INCREASED STREAM SEDIMENTATION ASSOCIATED WITH LOGGING ACTIVITY AND ITS EFFECTS UPON SALMONID FISHES

by

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INTRODUCTION

Man's land-use activities, particularly logging, are of direct concern to those managing the land and water resources of this country's forests. Because of the intimate relationship between the terrestrial environment and the aquatic ecosystem, disturbance of the land through the harvesting of timber may affect both the quality and volume of water draining the land. In much of the western United States, forest watersheds provide living space and spawning area for a variety of valuable salmonid fishes. As demands for lumber and wood products grow, it is increasingly important to determine the effects of logging upon the stream ecosystem.

Perhaps one of the most intensively studied changes which may result from logging has been that of accelerated soil erosion. Following logging, the rate of soil loss may be increased 100 fold and may exceed rates of soil formation resulting in a net soil loss (Curry, 1971). In discussing major causes of damage to fisheries resources, Cordone and Kelly (1961) cite accelerated erosion as being the most insidious form of watershed damage because "...it is often unspectacular and goes unnoticed from one year to the next." Tebo (1955) states that sedimentation of watersheds, necessarily occurring from accelerated soil erosion, "...is regarded as one of the most important factors contributing to a reduction in the acreage of desirable fishing waters in the United States." Although logging can increase stream sediment loads (Anderson, 1953; Chapman, 1962; Eschner and Larmoyeux, 1963; Dyrness, 1967; Hall and Lantz, 1969; Brown and Krygier, 1971; Curry, 1971), the variability between watersheds, due to many factors, makes generalization difficult. As such, it will be the purpose of this essay to examine briefly how and to what extent logging activity may increase stream sediment loads, and also to assess what effects, if any, such increased sediment has upon both resident and migratory populations of salmonid fishes.

SOIL EROSION

Soil erosion denotes the wearing away of the soil surface by agents of water, wind, or ice (Dyrness, 1967). Removal rates exceeding the norm are referred to as accelerated erosion, and are generally associated with a removal or disturbance of vegetation (Lowdermilk, 1934). As might be expected, man is the single most important factor in the cause of accelerated erosion (Utah State, 1973b). In forested regions, accelerated erosion by water is a major factor contributing to increased stream sedimentation. Such erosion occurs when the quantity of water being added to the soil by precipitation exceeds the infiltration capacity of the soil (Horton, 1945; Dyrness, 1967; Harris, 1971; Utah State, 1973a).

Surficial Soil Erosion

The erosion of soil particles from the land surface follows a general sequence of events. First, the impact of individual raindrops detaches small soil particles from larger aggregates at the soil surface, and throws them into suspension (Horton, 1945; Dyrness, 1967). As the infiltration capacity of the soil is exceeded, surface run-off begins. Initially it is unchannelized and results in sheet erosion. In time, however, channelization occurs first as small parallel rills, then as gullies, and finally as well defined drainageways

(Horton, 1945; Utah State, 1973b). Under short term conditions this process may never go beyond the rill or gully stage due to revegetation or stabilization of the soil surface. Once the particles of soil material are removed, they are transported by run-off water and either redeposited on the land or in a watershed draining the land.

Although the variables which control both the rate and extent of erosion and sedimentation are numerous, they may be placed into the following general categories for discussion: vegetation, including both the quality and quantity of plant and litter cover; climatic conditions; soil characteristics; topographic configuration, particularly slope angle and length; and existing land use practices.

Vegetation.

Horton (1941) states that vegetal cover is the most important factor in soil's initial resistance to erosion while Dyrness (1967) refers to vegetation as being the "greatest deterrent" to soil erosion. Plants and litter provide cover which breaks the force of raindrops (Lowdermilk, 1934; Horton, 1945), thus minimizing their ability to detach soil particles. Aside from providing cover, plants provide root systems which enhance the stability of the soil. Fine soil particles adhere to root hairs, while plant roots near the surface physically bind the soil (Horton, 1945). Additionally, plant parts also obstruct the movement of overland flow decreasing its velocity and in turn both its removal and transport power (Haupt, 1959).

Litter cover not only provides a mat of highly absorptive material at the soil surface but also provides humic compounds to the soil. As noted by Dyrness (1967), "The overwhelming influence of litter cover in the maintenance of surface soil conditions favorable to rapid infiltration is repeatedly stressed in the literature."

Climatic Conditions.

The moisture regime of an area may be an extremely important factor determining the extent and severity of erosion and sedimentation. Not only can moisture be a factor in determining the type and density of vegetation, it may also be a factor in determining the nature and depth of a soil. Of more direct concern, however, is how water, particularly rainfall, is delivered to the soil surface. As mentioned previously, since run-off, hence erosion and transport of soil, will not occur until the infiltration capacity of a soil has been exceeded, both the frequency and intensity of rainfall are important. The frequency of rainfall in part determines the amount of moisture in the soil at any given time. Thus, in areas having a prolonged rainy season, the soil may remain in a near saturated condition, and may show run-off during rainfall of even light intensity. Storms or series of storms which persist for several days or weeks at a time may also saturate the soil and initiate run-off. In general, the more intense the rainfall, the greater the rate of addition of water to the soil, and hence the sooner the initiation of run-off.

Another important feature of rainfall is its ability to reduce the surface porosity of a soil. This occurs primarily due to the destruction of surficial soil structure by raindrop impact (Dyrness, 1967). As soil aggregates are broken down, fine particles of material in suspension are washed into soil pore spaces where they accumulate. Subsequently, the accumulation of these particles along with the swelling of organic colloids can drastically affect the infiltration capacity of a given soil in a rather short period of time (Horton, 1945).

Soil Characteristics.

The two most significant soil characteristics influencing its erodibility are: the infiltration capacity of a soil, and its structural or aggregate stability (Dyrness, 1967; Buckman and Brady, 1969). The two properties are closely related, particularly in the upper soil layers where the structural stability of aggregates in large part determines the infiltration capacity of the soil (Buckman and Brady, 1969). Factors influencing the infiltration capacity of a soil include:

1. Soil texture or the percentage composition of sand and clay sized particles in the soil. Coarse textured soils in general have higher infiltration capacities than do fine textured ones. As noted by Horton (1945), coarse, sandy soils have infiltration capacities which nearly always exceed rainfall intensity, and thus may show little or no erosion, even when sparsely vegetated. Parent material and time are factors

which determine, in large part, the texture of a soil.

