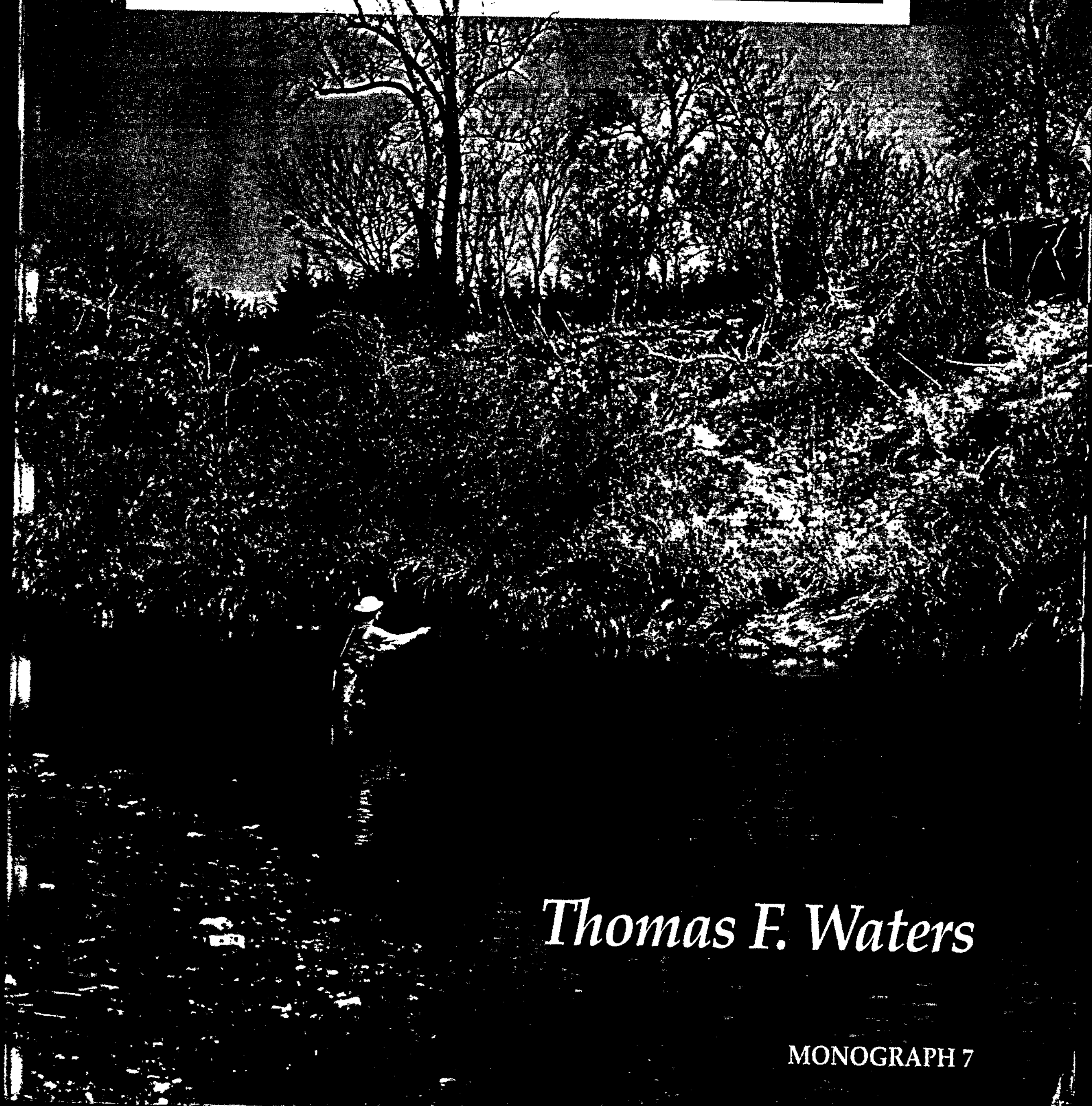
SEDIMENT IN STREAMS

Sources, Biological Effects and Control



Thomas F. Waters

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SEDIMENT IN STREAMS

Sources, Biological Effects, and Control

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EFFECTS OF DEPOSITED SEDIMENT ON BENTHIC INVERTEBRATES

The ecology of benthic invertebrates has long been the dominant research interest in stream ecology. Invertebrate biology constituted a major segment of the definitive work on stream ecology by Hynes (1970). However, the importance of the trophic relationship between benthos and fish productivity also has been recognized and researched extensively. Recently, the dependence of fish production upon benthos production has been challenged and modified to include other food resources, for example, in the attempt to resolve the Allen paradox (Allen 1951; Waters 1988). Nevertheless, the reliance of fish upon invertebrate production probably remains substantial in most streams. From the fisheries perspective, as well as others, the effect of excess sediment upon benthic invertebrates has become one of the most important concerns within the sediment pollution problem.

By definition, benthic invertebrates inhabit the stream bottom; therefore, any modification of the streambed by deposited sediment will most likely have a profound effect upon the benthic invertebrate community. Some of the many extensive studies of stream sediment include effects on both the benthos and fish. The influence of sediment deposition on the productivity of benthic organisms as food for fish is one of the most critical problems affecting stream fisheries.

The pervasiveness of deposited fine sediments in the benthic environment, however, was not recognized early. It was sometimes overlooked in stream fisheries studies, in contrast to the much more visible suspended sediment which stimulated the earliest concern about sediment as a stream pollutant. Greater emphasis on the relationship between deposited sediment and benthic invertebrates appeared in later investigations; the relationship now constitutes one of the major subjects in sediment studies.

Most published research dealing with deposited sediment and benthic invertebrates has focused on the general view of dependence by benthos on substrate particle size. In many early fisheries investigations, the principal concern for the invertebrate community—and its relationship to substrate composition—was as a fish-food resource. The review of Cordone and Kelley (1961) stimulated more intensive research into specific effects of anthropogenic sediment inputs.

Although not emphasizing the North American region, the early reviews by Chutter (1969) and later by Ryan (1991) offer many data of comparative signifi-

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cance. Chutter's review was worldwide but emphasized South African streams; he noted that complete smothering of the streambed was necessary to cause large reductions in invertebrates, but small streambed changes could bring about important species changes. Ryan reviewed the effects of both suspended sediment and deposited sediment on plants and invertebrates; he concluded that both of these biotic groups may be reduced rapidly by spates and that full biological recovery required long periods of time.

The relationship between benthos and sediment in streams is incorporated into three major topics: (1) correlation between benthos abundance and substrate particle size, (2) embeddedness of streambed substrates and loss of interstitial space, and (3) change in species composition with change in type of habitat.

First, the positive relationship between benthos abundance and substrate particle size was broadly accepted and appreciated as the main effect of streambed sedimentation. It was the principal influence in fisheries concerns about sediment in the few decades prior to Cordone and Kelley's (1961) review. Second, the dependence by benthos upon interstitial space in the streambed substrate was firmly confirmed by the appreciation of the influence of embeddedness of cobbles on invertebrates. Third, the relationship between substrate particle size and consequent taxonomic changes was appreciated as the result of change in type of habitat.

MAJOR REVIEWS

The most significant publication in its time on stream pollution by sediment was the seminal review by Cordone and Kelley (1961). The review summarized the work on invertebrates reported in about 12 papers published up to that time on sedimentation, including silt generated by mining operations, logging, dam construction, and other sources.

Cordone and Kelley (1961) raised concerns about several sublethal effects on fish, such as lowered body condition, slower growth, and reduced productivity—all correlated with reduced invertebrate food supply; they pointed out the need for continued research on these questions. They concluded that there was "... overwhelming evidence that the deposition of sediment in streams ... has destroyed insect and mussel populations." All reports to that time unanimously agreed that the adverse effect of deposited sediment on benthic invertebrates was serious.

Progress was made in the succeeding decade on the basic ecology of organism–substrate relations by K. W. Cummins (1962, 1964, 1966; Cummins and Lauff 1969). These publications stimulated further concern and research into the relationship between substrate particle size and stream invertebrates. Cummins's contributions were not necessarily concerned with anthropogenic sediment, but they spurred many studies on sediment as a pollutant. If a stream invertebrate biota responded in the way it did in the field studies and experiments of Cummins and his associates, the invertebrate benthos, it was argued, would respond similarly to anthropogenic sediment.

Cummins (1962) reviewed sampling and analysis techniques for both benthic fauna and streambed substrates. He emphasized the effects of the physical characteristics of the stream substrate on the distribution and ecology of benthic invertebrates. In addition to his table of particle-size terminology (Table 1, page 14), Cummins reviewed and cited the literature of technology for sampling and analyzing substrate composition up to about 1960.

The symposium on organism–substrate relations held in 1964 at the University of Pittsburgh's Pymatuning Laboratory of Ecology (Cummins et al. 1966) included the most extensive review of stream ecology at the time (Cummins 1966); 530 references were cited. In this review, Cummins made a strong argument for the inclusion of substrate sampling as standard practice for studies in benthic ecology. He also included a critical discussion of the prevailing technology of substrate sampling and analysis. An increased volume of research on the physical consequences of anthropogenic sediment (i.e., a drastic increase in quantities of small particle sizes) followed in succeeding decades, and the concept of sediment as a pollutant was firmly established.

Up to the mid-1960s, very few papers had dealt with the concept of anthropogenic sediment as a pollutant affecting biotic elements other than fish. Most early papers had considered the effect of turbidity, rather than deposited sediment, as the significant factor. The series of seminars on water pollution at the Robert A. Taft Sanitary Engineering Center, Cincinnati, Ohio (U.S. Public Health Service), in the 1950s was just beginning to consider sediment as a pollutant affecting aquatic life other than photosynthesizing plants and fish (Bartsch 1959; Wilson 1957, 1959). Hynes's (1966) book, the definitive work on aquatic pollution biology at the time, included very little on silt or sediment as a pollutant affecting stream invertebrates.

SUBSTRATE PARTICLE SIZE

A general appreciation of the dependence by benthos on substrate particle size was expressed early: the abundance of benthic invertebrates correlated positively with particle size. Many investigators observed a gradient of benthos abundance across the series of particle sizes (sand-gravel-pebble-cobble), and reported that the greatest abundances occurred in the larger sizes. Over several decades, this principle became well established (Needham 1928; Pennak and Van Gerpen 1947; Sprules 1947; Kimble and Wesche 1975). Minshall (1984) pointed out, however, that the more functional relationship may be between benthos abundance and substrate heterogeneity. Benthos abundance is least in homogeneous sand or silt and in large boulders and bedrock; abundance is greatest in the mixture of heterogeneous gravel, pebbles, and cobbles.

These relationships appear to hold true mainly for the principal taxa of insects available to fish—Ephemeroptera, Plecoptera, and Trichoptera (EPT). For example, higher densities of small burrowing organisms such as chironomid larvae and oligochaetes often occur in silt or muck (Benke et al. 1984); other exceptions include the crustacean *Gammarus* in sand (Waters 1984) and the burrowing mayfly *Hexagenia* in silt (Fremling 1960). Most fish-food organisms—those most available to foraging fish—appear to prosper best in the heterogeneity of pebble and cobble riffles. For many researchers, it followed that additions of anthropogenic sediment would result in loss of the best benthos habitat and

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Tailwater fisheries developed below high dams create clear water (and lower temperatures from hypolimnetic releases) through settling of suspended sediment in the reservoir. Such changes also produce alterations in benthic invertebrate taxa, often including tubificid worms coming from the reservoir—which are imitated by the anglers' red "San Juan worm" fly. Salmonids introduced usually include rainbow trout and brown trout. San Juan River, New Mexico.

consequently, reductions in invertebrate populations—an early speculation that has proven overwhelmingly true.

An interesting tangential element in the invertebrate-substrate particle-size relationship was later presented by Culp et al. (1983). Their experiments with different substrate mixtures highlighted the animals' need for organic detritus as food. Lack of organic detritus overrode the effect of substrate: without this food resource, density and biomass of invertebrates decreased significantly regardless of the substrate particle-size mixture.

Almost all early concern about sediment followed the substrate size principle. Siltation was regarded as a simple change from large to small particles, or visually, a covering of the original gravel and cobble substrates with silt and sand. Declines of benthos in heavily sedimented streambeds were the subject of alarms raised by Ellis (1931), who decried the loss of mussels in silted areas as a result of river navigation development in the upper Mississippi River. Since that time, many instances of marked reductions in species and population densities of mussels in the Mississippi River have been noted as a result of human activities, including expansion of navigation and increased river traffic. Generally, these reductions have been attributed to increased sedimentation of previously clean riffles and gravel (Ellis 1936; Marking and Bills 1980). Some authors have documented a wide range of substrate habitat preferences among mollusks (Harman 1972; Huehner 1987). Many reports have documented the loss of species after anthropogenic disturbance, such as dam construction, channelization, increased river traffic, and resulting siltation (Bates 1962; Stein 1972; Harman 1974; Parmalee 1993).

Many reports during the early decades of investigation—prior to Cordone and Kelley's (1961) review—involved the general effect of fine sediment additions that reduced fish food invertebrates. In the Klamath River and tributaries, California, "food organisms" were always observed at lower abundances in streams subject to sedimentation from mining operations (Taft and Shapovalov 1935). Sumner and Smith (1940) reported substantial reductions in "fish food organisms" in tributaries of the American and Yuba rivers, California. These streams had been subject to hydraulic gold mining, a process that produced enormous quantities of sediment, but which is now under much stricter control. Tebo (1955) observed lower abundances of bottom fauna in silted areas of a trout stream in the Coweeta Experimental Forest, North Carolina. Although recognizing the potential of "settleable solids" to adversely affect "fish food production," the Aquatic Life Advisory Committee (ORVWSC 1956) declined to set criteria because of lack of information at the time.

One of the most striking field examples was the 1958 siltation of the Truckee River and a tributary, Cold Creek, in California (Cordone and Pennoyer 1960). Fine sediment from a gravel-washing operation covered stream bottoms up to one foot in depth or more and reduced the substrate to a "hard, bedrock-like" condition. The bottom fauna densities and biomass in both streams were reduced to less than 10% of former levels. The authors concluded that the Truckee River was "severely damaged" up to 10.5 miles downstream from the sediment source.

SUBSTRATE EMBEDDEDNESS

Benthic insects within the EPT group usually inhabit the surface of stones and the interstitial spaces between and beneath large substrate particles such as pebbles and cobbles. Invertebrates in the hyporheic zone—deep within underlying gravel and in contiguous lateral gravel deposits—depend upon the flow of oxygen-containing water through the interstitial spaces. Consequently, research on specific effects of sediment included experiments wherein controlled amounts of sediments were added at increasing levels in order to observe invertebrate behavior and abundance over long periods.

