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CHAPTER FOUR

Fine Sediment and Salmonid Production: A Paradox

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ABSTRACT The term "sediment," as commonly used by fishery biologists, means fine sediment and excludes up to 90% of sedimentary material in streams. In mountainous terrain, hillslope erosion (primarily mass soil movements) provides periodic inputs of sediment into stream systems, often during periods of high flow when two major sediment transport mechanisms are active: (1) suspended sediment transport and (2) bedload transport. Suspended sediment consists primarily of silt and clay-size particles that may be rapidly transported downstream and locally deposited on floodplains and overbank storage locations or that may infiltrate into gravel interstices of the bed. Bedload transport, consisting primarily of coarse sands or larger particles, is complex and sporadic, and has major implications regarding channel morphology and the quality of spawning gravels. It is greatly affected by large roughness elements (logs, boulders, bedrock outcrops, etc.). Hence the impacts of sediment on fish habitat are influenced by both sediment availability and the subsequent routing of these materials through the channel system.

The effects of fine sediment on aquatic life have been studied intensively for more than three decades, both in situ and in the laboratory. Laboratory studies have demonstrated potential negative effects of fine sediment on macroinvertebrates, on survival and emergence of salmonid embryos and alevins, and on growth of salmonid fry. But there are significant difficulties in extrapolating these findings to the field. Nearly all laboratory survival studies have used simplified unnatural gravel mixtures to test incubation and emergence of salmonid fry. Also, mitigating factors in streams, such as structural roughness elements and spawning behavior of female salmonids, complicate direct field application of laboratory studies. Nevertheless, forest practice rules designed to minimize fine sediment and turbidity in streams have resulted primarily from laboratory studies. The relatively few studies dealing with the effects of sediment from forest management in natural environments have been less conclusive. Some negative effects observed in the laboratory also occur from acute or chronic sedimentation in the field. The problem with interpreting the results of field studies is that increased fine sediment from forest management is almost always accompanied by other environmental effects. Also, field studies have shown both increases and decreases in salmonid populations associated

with forest management. The studies have generally failed to isolate the effects of fine sediment from other habitat changes.

A more holistic view of the role of sediment in stream ecosystems is needed. Undisturbed streams in forests have stored abundant sediments in their channels and maintained an equilibrium between sediment input and sediment routing. An abundance of large organic debris and other roughness elements played an important role in the storage and routing of sediments. Forest management has broadly changed sediment storage and equilibrium in streams throughout much of the western United States. The general result has been a concurrent loss of roughness elements and accelerated routing of sediment through fluvial systems. There is evidence that stable channels containing stored sediment and large organic debris are more productive at every trophic level than either degraded channels mainly devoid of sediment or channels that are aggraded and unstable. Thus there seems to be a broad middle ground between too much and too little sediment in salmonid habitats.

Forest practice rules designed to minimize introduction of fine sediment into streams are justified, but in themselves do not ensure protection of salmonid habitats. These rules might result in improved water quality and a reduction in fine sediment in gravels, but they do not ensure protection of the physical structure of salmonid habitats. In fact, large losses of productive habitat have occurred while these rules were in force. The long-term emphasis of forest practice rules on control of water quality and fine sediment must be expanded to a more holistic view of salmonid habitat. Protection of streamside vegetation and physical structure of rearing habitat for juvenile salmonids must be given equal emphasis.

Webster defines sediment as "material, or a mass of it, deposited as by water." Sediment thus would include a broad array of inorganic particle sizes, ranging from large cobbles to silt, as well as particulate organic material. Fishery biologists, taking a narrower view, have generally defined sediment as finely divided inorganic waterborne material below a certain specified diameter, usually several millimeters or less. Consequently, the term "sediment," as commonly used by fishery biologists, usually means fine sediment and excludes much of the sedimentary material in streams.

An inverse relationship between fine sediment and the reproductive success of salmonids was first reported by Harrison (1923). Several studies since that time have refined our knowledge of the effects of fine sediment on salmonid populations. But the state of our knowledge remains at a rudimentary level, because only the simplest aspects of interactions between sediment and salmonids have been explored. Studies conducted during the past few years--some not yet published--have made new and significant contributions, but much work remains to be done and many questions are still unanswered.

Because of the complexity of aquatic ecosystems, the relationships between sediment and salmonids have usually been studied in the laboratory where natural variability and complex biological and physical interactions can be minimized. Most studies have originated from environmental impact assessments and, by design, have investigated potential negative effects of fine sediment, even though some fine sediment appears to be an integral and essential part of healthy aquatic ecosystems and can exert a positive influence on salmonid production. The majority of laboratory studies have emphasized the effects of fine sediment on survival of salmonid embryos and emergence of fry in the intragravel environment, but few have attempted to extrapolate the results to the field. Other laboratory studies have investigated the effects of suspended sediment on survival, growth, and migration of salmonids, but the results of such studies have rarely been accurately transferred to natural salmonid habitats.

The past focus on effects of deposited fine sediment on salmonid reproduction and of suspended sediment on salmonid survival and growth has diverted attention from the more insidious effects of sedimentation on stream morphology and habitat structure. Changes in the sediment equilibrium in streams can cause channel aggradation, instability, and substantial change in freshwater rearing habitat of salmonids. Channel changes from accelerated sedimentation resulting from forest management have been recognized and documented (Lyons and Beschta 1983, Sullivan, this volume), but related changes in salmonid rearing habitats, population size and structure, and fish community structure are poorly documented. Part of the reason is that forest management activities cause multiple changes in aquatic ecosystems, and isolating the effects of sedimentation is difficult.

The physical, chemical, and biological components of aquatic ecosytems interact in complex and variable ways, and studies of sediment-salmonid interactions have not addressed this complexity. The relationship needs to be examined in a broader context. The question is not whether sediment reduces survival of salmonid embryos or growth of juveniles, but rather when is sediment a factor limiting production of salmonid populations? To answer this question, the effects of sedimentation must be considered within the context of the total freshwater life history of each salmonid species and the ecosystem within which it resides.

The overall effect of fine sediment on salmonids is related to the species and race of fish, duration of freshwater rearing, spawning escapement within a stream system, presence of other salmonid or nonsalmonid species, availability of spawning and rearing habitat, stream gradient, channel morphology, sequence of flow events, basin lithology, and history of land use. These factors are highly interactive and in combination can be either synergistic or antagonistic. The number and interactive nature of these factors preclude simple generalizations regarding the effects of sediment on salmonid populations. The purpose of this paper is to examine state-of-the-art knowledge of the effects of sediment on salmonids. A clearer perception of the relationship is emerging from recent studies that have provided some new and more accurate perspectives.

FOREST MANAGEMENT AND SEDIMENT PRODUCTION

Mass soil movements are the predominant erosional processes in forest environments of the Pacific Northwest (Swanston 1974, 1980, 1985, O'Loughlin and Pearce 1984, Ice 1985, Sidle et al. 1985, Swanson et al., this volume), and they supply large quantities of soil, rock, and organic materials to streams. The transport of these materials to the fluvial system may be slow, as in soil mantle creep, or rapid, as in debris avalanches and flows. Such pulses of material are often large enough to overwhelm temporarily the transporting capabilities of a stream; hence deposition occurs along and in the channel.

Although most mass soil movements appear to be initiated by large rainfall or runoff events, local site and terrain conditions have a controlling influence on the effects of subsequent hydrologic events and management activities. A wide range of studies have shown that activities associated with forest operations (road construction and maintenance, harvesting, slash disposal, and site preparation) can significantly influence the availability of sediment to streams (Ice 1979, 1985, Brown 1983, Sidle et al. 1985).

Forest roads can substantially increase the frequency of mass soil movements in steep watersheds. The effects of roads on hydrologic processes and sediment availability generally increase with the steepness of the terrain. Because of the variety of potential failure mechanisms, managers need a wide range of skills in locating and designing roads, in soil mechanics and in hydrology, so that road construction practices can be adapted to match terrain features (Yee and Roelofs 1980).

Road surfaces can be major nonpoint sources of fine-grained sediments. Gravel surfaced logging roads can produce large amounts of sediment when they are used by logging trucks (Reid and Dunne 1984). In the Clearwater River basin in Washington, for example, the amount of material less than 2 mm diameter that washes off roads can equal the amount produced by landslides.

Even in areas with unstable terrain, only a small percentage of the total land base is usually affected by natural or road-related failures. In contrast, a large proportion of the stream system can be affected from direct inputs of sediment from these failures, and subsequent sediment transport downstream. Hence, even though on-site costs associated with road-related failures (land taken out of production, reduced growth of trees, road reconstruction and repair) may often be small, the large proportion of stream systems affected by such failures can have substantial costs in terms of impacts on fluvial systems and aquatic resources.

Timber harvesting operations have variable effects on sediment production. If timber is not felled directly into stream channels, felling and bucking usually have little direct impact on mass soil or surface erosion processes. Buffer strips, in addition to their role in controlling temperatures, may be effective in preventing disturbance to stream channels during the felling and yarding operations (Dykstra and Froehlich 1976, Steinblums et al. 1984).

Yarding operations can cause extensive ground disturbance in harvested areas; however, cable systems that partly or fully suspend logs generally cause minimal disturbance to the soil surface. Tractor logging, even on gentle terrain, can result in considerable ground disturbance and soil compaction. Much of the rapid transmission of water from the surface to the groundwater table during storms is through macrochannel networks formed from decomposed root systems (Hetherington 1982). The relatively high percentage of bare and compacted ground associated with tractor logging can reduce access and capacity of these subsurface channels, causing soil slumps and increased surface erosion. The effects of compaction are especially important, because they have long-term consequences on the hydrologic characteristics of soils and the potential productivity of second-growth forests (Froehlich and McNabb 1984).

After forest trees are felled, bucked, and yarded, slash disposal and site preparation practices are usually implemented to provide for improved seedling growth, ease of planting, and reduced fire hazard. The effect of these practices on local site erosion depends on several factors: (1) Intensity of disturbance. For example, where fire is used following logging, a "cool" burn may create no adverse hydrologic or soil erosion effects. In contrast, a relatively "hot" burn may create extensive areas of bare soil and localized hydrophobic conditions analogous to the effects of catastrophic wildfire. Another example is the use of tractor piling and burning that can cause extensive compaction, as opposed to broadcast burning with essentially no associated compaction. (2) Areal extent of the disturbance. Practices that expose soil over wide areas would be expected to have higher on-site losses of soil than those with relatively small areas of exposed soil. (3) Proximity of the disturbance to the channel system. Because of the relatively large amounts of soil and sediment in storage along many channels, activities close to the channel are more likely to cause accelerated erosion than those conducted farther from the channel, especially if riparian vegetation is killed and streamside roots die and decompose. Such loss of root strength can accelerate channel erosion (Hartman et al., this volume).

For almost all forestry activities (road building, yarding, and site preparation), as hillslope gradient increases, so does the potential for accelerating the entry of soil, rock, and organic debris into channel systems. Hence management practices in steep terrain usually need to be modified so that their potential effects on slope stability are minimized. Even though our general appreciation of the importance of mass failures in shaping landscapes and influencing stream systems has increased greatly in the past several decades, our understanding of cause and effect and the application of this knowledge has perhaps not kept pace.

SEDIMENT PROCESSING BY FOREST STREAMS

The process of sedimentation involves (1) detachment and entrainment of individual particles by flowing water, (2) transport, and (3) deposition. Thus sediment transport within the stream system involves the integration of processes operating on many temporal and spatial scales. Mass soil movements not only provide a wide range of particle sizes for transport but also can physically modify channel characteristics and thus influence fluvial transport processes.

Once soil and organic materials have arrived at a channel, their continued downstream movement (if any) will depend on many factors, including characteristics of the materials (particle sizes and amounts), hydraulic forces (frequency and magnitude of high flows, size of stream, etc.), and the occurrence of large "roughness elements" (large trees and root systems, boulders, bedrock outcrops, etc.) that provide stability to many channels.