2. Organic content. Organic compounds in the soil tend to encourage granulation (Buckman and Brady, 1969) and to act as binding agents in forming water stable aggregates (Horton, 1945; Buckman and Brady, 1969). In general, the greater the amount of organic matter in a soil, the greater the infiltration capacity, other things being equal.

3. Biological structures and organisms. Particularly in surface horizons, structures such as plant roots, root perforations, and worm, insect, and animal burrows tend to enhance the infiltration capacity of a soil (Horton, 1945). In addition, biological organisms including worms, insects, and burrowing rodents may have important effects upon soil structure and hence infiltration capacity. Primarily, they function to incorporate organic matter in the soil either directly through harvesting and digestion, or indirectly by providing partially processed organic substrata for humification by bacteria and fungi (Buckman and Brady, 1969).

4. Depth of soil to hardpan or bedrock. In general, the greater the depth to an impervious layer the greater the infiltration capacity of a soil (Buckman and Brady, 1969).

5. Swelling clay content. Swelling clays, particularly those of the montmorillonitic group, may swell upon wetting and form an impervious layer. Such clays may often be the cause of a perched water table.

The structural or aggregate stability of a soil affects the degree of soil erosion by minimizing the potential detachment of soil particles by raindrop impact and run-off (Buckman and Brady, 1969; Harris, 1971). Although the causes for varying degrees of aggregate stability are poorly understood, the presence or absence of certain binding agents is believed to be an important controlling factor (Buckman and Brady, 1969). Although different soil types apparently have different combinations of binding agents (Harris, 1971), some elements known to possess stabilizing properties are: various organic compounds, different types of clays, and certain inorganic compounds, e.g., iron oxides.

Topographic Configuration.

The major topographic variables which control soil erosion are slope angle and slope length. Although slope angle plays a role in determining soil depth (Buol, et al., 1973) and the likelihood of run-off (Buckman and Brady, 1969), its major role in soil erosion is in controlling the velocity of overland flow (Horton, 1945; Dyrness, 1967; Buckman and Brady, 1969). The greater the velocity, the greater the potential for erosion. "Theoretically, a doubling of the velocity enables water to move particles 64 times larger, allows it to carry 32 times more material in suspension, and makes the erosive power in total 4 times greater" (Buckman and Brady, 1969).

Slope length is of importance because it determines the area over which run-off may accumulate; hence the volume of water available for soil erosion (Horton, 1945; Dyrness, 1967; Buckman and Brady, 1969). Slope length in turn is directly affected by the general topographic relief, including slope width, presence of natural obstructions, and density of drainage channels dissecting the slope.

Land Use Practices.

As mentioned previously, man is the single most important cause of accelerated soil erosion. Consequently, the way in which man uses a given piece of land may drastically affect its potential for erosion. The clearing and cultivation of land may change the structure of the soil (Buckman and Brady, 1969), and will obviously modify the type and extent of vegetative cover. Logging, in its variety of forms, may affect the erosion potential of the land by disturbance or removal of vegetation, compaction and/or disturbance of the soil, concentration of run-off, modification of topography, etc. Other activities such as urbanization may cause similar changes.

Soil Mass Movement

Soil mass movement may also contribute to increased sediment loads in streams. As described by Dyrness (1967), this form of accelerated erosion involves the simultaneous movement of large quantities of soil under the influence of gravity and is often facilitated by lubrication of the soil body by large amounts of water. Major forms of soil mass movement are slow flowage (creep), rapid flowage (earth flows and debris avalanches), and landslides (slumps and debris slides), (Utah State, 1973a). Factors promoting this form of erosion generally function to reduce the stable arrangement of individual soil particles comprising the soil body. Such factors may be natural or man-influenced. They include: removal of slope supporting material by stream erosion, or, road cutting; oversteepening of slopes by road fill; increasing of slope loads by piling of debris, concentration of drainage water, or, by road filling; and removal of vegetation (Utah State, 1973a). Although no long term studies relating the frequency of mass movement before and after logging activities was found, numerous authors report frequent occurrences of such movement during and immediately after logging (Wustenberg, 1954; Chapman, 1962; Dyrness, 1967; Brown and Krygier, 1971). Such occurrences seem to be particularly common along logging roadways.

SEDIMENTATION

Overland Transport

Perhaps one of the most surprising weaknesses in studies discussing relationships between soil erosion and stream sediment loads is the inadequate description of overland transport of removed material and factors which control its deposition in streams. Although it is tacitly assumed by most authors that accelerated erosion results in increased stream sediment loads, there appear to be no data which quantitatively relate the factors controlling either the likelihood or amount of eroded soil which will ultimately be expressed as stream sediment load. Although the hydraulics of overland flow are not fully understood (Leopold, et al., 1964) some generalizations may be made.

Overland flow may occur either in small rills or as sheets of water of moderate depth over relatively large areas (Leopold, et al., 1964). In time, sheet flow will gradually channelize into rill flow. This is due primarily to irregularities in micro-relief of the soil surface which function to concentrate sheet flow (Leopold, et al., 1964). Regarding the ability of sheet flow to carry eroded soil material, Horton (1970) states that the following facts appear to be well established:

"1. The transporting power of sheet flow, increases with the amount of eddy energy due to surface resistance.

2. The transporting power of sheet flow must vary at least as the square, and perhaps as some higher power, of the velocity.

3. There is a maximum limiting volume of eroded material which can be transported in suspension by a unit volume of overland flow at a given velocity."

Velocity of sheet flow is in turn controlled by surface "roughness," depth of flow, and slope angle (Leopold, et al., 1964).

As sheet flow becomes concentrated into rills, gullies, or ephemeral drainageways its transporting power would be expected to increase due to both increased velocity and volume. The amount of surface flow and sediment collected in this manner would depend upon the density of the channel system; a factor controlled by the interaction of various soil variables previously discussed.