The first such long-term field study on invertebrates was conducted in relation to sediment in mountain streams of central Idaho (Bjornn et al. 1974; Bjornn et al. 1977). Road construction for logging and mining was the main source of fine sediment. The investigations included studies of sediment transport and effects of sediment on juvenile salmonid habitat and benthic insects. The invertebrate research included: (1) investigation of insect abundance and drift with varied sediment composition in a number of natural streams, (2) experimental additions of sediment to riffles in natural streams, and (3) experiments in laboratory streams. The research program extended from 1972 through 1975.

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In natural streams, riffles with the most sediment contained the lowest abundance of insects, but small amounts of sediment added to natural riffles did not greatly affect insect abundance or drift.

In the laboratory streams, a major finding was related to the degree of embeddedness of cobbles. The authors concluded that a small amount of fine sediment around cobbles (zero to one-third embeddedness, i.e., the fraction of cobble surface fixed into surrounding sediment) represented the natural condition. At an embeddedness of more than one-third, insect abundance declined greatly (by about 50%), especially for riffle-inhabiting taxa. When a streambed plot was later cleaned of fine sediment, mayflies and stoneflies increased by up to eightfold.

These findings were supported by other experiments where sediments were applied to laboratory stream sections (McClelland and Brusven 1986). The behavior and distribution of riffle insects were observed in relation to the fraction of cobble embeddedness. All species in the EPT preferred the control treatment of cobbles and gravel only; most species responded negatively to increasing amounts of sand and to greater cobble embeddedness. The authors attributed the results to the inability of nonburrowing forms (especially EPT) to gain access to areas beneath embedded cobbles.

Culp et al. (1986) performed an unusual field experiment in Carnation Creek, British Columbia, involving additions of sand (0.5–2.0 mm) to natural stream riffles. They explored the difference in effect of sediment in (1) riffles with low "tractive force" where added fine sediments were deposited and (2) riffles with high tractive force, where the particles, although not suspended, moved along the bottom substrate in a saltating manner. No previous studies had specifically differentiated between these two conditions. Whereas the deposited sediments had little effect (presumably in low amounts or over the short term), the saltating sediments in the high tractive force apparently scoured the animals and caused high catastrophic drift, with a decrease of more than 50% in benthic invertebrate density. Those taxa occupying upper stone surfaces drifted immediately; other taxa with deeper distributions were removed later, after the animals became active in diel patterns. Newbury (1984) provided a discussion of the physical aspects of tractive force acting on sediment particles. Whereas earlier publications speculated on the scouring effect of moving particles upon invertebrates, Culp et al. (1986) appears to be the only one to include empirical data.

Studies in Valley Creek, Minnesota, included the estimate of annual production by hydropsychid caddisflies upstream and downstream from a small reservoir managed as a sediment trap (Mackay and Waters 1986). The reservoir was located a short distance downstream from a major source of chronic sand input (dry gully). Most bottom habitat upstream from the reservoir was sand; the substrate downstream from the dam consisted of cobble riffles. Annual production by three species of hydropsychids was 5.8 g/m^2 (dry weight) upstream from the reservoir and 34.9 g/m^2 downstream from the dam. The downstream increase below the dam was attributed to the feeding behavior of these insects; to construct filtering catchnets, the hydropsychids required solid substrates and interstitial space available in the cobbles downstream from the dam, but lacking in the sandy streambed upstream from the reservoir.

Gammarus has been commonly reported in greatest abundances in fine-particle substrates, particularly sand, rather than in cobble riffles (Pentland 1930; Waters 1965; Marchant and Hynes 1981). This preference has been attributed to avoidance of strong currents (Marchant and Hynes 1981), but *Gammarus* is also known as a strong swimmer and can move easily in loose sand, where it probably feeds on intermixed fine organic detritus as a collector-gatherer. A 5-year study of annual production by *Gammarus* by substrate type in Valley Creek, Minnesota, showed highest production in sand and sand–gravel mixtures and lower production in gravel and cobbles (Waters 1984). Although production decreased in all substrate types as the result of heavy clay deposits, the reduction was most severe in sand that had become embedded with clay; production decreased by 90% in the clay and sand mixture compared to a 65% reduction in cobbles. These results suggested that whereas clean sand may be the preferred substrate for *Gammarus*, it was the clay embeddedness that negatively affected the habitat of *Gammarus*.

An exceptional study on Cullowhee Creek, North Carolina, an Appalachian Mountain stream affected both by logging and organic pollution from pastures, was conducted by Lemly (1982b). The stream was divided for study into three distinct reaches: an upstream, undisturbed uncut control; a reach sedimented by logging operations and residential construction; and a downstream segment additionally polluted with nutrient inputs from horse pastures. Species richness decreased longitudinally through the three reaches: 64 species in the upstream control, 50 species in the reach affected only by sediment, and 36 species in the downstream reach affected by both sediment and organic pollution. Diversity, density, and biomass were all decreased by the sediment alone, but in the organically polluted reach, density and biomass of dipterans were increased. Lemly also suggested that erosion of acidic Appalachian rock and increased input of resulting fine particles reduced the pH of stream water and eliminated some acid-intolerant species. In the sedimented reach alone, a buildup of inorganic particles on the gills and body surfaces of invertebrates was indicated as a source of mortality. Inorganic particles also reduced substrate heterogeneity and interstitial living space, even when the water appeared clear. In the organically polluted lowest reach, the development of *Sphaerotilus* on insect bodies appeared to further increase the adhesion of inorganic particles, thus further reducing gill function. The author suggested a synergistic effect of sediment and nutrient pollution.

Rutherford and Mackay (1986) attributed mortality among caddisfly pupae to silt that was deposited around the pupal case and caused an apparent loss of oxygen supply to the pupa. The authors pointed out that an encased pupa, unlike most other benthic invertebrate stages, cannot move away from poor environmental conditions such as low oxygen levels.

Amphibians were observed to behave similarly to invertebrates when faced with sedimentation. Corn and Bury (1989) observed populations of the tailed frog and three salamanders in 43 small streams in western Oregon. Twenty-three streams were in uncut watersheds; the other 20 had been logged 14–40 years previously. All streams had similar physical factors, except that the streams in logged watersheds had greater sediment deposits and smaller substrate particle

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sizes. All four species of amphibians had higher density and biomass in the streams in uncut watersheds than in those that were logged. The authors attributed the differences in amphibian populations to the need of larvae to develop in substrate interstices. They emphasized especially the long-term effect of logging along small, low-gradient streams, expressed concern for continued viable populations of these amphibians, and suggested some protective forest management measures.

TAXONOMIC ALTERATION

The long-held general principle of a correlation between invertebrate abundance and substrate particle size was originally formulated on the basis of density of invertebrates. In other words, through the particle-size series of fine to large substrate sizes, numbers of animals generally increased.

There were exceptions, however. For example, clay held very few invertebrates; silt, on the other hand, often held the greatest numbers, especially when the silt was mixed with organic matter. At the other end of the spectrum, boulders and bedrock, instead of holding the most (if the principle held true through the entire size spectrum), often held the fewest invertebrates. It now appears that the principle holds true mainly for insects of the EPT. Part of this discrepancy was probably because insects are more abundant in habitats of greatest heterogeneity, rather than of larger particle size (Minshall 1984). Habitats at both ends of the particle-size spectrum—clay-silt and boulder-bedrock—being essentially homogeneous, support few organisms, and habitats in the center of the spectrum—gravel through cobbles—being much more heterogeneous, hold the most. Another part of the discrepancy—the high abundances in the fine particle sizes—is due to the sometimes superabundance in numbers of small invertebrates of different taxa (e.g., burrowers such as chironomids and oligochaetes). These findings led to the currently accepted principle that when a large-particle habitat of gravel–cobble is changed to silt–sand, a taxonomic alteration also occurs.

In North Carolina, D. R. Lenat and his associates extensively investigated problems of stream pollution resulting from urban runoff, including sedimentation (Duda et al. 1979; Lenat et al. 1979; Lenat 1984; Lenat and Eagleson 1981). Whereas some pollution inputs could be identified from point sources, many could not, owing to the maze of urban development activities and uncontrolled waste disposals. Thus, they concluded that it is a mixture of inputs, including chemical pollution, toxic materials, oil and grease, organic materials, and sediment that degrade urban streams. City paving increases peak flows in streams and thus erosion. Whereas poorer stream conditions were found in large cities due to chemical and organic pollution, streams in smaller towns deteriorated mostly because of sediment and water flow changes (Lenat and Eagleson 1981).

The difficulty in measuring specific pollution sources led these investigators to use a biological monitoring procedure that used abundances of benthic invertebrates to assess stream degradation (Penrose et al. 1980; Lenat 1988). Stream waters of good quality were identified by the greater abundance of pollution-intolerant taxa, such as those in EPT and some Coleoptera; degraded streams contained pollution-tolerant Oligochaeta and some Chironomidae, often in densities higher than for EPT and Coleoptera.

An important value of using macroinvertebrates in an index to water quality lies in the long-term effects that invertebrates will reflect. Life cycles of one year or more will be influenced by changes in hydrological conditions over all seasons; the animals integrate all influences over the longer period. Their populations will reflect synergistic and antagonistic effects of a mixture of pollutants of all kinds—toxic, organic, and sediment (Lenat et al. 1979). Some caution, however, should be used in this regard: the possibility of invertebrate drift (e.g., from a clean upstream section to a polluted reach downstream) might result in incorrect conclusions about the presence of EPT organisms in the polluted reach.

In their major review, Lenat et al. (1979) summarized the use of biological monitoring in streams that receive nonpoint pollution from several sources such as urban runoff, road and highway construction, mining, and agriculture. Sediment was identified as a major component of nonpoint pollution, much more important from all sources (except urban runoff) than chemical pollution.

Lenat et al. (1979) summarized the effects of sediment upon benthic macroinvertebrates.

1. With small amounts of sediment, density and standing stock of the benthos may be decreased due to reduction of interstitial habitat, although structure and species richness may not change.
2. Greater sediment amounts that drastically change substrate type (i.e., from cobble–gravel to sand–silt) will change the number and type of taxa, thus altering community structure and species diversity, but often with increasing densities.

The classic change due to sediment is from a community of EPT to one mainly of oligochaetes and burrowing chironomids. Lenat et al. (1979) supported Cairns's (1977) application of "assimilative capacity" and pointed out that the capacity of a stream to process sediment input without damage to invertebrates depends upon stream gradient and flow. If gradient and flow are sufficient to move away sediments, little change will result. If sediment inputs exceed the stream's capacity to remove them, sediments will deposit and drastically alter the invertebrate community. Lenat et al. (1979) described the difference as being between "habitat reduction" and "habitat change."

The North Carolina investigators further studied the effects of sediment input upon macroinvertebrates in two Piedmont streams, particularly with respect to the above two modes of influence (Lenat et al. 1981). They also described a "stable-sand community" in streambeds where heavy sand deposits at low flow will encourage a periphyton community, which in turn attracts an invertebrate community of grazers. The stable-sand community may be destroyed and washed away under subsequent higher flows. The stable-sand community, however, has the effect of reducing the abundance of those kinds of invertebrates that serve as fish food.

The results of Hall et al. (1984) also demonstrated the difference between taxa that are tolerant and those that are intolerant of fine sediments. In several experiments with artificial channels, the density of chironomids, amphipods, snails, and oligochaetes increased with increasing sediment and embeddedness. Abundances of EPT, when initially present at substantial levels, declined with

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increasing sediment. Similarly, Whiting and Clifford (1983) observed fewer species of Ephemeroptera, Trichoptera, Simuliidae, and Amphipoda, and increased numbers of Tubificidae, in reaches of a stream flowing through Edmonton, Alberta. They attributed the effects to siltation and other runoff components.

An increase in work on the basic ecology of organism–substrate relationships confirmed the general conclusion that coarser particles (gravel, pebbles, cobbles) are preferred by EPT (the most preferred and available fish-food organisms), whereas fine-particle substrates (sand, silt) are inhabited by chironomid larvae and other burrowing forms that often are not readily available to foraging fish (Erman and Erman 1984; Minshall 1984). These are the conclusions most often reached by investigators studying the effects of sediment from anthropogenic sources, which almost invariably increase fine particle accumulations and alter the mix of invertebrate taxa.

SHORT-TERM AND EPISODIC EVENTS

The biological effect of episodic inputs has been found generally to be temporary. Rapid recovery often results from steep gradients and invertebrate drift from upstream reaches.

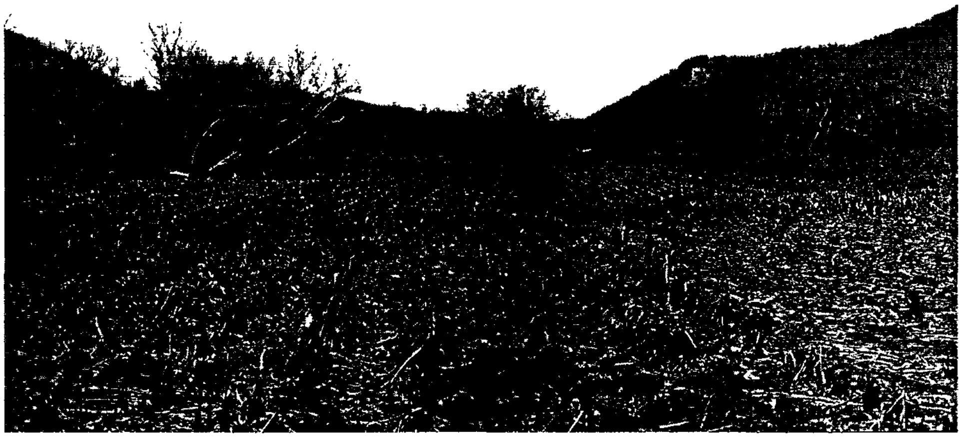
For example, sediment from highway construction at a high elevation in the Rocky Mountains severely reduced invertebrate density and biomass, but recovery was rapid due to steep stream gradients and quick flushing of deposits (Cline et al. 1982). In an Ohio stream, sediments from eroding deposits of glacial lacustrine silt, although natural, simulated episodic events. The glacial silt periodically reduced benthic macroinvertebrates up to 5 km downstream from the site (DeWalt and Olive 1988). However, after one of the glacial silt deposits was completely eroded, sediment input ceased, the stream deposits cleared, and drift from upstream quickly restored benthic populations. In British Columbia, temporary siltation from a pipeline crossing reduced local benthos populations by up to 74% but benthos recovery was rapid after construction stopped (Tsui and McCart 1981).

SEDIMENT SOURCES AND INVERTEBRATES

Although sediment from many sources may have much the same effect, some differences have been often observed. For example, sediment inputs from soil erosion of agricultural fields will probably be long-term, at least until tillage practices change. Eroded soil from row-crop fields often includes the finest particles. Sediment from bridge construction, on the other hand, may be short-lived. Nonpoint pollution from urban development that contains large amounts of sediment will most likely contain other pollutants, as will waste from some mining operations. Consequently, the biological effects of sediment from different sources may vary in duration, seasonality, and severity, and sometimes with unknown synergistic effects in a mixture of pollutants.

