaction Program in the Queen Charlotte Islands (Poulin 1984) can address cumulative effects by simultaneously examining many watersheds in various stages of forest-harvesting development. A synoptic survey design has been proposed for a major new research initiative by the Pacific Biological Station of the Canada Department of Fisheries and Oceans (I. Williams, personal communication).

Management actions to deal with cumulative effects suffer from constraints other than lack of information. The costs of dealing with cumulative effects often are large and must be borne by agencies or jurisdictions that may be reluctant to act because of poor short-term benefit:cost ratios. The question of future accountability for historical effects on public or private fisheries resources is increasingly important as management responsibility shifts to or from the private sector. The long-term effects of changes in physical processes on fish habitats are also confounded by various intensities of use by commercial and sport fisheries, and by urban and industrial development.

Despite these qualifications, the previous discussions of processes linking timber harvest and silviculture to salmonid habitats suggest five main categories of cumulative effects:

- changes in timing or magnitude of small or large runoff events;
- changes in the stability of stream banks;
- changes in the supply of sediment to channels;
- changes in sediment storage and structure in channels, especially those involving large woody debris; and
- changes in energy relationships involving water temperature, snowmelt, and freezing.

The time frame of these changes, especially in the context of normal forest management planning, defines their "cumulative" nature. The persistence of and recovery from changes in the stream ecosystem form a useful analytical framework for examining typical cases of cumulative effects.

Persistence and Recovery

Although change is a normal feature of stream ecosystems, the amount of change tends to vary within limits that are characteristic of a given stream when flow regime, sediment supply, and channel structure are not perturbed. Biological systems have analogous properties, both in individuals and in populations (i.e., homeostasis).

Geologists have also discovered that some rivers have historically undergone episodes of major sedimentation and erosion associated with hundred- or thousand-year events (Benda et al. 1987) and recent climate changes may have profound effects on channel equilibrium. However, we will consider cumulative effects in the time scale of forest-harvesting activity.

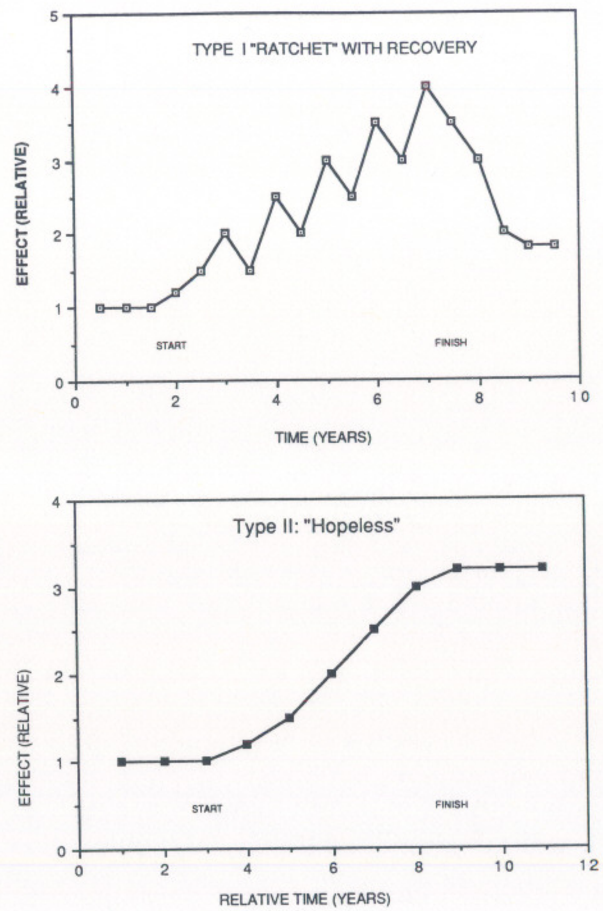

FIGURE 6.8.—Cumulative effects of forest harvesting on streams: type 1 (incremental but reversible changes) and type 2 (irreversible changes).

Foresters and other land managers purposefully impose changes on the ecosystem. We will examine four cases that illustrate different degrees of persistence and recovery. For convenience, they can be classified into two general types, those from which some degree of recovery is possible (type 1) and those from which it is not (type 2). Figure 6.8 graphically illustrates the two types.

Type-1 cumulative effect: incremental change.—Type-1 situations involve management-induced effects that individually are not overwhelming, but that, if compounded, will continue to force the stream into new configurations to the detriment of fish habitat. Type-1 cumulative effects can be corrected if necessary management actions are taken.