Streams are integrated systems whereby processes operating in individual reaches affect those in other reaches. For example, within a given drainage basin, the first- and second-order streams in headwater catchments usually have steep gradients and are thus efficient at moving sediment downstream. As this sediment works its way downstream, it encounters a general decrease in channel gradient where deposition, particularly for the coarser size fractions, may occur. The occurrence of local or widespread deposition along a reach may encourage channel instability and cause the channel to migrate laterally. Such lateral migrations, if unhindered by streamside vegetation or other large roughness elements, may undercut the toes of adjacent hillslopes and further increase the availability of sediment to the stream. Hence, once a pulse of sediment from a mass soil movement enters a channel, continued downstream changes in channel form, composition of the banks and bed, and other features may occur.

The magnitude of channel changes associated with a given input of sediment depends on the amount of sediment, the period during which it becomes available to the channel, the particle size composition of the sediment, and the characteristics and stability of the channel. Fine sediments are more easily moved downstream and through the stream system; larger particles have longer residence times and a greater influence on channel morphology.

When fine sediments are in transport, the intrusion or infiltration of some of the particles into relatively clean or porous streambed gravels will occur. Intrusion of fines may occur initially in the upper 10 cm of the streambed (Beschta and Jackson 1979). If the source of fines persists, increased amounts of fines may settle deeper into the streambed as the gravels are exposed to more and larger freshets (Scrivener and Brownlee, in press). Thus residence times are also a function of the depth to which intrusion occurs.

Two modes of sediment transport are typically delineated in streams: (1) suspended load transport, whereby the turbulence of flowing water is sufficient to entrain and maintain particles in suspension (typically clay and silt sizes <0.1 mm in diameter), and (2) bedload transport. During freshets, bedload generally consists of particles >1 mm in diameter, which roll, slide, or saltate downstream close to the bed. Although fine to coarse sand-size particles (approximately 0.1 to 1 mm in diameter) are usually transported as bedload, these particles can also be carried as suspended sediment depending on local hydraulic conditions.

The transport of suspended sediment can occur over a wide range of flow conditions. Because the hydraulic forces required to keep these particles in suspension are relatively low, once entrained they are rapidly moved downstream. Most of the suspended sediment carried by mountain streams is transported during periods of high streamflow. As flows increase during a major streamflow event, both flow velocities and wetted perimeter similarly increase. There is also a headward extension of the stream system (as intermittent and ephemeral channels come into play), resulting in an increased channel network and adjacent source areas for both runoff and sediment. The net result is that rising limbs of storm hydrographs usually have greater concentrations of suspended sediment than during receding flows; early runoff events of each fall have greater concentrations than similar flow events in the winter or spring. For snowmelt systems associated with higher elevation watersheds in the Pacific Northwest, the rising limb of the snowmelt hydrograph will carry most of the sediment.

Nearly all forestry operations create some degree of soil disturbance. If these activities result in appreciable bare soil with an associated increase in surface erosion or a greater frequency of mass failures, increased sediment delivery to a channel can be expected. Because of the ease of transport associated with clay- and silt-size particles, such particles move downstream at a velocity similar to that of the flowing water, with little opportunity for deposition. Some of these fines, however, may be trapped in gravel substrates (Beschta and Jackson 1979, Adams and Beschta 1980). The intrusion or infiltration of fines into streambed gravels can thus alter the quality of the bed for spawning by fish or for use by other instream biota.

Increases in turbidity are directly related to increased concentrations of suspended sediment in streams. Thus turbidity can be used as a surrogate variable for indexing relative sediment concentrations (Beschta 1980). Both suspended sediment concentrations and turbidity are relatively sensitive indicators of changes to instream sediment availability brought about by natural or man-caused factors.

The downstream routing of bedload sediment is controlled by interactions between bedload particle sizes, channel morphology, and flow conditions to produce the complex hydraulic conditions necessary for transport (Leopold et al. 1964, Richards 1982). The average downstream velocity of bedload particles is much slower than that of the water. Because particle velocities are dependent on size, larger particles move more slowly and shorter distances than smaller particles. Thus, as portions of the channel bed or banks undergo scour, transport, and deposition, a sorting process occurs (Keller 1971). Smaller bedload particles are transported farther and faster downstream, leaving the larger particles behind. Additional fine bedload sediments are continually available from upstream sources, and thus the particle size composition of the deposited gravel bed reflects a balance of several factors operating simultaneously. If the resupply of smaller bedload particles from upstream sources is reduced, the deposited gravels should reflect a coarsening (i.e., an increase in median particle diameter and a concurrent decrease in "percent fines"). This phenomenon is often apparent immediately below debris jams, which can act as sediment traps. Conversely, if upstream sources of fine bedload sediments are increased because of natural or human factors, an opposite change in the particle size distribution of the deposited gravels should occur.

Because relatively high flows are required to disrupt the armor layer of gravel bedded streams, significant bedload transport in many streams may be limited to only a few days each year. It is during these brief periods that important and long-term changes in channel morphology and composition of the bed material occur. For example, if large amounts of bedload sediments were to enter a channel from a mass failure, localized deposition would be expected near the point of entry and would result in pronounced channel changes. If, however, the increased bedload sediments came from several smaller sources scattered along the stream, changes in channel characteristics could be relatively subtle. In any case, increases of bedload sediments to a stream will result in increased storage, hence changes in channel morphology. If the original channel was a single, well-defined channel and had frequent and relatively deep pools and a small width-to-depth ratio, then additional bedload sediments would be expected to decrease the number and depths of pools. Persistent increases in bedload sediments may also cause widening of the channel and loss of well-defined banks. Ultimately, a braided channel characterized by several small channels at low flow, midchannel point bars, and a wide shallow channel at high flows will result. Recovery of the channel to its original form is generally a much slower process.

Excessive aggradation of channels with coarse-grained sediments can cause reaches of streams to become dry in summer as surface flows infiltrate and percolate through the substrate. As a result, formerly productive anadromous streams have been converted to dry channels. Although these channels often have plentiful spawning gravels in winter, their usefulness as summer rearing habitat has been lost. These situations have been observed in western Oregon and Washington, but the extent of the problem has not been documented for the entire Pacific Northwest.

Where channels have relatively uniform morphology and are "sediment poor," mass failures may create diversity in channel characteristics and longitudinal profiles by adding accumulations of boulder, rubble, gravel, and woody debris. In these situations, the sediment inputs may have long-term beneficial effects on fish habitat (Everest and Meehan 1981). Thus mass failures have a variable role in their influence on channel morphology and their effect on aquatic habitat for fish and other organisms.

In low gradient channels (<5%) that are not "sediment poor" or bedrock controlled, the depth and occurrence of pools may be one of the most sensitive indicators that the amount (or size) of bedload sediment is changing. Increased coarse sediment will fill pools as the stream adjusts. If bedload increases are large and occur over a sufficiently long time, channel banks will eventually deteriorate because of increased shear stress, and stream widening will occur. The removal of streamside vegetation or large woody debris along the banks during logging may also initiate a widening of the channel or may aggravate the effects of sedimentation (Toews and Moore 1982). Root systems of live trees occupying channel banks can locally influence channel characteristics for decades and even centuries. Once the trees die and fall into a stream, they can affect channel features for long periods. Woody debris (primarily the bole and attached roots system) can thus have long-term impacts on the morphology of mountain streams. Although localized channel erosion can occur, the entry of large woody debris into a channel system generally lowers local channel gradients (by creating a step-pool longitudinal profile or increased channel sinuosity) and thus slows the downstream routing of coarse sediments. Management practices that affect streamside vegetation, woody debris in the channel, or the availability of bedload sediments can therefore have long-term impacts on channel characteristics (Beschta and Platts 1986).

Land managers must continue to recognize the important effects that their activities can have on erosional processes. Where the potential for accelerated erosion exists, preventative or mitigative measures can often be implemented to ensure that management activities will not cause significant adverse on-site effects. Unreasonable impacts on stream ecosystems can thus be avoided.

FOREST MANAGEMENT AND SEDIMENTATION

The effects of forest management activities on salmonid spawning habitat have ranged from severe to undetectable. Probably the most severe effects occurred in the South Fork Salmon River, Idaho (Platts and Megahan 1975). Fifteen years of heavy logging and road construction in the South Fork basin in the Idaho batholith, followed by large floods in 1962, 1964, and 1965, caused massive sedimentation in the river. Roads were the largest contributor of sediment (Megahan and Kidd 1972). Spawning, rearing, and holding habitats of summer Chinook salmon and summer steelhead were inundated with fine granitic sediments. In 1966, fine sediment in spawning areas ranged from 45 to 80% particles <4.7 mm diameter, and holding pools for adults were filled with sediment to a depth of 2 m or more. A moratorium was declared on timber harvest and road construction in the basin in 1966. By 1974, fine sediments in spawning areas had decreased to near optimum levels (12 to 26%) for the basin, and sediment in pools had been mainly removed by spring freshets.

Another example of massive sedimentation related to land management, roads, and a major runoff event occurred in Zayante Creek, a tributary of the San Lorenzo River, California (Coats et al. 1985). Historically the San Lorenzo River and its tributaries had large runs of steelhead trout (>20,000) and coho salmon (2,500 to 10,000), but by 1979 anadromous runs in the basin had greatly declined because of forest management, grazing, quarrying, and urbanization. Habitat damage was related to sedimentation of spawning gravels and filling of pools, degradation of water quality, diversion of streamflow, and barriers to migration (Santa Cruz County Planning Department 1979). In January 1982, a storm with a recurrence period of 100+ years struck the Zayante basin, causing major landsliding and aggradation of all reaches of the stream channel. Pools in both lower Zayante Creek and the San Lorenzo River were filled with sediment, and many riffles were completely covered. Steep gradient reaches of Zayante Creek recovered rapidly as sediment was transported downstream. The lower reaches of Zayante Creek and the San Lorenzo were still inundated with sediment the following year and are expected to remain so for several years. Additional damage to the habitat of anadromous salmonids is expected as upstream sediments are transported and deposited in low gradient downstream reaches.

Other studies have shown smaller increases in fine sediments in stream substrates after logging and road construction. The effects on salmonids have been variable but usually less severe and of shorter duration when the size of sediment source areas was quickly reduced. For example, Burns (1972) found increases in sediment in the South Fork of Caspar Creek, California, after road construction and logging (some road waste was sidecast directly into the stream), and the effects persisted for at least two years.

In a detailed study of the effect of sediment on pink salmon in Alaska, the percentage of fine sediment <0.83 mm in diameter increased in all study areas for six years during logging and remained at elevated levels for three years after logging. Fines increased 6 to 8% as a result of logging (Smedley 1968, Kingsbury 1973), and low survival of the 1966 brood of pink salmon was attributed to sedimentation of spawning areas (Smedley et al. 1970). Substantial increases in fine sediments were observed in the Harris River, Alaska, after logging, but sediment levels returned to normal within five years (McNeil and Ahnell 1964, Sheridan and McNeil 1968). Significant increases in fine sediment related to logging have been demonstrated on other Alaska streams, although the increases generally lasted less than five years (Sheridan et al. 1966, Sheridan et al. 1984).

Cederholm et al. (1981) found increases in fines in the bed of the Clearwater River, Washington, and related the increases to the amount of roading in the basin. They concluded that when the area of logging roads exceeded 3% of the basin area, the intragravel fine sediment would be likely to exceed levels found in undisturbed basins. Although the increases in fines in the Clearwater appeared to be persistent, they rarely exceeded 20% for particles <0.83 mm in diameter, a level generally considered detrimental to salmonid reproduction. Data from the Carnation Creek watershed study, Vancouver Island, British Columbia (Scrivener and Brownlee 1982), indicate an increase in fines between 0.3 and 9.6 mm in diameter within the top 12 cm layer of riffle gravels three years after logging was begun. As streambank root systems decomposed over the next five years and large winter freshets redistributed large organic debris in the stream, more fines accumulated and intruded deeper into the bed (Scrivener and Brownlee, in press). Changes in riffle gravels are still accelerating eight years after logging. Other studies (for example, Bachman 1958, Fredriksen 1970, Anderson 1971, Brown and Krygier 1971, Swanson and Dyrness 1975) have also reported increases in suspended sediments after roading and logging.