Although the tree felling phase of logging would increase the potential for surface run-off by disturbing the soil and removing cover, it may prevent accelerated soil erosion by increasing the amount of debris at the ground surface. Such an increase in the number of obstructions to surface run-off would minimize its velocity and hence its ability to remove and transport soil material. Other facets of logging activity (road building, yarding, tractor hauling, slash burning, etc.), however, apparently more than compensate for this in a number of ways.

Factors controlling whether or not eroded material is deposited in major drainageways, and in what quantity, appear to be both complex and unquantified. In this regard perhaps the most obvious controlling factor is the proximity of logging disturbance to a waterway. Even this factor, however, is complicated by variations in slope, type and density of vegetation, size of particles being transported, method of logging, etc.

Stream Transport

The transportation of eroded soil solids in a stream channel occurs either as bed load or as suspended load. Bed load consists of that material which is carried along, on, or near the solid boundary of the stream bed (Horton, 1970). Although there is no precise point which separates bed load from suspended load, those materials which are carried in suspension above the bed are considered to comprise the latter category. According to Cooper (1965), "In natural streams or rivers the size of the materials in each of these categories will vary along the river depending upon the hydraulic characteristics of the stream. The suspended load of one section of river may become the bed load of another section and vice versa." The total quantity of material transported will depend upon the amount of material available for transport and stream discharge (Cooper, 1965; Mapes, 1969). In general, materials larger than 0.1mm in diameter will be dependent upon both velocity and turbulence for transport while fine sand, silt, and clay-sized particles may be transported in suspension independent of velocity or turbulence (Cooper, 1965; Mapes, 1969). Even though finer particles may remain in suspension largely independent of velocity, they may be removed from transport by either coming to rest between larger stable particles on the stream bottom, or by settling out in the laminar sub-layer flow of the stream bed (Cooper, 1965). This removal of fine, suspended sediment within the streambed will be of further interest because of its potential affect on the permeability of stream bed materials (Gangmark and Bakkala, 1960; McNeil and Ahnell, 1964; Cooper, 1965).

The total amount of sediment material transported per unit time by a stream is known as sediment yield. Such a measure is generally used as an indication of the rate of soil erosion occurring in a watershed. The sediment yield of a watershed is controlled by three major sets of variables (Anderson, 1953): hydrologic events, including storms and streamflow changes; inherent watershed variables, including geology, physiography, and drainage density; and watershed conditions and land use, which are subject to change in relatively short periods of time.

Hydrologic Events.

Such events are largely an expression of climatic conditions in a given area. In most of the streams of the Pacific Northwest periods of high discharge and increased sedimentation are largely a result of major winter storms or series of storms (Fredriksen, 1970; Brown and Krygier, 1971). Particularly in mountain watersheds of this region, the bulk of sediment yield is carried during infrequent periods of heavy precipitation. Thus, greatly increased sediment loads are generally transitory and are largely confined to the winter season.

Inherent Watershed Variables.

These variables influence both the quantity and quality of water and sediment carried by a watershed. In turn, these variables are also important in determining the nature and hence erodibility of soils. Mapes (1969) working in southeastern Washington determined that the relative increase in sediment load in streams resulting from logging or disturbance was directly controlled by the nature of parent or bedrock material. Due to the potential variations of parent material in or between watersheds of a given area, comparison of sedimentation rates following similar land treatments is uncertain at best.

Watershed Conditions and Land Use.

Anyone observing a small mountain watershed following clearcut logging is readily made aware that man's chosen use of the land can rapidly change its condition or at least its appearance. Anderson (1954) in studying 29 major watersheds of Oregon found that sediment yield was significantly affected by various forms of land use including logging. Since this land use may occur using a variety of different harvesting techniques and conservation practices, the next section of this paper will examine the effects these techniques and practices have on the sediment loads of streams.

LOGGING EFFECTS ON STREAM SEDIMENT LOADS

The sediment loads of streams draining undisturbed forests are generally low (Packer, 1967). During low discharge, suspended sediment concentrations often remain below 10 parts per million (Lieberman and Hoover, 1948; Eschner and Larmoyeux, 1963; Fredriksen, 1970; Brown and Krygier, 1971). Even during periods of high discharge, which accompany heavy rainfall or rapid snow melt, undisturbed sediment concentrations seldomly exceed 100 parts per million. As stated by Packer (1967), "Except for landslips or slumping of banks into stream channels, water quality is seldom harmed by sediment from undisturbed forest slopes."

Disturbance of mountain watersheds by logging may produce significant increases in stream sediment loads (Lieberman and Hoover, 1948; Anderson, 1953; Wastenberg, 1954; Tebo, 1955; Eschner and Larmoyeux, 1963; Fredriksen, 1970; Brown and Krygier, 1971). Although such increases are of varying magnitude and duration due to a number of factors, they commonly are many times the level expected under undisturbed conditions; particularly when logging activities coincide with periods of high stream discharge. Increases in <u>average</u> suspended sediment concentrations, following logging, may range from 3 (Brown and Krygier, 1970) to 20 (Lieberman and Hoover, 1948) times normal, increases in maximum suspended sediment concentration ranging from 80 (Fredriksen, 1970) to 10,000 (Eschner and Larmoyeux, 1963) times normal, and increases in annual sediment yield from 2 to 150 (Fredriksen, 1970) times normal. These figures give some idea of the magnitude of change possible in certain logging treatments, although they do not point out specific causative factors.

The Logging Operation

Logging operations may be broken down into three general phases: felling the timber; its removal from the land; and post-logging debris or slash burning. As might be expected, there are numerous techniques employed within each of these categories. Due to the large number of possible combinations thus provided, review will of necessity be in rather general terms.

Timber Felling.

One of the few watershed-scale studies to assess the isolated effects of tree felling on water quality was done at the Coweeta Experimental Forest in the Southern Appalachian Mountains by Lieberman and Hoover (1948). This area receives most of its precipitation as rainfall which is evenly distributed throughout the year. At the end of a five year calibration period for a 33 acre experimental watershed, all major vegetation was cut and left lying in place. Although there was a 65 percent increase in the water yield during the first year following cutting, there was no apparent increase in the rate of soil erosion or subsequent stream sedimentation. Though the authors conclude that tree felling alone did not cause increases in soil erosion, it must be remembered that vegetation left in place after cutting would both shield the soil from rainfall and provide numerous obstructions to slow overland flow and trap transported sediment. Additionally, due to differences in forest vegetation, parent material and geologic age, extrapolation of these results to coniferous forests of the west may be of questionable value.