Agriculture

Whereas sedimentation from agricultural sources is recognized as being among the most severe, affecting mainly warmwater streams and midwestern



Row crops on the floodplain beside a southern Minnesota trout stream can produce sediment that severely reduces bottom fauna production. The stream, located at left behind trees and shrubs, appears partly protected by a buffering riparian zone.

trout streams, little definitive research on corresponding biological effects has been published. Particularly lacking are long-term studies of the effects of chronic sediment input, such as that which might derive from nonpoint agricultural sources. Unlike work on salmonid reproductive success (discussed later), little precise experimental work has been done in the laboratory on agricultural sediment and invertebrates.

The laboratory stream experiments of Cummins and Lauff (1969) were intended to delineate the basic behavior of benthic invertebrates as related to substrate particle size. Their studies were some of the first experimental research to employ artificial channels to investigate the behavior of stream invertebrates. The authors tested the preference of 10 species of common stream invertebrates for substrate particle size. Animals included mainly EPT, plus one member from each of the genera *Simulium*, *Stenelmis*, *Tipula*, and one snail. Brusven and Prather (1974) conducted similar experiments in laboratory streams, using five species from EPT and Diptera. Although their experiments (like those of Cummins and Lauff) dealt with the basic ecology of the stream invertebrates, they were motivated by concern for sediment as a pollutant resulting from agricultural practice and other anthropogenic sources.

In a specific agriculture-related study, Cooper (1987) reported the effects of heavy sedimentation in Bear Creek, Mississippi, a tributary of the Yazoo River. Sediment input was seasonal; the greatest amounts reached the stream during high rainfall from agricultural fields. The author reported lowest annual production and diversity for invertebrates in those reaches most severely affected by the sediment. During periods of heavy deposition, sensitive species could not survive in some reaches of stream, and invertebrate production was entirely dependent upon pollution-tolerant forms.

Kohlhepp and Hellenthal (1992) estimated annual production by the benthos in Juday Creek, Indiana, which was severely affected by sediment resulting from drainage maintenance (i.e., snag and debris removal). Annual production by five insect species decreased by 78%. The authors emphasized an important functional advantage in using production data, which can be converted into caloric units and thus relate changes in production to stream energy flow through the invertebrate populations.

Using a functional approach, Berkman and Rabeni (1987) studied the effect of siltation in streams located in a largely agricultural area of Missouri. They related siltation specifically to the abundances of various feeding guilds of fishes as they were influenced by the distribution and abundance of invertebrate foods. Effects of siltation differed among the feeding groups; the greatest influence of silt was on the reduction in abundance of the "herbivore" group (central stonerollers) and "benthic insectivores" (several suckers and redhorses, madtoms, and darters), mostly riffle feeding fishes. No feeding guild responded positively to the silt.

Forestry

Studies on effects of logging and other forest management practices constitute a large segment of the literature pertaining to macroinvertebrates. Most of these studies have been conducted in relation to fisheries problems with sediment, usually in areas with steep hillslopes.

Slaney et al. (1977a) were concerned with influences on invertebrate fish food supply as part of the rearing habitat for juvenile steelhead trout. Comparing logged and unlogged areas in interior British Columbia, they reported much lower insect standing stocks and drift from the logged areas. They attributed these effects to the loss of benthic habitat owing to sediment accumulation in the interstitial spaces in stony substrates (i.e., embedded gravel and cobbles). The most severe effects were noted where felling and log skidding were done near the stream. They also reported on experimental additions of sediment, which reduced insect biomass by 75%.

Culp and Davies (1983) also evaluated the effect of buffer strips as part of the Carnation Creek studies in British Columbia. They concluded that without the buffer strips the stream was vulnerable to extensive sedimentation (<0.9 mm particle size) and streambank erosion; also, allochthonous input decreased. The open canopy allowed more sunlight, but primary production did not increase because phosphorus, rather than light, was previously limiting.

Many reports on sediment from forestry sources were concerned with several effects of logging. Other factors affecting macroinvertebrates were elevated water temperatures and increased autochthonous primary production. In some cases, canopy removal and greater sunlight increased production of invertebrates, which followed a greater food supply of autochthonous primary producers (Duncan and Brusven 1985; Noel et al. 1986; Wallace and Gurtz 1986).

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Gurtz and Wallace (1984) concluded that the type and size of substrate particles mediated the effect of clear-cutting on streams in the Coweeta Hydrologic Laboratory, North Carolina. They observed that although invertebrates decreased in fine-particle substrates, the benthos increased on moss-covered rock faces due to increased light and primary production by the moss.

Mining

Mining wastes have been blamed for many instances of invertebrate reductions and losses. Some short-term operations have had short-lived effects, but changes in invertebrate populations in streams receiving mining wastes over long periods have proven to be essentially permanent.

Gold-mining operations in western North America have received extensive research attention to deposited sediment and macroinvertebrates. In studies of Arctic grayling streams in interior Alaska, LaPerriere et al. (1983) compared streams in watersheds subjected to placer gold mining with unmined streams. They reported significant reductions in invertebrate populations in the mined streams as compared to unmined ones. Simuliidae (Diptera) and EPT all markedly decreased, whereas Chironomidae increased. These results were attributed to the greater extent of embeddedness of substrates by the mining-derived silt.

Other gold-mining studies included the use of short-term suction dredging, an increasingly popular method but one that entrains aquatic organisms and also causes heavy sediment deposits (Thomas 1985; Harvey 1986; Somer and Hassler 1992). Some suction dredging is recreational, and this does not appear severe with respect to the extent of reductions in benthos downstream. Decreases in macroinvertebrates usually occurred only in the area immediately downstream from the dredging and recovery was rapid. In Thomas's (1985) study, sediment deposits occurred within an area 6–11 m downstream from the dredging site; no effects on benthos were noted farther downstream. Somer and Hassler (1992) reported increased sedimentation and decreased invertebrate populations downstream from dredge sites, but recovery occurred through dredge-hole filling and removal of sediment from the site by subsequent high flows.

Sediment from abandoned mines was an important, long-lasting "disruptive force" in Appalachian streams (Branson and Batch 1972). Benthos abundances were reduced by up to 90%. The studies of Forshage and Carter (1974) on continuous gravel dredging in the Brazos River, Texas, included the report of long-lasting macroinvertebrate declines of up to 97%.

Urban Development

Nonpoint pollution from urban areas often carries large amounts of eroded sediment, but it also carries other substances that affect invertebrates. Road salt, chemical fertilizers, and toxic materials of diverse kinds frequently are included, making it difficult or impossible to differentiate the attributable sources and their effects on the benthos. A common situation is the relatively clean stream emerging from forested or wild land, which then flows through a highly developed urban area to emerge in a heavily sedimented, degraded condition.

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A typical example is the study by Hachmöller et al. (1991) on the effect of urbanization in a small suburban stream in Washington State. The stream comprised four distinct types of environment, probably typifying many urban streams: (1) an upper forested site with a rocky, diverse substrate; (2) a channelized reach with an open canopy and a homogeneous bottom substrate; (3) a reach through an urban park with poor water quality; and (4) an urbanized estuarine reach near the mouth of the stream, badly polluted and turbid. The authors' main finding relating to sedimentation was in the difference between the upper, forested reach and the channelized section; species and densities of EPT declined in the homogeneous substrate of the channelized reach.

Roads and Highways

In addition to service roads (usually unpaved) that attend extractive operations such as logging and mining, the construction of public highways also can generate large amounts of fine sediment and severely influence stream invertebrates.

One of the earliest field studies that documented adverse effects of sediment from road construction on stream invertebrates was by King and Ball (1964, 1967). They studied the Red Cedar River, which flowed through the campus of Michigan State University and which received enormous sediment inputs from the construction of Interstate Highway 96 across the southern part of the state. Major concerns were for smallmouth bass habitat, but the authors also noted a "... drastically reduced production of the biotic community of the Red Cedar River," amounting to a 68% reduction in periphyton and a 58% reduction in the heterotrophic community.

In Canada's far north, Brunskill et al. (1973), Rosenberg and Snow (1975a, 1975b), and Rosenberg and Wiens (1978, 1980) investigated problems related to oil development in the Mackenzie River region. Experimental additions of sediment to the Harris River, a tributary of the Mackenzie River, resulted in large increases in invertebrate drift which, if sustained, could reduce benthic standing stocks (Rosenberg and Snow 1975a; Rosenberg and Wiens 1978). Rosenberg and Snow (1975b) concluded that deposited sediment was much more detrimental to invertebrates than was suspended sediment and proposed a plan for environmental control of sediment. The plan further recommended development of predictive capability so that sediment inputs could be calculated and consequently controlled at a level that would be naturally flushed out of a stream, thus avoiding long-term effects on the invertebrate community.

In an Ontario highway construction project, invertebrates were denuded from the affected stream area, but populations returned to normal after the construction activity was completed—a rapid recolonization attributed to drift from upstream (Barton 1977). Other highway and road construction projects were studied by Reed (1977) in Virginia and by Chisholm and Downs (1978) in West Virginia. In both cases, benthic invertebrates were reduced substantially by deposited sediment, but drift from upstream recolonized the affected area.

SEDIMENT AND INVERTEBRATE–FISH RELATIONSHIPS

A major concern in the relationship between sediment and invertebrates is the question of the effect on fish production as the result of reduced invertebrate production due to sediment. In a brief review, Hall et al. (1984) pointed out the decided lack of published research on this aspect of the sediment–invertebrate problem. An obvious and important element is the change in macroinvertebrate taxa with sediment—from EPT (common prey of fish) to burrowing forms such as chironomids and oligochaetes (much less available to fish). However, virtually no reports on the effects of these kinds of invertebrate changes due to sediment on fish production exist in the literature. A larger literature exists on the basic relationship between benthos and fish production (Waters 1982, 1993), but research efforts generally have not been concerned with sediment.

A few exceptional studies, however, have included some aspects. Brusven and Rose (1981), using laboratory streams, observed the feeding behavior of a sculpin as affected by various sand–pebble–cobble mixtures. They reported that feeding efficiency appreciably increased with increasing percentages of smaller particles; large amounts of sand apparently made the invertebrates (EPT) more available to the sculpin by reducing insect cover. In other laboratory stream experiments, Crouse et al. (1981) noted decreased production by juvenile chinook salmon as the result of sediment-induced reductions in benthic invertebrates available to the fish.

Murphy et al. (1981), in studies of forest clear-cutting in Cascade Mountain streams in Oregon, reported increases in all components of the stream communities. Higher levels of primary production, increased densities or biomass of benthos, invertebrate drift, salamanders, and trout were attributed in sequence to the increase in light due to canopy removal. They also pointed out that these positive changes may mask the potential negative effects of sedimentation.

Two long-term projects entailing sediment effects included both invertebrates and fish. Alexander and Hansen (1986) added large quantities of sand to a trout stream in Michigan to determine effects on a brook trout population. Pre-treatment studies continued for an initial 5-year period. Experimental additions of sand were made daily for the next 5-year period and posttreatment studies continued for a third 5-year period. After the sand application, benthos densities and biomass dropped to less than half of pretreatment levels and the abundance of brook trout also decreased to less than half of former levels (discussed later). The sand additions affected small, burrowing invertebrates more than larger forms, because of the physical effects of the continually moving sand bed load.

In Valley Creek, Minnesota, a highly productive trout stream, severe sedimentation by clay drastically reduced annual production by both trout and their principal food, *Gammarus pseudolimnaeus* (Waters and Hokenstrom 1980; Waters 1982). The sedimentation occurred in 1970 and 1971, about midway in a 5-year study to estimate production by the *Gammarus*. The sediment apparently was the result of residential development in the upper catchment. Annual production by the *Gammarus* dropped from 271 and 231 kg/ha (dry weight) in the 2 years before sedimentation to 148 and 64 kg/ha—a maximum decrease of about 75%. Some recovery was evident in the next year; production increased to 101 kg/ha. Valley Creek normally contained much sand as well as clean cobble riffles. The sedimentation consisted largely of clay that saturated the streambed; even after the initial turbidity had cleared, the substrate appeared thoroughly saturated with

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clay. The physical habitat for the fish was not seriously affected, as pools and riffles remained visually clear of sediment, but decreases in trout production (about 60%) were associated with the loss of their main food resource (i.e., *Gammarus*).

CONCLUSIONS

The vitality and health of stream invertebrate populations is tied extremely closely to the particle size of streambed sediments. A change from gravel and cobble riffles to deposits of silt and sand results not only in a precipitate decrease in populations of those invertebrates most important as fish foods, but also a change in species from those inhabiting the interstitial spaces of larger particles to small, burrowing forms less available to foraging fish.

Three specific aspects of the sediment–invertebrate relationship have been described: (1) invertebrate abundance is correlated with substrate particle size; (2) fine sediment reduces the abundance of original populations by reducing interstitial habitat normally available in large-particle substrates (gravel, cobbles); and (3) species type, species richness, and diversity all change as the particle size of the substrate changes from large (gravel, cobbles) to small (sand, silt, clay).

Major interest in the first of these aspects has been directed toward the correlation between invertebrate abundance and substrate particle size, long-held as a general principle. This principle now appears more accurately applied to the Ephemeroptera, Plecoptera, and Trichoptera (EPT) which respond positively to a middle range of particles—gravel to cobbles. Within this range, EPT inhabit interstitial space, which improves with an increase in particle size through the sand-to-cobble range. The EPT group provides the most productive, preferred, and available foods for stream fishes.

Second, the principal effect of excess sediment on the streambed is increased embeddedness of cobbles and other large particles by fine sediments, which fill spaces below and between cobbles, thus reducing habitable area for EPT. The problem of embeddedness was intensively investigated by Bjornn et al. (1974, 1977) and McClelland and Brusven (1980), and thoroughly discussed in the extensive review by Chapman and McLeod (1987). A major advance was the quantification of embeddedness. Bjornn et al. (1974, 1977) measured embeddedness as the fraction of cobble surface fixed in the surrounding sediment and concluded that one-third embeddedness or less is probably the normal condition in streams. Above this level, however, insect populations decline substantially as habitat spaces become smaller and filled. Lenat et al. (1979, 1981) defined this effect as "habitat reduction," which results in a decrease in density and standing stock of existing species.

The third major effect, "habitat change," was also defined by Lenat as the transformation of large-substrate-type deposits to fine sediments. The changed habitat then results not only in the complete elimination of EPT, but also the development of a different invertebrate community—namely, small, burrowing forms such as chironomid larvae and oligochaetes. This change in community invertebrate type often results in greater abundance in numbers, but total standing stocks are often smaller. The burrowing habit of the smaller animals reduces

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their availability as food for fish. This seems sometimes to have perplexed early investigators who devised the classic correlation between substrate particle size and insect abundance—the correlation held true except for the finest particles of silt or muck, wherein numbers were high. Either major effect—a reduction in EPT or a change to burrowing forms—has a deleterious effect on stream fish populations by reducing the fish food resource.