The history of forest harvesting in the South Fork Salmon River, Idaho (Platts and Megahan 1975), illustrates a case in which successful recovery occurred. An analysis of this system's history by Sullivan et al. (1987) identified accelerated sedimentation caused by logging and road construction as the source of sediments that gradually inundated pools and degraded gravel quality for spawning fish.

A 12-year moratorium on logging activity, together with watershed rehabilitation measures, allowed the stream to export the fine material; gravel quality was restored and pools were reestablished. The stream was able to recover because sediment input was controlled and because the riparian vegetation remained intact, preserving the structural framework required for normal pool formation and gravel-sorting processes.

Another case of incremental degradation is illustrated by Carnation Creek, British Columbia. In this experimental basin, treatments involving riparian-zone timber removal over a 5-year period, compounded by an upstream debris torrent, have destabilized extensive sections of stream bank and channel (C. D. Harris 1988). In these sections, the channel has widened and established side channels through the adjacent floodplain (Powell 1988). Gravel quality in lower sections of the stream has progressively deteriorated and shows no signs of recovery (Scrivener and Brownlee 1982, 1989).

Recovery in Carnation Creek may be possible if stabilizing riparian vegetation is reestablished, large woody debris is reintroduced to the channel, and sufficient time is allowed to flush accumulated fines from the stream gravels. Time required for recovery will depend on the extent of purposive management actions.

Type-2 cumulative effect: irreversible change.—Type-2 cumulative effects involve changes to the basic watershed processes from which recovery is not possible because of very long time requirements, permanent shifts in social and economic objectives that preclude the required management action, or both.

Sedell and Froggatt (1984) documented the history of the Willamette River from 1854 to 1967. To facilitate transportation and log driving, the river was gradually cleaned of log jams, debris, and streamside trees. Most side channels were logged and cut off, resulting in a much-simplified channel (Figure 6.7) that has vastly reduced shoreline and off-channel habitats. These habitats will never be recovered due to the necessities of navigation and alternative uses of the floodplain land. In some large rivers, however—such as the lower Fraser River, British Columbia—habitat creation to offset industrial alienation may be possible.

A second case of type-2 cumulative effects is illustrated by old-growth timber harvesting adjacent to medium-size or large rivers that depend on very large woody debris. Rivers such as the Yakoun in the Queen Charlotte Islands, British Columbia, depend on spruce log debris 1–3 m in diameter for channel structure and bank stability (de Leeuw 1988). As a result of their loss, the channel is widening and redistributing stored gravel through processes similar to those in Carnation Creek.

Current forest management practices in the Queen Charlotte Islands call for a managed second-growth stand of 80- to 120-year-old trees, so a permanent shift in the size distribution of available large woody debris seems inevitable. This condition is replicated throughout the Pacific Northwest as industrial forests are converted from old-growth to managed stands. Its reversal will depend on implementing a rotation age of 300 or more years for riparian stands. Other resource values (e.g., wildlife and recreation) may contribute to the feasibility of this option in some areas.

These examples clearly show that forest-harvesting activity can have lasting and cumulative effects on fish habitat. Whether the effects can be overcome depends partly on the degree to which stream processes are distorted but more importantly, on the management time scale within which action can be taken. The next section discusses management options to minimize undesirable and maximize desirable effects on salmonid habitat.

Conclusions and Management Options

Management options for ensuring productive fish habitat have evolved considerably over the last 10–20 years as we have learned more about how stream and forest ecosystems function. In this section, we briefly examine the evolution of some successful logging guidelines and then some new directions that may be available for habitat management over the next few decades.

Evolution of Logging Guidelines

In the 1950s and 1960s, planning for fish habitat management took place, if at all, on the streambank, with a biologist and a forester examining the site and using experience and persuasion to arrive at an acceptable management plan. Decisions were usually made with the information at hand for that site, and supported by the policies of the agency with controlling jurisdiction. Much was assumed about what was good or bad, and stream "cleaning" was very popular. Many wheels, both round and square, were reinvented at each "on-site" inspection.

During the 1970s, fisheries agencies became increasingly involved in forest harvest planning and assessment, and began to consolidate and codify approaches to habitat management under various regulatory bodies for forest practices. This had the advantage of encouraging consistency, but the disadvantage of inflexibility with respect to differences among sites and processes. The early "P" or protection clauses used in British Columbia are good examples of guidelines that became inflexible rules (Brownlee and Morrison 1983).

Early guidelines tended to focus on practices that influenced water quality because research on large woody debris and channel geomorphology was not well established. There was considerable reliance on the mitigating influence of the streamside "buffer zone" of arbitrary width (e.g., 10 chains), without reference to the biophysical processes it was influencing. Stream classes, when used (Oregon, Washington), were based on relatively simple criteria such as species "significance" or stream width (e.g., 1 m, 10 m).