Timber Removal.

The removal phase of logging activity provides the greatest potential for watershed damage. Activities in this category include road building and maintenance, skidding and loading of timber, and timber transport. Logging roads, particularly those which are poorly located and constructed, are a major sediment source (Lieberman and Hoover, 1948; Anderson, 1953; Eschner and Larmoyeux, 1963; Packer, 1967; Fredriksen, 1970; Brown and Krygier, 1970; Megahan and Kidd, 1972). Packer (1967), in an excellent review of forest treatment effects on water quality, summarized the adverse features of logging roads as follows:

> Roads expose raw mineral soil, which compacts under travel and resists infiltration of water. Gouging into hills and mountains, roads open up subsurface seepage flows that drain out of road cuts onto road surfaces. Casting of large quantities of material downslope as road fill, exposes even larger areas of raw mineral soil to the erosional effects of rain and road surface run-off.

Road cuts on steep slopes having marginal stability may also increase the frequency and size of soil mass movements (Dyrness, 1967; Fredriksen, 1970; Utah State, 1973b). Additionally, improperly constructed drainageways on logging roads discharge large volumes of road surface run-off and may cause serious erosion on embankment slopes (Haupt, 1959).

Log skidding and skid trails have also been found to contribute to stream sedimentation (Lieberman and Hoover, 1948; Eschner and Larmoyeux, 1963; Packer, 1967; Brown and Krygier, 1971). Often times, log skidding may greatly disturb existing vegetation, creating deep, trough-shaped, skid trails in the soil mantle which concentrate surface run-off (Packer, 1967). Of the various skidding methods used (high-lead, skyline, tractor, horse, etc.), tractor skidding appears to cause the greatest amount of disturbance. Dyrness (1965) found that tractor logging "disturbed" 62 percent of a harvested area and caused serious soil compaction (average increase in bulk density of 48 percent) on 27 percent of the area. A high-lead system, also tested, "disturbed" only 41 percent of the area and caused serious soil compaction on only 9 percent of the plot. Other variables which increase sediment contributions by skid trails include: trail gradients in excess of 10 percent; improper placement, or absence, of waterbars; and proximity to stream channels (Packer, 1967).

Slash Burning.

Rates of soil erosion may also be increased by slash burning activities (Dyrness, 1967; Packer, 1967). Such burning activities may significantly reduce the concentration of organic matter in the upper soil (Dyrness, 1967), may reduce percolation rates of soil by reduction in macroscopic pore volume (Dyrness, 1967), and may remove vegetation and litter cover from the soil surface (Dyrness, 1967; Fredriksen, 1970). Such potential effects of burning are naturally dependent on both the severity of the burn and the initial erodibility of the soil.

Watershed Studies

Since this discussion has synthesized results of logging effects from widely separated areas of the country having diverse vegetative and geologic associations, it seems appropriate to examine briefly the results of two rather complete watershed studies carried out in the Pacific Northwest. Both studies utilized pre-treatment, hydrologic baseline periods of at least 6 years duration.

The first study was carried out by Fredriksen (1970) in the H. J. Andrews Experimental Forest in the Oregon Cascades. Soils in this area are generally deep, quite porous, and have high infiltration capacities. Under undisturbed conditions surficial erosion is rare and the major form of soil loss results from soil mass movement. The study involved three watersheds: a control; a 25 percent patch-cut area using high-lead yarding, with roads; and a clearcut area using skyline yarding, without roads. Annual sediment yield increases of 109 times normal for the patch-cut watershed and 3.3 times normal for the clearcut watershed resulted during an eight year logging and post-logging period. It should be pointed out that minimal sediment increases from the clearcut watershed are partially attributable to a four year period of timber removal which would allow partial revegetation during logging as well as the use of minimally disturbing, skyline yarding for timber removal. More complete results are listed in Table 1 below.

Watershed and means of transport	Yield		Relative yield	Soil loss
	1960-68	1963-68		
	Tons per square mile			*--Inches--*
Control:				
Suspended load	36	46	1.0	0.0006
Bedload	37	47	1.0	.0006
Total load	73	93	1.0	.0012
Clearcut without roads:				
Suspended load	--	195	4.2	.0027
Bedload	--	112	2.4	.0015
Total load	--	307	3.3	.0042
Patch-cut with roads:				
Suspended load	1,430	--	39.0	.0200
Bedload	6,550	--	178.0	.0900
Total load	7,980	--	109.0	.1100

Table 1. Mean annual soil loss from three watersheds H. J. Andrews Experimental Forest (Treatment and post treatment periods: 1960-68 for patch-cut watershed, and 1963-68 for clearcut watershed).
From Fredriksen (1970)

The bulk of increased sediment in both treatments was from soil mass movement with very little attributable to surface erosion. In the patch-cut watershed 93 percent of this material was contributed by movements originating along scrupulously constructed roadways. Measurable sediment increases persisted for more than 5 years following the patch-cut treatment, and for more than 2 years following clearcutting. As might be expected, the major portion of increased sediment was carried by these watersheds during a limited number of major winter storms.

The second study, by Brown and Krygier (1971), was part of a larger, ongoing study by Oregon State University to assess the effects of logging on three small watersheds in the Alsea River Basin. The soils of this area derive from highly weathered sandstone. They are generally shallower and more poorly drained than those in the previous study. Treatments included: a control; a 25 percent patch-cut watershed using skyline yarding, with roads, and a streamside buffer strip; and a clearcut area using unrestricted cable yarding with roads and no streamside buffer strip. Logging was carried out during summer and fall months. In the patch-cut watershed sediment yields were significantly higher than normal for two years following logging. After returning to near normal conditions, a landslide of road origin threatened to increase future sediment loads. On the clearcut watershed sediment yield was increased 3 to 4 times normal following logging and slash burning. Although this level gradually decreased with revegetation of the logged area, complete recovery was not expected for 5 to 6 years. Major amounts of increased sediment in all watersheds were carried during large winter storms. In this study, accelerated soil erosion appeared to be the major contributor of increased watershed sediment.