Construction activities that last only for short times (e.g., road construction, bridges, and pipeline crossings) usually produce transitory effects on invertebrate populations. Whereas the effects of fine-particle deposition may be deleterious to invertebrates in the immediate vicinity of the activity, benthic populations often recover rapidly as the sediment input ceases and deposits wash away downstream. Several factors facilitate rapid recovery of benthic populations:

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- insects with flying adults can renew populations quicker than nonflying forms such as mussels and crustaceans;
- undisturbed upstream reaches provide drifting invertebrates for recolonization;
- hydrologic factors (gradient, discharge, current velocity) control the rate of flushing of deposited sediment.

However, in the absence of these factors—especially in slow, low-gradient streams or where continuous erosion occurs on roadways after construction—sediment deposits and reduced or changed invertebrate populations may be long-lasting with respect to both time and downstream distance.

Ongoing operations in agricultural and urban, residential locations present a more long-lasting effect on stream invertebrates, partly because nonpoint sources of sediment are difficult to locate, identify, and control. Logging and other silvicultural operations may have either short-term or long-lasting effects; recovery may be relatively rapid in high-gradient mountain regions, or long-lasting in lower gradients or where poorly constructed logging roads contribute continually eroding sediments.

A contrary effect of logging in small watersheds or along headwater reaches is an increase in macroinvertebrate populations (Murphy and Hall 1981; Murphy et al. 1981; Gurtz and Wallace 1984). Opening the canopy permits more sunlight to reach the previously shaded stream bottom, the additional light increases photosynthesis, and the increased primary production provides more food to invertebrates, particularly grazers. These positive effects may override the deleterious effect of sedimentation in certain conditions. However, such an effect would not be expected in higher-order streams with more naturally open canopies.

Topics that Need Further Work

The specific effect of clay has not been explored sufficiently. Almost all published accounts of the effect of fine sediment on invertebrates have involved silt and sand categories without reference to clay, which may be more invasive into the hyporheic zone.

As opposed to the extensive work on fine sediments and salmonid reproduction, the research on benthic invertebrates includes very little on the effects of particle sizes. Although the paper of Quinn and Hickey (1990) is outside the stated geographical scope of this review, it nevertheless stands as a singular example of extensive research (88 streams in New Zealand) on particle size and benthic invertebrates that is greatly needed. Also related to this topic is the need for greater emphasis on the physical effects of sediment in the hyporheic zone and on invertebrates that inhabit this deeper stratum.

Almost all research published on the effect of fine sediments and benthos involves macroinvertebrates—those organisms, such as most aquatic insects, that are easily visible to the researcher. Virtually no sediment-related work has been done on the effect on the meiofauna, despite increasing evidence of its importance (Benke et al. 1984; Shiozawa 1986). These forms—benthic microcrustaceans such as Cladocera, Copepoda, and Ostracoda, and small insect forms—are crucial as first foods for many fishes, even in small swift streams. The effect of excessive clay deposits on these microinvertebrates in the streambed may be extremely important to stream fisheries and should be investigated.

A greater emphasis on the use of production data, particularly for benthic invertebrates, would greatly improve the analytic value of benthic information in assessing the effect of added sediment (or any other pollutant). Invertebrate annual production, expressed as a rate, would be more relevant to the production rate of carnivorous fish than would the static parameters of abundance and standing stock. A few workers have employed production data (Waters 1984; Mackay and Waters 1986; Cooper 1987; Kohlhepp and Hellenthal 1992), but the ideal practice would be to include production data as a standard technique in invertebrate and sediment investigations.

The paper by Culp et al. (1986) on the effects of high tractive force should spur further work that may be extremely beneficial. Their results suggest a condition wherein continuously moving particles saltating along the bottom might keep benthic populations at depressed levels, even when neither suspended sediment nor deposited sediment may be noticeable.

Further work on location and identification of nonpoint sediment sources is badly needed. This problem affects all components of the stream biological community.

Finally, the recent emphasis on a more holistic approach to stream ecological research and resource management requires that attention be paid to all aspects of surface disturbance in a watershed. Although sediment generation is often an important result of disturbance, sedimentation on the streambed remains as only one of many effects that influence invertebrate production and abundance. Altered flood regimes, changed channel morphology, increased lateral activity, and other hydrologic adjustments all interact with excess sediment (and other pollutants) to influence the invertebrate community.

EFFECTS OF SEDIMENT ON FISH

The loss or reduction of fish populations has long been associated with turbidity and siltation of streams. Early warnings about the damaging effects of sediment and "erosion silt" (Jordan 1889; Titcomb 1926; Ellis 1936) are representative of this early concern. Specific reasons for fish losses related to sediment have been among the most common objectives of research aimed at identifying causes and remedies.

The greatest attention has been paid to salmonids, particularly juvenile anadromous salmon, steelhead trout, and Arctic grayling in the Pacific Northwest. Additional attention has been paid to sediment problems with Atlantic salmon on the east coasts of Canada and the United States, and inland populations of stream trout (brook, brown, cutthroat). Less concern relative to sediment has been evident for anadromous pink and chum salmon, which do not spend their juvenile years in streams, as do other anadromous species.

Despite early cautions about sediment, however, general conclusions were not at first universally shared. The mining industry, particularly, was unconvinced. For example, from studies in the Rogue River, Oregon, sponsored by the Oregon State Department of Geology and Mineral Industries, Ward (1937–1938) concluded that mining activity was not harmful to fisheries. Ward stated, "Fish live and thrive in rivers carrying large loads of silt," and ". . . neither natural nor artificial erosion up to date has exerted any demonstrable change in the fish food supply. . . . " Upon these conclusions, the *California Mining Journal* for 1938 reported (gleefully, we may presume) that "young fish thrive on mud" (reported by Smith 1940). These conclusions, however, were contradicted by Sumner and Smith (1940), who criticized the experimental methods and analysis leading to Ward's results. After a half-century of the most rigorous research, it is now apparent that fine sediment, originating in a broad array of human activities (including mining), overwhelmingly constitutes one of the major environmental factors—perhaps the principal factor—in the degradation of stream fisheries.

In addition to Ellis's (1936) early paper on "erosion silt," few papers on the subject of sediment were published in that era, although it is apparent that water pollution was beginning to be a subject of concern. Trautman (1933) remarked upon the major causes of several kinds of pollutants that affected fish life, including silt from gravel processing and "soil washings" from newly cultivated fields. Pautske (1938) reported studies on coal washings, including slate and sand particles, which, when experimentally added to habitats of young steelhead and cutthroat trout, caused total mortality. Smith (1940) reviewed a number of studies related to placer gold mining activities in western streams and concluded that (1) though spawning salmon may run upstream through reaches of silty water, they spawn farther upstream in clear water; (2) mining silt is detrimental to incubating eggs in redds; and (3) mining silt blankets stream bottoms and causes high mortalities in the bottom fauna. Shaw and Maga (1943) commented on Ward's (1937–1938) conclusions and conducted their own laboratory experiments with silver (coho) salmon eggs, adding silt derived from placer gold mining in California; they reported much reduced survival of eggs in silted hatchery troughs relative to survival in clear control troughs.

In another early paper by Ellis (1944), which was actually a brief review of work on several aspects of water pollution, he included "suspensoids" as a pollutant and recommended that turbidity in streams should be limited such that light attenuation to one-millionth of incident surface light should not occur at a depth less than 5 m. Ellis (1944) quoted no previous reports that mentioned sediment as a pollutant, but he acknowledged the considerable sediment research at the then-U.S. Bureau of Fisheries laboratory at Columbia, Missouri.

Chapman (1988) credited Harrison (1923) with the first work on sediment and salmonid reproductive success. Harrison's work, however, appeared to be a basic study of the ecology of salmonid egg development related to potential artificial planting of eggs, rather than a consideration of fine sediment as a pollutant.

In subsequent years, concern increased greatly about sediment in salmonid redds, mainly those of western United States and Canadian salmon and steelhead streams. (The work by Wallen [1951] on warmwater fishes was an important exception.) Although field research and laboratory experiments were conducted, most results were presented only in unpublished agency reports; only a few publications were included in primary scientific journals (e.g., reviews by Wickett 1958 on factors affecting pink salmon and chum salmon and by Cordone and Kelley 1961).

Despite the lack of intensive research, it was clear at this early time that fine sediment in salmonid redds was greatly damaging. With loose gravel, survival was high; in redds heavily invaded with fines, survival was low. Cordone and Kelley (1961) also concluded that adult fish can survive suspended silt concentrations usually encountered in natural conditions but that they would succumb when concentrations reach the high levels that damage or coat gill surfaces. They also concluded, on the basis of research done on egg survival, that sedimentation in redds was one of the most important factors that limit natural salmonid reproduction, and that even moderate deposition was detrimental.

The effects of anthropogenic sediments on stream fish are divided into four main categories: (1) direct effect of suspended sediment, including turbidity; (2) effects on salmonid reproductive success in redds; (3) effects on reproductive success of warmwater, or nonsalmonid, fishes; and (4) effects of deposited sediment on the habitat of fry, juvenile, and adult fish.

In many cases, it is difficult to distinguish between the causes of any given effect. The four categories, however, provide a convenient and ecologically meaningful basis for discussion.

EFFECTS OF SUSPENDED SEDIMENT

Suspended sediment produces little or no direct mortality on adult fish at levels observed in natural, relatively unpolluted streams. Early papers were highly speculative, reporting only visual observations of muddy conditions associated with fish kills, or the result of extreme conditions produced in the laboratory (Cordone and Kelley 1961).

Early Observations

In his classic paper, Wallen (1951) reported studies on the effects of suspended sediment on warmwater fishes. His experiments included concentrations up to extremely high levels that caused direct mortalities. Working with 16 species of fish, he found little effect below concentrations of 100,000 ppm montmorillonite clay; fish death occurred at around 200,000 ppm. Mortality was due to clogging of opercular cavities and gill filaments, which presumably impaired respiration. Wallen cited a number of reports of suspended sediment in natural streams much lower than his experimental concentrations, and he thus concluded that suspended sediment was not a lethal condition in concentrations found in nature.

Subsequent results from other researchers on other fishes, particularly salmonids, also suggested deleterious effects at high concentrations. Herbert et al. (1961) reported adult brown trout populations seven times more abundant in a lightly polluted stream than in a Cornish (England) stream heavily polluted with china-clay wastes. They also reported the absence of trout fry in the heavily polluted stream and concluded that there was no reproduction in that stream. Median suspended sediment concentrations were 1,040 mg/L in the lightly polluted river, whereas in the heavily polluted stream the median level was 5,100 mg/L, and short-term maxima were noted up to 100,000 mg/L. Benthic invertebrates were also recorded at much lower densities in the highly polluted stream.

Similarly, Herbert and Merkens (1961) subjected rainbow trout yearlings to different levels of suspended sediment concentration for extended periods of time. They reported substantial direct mortality (>50%) at levels of 270 and 810 mg/L. At lower levels (30 and 90 mg/L) most fish survived up to 185 days. They also observed some disease ("fin rot") and gill damage in fish that died; they emphasized that sublethal concentrations may produce stress in natural river conditions.

Direct Mortality

Intensive investigation of direct mortality due to suspended sediment was not undertaken until recently. In an extensive review, Lloyd (1987) quoted a number of unpublished reports that included results as either fatal or lowered survival; most of these included suspended sediment concentrations from 500 to 6,000 mg/L. Sigler et al. (1984) reported some mortality of very young coho salmon and steelhead trout fry at about 500 to 1,500 mg/L. In laboratory experiments, however, McLeay et al. (1984) reported survival of Arctic grayling underyearlings which had been subjected to prolonged exposure to mining silt in concentrations of 1,000 mg/L. Also, McLeay et al. (1983) reported survival of similar fish acclimated to warm waters in stream cages and subjected to short exposures of concentrations up to 250,000 mg/L.

Obviously, the determination of precise concentrations of suspended sediment that cause acute mortality is difficult and results vary. In field conditions, it may be impossible to distinguish between the effects of suspended sediment and other mortality factors such as heavy metals in mined streams (LaPerriere et al. 1983; Scannell 1988), other toxicants, contaminated suspended sediment particles, and interactions of other effects that by themselves may be sublethal. Servizi and Martens (1991) observed in laboratory tests on acute lethality that smaller fish (coho salmon) were less tolerant to suspended sediment than were larger fish, and that tolerance to suspended sediment was greatest at some optimum temperature (7°C) than at lower (1°C) or higher (18°C) temperatures. In their studies of sediment from placer gold mining and its effects on Arctic grayling, Reynolds et al. (1989) used cage experiments to expose sac fry to suspended sediment in natural streams. Of the sac fry in a mined stream (turbidity >1,000 NTU) 50% died in 96 hours, whereas in an unmined stream only 13% died. Mortality in the mined stream was much higher for sac fry than for fingerlings and juveniles.

Sublethal Effects

Much more information is available on sublethal effects of suspended sediment. Most of these reports were based on laboratory experiments, wherein specific effects were observed critically and often quantified. Effects tested included (1) avoidance and distribution, (2) reduced feeding and growth, (3) respiratory impairment, (4) reduced tolerance to disease and toxicants, and (5) physiological stress (review by Lloyd 1987).

Avoidance and distribution.—Perhaps the most important sublethal effect of suspended sediment is the behavioral avoidance of turbid or silty water, resulting in long reaches or entire streams devoid of fish. Thus, the effect of avoidance may be the total preclusion of resident fish and juvenile anadromous salmonids. This factor destroys a stream as a productive fishery just as surely as if the population were killed. Many published reports have documented such effects.

Avoidance of water muddied from mining silt by spawning adult salmon was observed by Sumner and Smith (1940) in a California river. Avoidance by adult chinook salmon of a spawning stream that contained volcanic ash was reported by Whitman et al. (1982).

DeVore et al. (1980) reported on fish species and biomass in streams in the western Lake Superior region. Some contained red-clay suspended sediment with concentrations up to about 400 mg/L and some were relatively clear. The turbid, warm streams contained many warmwater species, whereas the clear streams contained few species, mostly salmonids. Total fish standing stocks in the turbid streams were about 80–100 kg/ha; in the clear streams (even though having few species) standing stocks were about the same, 50–120 kg/ha.

Birtwell et al. (1984) and Scannell (1988) concluded that Arctic grayling in Alaska streams were confined to clear water only and did not exist in streams

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heavily exposed to silt from placer gold mining. In work on the Fraser River, British Columbia, Servizi and Martens (1992) observed avoidance by young coho salmon of high suspended sediment derived from gold-mining spoils; they pointed out that coho salmon may move laterally to the sides of a river to avoid high turbidity.