Other studies investigating the relation between logging and fine sediment in stream gravels have shown no significant differences between logged and unlogged areas (e.g., Burns 1972, North Fork Noyo River; Moring 1975, Alsea watershed study; Sheridan et al. 1984, Alaska). Although all these studies showed temporary minor increases in sedimentation related to logging, statistically significant differences from prelogging conditions could not be demonstrated. Moring and Lantz (1974) studied twelve western Oregon streams for one year before and one year after logging. Logging methods included clearcutting with buffer strips, clearcutting without buffer strips, and road construction with partial thinning. Several effects of logging, including changes in gravel composition, were observed. The percentage of fine sediment <3.3 mm in diameter in gravel increased in six streams after logging and either decreased or remained unchanged in six. The largest increases (20 to 50%) in sedimentation were related to road construction or clearcut logging on both streambanks without benefit of buffer strips. Only one of four streams with clearcutting and buffer strips showed an increase in intragravel fines. Distribution of fine sediments in gravels varied much more after logging.

Without further exhaustive review of the literature, some conclusions become apparent. Erosion after timber harvest and roading can increase fine sediment in streambed gravels and can fill pools and other habitats with sediment. The degree to which this occurs varies greatly and is based on physical phenomena and the type and extent of activity (Swanson et al., this volume). Cederholm et al. (1981) pointed out that sediment increases in the Clearwater River were associated with pre-1972 roads that were not built to refined engineering standards. Current forest management practices are undoubtedly better than those used a decade or more ago and probably contribute less total sediment to streams than their predecessors did.

Major changes in forest practices have occurred in the Pacific Northwest in the past ten to fifteen years, including better road engineering, improved yarding systems, changes in harvest scheduling, and treatment of slash. The extent to which improved forest practices reduce the potential for sedimentation, however, is not known. Many of these practices have not been fully tested, since much of this area has not experienced major storm and runoff events during that time.

VARIABILITY OF FINE SEDIMENTS IN STREAMBEDS

Variability is the key word used to describe the amount and texture of fine sediment in the substrate of western rivers and streams occupied by resident and anadromous salmonids. On a macroscale the variability is related to geographic, geomorphic, geologic, meteorologic, and hydrologic differences that combine in numerous permutations throughout the West. On a microscale, parameters such as stream gradient, channel morphology, watershed slopes, armor layer, hydrograph shape, and land use influence the quantity of fine sediments in streams

(Adams and Beschta 1980, Hall and Ice 1981, Beschta, in press). These physical characteristics of watersheds, at both the macrolevel and the microlevel, are responsible for wide variation in fine sediment between streams, between riffles of the same stream, and even within riffles of the same stream.

Variability Between Streams

The topography of Pacific coastal regions is dominated by geologically young steep lands characterized by rapid uplift, high annual precipitation, and rapid downcutting. Interior lands of the West are generally older, are more geologically stable, and receive only moderate amounts of precipitation. Precipitation in the West is variable not only in amount but also in form and intensity. Along the coast and in interior valleys of Washington, Oregon, and British Columbia, precipitation occurs mostly as winter and spring rains of varying intensity, whereas high elevation coastal areas and most of the interior West receive precipitation mostly as snow. The result is a radically different annual hydrograph and regimen of stream energy for these major climatic zones (Figure 1). Northern interior British Columbia and southeastern Alaska are characterized by moderate to heavy rainfall in spring, summer, and autumn, and moderate accumulations of snow in winter. This creates another variation in the annual hydrograph. Systems that are primarily fed by springs also influence the type of annual hydrograph. The ability of streams to move or store bedload sediments is directly related to basin relief and the regimen of annual runoff.

The parent material in a basin, its weathering rate, the texture of sediment and soils produced through weathering, and erodibility also have a great influence on the amount, texture, and behavior of fine sediments in streams. For example, fine sediments composed predominantly of coarse sand from 0.5 to 2.0 mm in diameter in streams of the Idaho batholith can account for 20 to 75% of the volume of substrate samples (Bjornn et al. 1977). The substrate of eighteen Alaska streams averaged <10% fine sediments (<0.83 mm) by weight in 2,000 samples collected between 1963 and 1971 (Sheridan et al. 1984), and the average size of fine sediment particles was smaller than observed in Idaho. Variability in fine sediments between unlogged streams ranged from 5.0 to 11.7% particles <0.83 mm in diameter.

Adams and Beschta (1980) studied gravel bed composition in twenty-one streams of the Oregon Coast Range and found that fine sediments <1 mm diameter averaged from 10.6 to 29.4% between streams in unlogged watersheds. Regression analysis indicated that, within this relatively homogenous climatic and physiographic region, the characteristics most strongly influencing fine sediment in streams in undisturbed watersheds were watershed slope, area, and relief. Everest et al. (1982) reported wide variations in fine sediments between four streams in the Rogue River basin of southwestern Oregon. The streams all have a history of logging and residential land use, but average fine sediment <1 mm in diameter in the substrate varied from 8.3 to 25.5% between streams.

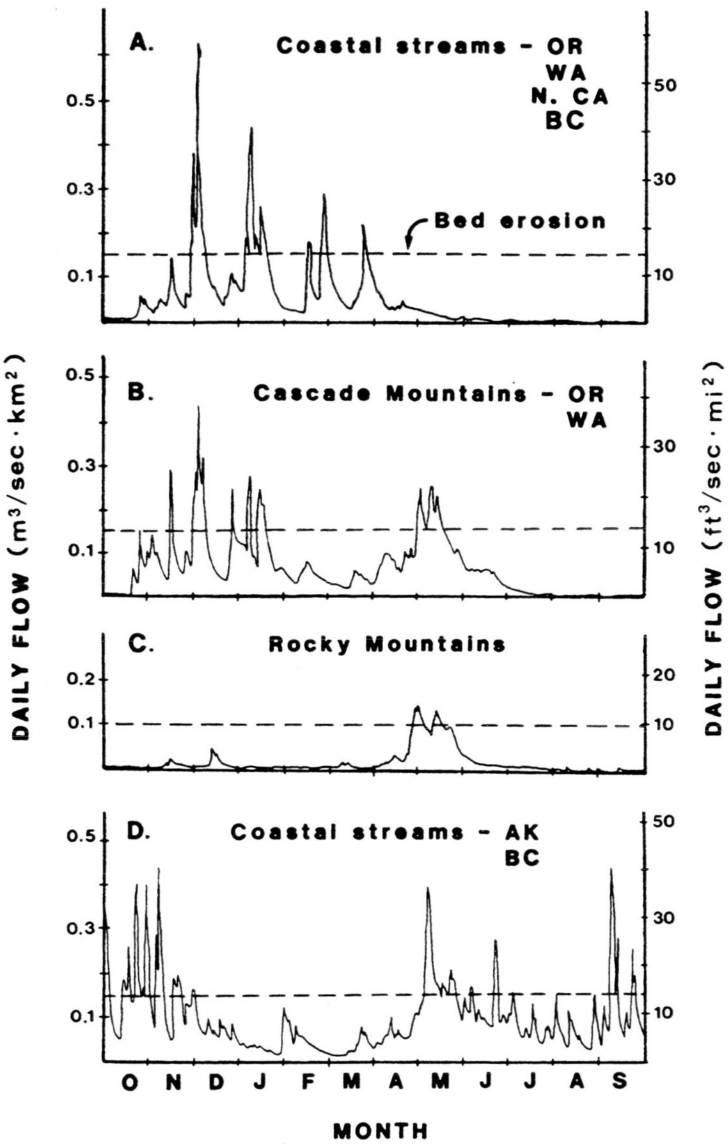

Figure 1. Representative hydrographs for western watersheds. Hydrograph A is typical of coastal British Columbia from the 49th parallel to Prince Rupert, and hydrograph D is typical of northern interior British Columbia.

Duncan and Ward (1985) studied the composition of substrates in twelve southwestern Washington watersheds that had been actively managed for commercial timber production. They found that the amount of fine sediment in substrate samples ranged from 7.6 to 15.5% particles <2 mm between streams, but the sediment was more closely correlated with the lithology and soils of the watersheds than with the intensity of land use. Streams dominated by basalt rock had a higher percentage of coarse sand 0.5 to 2.0 mm and a lower percentage of silt and clay particles <0.063 mm than did streams dominated by siltstone and sandstone rock.

The foregoing data indicate that substantial differences in average texture and amount of fine sediment in streams can be expected between watersheds, even when the watersheds occur in relatively homogenous physiographic regions. Also, high variability independent of the effects of land use is evident.

Variability Within Streams

Spatial and temporal variability of fine sediments on different riffles within streams is also high. Data reported by Adams and Beschta (1980) for twenty-one streams in the Oregon Coast Range showed that 75% of all comparisons between plots within the same stream were significantly different. Studies done in the Rogue basin by Everest, Meehan, and Lotspeich (in preparation) also indicate high variability in fines <1 mm in diameter between riffles within the same stream. The largest variability was noted in streams with high average sediment content in the bed; average fines ranged from 7.0 to 20.7% in different riffles used by steelhead trout and 6.6 to 54.3% in different riffles used by chinook salmon. Streams with low average fine sediment content in the bed had much lower variability. A difference among areas was also apparent on Carnation Creek prior to logging (Scrivener and Brownlee 1982, in press).

Variability in fine sediment between riffles of the same stream appears to be related to several physical phenomena. Although the reasons for this variability have not been thoroughly explored, weak correlations (0.35 to 0.52) between fine sediment and several watershed variables indicate that stream gradient and average diameter of particles in the armor layer are inversely correlated with fines, whereas channel stability is directly correlated with fines (Adams and Beschta 1980). On more of a microscale, observations (Keller et al. 1981) indicate that such channel roughness features as large organic debris, boulders, bedrock outcrops, and channel constrictions all hydraulically sort stream sediments during periods of high flow and thus create localized areas of gravel with low fine sediment content. Such "islands" of clean gravel may occur frequently in streams with high average fine sediment content if enough roughness elements are present in the channel. The importance of large organic debris in providing the hydraulic variability needed to maintain salmonid spawning habitat has been noted by Keller et al. (1981) and Coats et al. (1985).

There is also significant vertical variability of fines in stream substrates. Adams and Beschta (1980), Everest et al. (1982), and Scrivener and Brownlee (1982) report significant increases in fines with depth in the streambed. The surface of riffles is subject to annual flushing flows that transport fine sediments and leave behind an armor of large particles that are less subject to hydraulic displacement. Data collected in the Rogue basin (Everest et al. 1982) indicate that vertical stratification is most variable in streams with high average fine sediment content.

The fine sediment content of riffles varies seasonally, the highest levels in late summer and the lowest in late winter after flushing flows have occurred (Shapley and Bishop 1965, Sheridan and McNeil 1968, Adams and Beschta 1980, Scrivener and Brownlee 1982). The flushing effects, apparently intermittent for a given event, occur in localized areas where flows are powerful enough to disturb the gravel bed (Adams and Beschta 1980).

Variability Within Riffles

Substantial variability in fine sediment content has also been noted in samples collected on a single riffle. Adams and Beschta (1980) collected sixteen samples from a 1.2 by 1.2 m grid on a single riffle in Flynn Creek, Oregon. Fines contents in samples parallel and perpendicular to the flow were significantly different in the Latin Square design. The greatest differences, 16.6 to 26.9%, occurred across the riffle. Everest, Meehan, and Lotspeich (in preparation) have also examined within-riffle variability of fines in three 10 cm strata in samples drawn from 2 by 2 m grids in four streams in the Rogue basin, Oregon. Although variability within a given grid was usually substantial, only two of twenty-four within-riffle comparisons showed statistically significant differences. The greatest variability was in streams with high average fine sediment content in riffles.

Although past studies have documented that fine sediment in riffles is highly variable between streams, between riffles of the same stream, and within riffles of the same stream, some trends are apparent. Variability decreases as sampling moves from the broadest scope (between streams) to the narrowest scope (within riffles of the same stream). Also, variability between and within riffles of the same stream appears to be greatest in streams with high average fine sediment content.

Variability of fine sediments is high even in undisturbed watersheds, particularly those with an abundance of large roughness elements, and it seems doubtful that an enforceable criterion for maximum allowable fine sediment in stream substrates is realistic. With such high variability of fines between and within riffles of the same stream, a random sampling design that can detect small changes in substrate composition would be difficult to develop and execute, and it might be prohibitively expensive. It would be more realistic to develop such a sediment criterion for salmonid redds, because fish carefully select spawning sites and change the composition of the substrate by displacing fines downstream as they spawn. Sampling redds, or mass spawned beds in the case of pink and chum salmon, just prior to emergence would reduce potential spatial and temporal variability in fines and would document the actual conditions that salmonid fry would have to contend with during emergence (Everest et al. 1982).