In very general terms, it is apparent that virtually all methods of logging activity result in above normal stream sediment concentrations. Such increases may be particularly dramatic when logging is carried out during wet, winter periods. Differing degrees of soil or slope disturbance contribute to the severity of accelerated erosion and subsequently to the magnitude and duration of sediment increase. Major causative factors in this regard appear to be logging roads, skid trails, and slash-burned slopes. Although watershed recovery times following logging are variable, significant increases in annual sediment yields may persist for many years. This is especially true for areas which experience major soil mass movements in conjunction with, or, as a result of, logging disturbances. Potential effects of these physical alterations to the stream environment upon resident and migratory salmonid fishes will be discussed in the next section of this essay.

SEDIMENT EFFECTS ON SALMONIDS

Long before man began to harvest the timber of mountain watersheds, there were well established populations of resident and migratory salmonids. In order to survive, these species must certainly have had to adapt to the relative instability of the stream habitat. Natural agents such as fire, soil mass movement, and flooding, most surely, provided fluctuations in both the physical and chemical nature of these aquatic environments. With the coming of man, however, the natural conditions of these watersheds have often been altered. In many cases, man's land use has served to increase the magnitude of previously normal environmental fluctuation; to prolong the duration of formerly short-term, adverse conditions; or to increase the frequency of normally rare events. In this regard, one would expect that salmonids and other stream biota would be resistant to increased doses of suspended and bed-load sediment, periodically swept through stream channels by floods or high water. Whether the same organisms are unharmed by such changes as have been discussed in the previous section of this essay, however, has been the subject of much investigation.

Attempts to determine whether increased sediment loads are directly harmful to fish are generally confounded by a number of factors. Some of these include:

1. Variations in the type and size of sediment.

2. Temporal and spatial differences in concentrations of suspended and bed-load sediment.

3. Inherent environmental differences which may change independently of sediment concentration.

4. Differences in physiological requirements of different species and even different age groups of the same species.

5. Differences in the physiological well-being of fishes brought about by other changes to the environment.

Since many of these factors are difficult or impossible to measure under field conditions, some of the most definitive results might be expected to come from carefully controlled, laboratory experiments. These, for the most part, are lacking.

Direct Effects

Wallen (1951) has provided some of the most complete data from controlled experiments on the direct effects of suspended sediment on fish. He used 16 species (380 individuals) of warm water fishes under controlled aquarium conditions. Varying turbidity levels were maintained by regular additions of silt and montmorillonite clay. Periods of continuous exposure were 28 days or less.

Rather surprisingly, most individuals of all species were able to endure turbidities of greater than 100,000 ppm for periods of one week or more. These same individuals, however, suscumbed at concentrations of 175,000 to 225,000 ppm. Death at lethal turbidity levels generally occurred from 15 minutes to 2 hours after initial exposure. Post-mortem examination of test individuals revealed that in all cases opercular cavities and gill filaments were matted with silt and clay particles from the water. Apparently this material served to block normal gas exchange activities between incoming water and gill filament cells causing death by a combination of anoxemia and carbon dioxide retention. There was no physical damage found to gills or body surfaces by these particles in suspension. Wallen concludes from this investigation, "...the direct effect of montmorillonite clay turbidity is not a lethal condition in the life of juvenile to adult fishes at turbidities found in nature."

There are some apparent drawbacks in this particular study. Wallen did not monitor the general physiological fitness or growth rates of fish during these experiments. By doing so experimental stress effects could have been determined. As well, subtle changes in normal body functions might have been detected at sub-lethal concentrations. Even with partial coating of gill filaments by sediment, normal excretory and salt balance functions might be impaired. Such changes could ultimately result in death given exposure periods of greater than four weeks. Additionally, because no larval forms were tested, little can be said about the effects of suspended sediment on developing individuals.

Although no similar studies for salmonids were reviewed, some general results have been reported. Wilber (1969) relates that at turbidities, induced by diatomaceous earth, as low as 270 ppm rainbow trout died. Autopsies revealed severe clogging of opercular cavities and gill filaments. The author maintains that concentrations of suspended sediment greater than 90 ppm are associated with reduced survival in this salmonid, while concentrations below 30 ppm are readily tolerable. Although he states that immature fish have less resistance and may be harmed by any degree of turbidity which persists for a prolonged period, there are no confirming data forwarded.

Other authors have reported direct effects of increased sediment as by-products of more general investigations. Gammon (1970) noted that most species of warm water fish in a small central Indiana stream, would avoid turbidities of 150-200 ppm (4 to 5 times normal) particularly in the spring by up or downstream migrations. During summer months, however, such movement would not occur until settled material had completely altered the habitat. Eschner and Larmoyeux (1963), working in the southern Appalachian Mountains, noted rather generally that high loads of sediment can cause inflammation of gill membranes and the eventual death of young trout. Wustenberg (1954), observing logging effects on stream biota in the H. J. Andrews forest, found that native cutthroat trout populations were completely eliminated from three small tributaries. This was a result of stream changes from logging. Although he did not identify specific causes, he related that the major changes associated with logging were dramatic increases in both bedload and suspended sediment concentrations. That these increases were a major factor in the disappearance of the trout populations seems likely, but whether the increased sediment had a direct effect upon their demise cannot be answered.

Based on existing data, very few conclusions can be reached regarding the direct effect of increased sediment on salmonids; or any other game fish for that matter. Since greatly increased stream turbidities from logging are generally of short duration, it might be expected that any directly harmful effects would result from the less dramatic, more prolonged sediment increases. Such increases could impair certain physiological functions, and ultimately lead to increased mortality in the less fit individuals of a population. Long-term sediment increases might also cause a reduction in individual resistance to various environmental stresses. Simultaneously, logging could increase the magnitude of the various stresses (water temperature, dissolved oxygen concentration, dissolved salt concentrations, etc.) to the point that greatly increased mortality rates would result in time. Discussing increased mortality rates in fish Wilber (1969) states, "Excessive amounts of silt can act synergistically with harmful environmental factors to potentiate the action." Such indirect influence would likely be most severe in young and developing stages of salmonid fishes.