Much research on avoidance of silty water has been conducted in laboratory and field experiments. Juvenile coho salmon (Bisson and Bilby 1982) and young Arctic grayling (Scannell 1988) avoided high concentrations of suspended sediment (as measured by turbidity in NTU). Coho salmon avoided turbidity greater than 70 NTU, and Arctic grayling avoided turbidity greater than 20 NTU. Sigler et al. (1984) also observed that juvenile coho salmon and steelhead trout avoided turbid water in laboratory experiments. McLeay et al. (1984, 1987) observed Arctic grayling that moved in a downstream direction in laboratory streams when subjected to mining silt. Berg and Northcote (1985) observed that juvenile coho salmon exposed to short-term pulses of suspended sediment dispersed from established territories.

In experimental stream channels related to long-term studies on coho salmon in the Clearwater River, Washington, Cederholm and Reid (1987) subjected juvenile coho salmon to three levels of suspended sediment concentrations: clear water (0 mg/L); medium suspended sediment (1,000–4,000 mg/L); and high suspended sediment (4,000–12,000 mg/L). They observed that the fish preferred clear and medium conditions, suggesting that juvenile fish preferentially avoid high suspended sediment conditions in silty streams. Furthermore, they observed evidence of stress in the fish—an increased rate of opercular movement and "coughing"; sediment accumulations on gill filaments; and declines in prey capture success—at the higher suspended sediment concentrations.

In a different approach involving competition between species, Gradall and Swenson (1982) concluded that red-clay turbidity favored the creek chub over brook trout in sympatric populations in small streams. The creek chub preferred the cover provided by suspended sediment turbidity, whereas brook trout preferred clearer water.

Reduced feeding and growth.—One of the major sublethal effects of high suspended sediment is the loss of visual capability, leading to reduced feeding and depressed growth rate. Several researchers have reported decreased feeding and growth by fish in turbid conditions resulting from suspended sediment. For example, Cleary (1956) and Larimore (1975) noted that turbidity in smallmouth bass streams caused very young fry to be displaced downstream due to the loss of visual orientation. The bass left areas where they fed on the microcrustaceans so important to early fry stages.

Most research on feeding and growth, however, has been experimental. McLeay et al. (1984, 1987) reported impaired feeding ability by Arctic grayling exposed to placer mining silt; Reynolds et al. (1989) reported similar results for Arctic grayling in cage experiments in Alaska streams. Redding et al. (1987) observed little or no feeding by juvenile coho salmon and steelhead trout exposed to suspended sediment in Oregon laboratory experiments, and Berg and Northcote (1985) reported reduced feeding by juvenile coho salmon on drift (brine shrimp) in laboratory tests. In most cases, vision impairment due to suspended sediment turbidity was determined to be the factor that reduced the ability of the fish to capture prey (Sykora et al. 1972; Berg 1982).

Respiratory impairment.—Despite early speculation about gill damage by suspended sediment (Cordone and Kelley 1961; Herbert and Merkens 1961), few reports indicated gill damage and impairment of respiratory function as a source of mortality (McLeay et al. 1987; Redding et al. 1987; Reynolds et al. 1989). Whereas high suspended sediment concentrations may not be immediately fatal, thickening of the gill epithelium may cause some loss of respiratory function (Bell 1973).

Berg and Northcote (1985) reported increased gill-flaring in high turbidities due to suspended sediment; this was viewed as an attempt by fish to cleanse their gill surfaces of suspended sediment particles. Similarly, Servizi and Martens (1992) recorded an eightfold increase in "cough" frequency over controls at suspended sediment concentrations of 230 mg/L. It seems likely that fish have evolved behavioral or physiological adaptations to temporary high concentrations of suspended sediment in order to survive short-term conditions caused by natural spates and floods. Chronic high suspended sediment concentrations that are initiated by anthropogenic sources, however, may not be tolerated.

Studying the effect of Mount St. Helens volcanic ash on chinook and sockeye salmon smolts, Newcomb and Flagg (1983) reported total mortality at very high ash levels (25% ash by volume) but no mortality at less than 5% ash. Based on the appearance of the gills, they suggested that impaired oxygen exchange was the primary cause of death, but they concluded that most airborne ashfalls would not cause acute mortality.

Reduced tolerance to disease and toxicants.—Another potential sublethal effect of suspended sediment is decreased tolerance to disease and toxicants. Several investigators have commented on this possibility, although it does not appear to have been researched intensively. Redding et al. (1987) observed higher mortality in young steelhead trout exposed to a combination of suspended sediment (2.5 g/L) and the bacterial pathogen *Vibrio anguillarum* than in trout exposed to the bacterium alone. Infection in coho salmon fry by a viral kidney disease also resulted in mortality when the fish were exposed to suspended sediment. Goldes et al. (1988) suggested that observed gill lesions were the result of kaolin clay that created a favorable environment for protozoan colonization. McLeay et al. (1984, 1987) reported decreased tolerance of Arctic grayling to an experimental toxicant (pentachlorophenol) in high concentrations of suspended sediment (up to 250 g/L), compared to the toxicant alone.

It appears that suspended sediment induces stress at some raised level of concentration and that such stress tends to reduce the tolerance of fish to a number of environmental factors, including exposure to disease and toxicants. The possibility of further sediment-related problems of disease and toxicants needs more research.

Physiological stress.—Exposure to sublethal levels of suspended sediment may induce physiological stress, which in turn may reduce the ability of the fish to perform vital functions. Redding et al. (1987) reported physiological changes indicative of stress in coho salmon and steelhead trout, including elevated plasma cortisol, plasma glucose, and hematocrits; no direct mortality occurred. The authors concluded that such stress may not be severe, but it may reduce the ability of the fish to feed or resist disease. Servizi and Martens (1992) also reported elevated serum glucose in coho salmon at high suspended sediment levels. In their reviews, Hall (1984a) and Lloyd (1987) included other reports from the unpublished literature that implicated suspended sediment as a factor which induced stress, intolerance, and behavioral problems.

In a recent review, Newcombe and MacDonald (1991) pointed out that in most published studies of suspended sediment and fish, only concentrations were given; they further pointed out that the duration of exposure is essential for more complete understanding of the effects of suspended sediment. They proposed a dose–concentration duration–response model; however, the size of suspended sediment particles, a possible important factor, was not included in the model. The authors also provided a valuable set of three tables listing (1) direct mortality due to suspended sediment, including suspended sediment concentration and duration of exposure (19 papers); (2) sublethal responses (13 papers); and (3) behavioral responses (13 papers). All fish species listed were salmonids. Not all references were for inorganic or suspended sediments, but the high mortality noted in the research cited by Newcombe and MacDonald (1991) points up the need for inclusion of exposure duration. The authors also included a similar table on responses of invertebrates, discussed in a previous section.

Warmwater Fishes

Studies of either direct mortality or sublethal effects of suspended sediment on warmwater fish species are relatively few in the literature. Warmwater streams, although supporting many species, do not appear to attract research support to the same degree as do salmonid streams. Another reason may be that because warmwater streams are often muddy with silt or sand bottoms, their fish species may be perceived to have evolved tolerances to occasional high concentrations of suspended sediment. Some greater effects of deposited sediment have been reported, however, especially on reproductive success, and these are reported in a later section.

The work of Wallen (1951), cited previously, remains the most instructive about suspended sediment effects in warmwater fishes, although not all of the fishes he studied were stream inhabitants. The clogging of gills, and thus respiratory impairment, and induction of disease and parasites have been suggested as effects of suspended sediment (Trautman 1933; Pautske 1938; Wallen 1951).

Despite the observation of seemingly viable fish communities in sometimes extremely turbid and silty conditions, some warmwater species have disappeared over the long term (Larimore and Smith 1963; Smith 1971; Trautman 1981). Muncy et al. (1979), in their extensive review on suspended sediment and warmwater fish, concluded that great variation exists among these species in tolerance to suspended sediment, and that the loss of some species from an otherwise apparently viable fish community eventually may have severe disruptive effects on the system as a whole. They emphasized the need for further research that addresses effects on warmwater species intolerant to suspended sediment.

EFFECTS ON REPRODUCTIVE SUCCESS OF TROUT AND SALMON

The relationship between sediment and salmonid reproductive success has been the subject of greatest concern among all aspects of sediment pollution. Two major reasons for this priority are apparent.

First, salmonids appear as the most favored freshwater recreational fisheries, including adult anadromous salmon on both continental coasts, native anadromous steelhead trout (rainbow trout) in Pacific coast streams and introduced populations in the Great Lakes, as well as inland trout populations (brook, brown, cutthroat, and other trout) across the continent. Second, all North American salmon and trout (except the lake trout) use redds (in flowing waters) in their reproductive strategy, a design that unfortunately functions as a highly efficient "sediment trap," with dramatic and often catastrophic effects on eggs and sac fry.

Through the series of events leading to successful reproduction by salmonids, it is difficult to distinguish between the effects of suspended and deposited sediments, therefore the two components will be treated together, to some extent, in the following discussions. The reason for this special vulnerability is that developing eggs and embryos, as well as newly hatched sac fry, must be supplied by intragravel flow of oxygen-rich water, the chief source of which in many instances is the flowing stream. Deposits of larger particles that may bury the redd completely, or the scouring by floodwaters that eliminates the redd entirely, will have obvious destructive effects.

Three specific effects of sediment on salmonid redds have been recognized: (1) filling of interstitial spaces in the redd by depositing sediment, thus reducing or preventing further flow of water through the redd and the supply of oxygen to the embryos or sac fry; (2) smothering of embryos and sac fry by high concentrations of suspended sediment particles that enter the redd; and (3) entrapment of emerging fry if an armor of consolidated sediments is deposited on the surface of the redd.

In the early period of investigation (pre-1960), these effects were not always recognized separately; often the lack of reproductive success, in its total result, was subjectively associated with a highly visible sedimented stream. Furthermore, the three specific effects cannot always be empirically separated, as indeed they may overlap, in given circumstances. Consequently, in the following discussions they are not treated separately except as the investigator may have handled experiments or specific results.

A fairly large literature has accumulated on methods of measuring conditions in salmonid redds, including substrate particle size and location, distribution of eggs, and presence of invertebrates. Whereas no comprehensive effort was made to include this literature in the present review, some papers most specifically related to salmonid reproduction are included in appropriate sections. The most comprehensive review of methods pertaining to sampling streams and riparian conditions is that by Platts et al. (1983).

Literature Overview

After the stimulus provided by Cordone and Kelley's (1961) review article, research on sediment in salmonid redds increased greatly in the 1960s and 1970s. The most intensive specific effort was soon placed on particle sizes of sediment. The stimulating paper by McNeil and Ahnell (1964) included data on fine sediment in salmon redds in Alaska streams, as well as an emphasis on logging as a major source of fine sediment. The papers by Lantz (1967) and Hall and Lantz (1969) further emphasized logging practices as major sources of sediment; they described the Alsea Watershed Study in Oregon, which included experimental logging in salmonid research.

In the next few decades, many more papers were published on the production of excess sediment from forestry practices and the effect on salmonid reproduction. In addition to the problem of fines reducing water flow and oxygen to redds, sac fry entrapment also stimulated much research in the Alsea study at about the same time (Koski 1966). Other major research programs included long-term studies on the South Fork Salmon River, in Idaho (Platts and Megahan 1975) and on Carnation Creek, British Columbia (Hartman 1982).

Some attention was paid also to Atlantic salmon and inland trout fisheries. These reports included studies on redds of Atlantic salmon in eastern Canada, brook trout in the upper Great Lakes and southern Appalachian regions, and a few other trout populations.

Early Research

In a recent review, Chapman (1988) assigned credit for the first published effort to describe the deleterious effect of fine sediment in salmonid redds to Harrison (1923). At that time, a major effort of fisheries management was the augmentation of fish populations, extension of fish distributions, and restoration of damaged fisheries—all by stocking. Within that management effort, Harrison devised techniques for planting eyed eggs in remote locations, using an "egg planting box" buried in the gravel. He experimented with different sized gravel—from the size of a pea to hickory nut to walnut—variously mixed with clay, silt, and sand. Using these quaint but contemporary units of his day, Harrison then noted survival rates in the different mixtures and reported lower survival in the mixtures with finer sediments.

Further observations of the lack of salmonid spawning and reproductive success in muddy waters were made in the next few decades. The extensive set of observations by Hobbs (1937) of redds made by the introduced chinook salmon and brown trout in streams of South Island, New Zealand, probably stands as the earliest quantitative measures of salmonid egg survival in redds where fine particles (<0.03 in) were also measured. Hobbs concluded that the highest mortality of eggs occurred in the "dirtiest" redds—those with highest percentages of fines. In North America, a few primitive experiments were conducted with gravel and silt, usually in hatchery facilities, slowly building to an accepted conclusion that silty conditions were injurious to developing embryos in salmonid redds (Shapovalov and Berrian 1940; Smith 1940; Shaw and Maga 1943). Wolf (1950), writing in the British *Salmon and Trout Magazine*, reviewed the history of Atlantic salmon fisheries in Canadian tributaries of Lake Ontario. He referred to the immense spawning runs that occurred in the late 1800s but subsequently decreased to almost a total loss. He attributed the decrease to "silting down" of spawning areas by sediment from agricultural cultivation.

In one of the first papers to cite the idea of the salmonid redd as a sediment trap, Moffett (1949) reported on the effects of Shasta Dam (Sacramento River, California), which cleared the river of sediment by deposition in the reservoir and lowered water temperature in a downstream reach. Similarly, Patrick (1976) described the deposition of sediment behind Clark Hill Dam on the Savannah River, which resulted in reduced sediment downstream from the dam and consequently increased numbers of species of algae, arthropods, and fishes.

Research increased slowly in the 1950s. Details of salmonid reproduction, spawning behavior, redd construction, and redd size and density were described for four species of Pacific salmon by Burner (1951). His research was done in connection with attempts to relocate salmon runs in the Columbia River, runs in which spawning fish had been blocked by Grand Coulee Dam. He also noted that fish avoided gravels that were tightly cemented with silt and clay and that almost all successful redds had less than 10% mud, silt, and sand. The classic paper by Stuart (1953) similarly described reproductive behavior of brown trout in Scotland; from laboratory experiments, he concluded that although small, intermittent applications of silt could be washed away by sac fry movements, heavier and continuous silt treatments were lethal.

Further experimental work involved the planting of eggs (Shelton 1955; Gangmark and Bakkala 1960) to investigate if silt prevented sufficient flow of oxygen-containing water. However, Wickett (1954) concluded that "surface silt" on top of the redd did not cause mortality unless it also entered the redd gravel and obstructed water flow. Later, experiments with artificial additions of sediment to spawning gravels supported the conclusion that silt deposited only on top of the redds did not reduce oxygen (Shapley and Bishop 1965).

The recognition of silt and mud as a form of water pollution was expressed early by Ellis (1936), but the paper by Peters (1965) appears among the first work related to salmonid reproductive success to be included in a major publication on water pollution. Peters (1967) also identified agricultural practices that contributed large quantities of sediment to a Montana trout stream. Eyed rainbow trout eggs were placed in Vibert boxes (Anonymous 1951) and stocked in artificial redds located in stream areas variously affected by sediment. Mean suspended sediment concentrations ranged from 20 to 400 mg/L, with overall extremes of 12–1,240 mg/L. The emphasis was on water flow and oxygen supply, both of which decreased at the higher sediment concentrations. Mortality of the rainbow trout eggs increased dramatically with higher concentrations of suspended sediment. This was a rare example of excess sediment from an agricultural source affecting salmonid reproduction.