EFFECTS OF SEDIMENTATION ON SALMONIDS

The effects of fine sediments on salmonids have been studied in both the laboratory and the field for more than sixty years. Several thorough literature reviews on the subject have been published

(Cordone and Kelley 1961, Gibbons and Salo 1973, Sorenson et al. 1977, Iwamoto et al. 1978, Hall 1984, Hall et al. 1984, Chevalier et al. 1984), and the reader is referred to these for details. We have not attempted to make another review; our purpose is to summarize the pertinent findings of past studies and interpret their usefulness for guiding land management activities.

Sediment has been the focus of attention by biologists investigating the potential impacts of many human land use activities for decades. Most studies on salmonids have been concerned with the effects of sedimentation on egg and fry survival and the effects of suspended sediment on juvenile survival; however, little effort has been made to relate sediment to salmonid abundance through the concept of limiting factors.

Laboratory Studies

Most laboratory studies have resulted from the need to separate the effects of individual variables such as sediment from the confounding of results caused by multiple variables typically found in field studies. Although laboratory studies have in some ways lacked consistency, they have established some important relationships between fine sediments and salmonids. One problem that precludes direct comparison of the results of laboratory and field studies is that scientists have not used a consistent criterion for fine sediment. The most commonly used criterion of fine sediment is particles <0.83 mm; however, particle sizes of <6.4 mm, <4.8 mm, <3.3 mm, <1.7 mm, <1.0, and others have also been used. These different criteria generally represent the best correlatives of survival and sediment from a variety of studies and probably reflect differences in sediment type or species adaptations.

Several laboratory studies have documented that fine sediment can reduce the reproductive success of salmonids. Fine sediments generally reduce the permeability of gravels (Terhune 1958, McNeil and Ahnell 1964), the intragravel water flow (Vaux 1962, Cooper 1965), and the availability of dissolved oxygen for developing embryos (Daykin 1965, Cooper 1965). Low dissolved oxygen can cause direct mortality (Wickett 1954, Alderdice et al. 1958) or delay the development of alevins (Shumway et al. 1964, Brannon 1965). Fry delayed in their timing of emergence are thought to be less able to compete for environmental resources than their larger cohorts that have undergone normal development and emergence.

Although study results identify several dissolved oxygen levels that are described as dangerously low for developing embryos, there seems to be a consensus that intragravel dissolved oxygen should not drop below 5 mg/l during incubation.

Fine sediments can also physically interfere with emergence success of salmonid fry by occluding interstitial pore space. The greater the proportion of fine sediments in redds, the greater the likelihood that fry hatching from normally developed embryos will be entrapped and unable to emerge (Figure 2). Several authors have found a sensitive

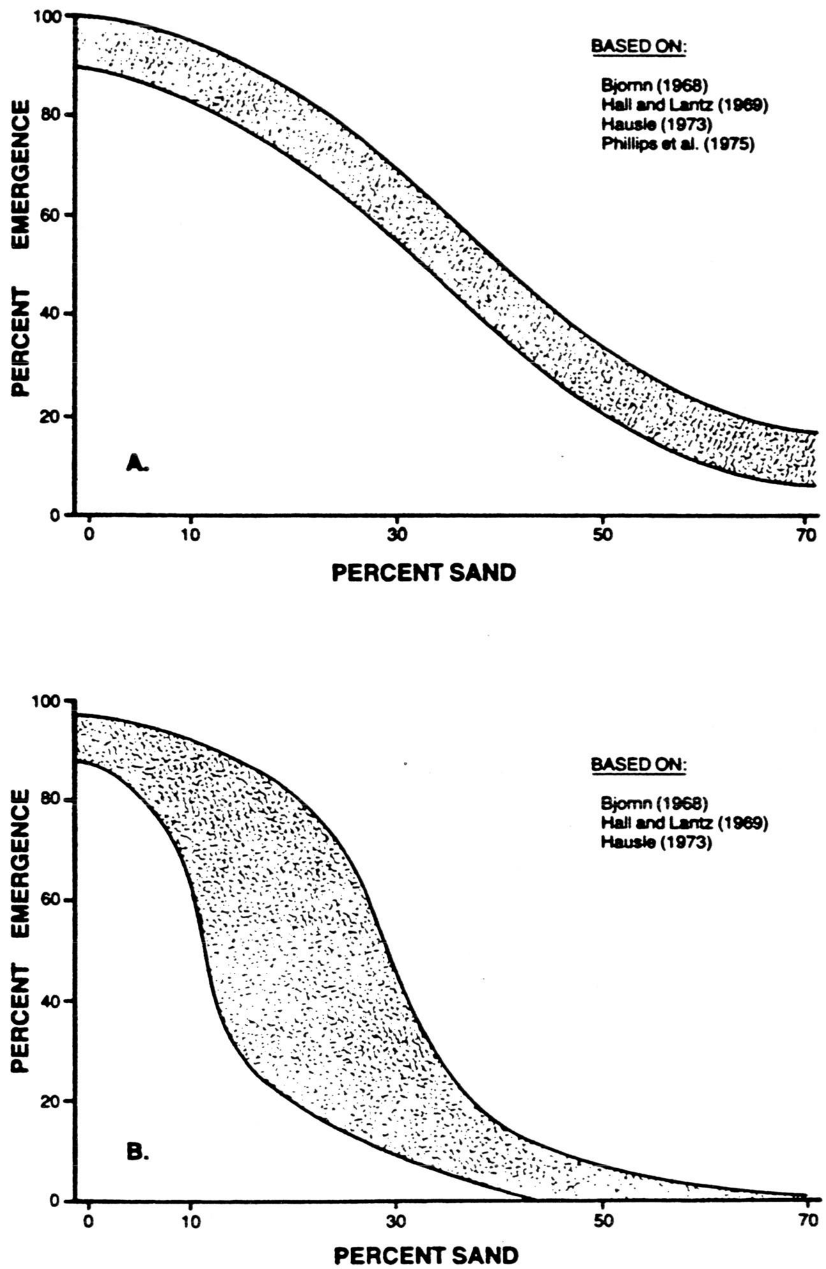

Figure 2. Composite experimental inverse relationship between percentage of fine sands in gravels and survival-to-emergence of salmonids: (A) alevins put into artificial redds; (B) eggs deposited in redds (from Cederholm and Salo 1979).

inverse relationship between fines and fry survival (Bjornn 1968, Phillips et al. 1975), with decreases in survival ranging up to 3.4% (Cederholm et al. 1981) for each 1% increase in fine sediment. At least a dozen other laboratory studies have also documented an inverse relationship between fines and fry survival.

Sedimentation has also been shown to affect salmonid production in spawning channels, a controlled stream environment that is perhaps more closely related to the laboratory than natural environments are. For example, Shelton and Pollock (1966) demonstrated that low survival of chinook salmon eggs in an incubation channel occurred when 15 to 30% of the voids in the gravel bed were filled with sediment. Cooper (1977) reported significant reduction in egg-to-fry survival (20 to 30%) of pink and sockeye salmon at several spawning channels in the Fraser River system. Once cleaned of fine sediment, these channels produced high survivals. The maintenance of high survivals in spawning channels is based on the concept of increased intragravel flow through streamflow control and on gravels relatively free of fine sediments. The loss of thousands or even millions of fry because of sedimentation is significant, and considerable effort has been expended on removing and preventing sediment from accumulating in these channels. Observations from spawning channels demonstrate that fine sediment in environments with uniform channels, streamflow, and gravel composition encourage deposition and retention of fine sediments and cause significant reductions in reproductive success of salmonids.

Laboratory studies have shown that substrate size and fine sediments can affect the community structure and abundance of aquatic macroinvertebrates, the primary source of food for stream-dwelling salmonids (Williams and Mundie 1978). Certain groups of organisms favored as food items (mayflies, caddisflies, stoneflies) that prefer large substrate particles in riffles are negatively affected by fine sediment, whereas other groups (e.g., midges) are quite tolerant.

Laboratory studies have also shown that suspended sediments in extreme concentration (>20,000 mg/l) can cause direct mortality of salmonids, but such concentrations are rarely found in nature. Noggle (1978) has demonstrated that the tolerance of juvenile coho salmon to suspended sediment varies seasonally; highest tolerance is in the fall when increased suspended sediment normally occurs in streams. Bisson and Bilby (1982) showed that groups of coho salmon parr acclimated to clear water (<0.3 Nephlometric Turbidity Units, NTU) and turbid water (2 to 15 NTU) in summer showed significant avoidance when exposed to suspended sediment in excess of 70 NTU and 100 NTU, respectively. Sublethal effects of chronic suspended sediment on steelhead trout and coho salmon fry include reduced growth rate (Sigler et al. 1984) and an inability of smaller fry reared in turbid water to compete for food and space with their larger cohorts reared in clear water (Sigler and Bjornn 1980). Noggle (1978) found that the ability of coho salmon fingerlings to capture prey organisms was lost at suspended sediment concentrations of 300 to 400 mg/l. Redding et al. (in press) studied the relationship between suspended sediment and stress in juvenile coho salmon and steelhead trout. They found that high levels of suspended sediment (2,000 to 3,000 mg/l) produced an initial mild stress response, but the fish adapted quickly. An interesting part of the study indicated that fish previously stressed by suspended sediment were less resistant to infection when exposed to *Vibrio anguillarum* than fish that had not been exposed to turbid waters.

Although laboratory studies have been valuable in establishing potential effects of fine sediment on salmonids, the results generally cannot be used to guide decisions affecting forest management practices. All laboratory studies have, out of necessity, investigated the effects of fine sediment out of context with natural aquatic ecosystems and are therefore highly simplistic. None of these studies can assist managers in determining if sediment is limiting natural populations of salmonids. What can be inferred from laboratory studies is that at some specific life stages salmonids are vulnerable to deposited and suspended inorganic sediment in closely controlled studies.

Field Studies

A few studies (e.g., Platts and Megahan 1975, Coats et al. 1985) have shown that acute massive sedimentation can cause major changes in salmonid spawning and rearing habitat. Sedimentation of this magnitude from forest management is occurring less frequently, presumably as a result of improved forest management practices. What do field studies show about the more subtle and common chronic effects of sedimentation associated with forest management? The exact effects of chronic sedimentation on salmonids have been difficult to ascertain because of the complexity inherent in studying natural ecosystems. Part of the problem of documenting effects of sediment generated by forest management results from the concurrent multiple environmental changes caused by natural events (such as large storms) and management activities. Roads and logging activities near streams cause simultaneous changes in sediment loads, solar radiation, channel morphology, water temperature, streamflow, and other features of the stream environment. Isolating the effects of sediment that can interact antagonistically or synergistically with other effects is difficult. Also, the various salmonid species utilizing forested watersheds exhibit numerous variations in life history patterns, behavior, and habitat preferences, and therefore exhibit different responses to sedimentation. To further complicate matters, salmonids have several adaptive behavioral mechanisms that allow them to cope with substantial spatial and temporal variability of sediments in streams. Despite these factors, some effects of chronic sedimentation on salmonids in natural streams have been documented.

In a preceding section, we cited studies showing that the effects of forest management activities on sedimentation of salmonid habitat have varied from inconclusive to severe. Platts and Megahan (1975) speculated that the massive sedimentation in the South Fork Salmon River, Idaho, reduced the run of summer chinook salmon into that system. Sediment was undoubtedly a contributor to the decline of the run, but its effects could not be separated from simultaneous high mortality of upstream and downstream migrants at dams on the Snake and Columbia rivers. Coats et al. (1985) indicate that sedimentation in the San Lorenzo River was primarily responsible for the decline of steelhead trout and coho salmon in that system, but their conclusion is clouded by simultaneous losses of habitat to barriers in the basin and to an intensive sport and commercial fishery. A study by Everest and Meehan (1981) on the effects of debris torrents on salmonid habitat in Knowles Creek, Oregon, a system severely damaged by land management practices, showed localized increases of fine sediment in riffles and also a total increase in available spawning habitat resulting from deposition of inorganic sediments associated with mass failures (primarily debris avalanches and torrents). Also, increased habitat complexity from additions of organic and inorganic materials into this mainly bedrock-controlled stream improved rearing habitat and increased the numbers of underyearling coho in areas affected by torrent deposition. Large sediment accumulations in the stream caused by torrents were found to be highly active sites for anaerobic processing of nutrients; coho salmon rearing downstream of such areas were larger than their cohorts rearing upstream.