Effects on the Development of Embryos and Larvae

The quality of the spawning bed environment, in large part, determines the survival of salmonid embryos and larvae (Shapavlov and Taft, 1954; Gangmark and Bakkala, 1960; Coble, 1960, 1961; McNeil and Ahnell, 1964; Shumway et al., 1964; Cooper, 1965) and the size and fitness of emerging larvae (Shumway et al., 1964; Koski, 1966; McNeil, 1966). Characteristics of the spawning bed which are important to successful salmonid development and which are potentially affected by increased quantities of sediment include:

1. Size composition of bottom materials. The size composition of spawning bed gravel influences the quality of water which bathes developing salmonids by influencing rates of flow within spawning beds and rates of exchange between stream and intragravel water (Coble, 1960; McNeil and Ahnell, 1964; Shumway et al., 1964; Cooper, 1965; Brown and Krygier, 1971). These authors have found that there is an inverse relationship between the amount of fine material (sands, silts, and clays) in spawning gravel and the rate of water flow and exchange. Cooper (1965) has shown that the depth of stream and subsurface water exchange is also limited by these fine materials. In addition, increased amounts of fine sediment have also been found to impede larval emergence from spawning gravel (Koski, 1966; Hall and Lantz, 1971).

2. Water quality. For successful development, salmonid embryos and larvae require water of suitable temperature,

ample dissolved oxygen, and relatively free of toxic substances (McNeil and Ahnell, 1964). The quantity of dissolved oxygen available to an embryo or larva is dependent upon its concentration in the water and the water velocity (McNeil, 1966). By reducing the permeability of gravel, fine materials have been shown to limit the rate at which dissolved oxygen is supplied to developing salmonids (Gangmark and Bakkala, 1960; Cordone and Kelly, 1961; Shapley and Bevan, 1961; Shumway et al., 1964; Cooper, 1965; McNeil, 1966; Hall and Lantz, 1970). Similarly, a reduction in permeability has also been thought to inhibit the removal of potentially toxic metabolic waste products, primarily free carbon dioxide and ammonia (Gangmark and Bakkala, 1960; Shapley and Bevan, 1961; Shumway et al., 1964; McNeil, 1966; Hall and Lantz, 1970).

3. Intragravel water velocity. Reductions in the velocity of intragravel water by fine materials may affect the quality of water bathing salmonid embryo and larvae. Other factors being equal, a direct relationship has been reported to exist between the survival rate of salmonid embryos and intragravel velocity (Gangmark and Bakkala, 1960; Coble, 1960, 1961).

4. Stability of spawning bed materials. The stability of spawning bed materials depends upon particle size distribution, stream discharge characteristics, and stream channel configurations (Leopold et al., 1964; Cooper, 1965). Increases in stream sediment occurring as bed-load may result in shifting

bottom deposits (Cooper, 1965). Subsequent movement of these deposits through spawning bed areas can cause increased embryo and larva mortality by mechanical disturbance, or by entombment (Ganmark and Bakkala, 1960; Shapley and Bevan, 1961; Koski, 1966).

The adverse effects of sediment on the early developmental stages of salmonids occurs primarily as a result of sediment deposition on or within the spawning gravel. Since surface deposition of fine sediment material would not generally be expected to occur in the relatively swift, riffle areas preferred by spawning salmonids, the effects accruing to subsurface deposition of fine materials are of major importance.

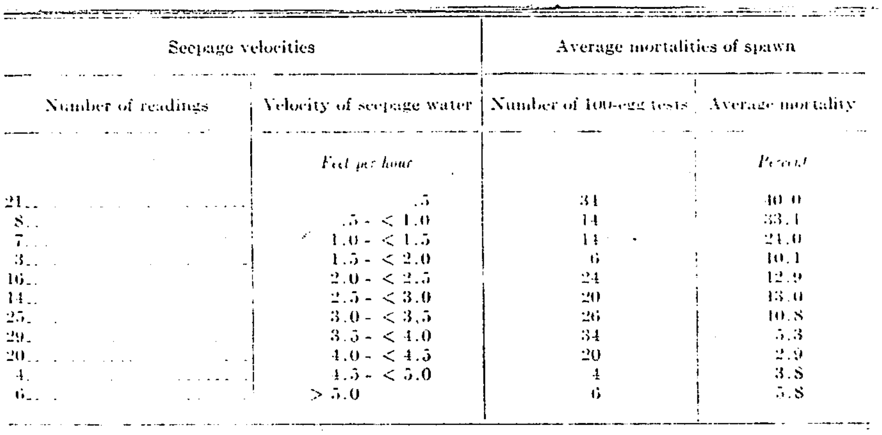
Cooper (1965) conducted laboratory investigations to assess quantitatively the effects of sediment deposition (upon and within spawning bed materials) on the rate of intragravel flow and exchange. He used test troughs filled with spawning gravel from a nearby stream. Concentrations of suspended sediment ranging from 200 ppm to 2000 ppm were introduced into a regulated water flow by addition of silt and clay-sized material. Exposure periods ranged from 30 to 152 hours and surface velocities from 0 - 60 cm/sec. Flow characteristics were monitored throughout each experiment.

These studies showed that surficial deposition of sediment materials in quantities less than 10 percent of the total gravel weight significantly reduced gravel permeability and subsurface flow. Finer sediment materials were more effective in this regard than were coarser ones.

The experiments also provided data which shows that streambed gravel can act as a filter in removing suspended sediments from the water. At suspended concentrations of 200 ppm maintained for six days, the velocity of intragravel flow was reduced 100 fold. Such a reduction related to a 70 percent decrease in expected embryo survival for sockeye and pink salmon. Although these results were obtained in a laboratory under conditions of constant flow and turbidity, and do not account for interactions of other variables such as concentration of dissolved oxygen and temperature, they do show the rather dramatic effects that even moderate concentrations of suspended sediment may have upon intragravel water flow in spawning bed materials.

Cooper concludes, "The results show that the least damaging effect on salmon eggs would occur with very coarse gravel, and the most severe effect would occur with fine gravel such as found in typical spawning beds. The prevention of deposition of sediment upon or within a spawning bed is shown to be essential to a high survival rate of salmon eggs to emergent fry."

Gangmark and Bakkala (1960), as a result of research done on Mill Creek in California, have found that there is a direct relationship between the velocity of seepage in gravel (presumably referring to apparent velocity*) near planted king salmon eggs and the embryo survival of those eggs. Measurements of seepage velocity were obtained using plastic standpipes placed within artificially dug redds. Mortality rates of eggs were determined by their placement in plastic containers and subsequent burial at depths of 12 to 14 inches within the simulated redds.