Early Major Reviews

The review of Cordone and Kelley (1961) was the first comprehensive literature review on the effect of sediment on all components of the biological community in streams, including salmonid reproduction. Although this body of literature was relatively small at the time, their review was a watershed event in historical context; it served as a linch-pin for the immense work on salmonid reproduction to come in following decades. Cordone and Kelley emphasized the importance of fine sediment in salmonid redds and its injurious effect. They cited about 25 publications on this subject, although not all presented sediment data. Their general conclusions were (1) eggs and sac fry are killed as the result of smothering by suspended sediments entering the redd; (2) sediments obstruct the flow of water and its oxygen supply through the redd, causing asphyxiation; (3) continuous applications of small quantities of sediment into the redd are more detrimental than short-term, sudden flushes; and (4) sediment is one of the most important environmental factors that influence the success of salmonid spawning.

Cordone and Kelley (1961) reviewed some of the techniques developed for measuring water flow through the redd. They also identified some sediment sources (e.g., gravel washing and mining effluents). No mention was made of logging practices, which were to become extremely important in later years, especially in the salmon streams of the Pacific Northwest. Very little was cited on the measurement of either particle size of sediments, the identification of "fines" in redds, or the concentration of suspended sediment, all of which later were to receive much more attention.

Many subsequent reviews dealt wholly or in part with the problem of sediment in salmonid redds. Some summaries, dealing generally with the effects of sediment on salmonid productivity, invariably focused on the problem of reproductive success in the redd. These early reviews included

- Phillips (1971)—part of a symposium on forest-land use and streams and a review of most pioneering work in Alaska and Oregon salmon streams;
- Gibbons and Salo (1973)—a large annotated bibliography and discussion, the first major review to indict forestry practice as an important source of sediment adversely affecting salmonid reproduction;
- Platts et al. (1979)—a USEPA report that dealt primarily with sediment particle sizes and their potential effect in the redd;
- Reiser and Bjornn (1979)—part of a larger review of forest management and salmonid stream habitat in the Pacific Northwest.

Most of these early reviews further emphasized forestry practices as sources of sediment in salmonid redds; they provided a great base for the intensive research that followed.

Sediment Particle Size and Gravel Permeability

The effect of suspended sediment, deposited in the redd and potentially reducing water flow and smothering eggs, is a function of sediment particle sizes. Gravel permeability in the redd becomes of first importance, because sediment particle sizes also determine the pore openings in the redd gravel. With small pore openings, more suspended sediments are deposited and water flow is further reduced, compared with larger pore openings.

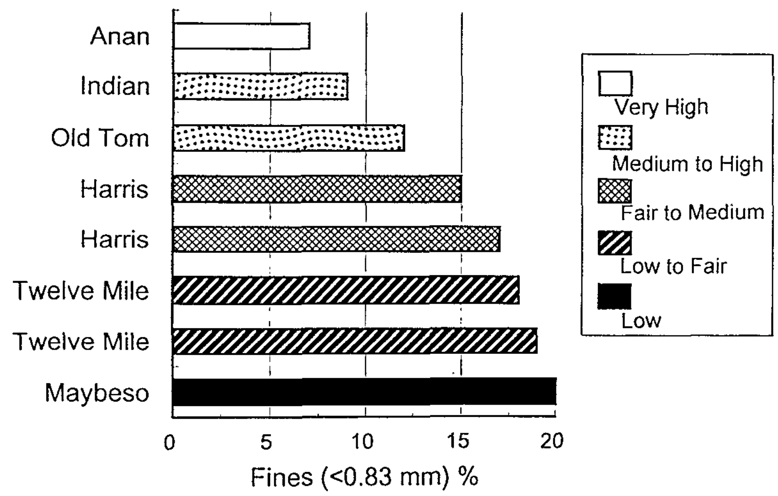

FIGURE 9.—Pink salmon escapement in Alaska streams in relation to percent fines less than 0.83 mm in spawning gravel (from McNeil and Ahnell 1964).

In a brief historical perspective, Chapman (1988) noted some of the pioneering papers in which investigations of fish reproductive success mainly consisted of observations that redds with silt resulted in a lower survival of embryos (e.g., Shaw and Maga 1943; Shelton 1955). With this realization of the importance of fine sediment in spawning gravels, research attention turned to defining the responsible fine particle sizes. Many reports from laboratory and field studies have related survival and emergence to the presence and proportions of fines of specified sizes.

Obviously, such definitions must be based on the function of the particles in their effects on reproductive success. Such an approach was taken by McNeil and Ahnell (1964) in their studies of pink salmon spawning in Alaska. They concluded that the greatest spawning success was in streams with the fewest fines (<0.833 mm, coarse sand and finer) in the redd—apparently the first size definition of "fines" (Figure 9). The selection of the 0.833 mm size was made because they found the best negative correlation between permeability of the gravel bed and the percentage (by volume) of particles less than 0.833 mm (passing through a sieve of that size mesh). The selection of 0.833 mm by McNeil and Ahnell (1964) was further examined by many others.

McNeil and Ahnell (1964) also made one of the first observations of the effect of timber harvest on sediment production and deposition in spawning beds, especially of particles less than 0.833 mm in size. They described a corer-type sampler for collecting material from the spawning bed, including fine sizes, the contents of which were later sieved for grading. The device, which became known as the McNeil corer, was used widely (Figure 10).

Sheridan and McNeil (1968) continued research on the Alaska streams and fine sediments and reported that, although logging increased sediments less than 0.833 mm in spawning gravels, the increase was temporary. The authors sug-

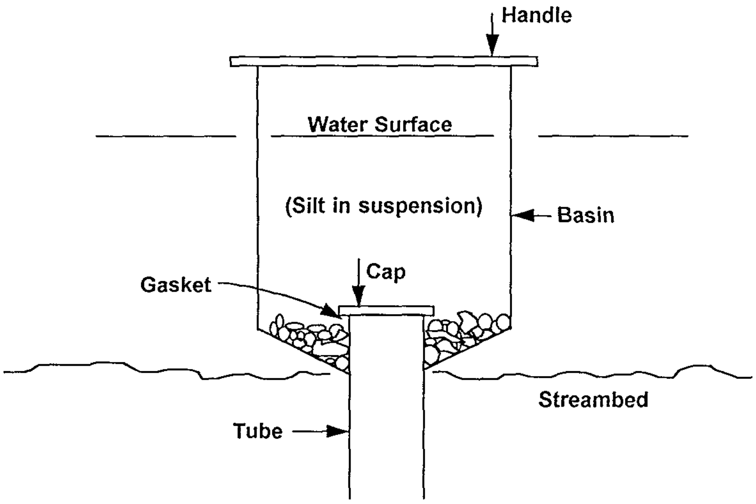

FIGURE 10.—The "McNeil corer," a substrate sampling device retaining fine sediments in spawning gravel studies (from McNeil and Ahnell 1964).

gested that spawning activity by abundant adults assisted in clearing fine sediments from spawning beds. Subsequent investigators also reported this effect (Everest et al. 1987; Bjornn and Reiser 1991). They furthermore suggested that when large particles settle into a redd as the result of redd-digging by female fish, the large particles provide a measure of protection.

Several studies conducted under the auspices of the National Council of the Paper Industry for Air and Stream Improvement (NCASI), New York, contributed valuable insight into the question of the effect of sediment particle sizes. Laboratory experiments on the survival of rainbow trout embryos in different redd-substrate mixtures supported previous results that fines less than 0.8 mm were most damaging, whereas larger particles had much less effect (Hall 1984b). However, Hall stressed the need for more detailed data on the effect of specific sizes of fine sediments.

Another series of NCASI laboratory experiments included three species of Pacific salmon—coho, chinook, and chum—in which survival from eyed eggs to emergence was measured against a series of spawning gravel mixtures (Hall 1986). The range of percentage of fines less than 0.8 mm in the experimental mixtures was 0–50%. Although the control mixture (<0.8 mm = 0) permitted survival of 50–75% for the three species, survival at 10% fines was only 7–10% and in mixtures with more than 10% fines, survival was minimal.

Tagart (1984) also observed an inverse relationship between survival of coho salmon eggs and fines less than 0.85 mm in natural redds in tributaries of the Clearwater River, Washington. In further laboratory experiments with steelhead trout and chinook salmon eggs, Reiser and White (1988) observed little survival beyond 10–20% fines less than 0.84 mm. Eyed steelhead eggs survived better than green eggs, but not beyond the 20% fines level.

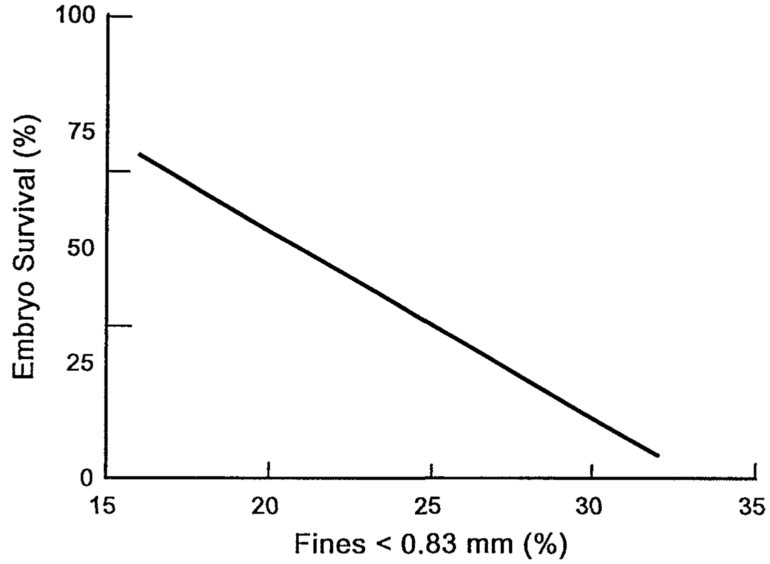

FIGURE 11.—Coho salmon embryo survival (percent) in relation to percent fine particles less than 0.83 mm (by volume) in spawning gravel (from Hall and Lantz 1969).

The level of 20% fines less than 0.8 mm became well established and was accepted by many investigators as the criterion above which significant mortality of embryos could be expected (Figure 11).

Permeability of spawning gravel has received similar attention from researchers investigating salmonid reproductive success. Cooper (1965), investigating sockeye salmon spawning in inland streams of British Columbia, was concerned primarily with water flow through the redd and permeability of redd gravel relative to pore size. With small pore size, more suspended sediments were deposited and water flow was reduced, although Cooper did not define the particle size of fines deposited in redds. Shelton and Pollock (1966) investigated the role of sediment in spawning gravel by measuring the percentage of gravel voids filled by silt. When 35% of voids were filled, salmon egg mortality was 85%; when void siltation was reduced, mortality dropped to as low as 10%. The authors were mainly concerned with oxygen supply. They used an upper part of an artificial channel as a settling basin to control sediment input to the experimental spawning gravel.

Sediment in the Egg Pocket: A Finer Resolution

The use of particle-size categories, particularly as percentages below specific size limits, involved high variability in egg survival, as observed by many researchers. An improvement over particle-size percentage was a measure of central tendency—particularly the geometric mean diameter—calculated from all particles in the spawning gravel smaller than gravel-sized particles (e.g., 25.4 mm).

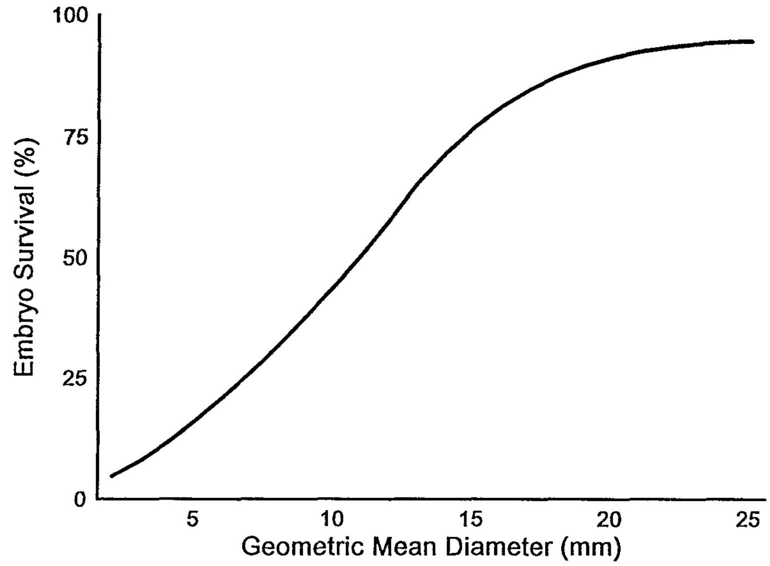

FIGURE 12.—Salmonid embryo survival (percent) in relation to geometric mean diameter of substrate particles in spawning gravel. Survival data are combined survivals of coho and sockeye salmon and steelhead and cutthroat trout (from Shirazi and Seim 1979).

In their studies in the South Fork Salmon River, Platts et al. (1979) questioned the use of percent concentrations of fines and suggested instead the use of the geometric mean diameter of substrate particles, obtaining data from strata in a vertical distribution of redd gravel (Figure 12). The geometric mean, they concluded, was at least as good a predictor of egg survival as percentage fines. They further suggested that a certain quantity of fines is beneficial in the redd, with which Everest et al. (1987) later agreed. Shirazi and Seim (1979) also presented convincing evidence for the superiority of the geometric mean.

Another measure of central tendency, the fredle index, was developed further as another predictor of egg survival (Lotspeich and Everest 1981; Beschta 1982) (Figure 13). The fredle index relates mean particle diameter (such as the geometric mean) to its variance. Lotspeich and Everest (1981) used the data of Phillips et al. (1975) to show a strong correlation between the fredle index and survival to emergence of steelhead trout and coho salmon fry. Sheridan et al. (1984), upon analysis of more than 2,000 streambed samples from pink salmon spawning riffles in southeastern Alaska, reported agreement between the fredle index and percent fines less than 0.83 mm. Young et al. (1991), using cutthroat trout eggs, conducted extensive laboratory experiments with 15 statistics on survival to emergence against substrate composition. They concluded that measures of central tendency (e.g., mean particle size, fredle index), especially the geometric mean, performed better than percent fines in predicting embryo survival.