Channel aggradation from mass erosion can cause intermittent summer flow and can reduce summer rearing habitat for salmonids. For example, a tributary of the Clearwater River, Washington, now has ephemeral flow following a logging-related debris torrent. Coho smolt production in that tributary has dropped from an estimated 350 to 1,000 fish per year to fewer than 100 (Cederholm and Reid, this volume). Similarly, several thousand square meters of summer rearing habitat for juvenile steelhead have been lost on the East Fork of Butler Creek in the Elk River basin of Oregon, where the stream is dry in summer from logging-related channel aggradation. These habitat changes, however, were caused by mass infusion of unsorted inorganic particles rather than an influx of fine sediment.

Field studies designed to assess factors responsible for egg-to-fry mortality have been conducted for several species across a broad range of habitats. In a pioneering study, Hobbs (1937) sampled the sediment in redds of chinook salmon and brown and rainbow trout in several New Zealand streams. He found a direct correlation between mortality of eggs and amounts of material that would pass through a 0.8 mm screen. Differences of only a few percent appeared to greatly affect mortality.

McNeil and Ahnell (1964) found an inverse correlation between escapement of pink salmon from six Alaska streams and the percentage of sediment less than 0.833 mm in the stream substrate. Shapley (1964) determined similar correlations ($r = -0.80$) between the maximum number of preemergent pink salmon fry produced and the mean fractions of gravel less than 0.833 mm.

Koski (1966) found that the amount of fine sediments <3.327 mm in diameter in twenty-one individual coho salmon redds from forested streams in Oregon had the highest correlations with survival-to-emergence of all factors studied (gravel permeability, dissolved oxygen, and gravel stability). Fry emerging from redds with greater amounts of fine sediments experienced high mortalities and a higher rate of prematurity.

In a controlled field experiment simulating a natural stream, Koski (1975) isolated the effects of the fine sediment from other variables by allowing chum salmon to spawn naturally (density, 4.7 m^2/female) in a range of gravel mixtures typically used by these fish. Major factors affecting variation in survival, spawner density and streamflow, were controlled. Survival from egg deposition to emergence ranged from 7 to 88% and was significantly and inversely correlated with the amount of fine sediment (sand <3.327 mm). Silt (fines <0.015 mm) in the gravel was not directly related to survival; however, when the total amount of sand and silt exceeded 35%, both intragravel dissolved oxygen content and survival were reduced. Fry quality characteristics were also affected by the amount of streambed sediment (Koski 1981). A higher percentage of sand resulted in earlier emergence, increased amount of prematurity, and smaller size of fry. These characteristics have been shown to be inversely related to marine survival. The study confirmed that fine sediments in spawning gravels are a major determinant of egg and fry survival and that they might set an upper limit on survival even though other variables such as superimposition, dissolved oxygen, freezing, and scouring can significantly reduce survival and mask the effects of sediment.

Tagart (1976) investigated coho salmon survival from egg deposition to emergence in eight tributaries of the Clearwater River, Washington. In the first year of the study, survival-to-emergence was inversely correlated with sediments <0.850 mm and positively correlated with sediments 3.35 to 26.9 mm. The following year, however, no significant correlations were demonstrable. His data indicate that survival of coho salmon fry decreased with increasing fine sediment in redds, either from low dissolved oxygen or entrapment, or both. Tagart (1984) found that size of emergent fry decreases as fine sediment in redds increases.

Other studies have shown that increases in fine sediments in stream gravels affect salmonid fry and embryo survival. Johnson et al. (1952), in an investigation of the effects of a landslide on the Stillaguamish River, Washington, estimated that an additional 10% loss of eggs and fry might be attributed to siltation in the river, but this was not confirmed. McCrimmon (1954) correlated the degree of bottom sedimentation in gravel riffle areas with the percentage survival of underyearling Atlantic salmon. Sedimentation in pools resulted in low survival of fry even when adjacent riffle areas were free from sediments.

A study by Sowden and Power (1985) indicated that survival of rainbow trout fry in groundwater-fed streams in southwestern Ontario was more dependent on dissolved oxygen content and intragravel water velocity than on amount and texture of fine sediments.

The foregoing field experiments show that under certain circumstances fine sediments within the redd environment of salmonids can directly reduce egg-to-fry survival and fry quality by (1) suffocation of eggs and alevins, (2) reduced intragravel water flow and dissolved oxygen content, and (3) a physical barrier to emergence. The amount of fine sediment that is detrimental is related to particle size, size composition of the spawning gravels, species or stock of fish, and timing of deposition; however, less is known about how bed composition influences other factors that may have a significant effect on the ultimate success and survival of incubating eggs. For example, how does the proportion of fines affect the frequency of local scour and fill or the depth of scour during high flow events? How does the amount of fines affect the general deposition process and resulting bed morphology (Jackson and Beschta 1984), which in turn can influence the hydraulic roughness of the riffle and the intragravel flow of water? These and other physical factors have been mainly ignored in field studies.

Investigations of pink and chum salmon egg and alevin survival in Sashin Creek, Alaska, indicate that numbers of emergent fry in that system are more closely controlled by spawning escapement than by sediment in spawning gravels (McNeil 1969). A maximum production of about 500 fry/m^2 occurred at egg depositions of 2,000 to 3,000/m^2. Either increases or decreases from this optimum range of egg deposition resulted in substantially decreased fry production. McNeil (1969) also noted that in 1964 the lower segment of the Sashin Creek spawning ground contained about six times more fine sediment per volume of gravel than the upper segment, but success of fry emergence did not appear to differ in the two segments. These data contradict previously cited studies of the effects of sediment on pink salmon in Alaska and indicate that even in pink salmon populations other factors can override the effects of sedimentation.

Burns (1972) showed mixed results in a study of logging effects on juvenile anadromous salmonids in northern California streams. Sediment increases were noted in all streams after logging, and steelhead trout and coho salmon biomass declined substantially in some streams but increased in others. In all streams the effects on salmonids seemed to be of short duration. The actual effects of sediment were difficult to isolate from other concurrent environmental changes caused by logging.

Studies by Moring and Lantz (1974) in the Oregon Coast Range included the effects of logging on sediment in gravels and stream morphology. Again, results were variable. As noted previously, the amount of fine sediment in spawning habitat increased in about half the streams. Nine streams lost pool area, and three lost spawning area after logging. One gained pool area and three gained spawning area. The morphological changes were the result of the physical effects of logging, not sedimentation. The importance of these changes was difficult to interpret because there was no extended period of study before or after logging. Coho salmon populations were apparently little affected by these changes, but cutthroat trout populations declined in three of the four streams where they occurred. Changes in cutthroat trout populations, however, were thought to be within the range of natural background variability.

Studies by Murphy and Hall (1981) in the Oregon Cascades in both logged and unlogged watersheds showed that opening the canopy of streams increased the biomass of trout even when sediment in the streambed increased at the same time. The effects of fine sediment on summer and winter rearing habitat of juvenile steelhead trout and chinook salmon in Idaho have been investigated by Stuehrenberg (1975) and Klamt (1976). Juveniles of both species were found to be quite tolerant, showing no significant differences in density in streams with substrates ranging from 26 to 52% fine sediment. When sediment was added experimentally to a riffle and pool in summer, fish density decreased in proportion to loss of pool volume. Density of age 0+ steelhead trout and chinook salmon decreased in the sedimented riffle in winter, whereas age 1+ steelhead in the pool were not affected. It was speculated that if extensive sedimentation occurred at the experimental level, substantial reductions in fish densities and growth might occur.

Sediment entering streams after the period of spring runoff was thought to have the highest potential for negative impacts, because it would remain in place until the next spring freshet.

Moring and Lantz (1975) showed increases in both suspended and deposited sediment in Needle Branch and Deer Creek, Oregon, after logging, but no concurrent reduction in coho salmon fry. The number of presumed coho salmon smolts produced by Needle Branch and Deer Creek after logging was only 63% and 78%, respectively, of the prelogging values (Hall et al., this volume). However, the number of coho salmon smolts emigrating from the control watershed during the same period was only 50% of the prelogging value. Scrivener and Brownlee (1982; in press) have shown that increased sedimentation after logging in Carnation Creek was correlated with reduced survival-to-emergence of chum and coho salmon fry. Sizes of emergent fry also decreased as fine sediment increased in the streambed. Although other interacting factors, such as changes in channel morphology, might have influenced fry survival, Scrivener and Brownlee (1982; in press) have provided the only studies to demonstrate that the effects of fine sediment from logging carry through to the outmigrant stage of chum salmon populations.

Studies designed to investigate the effects of sediment on interspecies interactions in mixed salmonid populations, or in fish communities composed of salmonids and nonsalmonids, are conspicuous by their absence in the literature. The ecological dominance of a given species is often determined by environmental variables. For example, Reeves (1984) showed that water temperature can determine species dominance in mixed populations of steelhead trout and redside shiners (Richardsonius balteatus). Shiners prevail in warm waters whereas steelhead trout dominate in cool water, all other habitat variables being equal. It is possible that subtle chronic sedimentation can tip the ecological balance in favor of one species in mixed salmonid populations, or in species communities composed of salmonids and nonsalmonids. This potential effect of sediment has scarcely been considered.

Wasserman et al. (1984) studied the effects of logging on aquatic macroinvertebrates in streams of the Olympic Peninsula, Washington. They found that within-stream variability was greater than between-stream variability to the extent that community size and structure could not be causally related to sediment or other effects having to do with logging. Bjornn et al. (1974) studied the relation between aquatic insects and sediment in streams in the Idaho batholith. They found lower densities of aquatic insects in heavily sedimented riffles, but the results showed little correlation with size or density of salmonids.

This is by no means an exhaustive review of the results of field studies, but the foregoing does indicate that at specific sites or reaches, salmonids can be affected and habitat can be lost to sedimentation. Field studies, however, have been mainly conclusive in assessing the extent and duration of the effects of chronic sedimentation on salmonid populations at the subbasin level. Although some studies indicate a localized reduction in emergence success or reduced biomass of rearing juveniles with one exception, none of the studies demonstrated an overall reduction in seaward migrant anadromous salmonids because of sedimentation. The exception is the Carnation Creek research (Scrivener and Brownlee 1982; in press) that links increases in streambed sediments with decreases in chum salmon fry outmigrants.

At least four conclusions can be drawn from the results of field studies: (1) effects of sediment on salmonids are more difficult to demonstrate in natural environments than in the laboratory; (2) effects of sedimentation are difficult to isolate from concurrent effects of other environmental variables; (3) effects of sediment, with the exception of the Carnation Creek study, have not been examined in the context of limiting factors; and (4) large gaps in knowledge of the ecological effects of sediment on salmonids and nonsalmonids exist in the literature. Also, it is difficult to draw conclusions from the results of field studies that will produce reliable guidelines for forest managers to use in setting standards for sedimentation. Several important reasons why sediment standards are difficult to establish and enforce are discussed by Iwamoto et al. (1978) in a thorough review of the subject. A primary difference between the results of laboratory studies and field studies is that physical features of natural streams and life histories and behavioral adaptations of salmonids mitigate the effects of sediment on fish populations in natural environments.

NATURAL MITIGATION OF THE EFFECTS OF FINE SEDIMENT IN STREAMS

We have reviewed papers showing that the fine sediment content of stream substrates is highly variable and that the amount of fine sediment can be increased by land management activities. We have also shown that the presence of increased sediment can be ephemeral or persistent depending on a number of factors. Laboratory and field studies have demonstrated that fine sediments have potential harmful effects on salmonids and their habitats. Despite all these findings, large and viable populations of salmonids persist in many streams with chronic loads of fine sediment (e.g., Eel River, California; Evans Creek and streams draining Tyee Sandstone formation in Oregon; South Fork Salmon River, Idaho; Toutle River, Washington, before the 1980 eruption of Mount St. Helens). What mechanisms allow salmonids to rear and reproduce successfully in such streams? Several studies have identified factors that mitigate the effects of fine sediment on salmonid spawning and rearing success in streams.