Seepage velocities		Average mortalities of spawn	
Number of readings	Velocity of seepage water	Number of 100-egg tests	Average mortality
	Feet per hour		*Percent*
21	.5	34	40.0
8	.5 - < 1.0	14	33.1
7	1.0 - < 1.5	14	21.0
3	1.5 - < 2.0	6	10.1
16	2.0 - < 2.5	24	12.9
14	2.5 - < 3.0	20	13.0
25	3.0 - < 3.5	26	10.8
29	3.5 - < 4.0	34	5.3
20	4.0 - < 4.5	20	2.9
4	4.5 - < 5.0	4	3.8
6	> 5.0	6	5.8

Table 2. Mortality rate of King Salmon in Relation to Velocity of Seepage in Gravel Adjacent to Planted Eggs (from Gangmark and Bakkala, 1960)

The authors also noted increases in mortality rates associated with reduced concentrations of dissolved oxygen below 5 mg/l. They state increased egg mortalities are caused

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*"The apparent velocity sometimes called the superficial or macroscopic velocity, is the rate of seepage expressed as the volume of liquid flowing per unit time through a unit area (of solids plus voids) normal to the direction of flow. The true, or pore velocity is the actual velocity of flow through the interstitial spaces, and differs from pore to pore" (Pollard, 1955).

indirectly by deposition of fine sediment materials in salmon redds. Such deposition acts to reduce the seepage velocity of water into the redds and ultimately leads to poor oxygen delivery to incubating eggs, lowered oxygen levels due to decomposing organic sediments, and reduced cleansing of metabolic waste products due to reduced exchange of surface and intragravel water.

Some limitations in this experiment are evident. By measuring only egg mortality, the significance of these variables in determining survival to emergence cannot be assessed. In constructing artificial redds, the authors presumably could not duplicate the cleansing of fine materials from the gravel that results from natural redd building by salmonids (McNeil and Ahnell, 1964). Additionally no monitoring of intragravel water was performed to determine the nature and concentration of metabolic waste products which were thought to have contributed to increased egg mortalities.

The influence of oxygen concentration and water movement on the growth of steelhead trout and coho salmon embryos was investigated in laboratory experiments reported by Shumway, Warren and Doudoroff (1964). Embryos of each salmonid were reared from fertilization of the eggs to hatching at a constant temperature of about 10°C., at varying concentrations of dissolved oxygen (2.5 - 11.5 mg/l), and at varying water velocities (3 - 750 cm/hr). Developing embryos were reared either on porous plates or in containers of glass beads which were to more closely simulate natural conditions.

Reductions in either the oxygen concentration or the water velocity at which salmonid embryos were reared tend to reduce the size of newly hatched larvae or to increase the length of the incubation period. The effect of the difference in water velocities tested was less than the difference in dissolved oxygen concentrations tested. Figure 1 shows some of these results. Mortality rates of the test embryos were not materially increased by reductions in the oxygen concentration above a level of 1.6 mg/l.

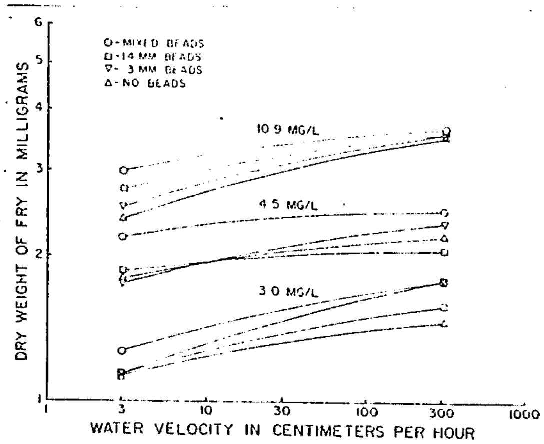

Figure 1. The mean dry weights of newly hatched steelhead trout fry under a variety of conditions; at various oxygen concentrations (mg/l) in relation to apparent water velocities.
(From Shumway, Warren and Duodoroff, 1964)

Although the significance of size reductions and hatching delay upon ultimate larvae survival was not tested, such effects might serve to reduce the emergence of small or weak fry, or to limit their ability successfully to reach maturity in the natural environment.

A more recent study, which addresses the relationship between environmental factors and salmonid survival from egg to emergence, is reported by Koski (1966) working with coho salmon. The study was part of a comprehensive pre-logging survey conducted by Oregon State University to gather baseline data on three small tributaries in the Alsea watershed. Redds of specific females were located and the number of eggs deposited in each was estimated by a linear regression model. A trap of nylon netting was installed over each study redd to catch emerging larvae. Plastic standpipes, similar to those used by Gangmark and Bakkala (1960), were used to monitor various environmental parameters within the redd. Survival of emerging larvae was evaluated in terms of gravel composition, gravel permeability, and dissolved oxygen concentration. Additionally, the size of the parent female and the environmental factors were examined in relation to the size and apparent fitness of emerging fry.

The size composition of the gravel (percent of particles less than .833 mm.) was the only factor which showed a

Tributary	Fines .833 mm (percent by volume)	Mean Length of Emergence (Days)	Length for 90 percent Emergence (Days)	Survival to Emergence (Percent)
Deer Creek	26.4	30	15	54.4
Needle Branch	32.8	35	16	25.1
Flynn Creek	34.2	39	20	13.6

*Redds with zero survival to emergence all contained greater than 35 percent by volume of fine materials.

Table 3. Some selected results on redd gravel composition as related to times for emergence and survival to emergence for coho salmon in three Oregon streams (results from Koski, 1966).

statistically significant correlation with coho survival from egg to emergence. As may be seen in Table 3, such a survival varies inversely with the percent of fine materials. The amount of fine materials also appeared to be directly related to the length of the emergence period.

Both the permeability* of the gravel and the weight of the female parent showed a direct influence on the weight of emergent larvae. In general, it was found that areas having the highest permeabilities produced the largest fry. In this regard Koski states, that although the permeability does not directly affect survival, it is a measure of the adequacy of the gravel to allow for a sufficient supply of water and dissolved oxygen to reach developing embryos and larvae.