During this era, numerous guidelines were developed that specialized in regionally limited procedures for particular forest practices. For example, Packer and Christensen's (1964) classic handbook on how to retard the surface transport of sediment on interior slopes still has application, and many jurisdictions (e.g., Toews and Wilford 1978; Harr 1981) proposed total cut limitations (percentage of watershed) to minimize runoff impacts.

However well intentioned, guidelines tended to become rules and even were incorporated into law in many states. Yet, as we have seen in this chapter, the quality and care with which logging is carried out can have much more bearing on fish habitat quality than what is specified in a planning document. In the 1980s, this knowledge was explicitly recognized in the development of the British Columbia Coastal Fishery/Forestry Guidelines (B.C. Ministry of Forests et al. 1988). In this document, state-of-the-art guidelines are presented as possible means to achieve various defined levels of habitat protection, which, in turn, are related to a stream reach's fishery value. However, the opportunity to devise better ways of meeting these levels of protection is left open to the initiative of the industries and agencies involved. This management philosophy is consistent with two important factors in guideline evolution today: the increasing "privatization" of public resource management responsibilities, and the increasing use of detailed site information and models instead of generalized guidelines.

New Directions

The challenge of resource managers today is both to understand the watershed processes that are important for a given decision and to have enough site information about that watershed to apply the knowledge. This book contributes to the first objective and suggests important types of data that should be gathered, but neither will be of much value without a management framework in which they can be used.

Two important ingredients are necessary to take advantage of *both* knowledge and data. The first is a cooperative attitude between agencies and industry, predicated on commitment from the most senior political levels to the integrated and sustainable management of resources. The second is the development of a technical information infrastructure that makes possible the sharing of knowledge and information *in the planning and decision-making environment*. Both the political and the technical support legs must be in place to move beyond the "spearchucking" days of the not-too-distant past.

Several extensions of current forestry and fisheries management policies have been suggested in previous sections. We list here some that we feel may contribute to the new directions we are seeking.

- *Long rotations*. Large trees have been proven necessary for the maintenance of channel integrity and productivity in most forest streams (Kaufmann 1987). They also contribute to many nonfisheries values. Yet rotation ages of more than 120 years (and much less on high-site land) seem absent from harvesting plans, despite their technical and economic feasibility. Urgent reevaluation of management strategies for remnant old-growth and older second-growth forests seems warranted.
- *Clear-cut stability modeling*. Distributed small-patch cuts have important advantages in some ecosystems, especially where snowpack manipulation is a priority. However, their universal application as a magical panacea, as with "leave strips" (strips of uncut trees between patches) is inappropriate in unstable or windthrow-prone terrain where road construction and edge effects should be minimized. In either situation, stability modeling would provide important management direction, and is almost universally lacking in normal harvest planning.
- *Privatization*. Some policy analysts (e.g., Pearse 1988) have suggested that the private sector (forest industry) should be given an increased role in the management of fish habitats in exchange for options on the forest resource. This approach offers savings of public management moneys in appropriate jurisdictions, but will be effective only if desired habitat and fishery values can be identified (Platts 1974; Paustian et al. 1983) and an effective performance audit is supported.
- *Regional index streams*. Very little stream assessment occurs after timber is harvested. Yet the postlogging condition of habitats is the best indicator of adequate harvesting practices. Index streams, considered typical of a regional situation, could be monitored as a check on policy similar to the ambient water quality monitoring of many states and provinces, and the index survey streams of the U.S. Geological Survey. When carried out over several decades (as, for example, in Carnation Creek), these assessments would focus discussion on processes and practices amenable (or not) to change. Without such assessments, most discussions about cumulative effects will remain academic.
- *Accelerated habitat restoration and enhancement*. In addition to maintaining existing stream habitats, managers need to identify opportunities to restore degraded streams to productive capacity. In most streams this means recreating geomorphic structures and sediment-storage opportunities through techniques such as placing logs or boulders, augmenting off-channel habitats, restoring riparian vegetation, and rebuilding fisheries stocks. A combination of restoration and enhancement measures may be necessary. For detailed examples see Canada Department of Fisheries and Oceans and B.C. Ministry of the Environment (1980) and Bustard (1984).

We conclude this section on management options, as we began the chapter, by suggesting that both timber and fish can be successfully managed in a watershed if timber and fishery managers communicate their needs and coordinate their activities. The technical knowledge base is more than sufficient if the necessary policies and attitudes are in place to support its use.

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