Reviewing published accounts in a search for criteria that would establish the level of fines causing deleterious effects in salmonid redds, Chapman (1988) noted

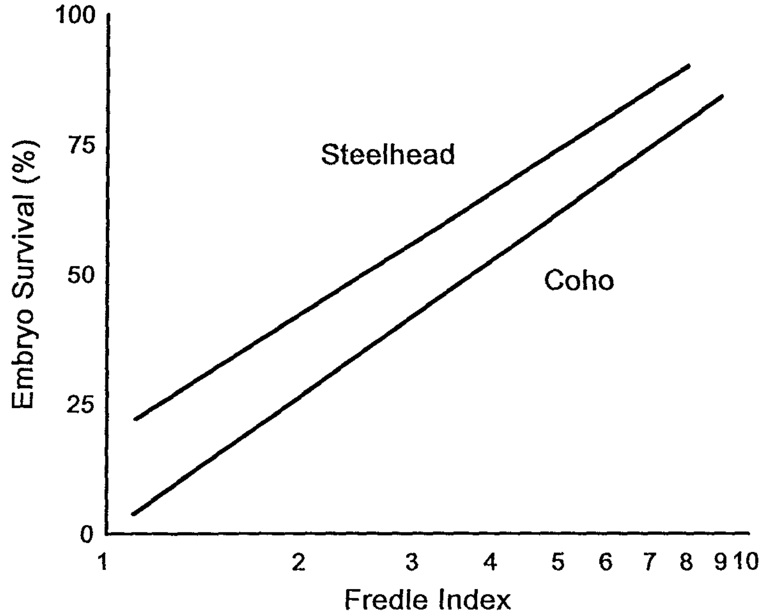

FIGURE 13.—Salmonid embryo survival (percent) in relation to the fredle index in spawning gravel (from Lotspeich and Everest 1981).

many laboratory reports relating sediment to egg survival, as well as to the success of fry emergence through overlying substrata. However, he lamented experimental conditions that did not relate necessarily to the immediate environment of the embryos—the egg pocket located in the centrum of the redd. He quoted the use of vertical strata sampling (Platts et al. 1979) as means of acquiring fine-scale data in egg pockets. On the basis of available laboratory data, he supported the hypothesis that permeability and particle size in the egg pocket are greater than in surrounding gravel, i.e., conditions are better in the egg pocket (probably as the result of redd-building activity of spawning females). Chapman made a cogent case for identification of these conditions and, thus, a finer scale of resolution.

Many papers described the characteristics of natural spawning beds, some from the completed redd but a few directly concerned with conditions in an individual egg pocket. The development of the freeze-core technique (Walkotten 1973, 1976; Everest et al. 1980; Lotspeich and Reid 1980; Platts and Penton 1980) made it possible to identify precisely the location of fertilized eggs and the nature and size of gravel and sediment particles in their immediate vicinity (Figure 14). Young et al. (1989) used the freeze-core technique to sample fines in brook trout redds and surrounding gravel; he reported fewer fines in the egg pocket. The frozen cores vary in weight greatly, from about 500 g with the single-probe technique of Walkotten (1973), to the larger ones obtained with the multi-probe unit of Platts and Penton (1986), which requires up to 5,000 lb of lift force. Despite these logistical drawbacks, the frozen cores allow accurate measurements and the

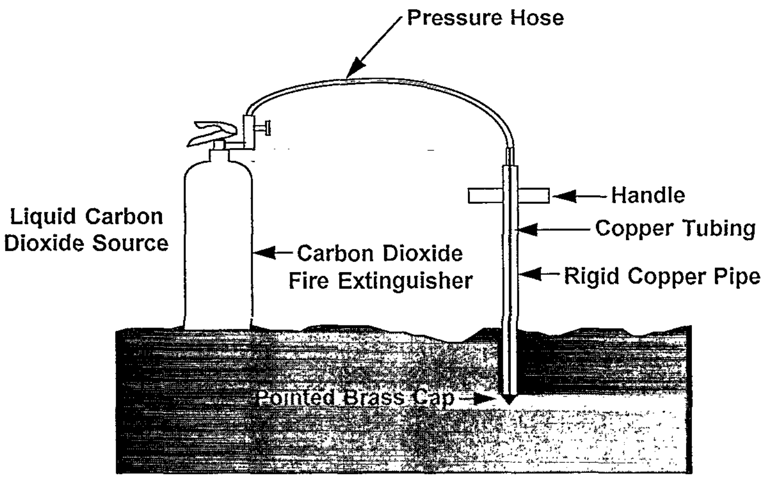

FIGURE 14.—Freeze-core sampler for extracting an intact core of salmonid redd substrate, including sediment from the egg pocket (from Walkotten 1973).

calculation of indices, such as percent fines, geometric mean diameter, and the fredle index, for those particles directly in the egg pocket. Lisle and Eads (1991) recently reviewed the use of several techniques aimed at measuring sediment conditions in spawning gravels, including bulk cores, freeze-cores, infiltration bags, and others.

Chapman (1988) concluded his review with the suggestion that future research should include data on permeability, oxygen, the fredle index, percent of fines less than 0.85 mm and less than 9.5 mm—the two particle sizes for which strong correlations have been found with embryo survival and sac fry emergence, respectively (Tappel and Bjornn 1983). Chapman outlined research phases that include such data from egg pockets. He predicted that when such egg-pocket data are used to correlate with survival, the high variability previously observed would be reduced.

Entrapment of Emerging Sac Fry

The satisfactory completion of the embryo stage for salmonid eggs in the redd is only the first step. Newly hatched sac fry must complete their development in the gravel and upon leaving the protection of their subsurface environment, eventually make their way to the surface of the streambed and to a free-swimming existence. However, sometimes that route is blocked by compacted sediment; entrapment (or entombment) and death of the fry result.

Whereas sediment particle sizes that impede water flow and cause asphyxiation to embryos are small (<0.84 mm), larger particles may permit water flow but still prevent fry emergence through an overhead stratum. First attention was drawn to the emergence problem by Koski (1966), in studies within the Alsea Watershed Study in Oregon. He observed that emergence of coho salmon fry was precluded by sediments less than 3.3 mm. Other work on fry emergence was

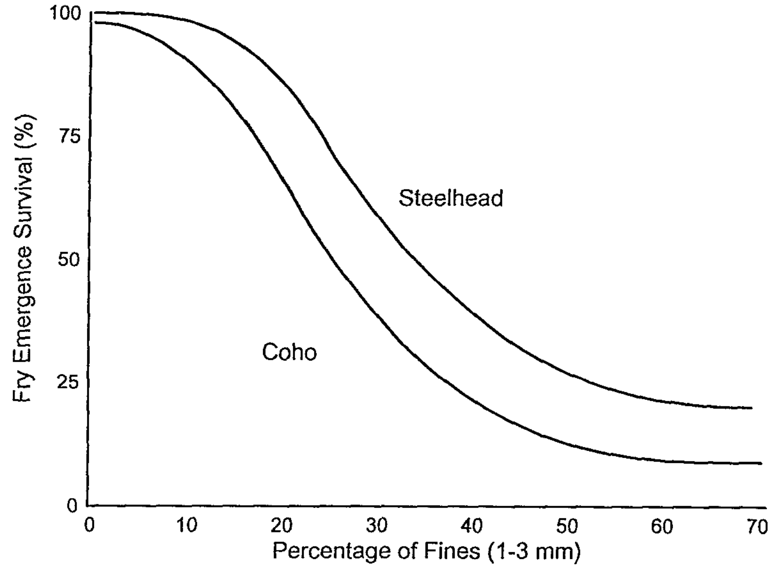

FIGURE 15.—Percent success of fry emerging from spawning redd in relation to percent fines 1–3 mm (from Hall and Lantz 1969).

conducted by Hall and Lantz (1969), Moring (1975a, 1975b), Moring and Lantz (1975), and Phillips et al. (1975). Clearly, past emphasis upon particle sizes and embryo survival in the redd was not the complete view of salmonid reproductive success. Similar results were reported within a fairly narrow range (about 2–6 mm) of particle sizes that prevent emergence (Hall and Lantz 1969; Platts et al. 1979) (Figure 15).

Dill and Northcote (1970) studied the effect of gravel particle size on emergence of coho salmon fry in British Columbia and reported that percent survival was not decreased by gravel sizes (1.9–3.2 cm), but emergence from the gravel by sac fry was delayed. In their recent review, Bjornn and Reiser (1991) concluded that emergence of sac fry from the redd may be impeded by sediments of 2–6.4 mm in percentages above about 10%.

Timber Harvest and Salmonid Reproduction

Timber harvest in the vast coniferous forests of the Pacific Northwest in the United States and in western Canada has received the greatest research attention as an important source of excess sediment in stream salmonid fisheries. The reasons for this attention include, in addition to the immense forest resources, the mountainous topography with steep hillslopes and the great importance of the salmonid fisheries that depend upon appropriate conditions in the many coastal and inland streams. Many watershed features combine to exert tremendous adverse effects by sediment on stream biota, most notably in reduction of reproductive success of all species of salmonids in the area, both anadromous and inland populations (Table 2).

TABLE 2.—Watershed features influencing the risk of sediment limiting salmonid reproductive success (from Everest et al. 1987).

Factor	Low risk	Intermediate risk	High risk
Hydrology	Winter rain hydrograph	Summer rain, winter snow, spring snowmelt hydrograph	Spring-fed hydrograph
Erosion	Surface erosion	Surface and mass erosion	Mass erosion, channel erosion
Geology	Volcanics	Sandstone, siltstones	Granitics
Hillslope	Gentle terrain	Moderate terrain	Steep lands
Stream gradient	High (>5%)	Moderate (1–5%)	Low (<1%)
Stream geometry	Narrow, deep		Shallow, wide
Streamside forest, woody debris	Abundant		Scarce

The several major research programs involving experimental logging in northwestern North America—the Alsea Watershed Study (Oregon), the South Fork Salmon River study (Idaho), and Carnation Creek Watershed project (British Columbia), are all long-term, continuing over several decades. They have contributed greatly to our present knowledge about the effects of sediment in salmonid reproduction. Consequently, this section deals primarily with a review of information having originated in studies of sediment from timber-harvest sources.

In most cases, large-scale commercial timber cutting began before the initiation of sediment research programs, so pre-timber cutting data were not available. The approach, therefore, often was experimental cutting, designed to obtain data from carefully planned logging operations in virgin forests. This approach was the main research design in most of the long-term studies, as well as in some other short-term projects.

Alsea Watershed Study.—The inclusion of the classic paper from the Alsea Watershed Study by Hall and Lantz (1969) in a major symposium on stream trout and salmon (Northcote 1969) was an important advance in the area of forestry–fisheries interactions. In the experimental logging in this Oregon project, three stream watersheds were treated in an experimental forest management program: one clear-cut, one cut in patches and retaining streamside buffer strips, and one uncut as a control (Moring 1975a, 1975b; Moring and Lants 1975) (Figure 3, page 29). Water flow in redds was severely affected in the clear-cut stream, and flow was reduced by more than 75% (Moring 1982). Suspended sediment increased significantly in the clear-cut watershed, but not in the patch-cut or control areas.

Investigators recorded survival of coho salmon eggs and observed a significant inverse relationship between survival and percentage of fine sediment particles less than 0.83 mm. The first report of entombment of emerging fry originated in this program (Koski 1966). Additional experiments on fry emergence resulted in the observation of a significant inverse relationship between successful fry emergence and fine sediment less than 3.3 mm in overhead gravel mixtures.

South Fork Salmon River (SFSR).—Research results from the SFSR study comprised major contributions on the effects of timber harvest on sediment generation and salmonid reproductive success (Platts 1970; Platts and Megahan 1975; Platts et al. 1989). The SFSR project has so far spanned more than a 25-year period. A tributary of the Salmon River in central Idaho (Figure 5, page 32), the SFSR historically was the major producer of steelhead trout and chinook salmon in Idaho. The terrain is steep, with most hillslope gradients of 40–70%—typical of this forested mountain region. A major factor in the SFSR sediment problem is its location in Idaho's central batholith of relatively soft, highly erodible granite. Enormous sediment problems developed early due to logging practices, particularly from roads, in the granitic watersheds.

Before logging began in the SFSR watershed in 1950, annual chinook salmon spawning runs were estimated at about 10,000 (the largest summer chinook salmon run in Idaho) and steelhead trout runs were about 3,000. After logging, runs of chinook salmon were estimated at 1,200 (down by 88%) and steelhead trout runs at 800 (down by 73%). With intense logging in 1950–1965, soil erosion rates increased by 350%, mainly due to road construction. More than 1,000 km of logging roads were constructed, two-thirds of which were on hillslopes of greater than 43% gradient. Forest erosion was accelerated by several storms, after which spawning areas were blanketed by up to 4 ft of sediment deposits (Platts 1970).

After a moratorium on logging and road construction was imposed on the SFSR watershed in 1968, the percentage of fines (<4.7 mm) in spawning gravels decreased from 48 to 25%; the percentage of gravel (4.75–76 mm) increased accordingly (Platts and Megahan 1975; Platts et al. 1989). The authors concluded that recovery under the logging moratorium—which sharply reduced sediment—was accomplished through natural river processes. Apparently, an equilibrium was reached between sediment input from the watershed and the ability of the river to remove sediment, although the low pre-logging sediment concentrations had not been attained.

Carnation Creek Watershed project.—This project also included experimental logging practices (Figure 6, page 34); it contributed greatly to rapidly accumulating knowledge on sediment–fisheries interactions, particularly on reproductive success of coho and chum salmon. Many details, summaries, and historical presentations from the project were included in papers by Hartman (1982), Scrivener and Brownlee (1982, 1989), and Hartman and Scrivener (1990). After logging, coho egg survival to emergence declined from 29 to 16% and chum salmon egg survival declined from 22 to 11%; these reductions were attributed to reduced permeability and oxygen levels in the redd. The size of emerged fry for both coho and chum salmon declined, the number of emerged coho salmon fry dropped to about one-third of previous levels, populations of juvenile steelhead and resident cutthroat trout declined by about 50%, and sculpin populations declined to about one-third of previous levels.

Alaska streams.—Much of the early work on sediment and salmonid reproduction was accomplished in Alaska streams by McNeil and Ahnell (1964) and Sheridan and McNeil (1968). These investigators presented some of the first data on fine sediments related to reproductive success and at the same time first indicted logging practices for erosion and sediment generation to streams (Figure 9, page 90). The work in Alaska stimulated much further research on forest management and timber-harvest sources of sediment.

Northern California.—Harvest techniques in northern California watersheds were studied by Burns (1970, 1972), who reported on effects of various logging practices. Road construction near streams, bulldozer operations on steep slopes, and heavy machine operations directly in stream channels were identified as contributing most in sediment production. Burns also reported substantial decreases in standing stocks of trout and salmon when sediments less than 0.83 mm diameter increased due to these logging practices. Little damage was sustained by fish populations when roads were constructed well away from streams, bulldozer operations were kept out of stream channels, and buffer strips of vegetation were retained along stream edges.