One important observation is that redd-building activities of female salmonids remove fine sediments from redds during spawning (Figure 3). The observation that spawning changes the textural composition of redds was first reported by Burner (1951), then by Semko (1954) and Cordone and Kelley (1961). Everest, Meehan, and Lotspeich (in preparation) have data to show that spawning female steelhead trout and chinook salmon in four tributaries of the Rogue River, Oregon, removed significant amounts of fines from redds. The cleaning effect was largest in streams with large amounts of fine sediment in the substrate. Chinook salmon in Evans Creek, a stream with a heavy load of

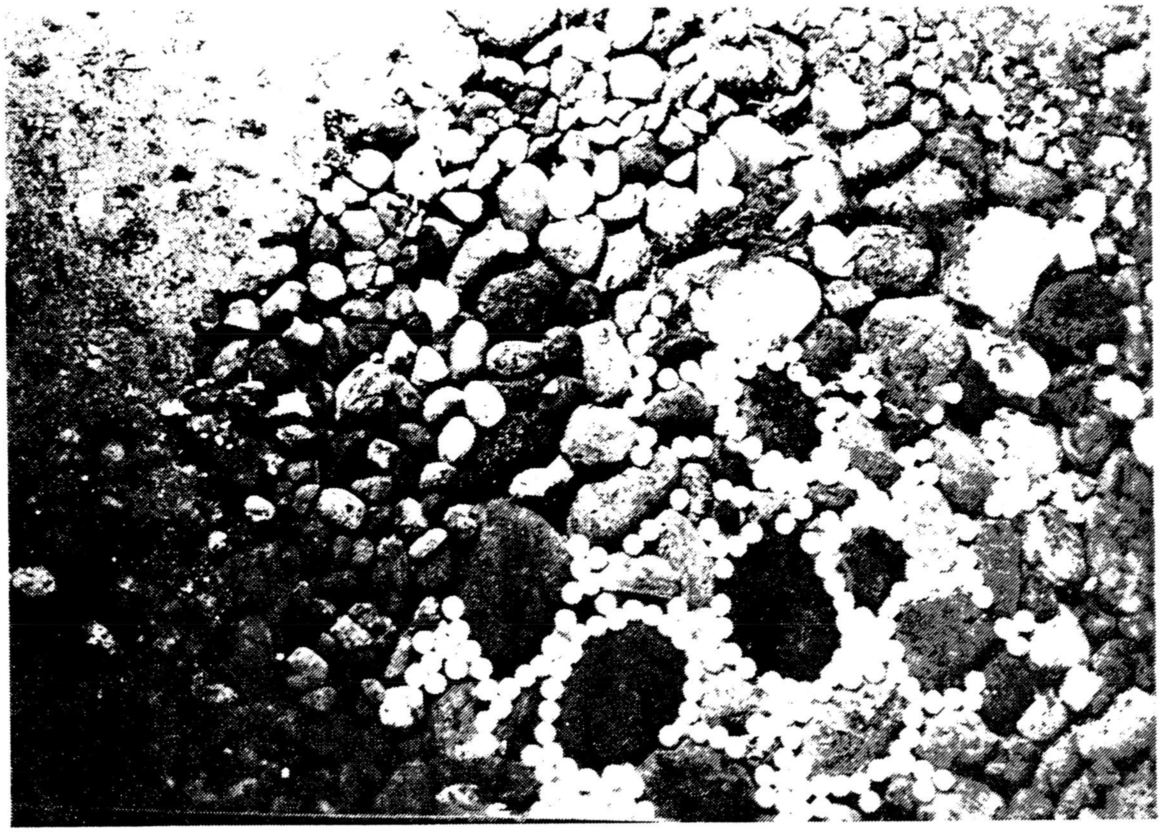

Figure 3. Redd pocket of a chum salmon immediately after egg deposition, viewed through a glass bottom stream channel. The cleansing action of the female has left large rocks in the center of the pocket; smaller materials and undisturbed fines are at periphery (K V. Koski and S. L. Schroder photograph).

weathered granitic sediments, reduced average fines <1 mm in diameter from 30.0% before spawning to 7.2% after spawning. Steelhead trout in Sams Creek, a stream with a heavy sediment load from a combination of weathered granitic formations and agricultural lands, reduced fines from 14.5% in undisturbed gravels to 7.5% in redds. Most of the cleaning effect in both streams persisted from spawning until emergence. Allen et al. (unpublished manuscript) have noted similar effects for coho salmon spawning in volcanic substrates of the Toutle River, Washington. Coho spawning near Spirit Lake reduced fine sediments (<3.2 mm) in redds from 21.6% to 9.1%. Koski (unpublished manuscript) found that pink salmon reduced fine sediment <0.83 mm in diameter from 8.2% to 6.5% in Kadashan Creek, a relatively large stream in southeastern Alaska. High densities of spawning chum salmon in the estuary of Carnation Creek also reduced fines in the bed (Scrivener and Brownlee 1982).

McNeil and Ahnell (1964) quantified the effects of pink salmon spawning on the removal of fine sediments. They found that in 1960 the percentage of fines (<0.833 mm) decreased from 14.8% to 11.5% during the spawning period in the Harris River. The effect of spawning on

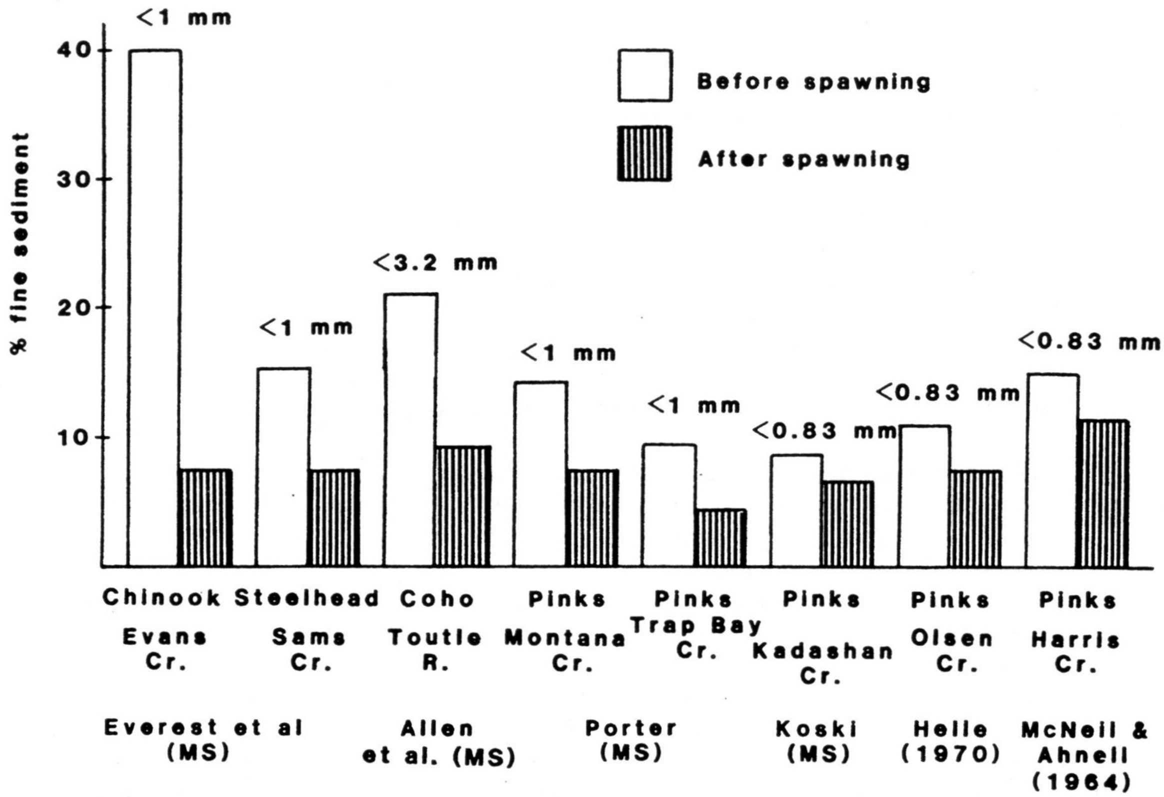

Figure 4. Percentage of fine sediment before and after spawning for several species of anadromous salmonids at various West Coast locations.

fines amounted to a 3.5% reduction in 1959 and 3.3% reduction in 1960 when the spawning density was 3.9 and 2.0 females/10 m^2, respectively. Cooper (1965) described similar cleaning effects in streams in British Columbia. Helle (1970) measured a 3.6% decrease (11.0% to 7.4%) in fine sediments <0.8 mm in diameter after pink salmon spawning in Olsen Creek, Prince William Sound, Alaska. Porter (in preparation) has collected data in southeastern Alaska showing that pink salmon spawning in Montana Creek and Trap Bay Creek reduced fines <1.0 mm in diameter from 14.2% to 7.4% and from 9.5% to 4.4%, respectively (Figure 4), but in some cases fine sediments returned to prespawning levels within one or two months.

Sheridan (1956) measured the area and volume of substrate materials moved by spawning pink salmon. He found that individual females dug an area of 5 to 10 m^2 and overturned 0.2 to 0.6 m^2 of material. McNeil and Ahnell (1964) estimated that individual females remove about 18 kg of fines <0.1 mm in diameter from redds. In a single spawning area, about 3,600 kg (4 tons) of fines were removed by 2,000 spawning female pink salmon. It is apparent from these data that large annual spawning escapements have a major impact on maintenance of high quality spawning habitat. When populations of spawning adults are reduced by habitat degradation or overfishing, the overall quality of spawning habitat may decline, because the annual cleaning effect exerted by spawners is diminished.

Removal of fine sediment (and finely divided organic matter) from redds by hydraulic sorting during spawning has two benefits: the potential for entrapment of emerging fry is reduced; and intragravel permeability, water flow, and oxygen transport to developing embryos are increased. Allen et al. (unpublished manuscript) noted an average increase of 4 mg/l dissolved oxygen in coho redds on the Toutle River compared with intragravel dissolved oxygen in undisturbed gravels nearby. Because of the removal of fine sediment from redds, and changes in the configuration of the streambed caused by redd construction (which significantly altered intragravel flow patterns), dissolved oxygen within redds was adequate for incubating embryos, whereas lethal oxygen levels persisted in undisturbed gravels.

"Clean" gravels can fill rapidly with fines if the surrounding streambed or surface water contains abundant sediment. Meehan and Swanston (1977) showed that gravel shape can have an effect on sediment accumulation in spawning gravels. Vaux (1967) and Beschta and Jackson (1979) described mechanisms whereby suspended sediment enters the streambed. The rate of particle collection in the streambed is attributable to three primary mechanisms: gravitational settling, interception, and sieving. The velocity of streamflow, concentration of suspended sediment, and area of gravel interstices all affect the rate of sedimentation. The location of redds in relation to the channel cross section is also important, because the majority of bedload sediments may be transported along a narrow portion of the cross section (Dietrich and Smith 1984). Once fine sediment is collected within the streambed, it remains until it is removed by freshets or spawning activity of fish.

The topographic features of redds may have a major effect on the rate at which "cleaned" gravels refill with fine sediments. This subject has not been thoroughly studied, but it is worth noting that completed redds have two topographic features that tend to minimize deposition of fine sediments in the area where embryos are incubating. When a female salmonid has completed spawning and burying eggs, the redd is left with a large pit on its upstream perimeter and a mounded tailspill downstream that contains the eggs (Figure 5). The pit acts as a natural settling basin for fine bedload sediments saltating downstream on freshets and may capture up to 0.25 m^3 of the heavier bedload particles before they reach the tailspill where the eggs are buried. Also, the mounded tailspill, which rises above the surrounding contours of the riffle, causes local acceleration of water velocity and fine sediment particles above and alongside the area containing the eggs. Consequently, fine sediments moving into the area of the tailspill remain in suspension from the accelerated velocity and increased turbulence and pass on downstream. These effects apparently operate until scour from high flow events obliterates the original contours of the redd, or until excessive sedimentation overwhelms the deposition-resistant features of the redd.