In a discussion of test results, the author states:

> A large amount of sediment in the gravel appears to act in at least two ways to the detriment of fry survival and emergence. Gravel in many cases apparently acts as a barrier restricting the movement and entombing the fry within the redd. Retention of the fry beyond the period of yolk utilization would result in a loss of vigor and fitness and thus hinder their ability to emerge. Entombment and extension of the period of emergence was demonstrated in the three streams."

Perhaps the major drawback of this particular experiment is the fact that determinations of gravel size-composition

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*Permeability relates the capacity of a gravel to transmit water. It is defined as the apparent velocity of water per unit of hydraulic gradient (Coble, 1960). Factors controlling permeability include water density and viscosity, porosity of the streambed, and the size, shape and arrangement of solids (McNeil and Ahnell, 1964).

within study redds were conducted only once, at the end of the study. Although such a procedure appears necessary to meet the aims of the work, it can only describe conditions at one point in time, after 90 percent of the larvae had emerged from the redds. Due to wide fluctuations in discharge and sediment concentration reported in these streams by the author and due to major changes in the permeability characteristics of the gravels over short periods of time and distance (Coble, 1960), the results obtained must be viewed in rather general terms. Certainly, however, this work moves to define long-term environmental conditions within the redd as they affect the successful development from egg to emergence of a salmonid species.

Due to the readily apparent lack of studies designed to assess the effects of logging-induced sediment increases on the successful development of salmonid embryos and larvae, specific conclusions are not possible. The general conclusion which can be reached, however, is that even moderate increases in stream sediment load caused by logging may indirectly function to reduce significantly the survival to emergence of developing salmonids, or to reduce their size and apparent fitness upon emergence. Primary relationships in this regard appear to derive from the ability of fine sediment materials to adversely alter the quality of the spawning bed environment.

Effects on Invertebrates

Increased stream sediment loads associated with logging may also affect salmonid populations by reducing the available food supply. Numerous authors have reported that aquatic insects and bottom fauna provide a major portion of the yearly food supply of various salmonid species, particularly during winter and spring seasons of the year (Shapavlov and Taft, 1954; Tebo, 1955; Chapman, 1961; Lowry, 1966). Tebo (1955) reports that aquatic bottom fauna comprises approximately 60 percent by weight of the yearly food intake of rainbow trout in streams of the Coweeta Experimental Forest. Chapman (1961) has found that roughly the same percentage of the yearly food intake of young coho salmon is provided by aquatic insects in three tributaries of the Alsea watershed. Additionally, Lowry (1966) indicates that about 50 percent of the food of cutthroat trout in the same streams is provided by aquatic insects.

As noted earlier, increases in stream sediment load may increase the proportion of fine materials present in the gravel substrate. If the increases are sufficiently severe, fine materials may fill the interstices and spaces around gravel, rubble, and other bottom irregularities, decreasing bottom productivity for aquatic algae (Chapman, 1961) and insects (Cordone and Kelly, 1964), and possible reducing protective cover for young fish.

Tebo (1955) reported results of extensive bottom sampling which followed logging on a small watershed in the southern

Appalachian Mountains. For a five month period following logging activity, there was a significantly lower, numerical, standing crop of bottom organisms at the station below the mouth of the logged watershed than above. This reduction was attributed to streambed accumulations of sediment material. Following three months of high water and flooding, which resorted bottom material and flushed out accumulated sediment, previous standing crop levels were restored. The author states, "Therefore, because of the dependence of trout on stream produced organisms, any outside factor, such as siltation, which reduces the normally low quantities of stream organisms will ultimately have a deleterious effect on the trout population." Unfortunately, data confirming this observation were not provided.

Wustenberg (1954) found that increased sediment loads following logging operations on a watershed in the H. J. Andrews Experimental Forest, caused a serious reduction in the number of trout food organisms. The duration of this reduction was in excess of one year. Again, however, no investigation was made to relate the ultimate effects of this food reduction on resident cutthroat trout populations.

Assessing the effects of varying concentrations of sediment on the biota of a small stream in Indiana, Gammon (1970) concludes that both settled sediment and increased loads of suspended sediment deleteriously affected the populations of aquatic macroinvertebrates in study riffles. Increases in suspended sediment concentration of four times the normal level caused significant decreases in the population density of macroinvertebrates. Such reductions appeared to occur even in the absence of visible accumulations of sediment on the bottom substrate. Normal population densities were restored in a matter of days, however, with reductions in suspended sediment to previous levels and by immigration of new individuals.

Although there appears to be a rather good indication that increases in sediment concentration and bottom deposition can reduce the food available to salmonids, no research describing the ultimate impact of this reduction on fish populations was found. Since the highest intake of aquatic food organisms by salmonids apparently occurs during the periods of highest potential sediment increase associated with logging (winter and spring), even relatively short term reductions in available food might adversely affect resident populations. This situation would likely be most pronounced in smaller tributaries, where both food and space are limited, and where damage due to increased sediment loads would be most severe.

CONCLUSIONS

1. Logging activity can, and often does, produce significant increases in stream sediment loads. The magnitude and/or duration of these increases is generally most severe following clearcut logging operations, particularly those operations which are carried out during wet, winter months. Major causative factors in this regard include: poorly engineered and constructed roadways and improperly designed skid trails.
2. The effect of even moderate sediment load increases upon salmonid populations is a reduction in both the number and general fitness of emergent young. Such a reduction is caused by accumulations of fine sediment material which adversely influence the physical and chemical quality of the spawning bed environment.

These conclusions do not address those situations where logging activity has caused complete destruction of the stream habitat. In such cases where the ruin of the stream is obvious, where gravel beds are buried under sediment, where debris completely chokes the channel, where no food producing rubble or gravel substrate remains, and where water temperatures commonly exceed 70 degrees Fahrenheit (Chapman, 1962) objective analysis is not required.

Probably the most apparent conclusion which can be reached, however, is that this subject offers tremendous opportunity for future research. Maximum returns on this research will likely be produced by comprehensive, long-term investigations conducted by interdisciplinary teams of researchers. It is suspected that the end result of such study will be the recognition that specific conclusions are restricted to individual geographic regions, or watersheds, and to their existing mix of salmonid species.

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