Another interesting and perhaps less well understood phenomenon is the construction of multiple redds by anadromous salmonids. Briggs (1953) observed that female coho and chinook salmon in Prairie Creek, California, frequently dug two or more redds per female and about half the redds examined contained no eggs. In other cases egg deposition

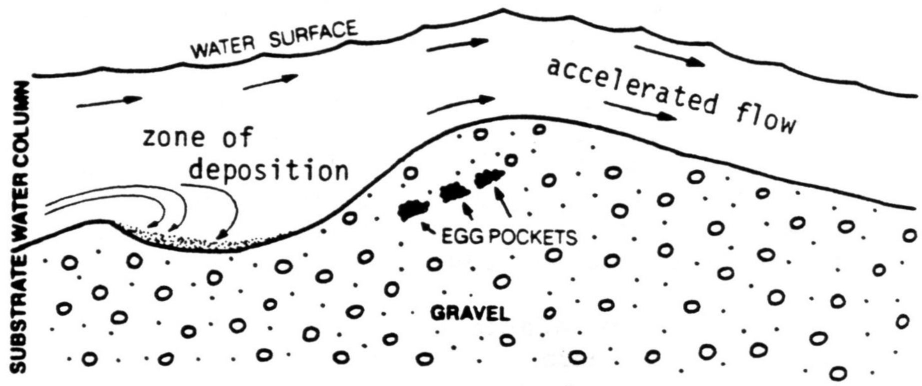

Figure 5. Topographic features of salmonid redds resist deposition of fine sediment in the area where embryos are incubating.

was apparently divided between redds. Moring and Lantz (1975) reported that 16 of 110 redds trapped during the Alsea watershed study produced no emergence. Some of these redds may have been devoid of eggs. Van de Berghe and Gross (1984) noted that coho salmon in Deer Creek, Washington, made from one to four redds per female; the average was 2.1 per female. The eggs of coho salmon in the Washington study were also divided between redds. Several speculations can be made concerning this behavior. Depositing eggs in several locations might reduce the risk of catastrophic loss to a single redd from environmental phenomena, predation, or disease. Also, the digging of false redds might indicate that fish do not deposit eggs if the correct environmental conditions are absent. That is, if the fish find too much fine sediment, or low dissolved oxygen, for example, they might abandon the redd and seek a better spawning site.

The observations of Briggs (1953) and van de Berghe and Gross (1984) complicate interpretation of the types of sediment-survival studies done by Koski (1966) and Tagart (1984). The results of those studies depended on an established size-fecundity relation for coho salmon and the assumption that all eggs from a single female were deposited in one redd. Because female coho salmon are known to frequently divide their eggs between two or more redds and the probability exists that more eggs are deposited where spawning conditions are most favorable, the results of those studies might be documenting both environmentally stimulated behavior of females and the effects of sediment on emergence of fry. The significance of this behavior to interpretation of the studies conducted by Koski (1966) and Tagart (1984) remains unknown.

Even in heavily sedimented streams, fish usually have a variety of microsites from which to choose an area for redd construction. Redd sites appear to be carefully selected, and often after digging is initiated fish abandon the site and move on, apparently seeking more suitable conditions (Briggs 1953). When conditions appear generally unfavorable for redd construction, another behavioral adaptation has been observed. Allen et al. (unpublished manuscript) described coho salmon spawning on the apex of large mounds of volcanic sediment in the Toutle River. Casual observation indicated that the substrate in the area was totally unsuitable for salmonid reproduction. Dense populations of coho salmon, however, used the area annually, and spawning activity both built and maintained the mounds, which in some cases were more than 1.5 m high. Similar mounds or dunes have been observed in chinook salmon spawning areas in Washington, Idaho, and Oregon (Huntington 1985). Dune building by salmonids improves the quality of spawning habitat and is most frequently observed in streams with reasonably controlled flows, such as downstream from lakes or dams.

Another spawning behavior adaptation was noted by Everest, Meehan, and Lotspeich (in preparation) for steelhead trout in the Rogue basin. Steelhead spawning in Sams Creek (heavy sedimentation) and Foots Creek (light sedimentation) showed differences in redd size and depth of egg deposition, even though the streams have similar size and flow characteristics, and spawner densities were roughly equal. Redds on Sams Creek were 48% larger than those on Foots Creek, and egg deposition was 25% shallower than on Foots Creek. Size of spawners did not appear to account for the differences, so it appears that females in the heavily sedimented stream spent more effort excavating redds to find the right conditions for spawning, and buried their eggs less deeply after spawning occurred. Steelhead embryos incubating at shallower depths in sedimented gravels might have an improved survival-to-emergence rate, but they might also be more vulnerable to scour than embryos incubating deeper within the substrate. This behavior probably does not occur where spawners are crowded and redd size is determined by territorial behavior.

The foregoing evidence suggests that spawning salmonids are not passive victims of the stream substrates in which they spawn but are able to significantly improve their chances of reproductive success through a variety of behaviorial adaptations.

Incubating embryos and emerging fry also have developed adaptive responses to cope with poor water quality and fine sediment in redds (Bams 1969). Embryos incubating in the presence of excess dissolved oxygen undergo a normal period of development from fertilization to hatching that is based primarily on water temperature. When reduced oxygen supplies approach the physiological demand for developing embryos, however, a "premature hatching" response occurs. Release of a stored hatching enzyme is triggered when oxygen demand and supply approach equilibrium, and hatching occurs within hours. Hatching approximately doubles the scope for oxygen uptake (Hayes et al. 1951) by eliminating the egg membrane and exposing the newly formed gills and body surfaces to oxygen-bearing water. Premature hatching is one adaptive feature, often related to low permeability and the presence of fine sediment, that may increase survival in the presence of low oxygen pressure in redds.

Another adaptive behavior used to cope with poor water quality in redds is "ventilation swimming" (Bams 1969). Poor water quality in the form of low dissolved oxygen or accumulation of metabolic wastes can be caused by fine sediments that reduce intragravel permeability. When carbon dioxide levels were experimentally increased in laboratory gravels containing alevins, an in-place swimming response occurred that served to ventilate the immediate interstitial area. Presumably the same type of behavior occurs in natural redds and improves the chemical composition of the microenvironment as needed.

Preemergent fry show an "emergency movement" response through the gravel when confronted with controlled reductions in intragravel water flow (Bams 1969). Young alevins burrowed rapidly and randomly through the gravel, whereas older ones made a rapid directed outmigration in response to declining flow. Presumably acute sedimentation could alter intragravel flow and trigger this kind of adaptive response, enhancing survival potential at least for older alevins.

Finally, preemergent fry have several adaptive mechanisms to cope with fine sediment infiltrating redd gravels (Bams 1969). Ventilation swimming keeps the immediate area surrounding the fry clean of fine sediment. Also, two gill-cleaning mechanisms are employed. A "coughing" response that reverses water flow over the gills is used to expel large sediment particles from the mouth; fine sediment particles settling on the gills are sloughed away under the gill covers with heavy secretions of mucus. Finally, when heavy loads of fine sediments are settling into the gravels, an escape response is triggered and fry rapidly emerge from the redd. Although these behavioral responses do not ensure survival of alevins under unfavorable conditions, they do increase the potential for survival.

Physical factors related primarily to the structural character of streams also temper the effects of sediment on salmonid spawning and rearing habitat. An abundance of roughness elements, such as large organic debris and boulders in streams, sets up complex hydraulic patterns that locally sort sediments, dig pools, and maximize the variety of spawning and rearing habitats available for salmonids (Keller et al. 1981, Coats et al. 1985). The result can be numerous islands of productive spawning and rearing habitat within a stream system that seasonally processes and transports large quantities of sediment. If sediment is increased and structural elements are decreased concurrently, such as by the removal of large woody debris during logging, negative synergistic effects might have an impact on salmonids. If the canopy is opened at the same time, a beneficial effect might be realized on site, but negative cumulative effects of elevated temperature and sediment could occur downstream. It is these kinds of interactions between the effects of sediment and other environmental changes that make field studies of sediment effects so difficult.

A conclusion to be drawn from the recent research is that salmonids have a number of ways of reducing the effects of abundant fine sediments on reproductive success. In cases of heavy chronic sedimentation, however, all of these activities are likely to become overwhelmed or ineffective and salmonid reproduction is likely to suffer. Also, maintenance of diversity in channel morphology can temper the effects of the fine sediment on spawning and rearing success of salmonids. Overall, salmonids appear to be well adapted to cope with natural variability of sediments in streams, and in some cases can cope with mildly accelerated sedimentation.

SEDIMENT AS A FACTOR LIMITING SALMONID POPULATIONS

Although the effects of sediment on salmonids and their habitats have been extensively investigated, the results of these studies have rarely been examined in the context of factors limiting natural populations of salmonids in stream basins or subbasins. The focus of much past research has been the effects of fine sediment on survival-to-emergence of salmonid fry. An inverse relationship has been documented in both the laboratory and the field that shows reduced survival of emergent fry as fine sediment in stream substrates increases. These findings demonstrate potential effects of sedimentation, but do not address the issue of limiting factors. If we assume that fine sediment in a system reduces reproductive success of salmonids, the next question is whether a reduction in fry results in fewer seaward migrant anadromous juveniles, or fewer resident adult salmonids. Few studies have produced results that will answer the question. The Alsea watershed study and the Carnation Creek study, however, do give some insight into the importance of sediment from forest management as a limiting factor on salmonid populations.

The Carnation Creek study documented increases of 4.8 and 4.7% in pea gravel and sand, respectively, in spawning areas eight years after logging was begun (Scrivener and Brownlee, in press). The study also compiled data on the number of seaward-moving chum and coho salmon fry and coho smolts, as well as juvenile coho salmon in Carnation Creek. Annual survival from potential egg deposition to emigrant chum fry is correlated with annual quality of spawning gravels. Survival has declined an average of 9.9% since 1978. Size of emigrants has also declined as gravel quality declined. Because chum salmon fry move to sea soon after emergence, one must assume that decreases in the numbers and size of fry should result in decreases in returning adults. As yet, however, no clear trend in numbers of returning adults, either up or down, has been evident (Hartman and Holtby 1982). Coho salmon egg-to-fry survival also decreased (13.9%) in relation to declining quality of spawning gravel, but at the same time the average number of coho salmon smolts leaving the basin increased 42% (Hartman et al., this volume). Other factors have compensated for decreased fry production caused by sedimentation. These positive impacts are attributed to a combination of logging- and climate-induced influences, including warmer water temperatures in winter, less severe winter freshets, increased solar radiation, and increased dissolved nutrients (Hartman et al. 1984). As a result, the smolt migration is now composed almost entirely of age 1+ coho, instead of the prelogging mixture of 1+ and 2+ smolts (Hartman et al., this volume). An increase in smolt production has resulted in an increase in adult returns in only one of seven years since 1979. Greater marine mortality was partially attributed to earlier smolt emigration that was induced by higher stream temperatures (Holtby 1986).

Results from the Alsea watershed study showed no identifiable link between sediment and the health of coho salmon populations as a result of logging (Moring and Lantz 1975). Fine sediments in the substrate of Needle Branch and Deer Creek increased slightly after logging, and a decrease in gravel permeability in Needle Branch was noted (Moring 1975). Sampling of individual redds showed no change in coho salmon fry survival from prelogging to postlogging years. Hall et al. (this volume) in a reassessment of data from the Alsea study indicate that the total number of coho outmigrants (presmolts and smolts) per female was reduced during postlogging years on Needle Branch. They concluded that reduced survival-to-emergence might be the reason, even though sampling of redds failed to show a difference in survival following logging. Mean size and biomass of juvenile coho salmon in Needle Branch and Deer Creek increased after logging, whereas biomass of coho salmon in Flynn Creek, the control watershed, decreased. Net production of coho salmon in Flynn Creek remained essentially unchanged during the study, but net production of coho salmon in Needle Branch and Deer Creek increased significantly after logging. The increases in production were apparently related to warmer water temperatures, increased dissolved nutrients, and increased solar radiation. Suspended sediments increased 205% in Needle Branch and 53% in Deer Creek after logging, whereas sediment discharge on Flynn Creek remained unchanged. Despite an increase in both deposited and suspended sediment in the logged watersheds, Moring and Lantz (1975) concluded that there were no adverse changes in juvenile coho population numbers or smolt yield as a result of logging.

The results of the foregoing studies clearly indicate that the effects of fine sediment on salmonids, especially coho salmon (the most studied species), are difficult to isolate from other environmental changes resulting from forest management. Forest management activities often cause concurrent changes in suspended and deposited sediments in streams, stream bank stability, dissolved nutrients, water temperature (see Beschta et al., this volume), light intensity, litter fall, stream channel morphology, and large organic debris. These changes, in combination, can produce negative, positive, or neutral effects on salmonid populations. Multiple effects of forest management on salmonids have rarely been examined in a basin context, so the present state of knowledge for predicting the effects of multiple concurrent changes or isolating the effects attributable to a single variable is not well developed.

What conclusions can be drawn, then, regarding sediment as a potential limiting factor for salmonid populations? Although state-of-the-art knowledge does not provide a detailed answer to the question, some generalizations can be made. Long-term watershed studies indicate that the effects of sediment on salmonid populations are not consistent for all species, and that the consistency is related partly to differences in life history, abundance, behavior, and habitat preferences of species. Salmonids that rear in fresh water for extended periods have less risk of being limited by sediment in spawning habitat than species whose young move directly to sea after emergence. Species with short freshwater residence times, such as pink and chum salmon, are more likely to have their populations limited by poor reproductive success

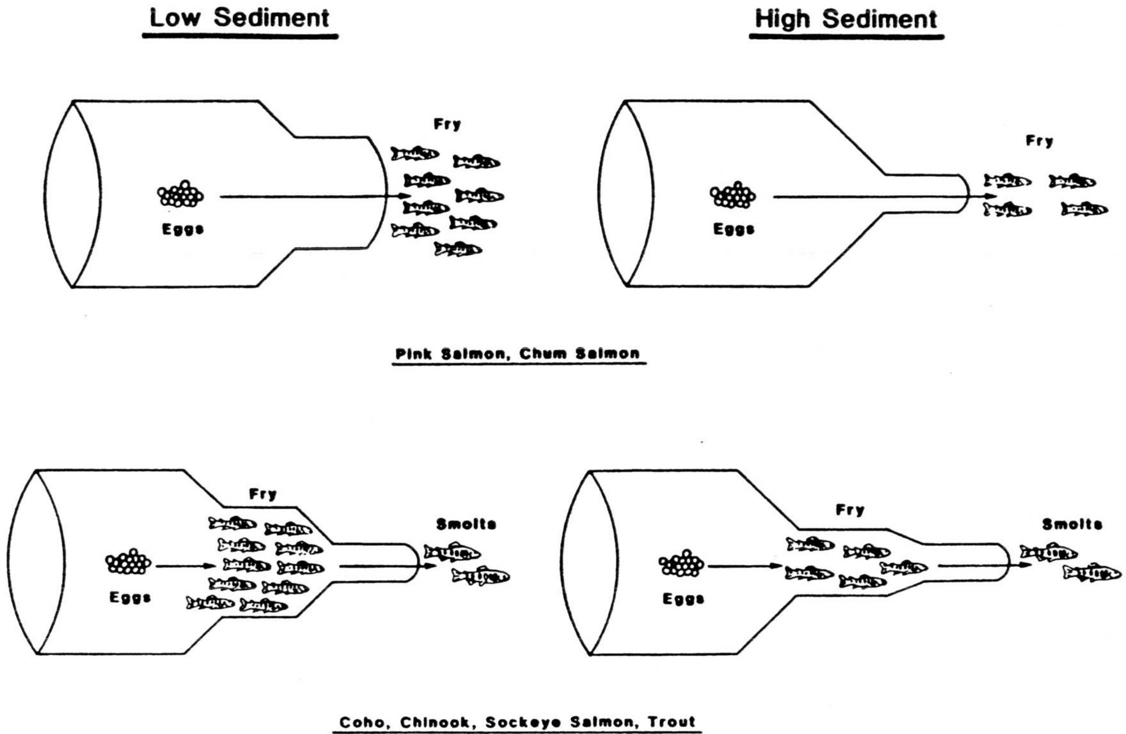

Figure 6. Sedimentation of spawning habitat as a factor limiting production of seaward migrant salmonids.

(McNeil 1966), especially if spawning escapement is low; and they are therefore vulnerable to the effects of sedimentation in streambed gravels (Figure 6). Generally, the more fry produced by these species, the larger the expected adult returns. Species with long freshwater residence times are less likely to be limited by spawning success but are vulnerable to gross sedimentation that causes changes in the channel morphology and diversity of rearing habitat. Species such as coho, chinook, and sockeye salmon, and trout are usually limited by available rearing habitat, except when seeding is extremely low. Because these species are territorial and partition their rearing habitat, each stream has a maximum carrying capacity. The bottleneck in production (Figure 6) for these species is often habitat diversity or food availability in summer and shelter in winter (Koski et al. 1984). Sediment may be limiting or may cause a shift in the dominant species if it diminishes food, cover, or preferred habitat for rearing juveniles. Sedimentation from road surfaces, for example, probably presents a greater hazard to pink and chum salmon populations than to coho salmon or steelhead trout populations, because roads produce a chronic supply of fine-grained sediments. Accelerated mass erosion in systems that are already rich in sediments could have negative effects on all species, because both spawning and rearing habitat would be affected.

Watershed characteristics such as hydrology, geology, stream gradient and geometry, geomorphology, and dominant erosive transport processes also affect the level of risk to salmonids from forestry-caused sedimentation (Table 1). Although the responses shown in the table are

Table 1. Factors influencing the risk that sediment will limit salmonid populations by degrading spawning habitat.

Factor	Level of Risk: Increasing → / Decreasing ←			
Hydrology	Winter rain hydrograph	Summer rain, winter snow hydrograph	Spring snowmelt hydrograph	Spring-fed hydrograph
Erosive process	Surface erosion	Surface and mass erosion, channel erosion		Mass erosion
Geology	Metavolcanics, volcanics	Sandstone, siltstones		Granitics
Hillslope geomorphology	Gentle terrain	Moderate terrain		Steep lands
Stream gradient	High gradient (>5%)	Moderate gradient (1-5%)		Low gradient (<1%)
Stream geometry	Narrow-deep ----------	----------	----------	Shallow-wide
Streamside forest, woody debris	Abundant ----------	----------	----------	Scarce
Salmonid species	Trout, Dolly Varden	Coho, spring and summer chinook	Fall chinook, sockeye salmon	Pink and chum salmon

broad generalizations, they do have some utility for recognizing the sets of circumstances that are likely to create the greatest risk to salmonid populations from sedimentation.

A final factor that affects risk from sedimentation is timing of sediment entry into a stream system. Sediment in natural systems is generally mobilized during large storms. If forest management activities introduce sediment to streams in the absence of a natural runoff event, then sediment deposition may create localized adverse impacts. For example, culvert installations in summer might release sediment downstream at low streamflow. The effects of such "off cycle" sedimentation are usually minor, because only a small area is affected and the sediment source area is ephemeral.

Persistent source areas of sediment are potentially more detrimental than more ephemeral sources. During freshets, intrusion of fines occurs in the top few centimeters of a stable streambed. Persistent sediment sources are subject to repeated freshets and to a greater probability of a major flow event; therefore, they are more likely to yield fines that intrude deeply over a large area of streambed. Fine sediments from persistent source areas might accumulate in streambed gravels for years, and an even longer period might be required before the fines are removed by scour effects.

The question remains, is fine sediment from forest management a factor limiting salmonid populations in natural stream systems? Because there is sufficient evidence to show that sediment is detrimental to salmonid reproduction, the answer seems to be that sediment has the potential to be a limiting factor, especially for pink and chum salmon. Despite this potential, sediment has rarely been documented as such--hence the apparent paradoxical relationship between fine sediment and salmonids in the forest environment. The inability to identify sediment resulting from forest management activities as a limiting factor is related to the complexity and variability of aquatic ecosystems and the multiple concurrent effects of forest management that interact in ways that are difficult to predict. One can conclude from the Alsea watershed and Carnation Creek studies, and numerous other studies, that the state of our knowledge of forestry-fishery interactions is still skeletal, including knowledge of sediment-fishery interactions.

CUMULATIVE EFFECTS OF SEDIMENTATION AND FISHING

Because the effects of sedimentation on salmonid populations can be misunderstood if they are examined out of the context of aquatic ecosystems, a more holistic perspective of the effects of land management on habitat is needed. This holistic approach must also include the effects of natural events and sport and commercial fishing on salmonid stocks.

The potential cumulative effects of sedimentation and fishing have been explored by Cederholm et al. (1981). They suggest that the types of compensatory mechanisms observed on Carnation Creek (Hartman and Holtby 1982), which allowed increased production of coho smolts in the face of concurrent reductions in fry survival, can be overtaxed by the cumulative effects of sedimentation and fishing. Cederholm et al. (1981) assume that low adult escapement coupled with elevated intragravel fine sediments can reduce smolts below the productive potential of the habitat. Using the Clearwater River, Washington, as an example, Cederholm et al. (1981) attempt to demonstrate that sedimentation and an overexploitive fishery might have resulted in a depressed coho salmon population. They concluded, however, that if the Clearwater River was receiving an adequate escapement of coho spawners, the effects of sedimentation would probably be minimal. In this case, both significant reductions in fishing pressure and improved protection of spawning habitat were recommended (also see Cederholm and Reid, this volume).

Investigations of cumulative effects of sedimentation and fishing are difficult and have rarely been attempted, but they appear to be fruitful areas for future research.

STREAMSIDE MANAGEMENT GUIDELINES AND SEDIMENT

Sedimentation is one of numerous potential effects of forest management on aquatic ecosystems. Management activities near streams frequently make simultaneous changes in sediment, temperature, streamflow regimen, bank stability, litter fall, large woody debris, dissolved nutrients, riparian community structure, solar radiation, and other environmental variables. The variables are highly interactive and in various combinations cause a variety of effects on stream biota, including salmonid populations. The interactive nature of these variables, and the fact that the effect of fine sediment as a limiting factor on many salmonid species is poorly known, makes it difficult to isolate the effect of sediment from other environmental variables. Consequently, development of specific quantitative sediment guidelines for forest managers is difficult. At the minimum, if specific guidelines are developed, they must take into account differences in salmonid species and differences in geographic and climatic zones.

Although knowledge of sediment-salmonid interactions is incomplete, some principles for sediment management are apparent. Salmonids are well adapted to steep western watersheds that are characterized by naturally high erosion rates and seasonal variability in streamflow. All salmonid species are able to cope with the natural temporal and spatial variability in sediments in these stream systems, but populations can be stressed or reduced by sedimentation that persistently exceeds natural levels under which the stock evolved. Forest management practices that cause sediment production to exceed the processing and transporting capability of streams for several seasons, or that alter the normal timing of sediment transport, have the greatest potential to damage salmonid populations.

The capability of a stream to mobilize and transport fine sediment is highly variable and dependent on numerous physical factors, which can vary from reach to reach within the same basin. This level of variability makes it practically impossible to develop useful universal guidelines or criteria for protecting stream biota from turbidity and fine sediment. Past establishment of such guidelines stemmed from the assumption that any sediment entering streams as a result of land management had negative effects on aquatic biota. In any situation, this assumption might or might not be true. Nevertheless, because the present state of knowledge of sediment-salmonid interactions is incomplete, the conservative stance of turbidity and sediment criteria developed by various states is prudent. At the minimum, managers should utilize established best management practices and attempt not to disrupt the spatial and temporal sediment equilibrium in streams.

On a more holistic scale, although fine sediment is an important component of stream environments, its control and effects must be considered within the context of stream ecosystems. Forest managers should aim to maintain the overall integrity of streams and streamside zones rather than focus on one variable such as sediment. The development and enforcement of turbidity criteria, for example, have probably reduced suspended sediment loads in streams and improved water quality. Concurrent with gains in water quality, however, have been massive long-term losses of salmonid habitat structure resulting from streamside timber harvest and removal of large woody debris from channels. Consequently, managers need to maintain a broad ecological perspective and keep in mind that streamside integrity is the key issue when they plan forest management activities.

Because forest management has simultaneous interacting effects on streams and streamside zones, no simple or complex guidelines will maintain the ecological integrity of streams in all situations. Consequently, if managers desire to manage an optimum mix of forest resources consistently, a staff of trained specialists is needed. Rather than relying on guidelines that have little flexibility from site to site, managers need to rely on the knowledge of foresters, engineers, hydrologists, ecologists, wildlife and fishery biologists, and other disciplines as needed, to tailor forest management operations to the constantly changing characteristics of the landscape and streamside areas.

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