By the early 1970s, concern about the effects of logging on fisheries, including sediment-related problems, and particularly in the Pacific Northwest, led to several major conferences on timber harvest and sediment. In one of the first symposia dedicated to the relationship between forest land use and stream biota (Krygier and Hall 1971), Phillips (1971) summarized the effects of sediment on trout and salmon, listing oxygen reduction in the redd and fry entrapment among other effects. A workshop at the University of Washington resulted in an extensive review and an annotated bibliography (Gibbons and Salo 1973); most of the papers were on salmonid reproduction. Major topics of the workshop addressed sources of sediment in forest management practices and its effects, including the filling of spawning gravel that results in reduction of oxygen supply and entrapment of emerging fry. However, in addition to these problems of excessive sediment, many other aspects of timber-harvest practice were included: effects on water temperature, shading and autochthonous photosynthesis, woody debris in stream channels, and reduction of allochthonous organic matter input.

Recent Major Reviews

Information accumulated by the middle to late 1980s led to several important reviews at a time when much research on salmonid fisheries and forestry-generated sediment had been completed. Almost all of these reviews concentrated on salmonid reproductive success and were primarily related to forestry in the Pacific Northwest.

The Meehan series.—A series of papers under the general title of "Influence of Forest and Rangeland Management on Anadromous Fish Habitat in the Western United States and Canada" was initiated in the late 1970s, edited by W. R. Meehan. The first of these concerned basic habitat requirements (Reiser and Bjornn 1979) and covered (among other subjects) the effect of turbidity on adult spawning, preferred gravel sizes for spawning, and the need for low percentages of fines in redds to allow water and oxygen flow. Other topics included the effect of deposited sediment on invertebrate food production and juvenile fish habitat. Other reports followed subsequently.

NCASI publications.—The research program of the National Council of the Paper Industry for Air and Stream Improvement (NCASI) resulted in the review by Hall (1984a), which emphasized the effects of forestry-generated sediment on salmonid redds and on juvenile rearing habitat. Methods for sampling fine sediment in redds were included, mainly the McNeil sampler (McNeil and Ahnell 1964) and the freeze-core samplers (Walkotten 1973; Everest et al. 1980; Platts and Penton 1980; Lotspeich and Reid 1981). Emphasis was placed on the need for further definition of "fines" in redds, the sizes of fines most damaging to hatching and emergence success, and the relationship of excessive fines to naturally occurring fine sediment concentrations. The need for vertical profiles of redd-gravel composition was pointed out. Many laboratory studies were reviewed, most of which indicated either reduced survival to hatching or reduced emergence by entrapment of emerging fry, or both. However, Hall (1984a) also noted the concern expressed for research on the vertical distribution of sediment in natural redds, in order to define the ambient conditions during successful embryo development and fry emergence. Hall included 67 references in this review, most of which dealt with problems of egg and fry success in salmonid redds.

Forestry–fisheries interactions.—In a book relating forest practices specifically to fisheries, edited by Salo and Cundy (1987), Everest et al. (1987) contributed a major review that summarized the extensive literature on the sediment and salmonid reproduction relationship known up to that time. They termed this relationship a "paradox," drawing the conclusion from the large literature originating in the Pacific Northwest that some fine sediment is natural in salmonid spawning gravels, and in fact may be essential, thus agreeing with Platts et al. (1979). Yet the literature is abundant with many research results that also demonstrate firmly the damaging effects of excessive fine sediment in salmonid redds. The authors pleaded for further work on the "middle ground" between too much and too little sediment (e.g., for a more holistic approach to research on sediment problems).

Everest et al. (1987) also reviewed the voluminous literature on fines in salmonid redds, with some reservation. Laboratory experiments, they pointed out, are often done with synthetic mixtures that probably do not effectively simulate natural redd composition. On the other hand, field studies are often confounded by other effects of forestry practice such as changes in water temperature. They also noted that the measurement of effects directly assignable to sedimentation is more demanding in natural environments and that it is still difficult to produce useful forest management guidelines that relate to sediment. Nevertheless, the evidence from all studies constitutes a strong indictment of excessive fine sediment in salmonid redds; many papers indicate that redd composition including 20% fines of less than 0.83 mm in size is detrimental.

Among biological effects of fine sediments, Everest et al. (1987) listed the blockage of intragravel water and oxygen, direct smothering and suffocation of

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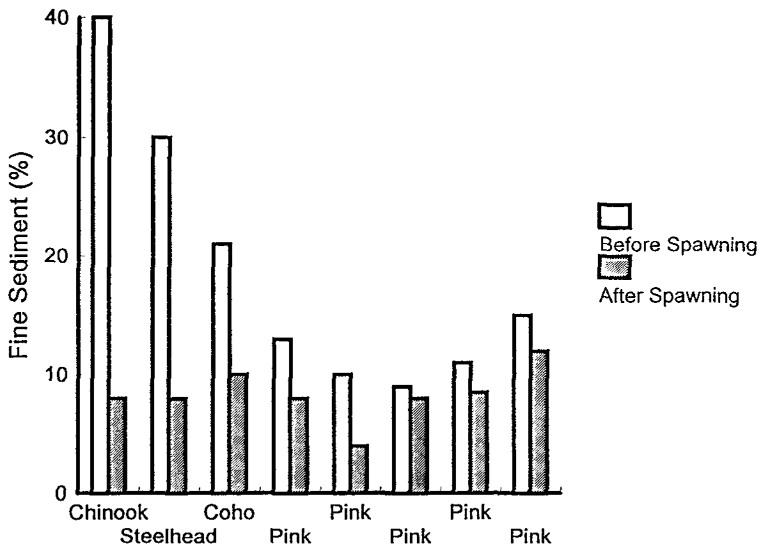

FIGURE 16.—Effect of adult cleaning of fines from spawning gravel during redd construction (from Everest et al. 1987).

eggs and sac fry, and entrapment of emerging fry. They reviewed indirect habitat effects such as the filling of pools and decreases in invertebrate production.

Everest et al. (1987) also pointed out some mitigating factors of fish behavior, mainly that redd-building by female salmonids results in a certain cleaning of fines from the gravel (Figure 16) and that fry behavior such as "coughing" and mucous production on gills assists sloughing of fine particles (Bams 1969). Channel diversity owing to boulders and large organic debris creates "islands" of more suitable spawning habitat, even in a heavily sedimented stream. The point was also made by Everest et al. (1987) that whereas most research included studies of survival in or from redds, little correlative evidence exists on the effect of sediment on populations or the return of adults. Later reports from the Carnation Creek studies, however, now appear to be major exceptions to that observation (Scrivener and Brownlee 1989; Hartman and Scrivener 1990). Everest et al. (1987) included the table of catchment features that influence the risk of limiting populations by damaged spawning habitat (Table 2).

Everest et al. (1987) concluded that all salmonid species can cope with the natural variability in sediments, but their populations can be reduced by persistent sedimentation that exceeds the natural levels under which they have evolved. They closed with a thoughtful and incisive view of future directions in forest management in relation to the salmonid fisheries of the Pacific Northwest. Rather than urge broad guidelines for forest management, however, they suggested that knowledge from a variety of related disciplines be used to tailor operations to specific areas and their changing characteristics.

Chapman's review.—Chapman (1988) presented a critique of previous attempts to define effects of sediment in redds, along with suggestions for the improvement of methods. His review appears to be an outgrowth of a larger report—much broader in scope and more detailed—on the effect of fine sediment that was prepared for the U.S. Environmental Protection Agency (Chapman and McLeod 1987). A historical perspective on research conducted on fines in salmonid redds was included, along with a plea for consideration of conditions in and around the centrum of the egg pocket. The USEPA report also included reviews of the effects of sediment on macroinvertebrate production and juvenile fish rearing habitat.

Forest–range management and salmonids.—The recent reference volume on forest and rangeland management and salmonid fishes, edited by Meehan (1991a) with contributions by many authors, covers a full range of topics within the main subject, including several aspects of sedimentation. This publication constitutes a major development in documenting progress in research on stream salmonid management, although the treatment of sedimentation was a small part. Sediment topics were: sources of sediment (mining and livestock grazing in addition to timber harvesting); specific attention to road construction; juvenile anadromous and resident salmonid rearing habitat; a little on invertebrate production; and mainly, effects on spawning, egg incubation, and fry emergence. The principal chapter on sediment was by Bjornn and Reiser (1991), who contributed an extensive and timely summary of salmonid habitat requirements in streams, including the problem of sediment in redds.

Salmonid Reproduction in Inland Trout Streams

Some of the earliest concerns about sediment affecting salmonid reproduction were expressed in relation to eastern trout streams. Tebo (1957), in a general account of research at the Coweeta Experimental Forest, North Carolina, expressed concern about siltation related to logging practices which he believed would interfere with the success of trout spawning.

Experimentally stocked trout eggs in artificial redds and in Vibert boxes (Anonymous 1951) have failed to survive in silted conditions (Peters 1965, 1967). Furthermore, Harshbarger and Porter (1979) observed better survival of brown trout eggs in natural redds than in Vibert boxes in a southern Appalachian stream. The boxes collected a higher concentration of sediment than did natural redds—an example of an experimental technique that might show a sediment problem when one did not exist.

In the upper reaches of tributaries to Flathead Lake, Montana and British Columbia, Shepard et al. (1985) studied the reproductive success and juvenile densities of bull trout. In experiments with stocked eggs in artificial redds, they reported survival to emergence of 5–50%; survival was significantly correlated with the percentage of fines (30–45%) smaller than 6.4 mm diameter in spawning gravel beds. At 26 stream sites, they found densities of juvenile bull trout ranging from 10 to 1,200 per hectare and correlated with fines less than 6.4 mm diameter in streambeds. Road development in the upper stream watersheds was indicated as the source of sediment. The bull trout population was adfluvial (i.e., spawning in upper stream reaches and maturing in Flathead Lake).

The first studies of sediment sizes and percentages in eastern trout redds were included in the experiments of Cloern (1976), who stocked coho salmon eggs in two Lake Michigan tributaries that were heavily silted. Sediment composition included 17% and 18% fines less than 0.84 mm. Cloern stocked the eggs in Vibert boxes and observed no survival in one stream and only 1.4% in the other.

The southern Appalachian Mountain region contains many trout streams which, although relatively infertile, attract high regard for their recreational fisheries. The brook trout was the only salmonid indigenous to the region; however, introductions of rainbow trout and brown trout have created greater diversity. Although the introduced species, especially the brown trout, have been highly successful in some streams, the reductions of brook trout distribution, especially due to rainbow trout introduction, have caused concern.

Like the Pacific Northwest, hillslopes in the Appalachian Mountains are exceedingly steep. The problem of sedimentation has caused much concern as the result of activities associated with timber harvest, road-building, mining, and other sediment-producing sources. Programs to preserve and protect the remaining brook trout stocks may require special measures to avoid sedimentation. Additional research on the influence of sediment on reproductive success of the brook trout in redds of these southern mountain streams may also be necessary.

West (1979) pointed out the lack of research on characteristics of spawning gravel in southern Appalachian trout streams, as compared with western studies on large salmonids. His studies in trout streams of western North Carolina appear unique in that area. In eight streams, West measured water velocity, dissolved oxygen, permeability, temperature, and bottom composition (particles 0.84 and 3.36 mm diameter) in spawning gravels. Associating these results with published data for other salmonids, he concluded that spawning gravels in the studied streams met requirements for successful embryo development. Except for one stream, the sand component was less than 20% and, with the one exception, the author believed that emergence of trout fry would not be impeded. However, although he reported physical and chemical information, he included no data on fish.

Later, West et al. (1982) experimentally planted eyed brook-trout eggs in two North Carolina streams—one relatively clear and one heavily sedimented—and reported large differences in reproductive success between the two streams. In the clear stream, 87% of the eggs hatched and 11% emerged; in the sedimented stream, 40% hatched and 6.4% emerged. The authors hypothesized that the major mortality factors in the sedimented stream were abrasion of eggs by suspended sediment and entrapment of sac fry by heavy deposited sediment. Trout standing stock in the clear stream was 3.7 times higher than in the sedimented stream. Subsequent observations by Dechant and West (1985) on natural redds of brown trout in two North Carolina streams suggested that sediment deposition during floods accounted partially for decreased reproductive success (along with the effects of scouring and anchor ice).

Additional concerns and studies on the effect of forestry practices on eastern streams were reported by Rutherford (1986) for Atlantic salmon in Nova Scotia, and by England (1987) for brook trout in national forests of Georgia, but details on redd conditions were not included.

Obviously, further study is needed on the effect of sediment in the highly valued salmonid streams of the Appalachian region. The work of West and his associates remains exemplary. In all probability, the southern Appalachian streams, with their steeply sloped watersheds that are highly susceptible to erosion, will show similar vulnerability to sedimentation as those in the Pacific Northwest—most critically with regard to salmonid reproductive success.

Water Source for Redds: Downwelling versus Upwelling

Throughout the extensive research on salmonid reproduction carried out in the Pacific Northwest, the underlying cause of sediment deposition in the redd was considered to be high suspended sediment levels in stream water. In redd construction reported from that region, adult salmonids select locations at the tail of pools or just upstream from riffles, where hydraulic pressure on the streambed increases and causes downwelling into the spawning gravel (Figure 17A).

Here, the source of water for the redd is the stream water that under conditions of high suspended sediment levels delivers sediment into the redd. The suspended sediment content and streambed deposits therefore are critical to sediment composition of redds. Essentially all research has shown a strong correlation between substrate composition (% fines, geometric mean diameter, fredle index) and embryo survival, where stream water was the source of oxygen for the redds (Sheridan 1962).

However, when the water source is groundwater, embryo survival will depend not so much on substrate composition or suspended sediment levels in the stream, but rather on the nature and quality of the groundwater. In this case, successful spawning can occur with redd construction in riffle areas with upwelling water, or even in slow-water locations with fine-particle streambeds.

Considerable evidence from midwestern and eastern regions indicates that the source of water for salmonid redds may be mainly upwelling groundwater (Figure 17B). Benson (1953) observed use of groundwater by spawning brook trout and brown trout in the Pigeon River, Michigan; Latta (1965) correlated young brook trout populations with years of higher groundwater input in the same stream. Webster and Eiriksdottir (1976) observed spawning of brook trout in upwelling water over a period of years in Adirondack streams of New York. They also reported that brook trout detect and select upwelling sites for spawning in laboratory tanks. Fraser (1985) recorded brook trout spawning in shoal areas of an Ontario lake at locations of upwelling groundwater.

Witzel and MacCrimmon (1983b) reported that brook trout selected redd sites containing fine particles in an Ontario stream. In studies of rainbow trout embryo survival in an Ontario tributary of Lake Erie, Sowden and Power (1985) noted survival up to about 50% among 19 natural redds, independent of substrate composition. They concluded that groundwater oxygen content was the limiting factor and suggested that survival above 50% requires a groundwater oxygen content exceeding 8 mg/L.

Similarly, the experiments of MacCrimmon and Gotz (1986) showed better survival of Atlantic salmon embryos—eyed egg to emergence—when water flow in laboratory incubators was upward and sediment was not compacted. Survival

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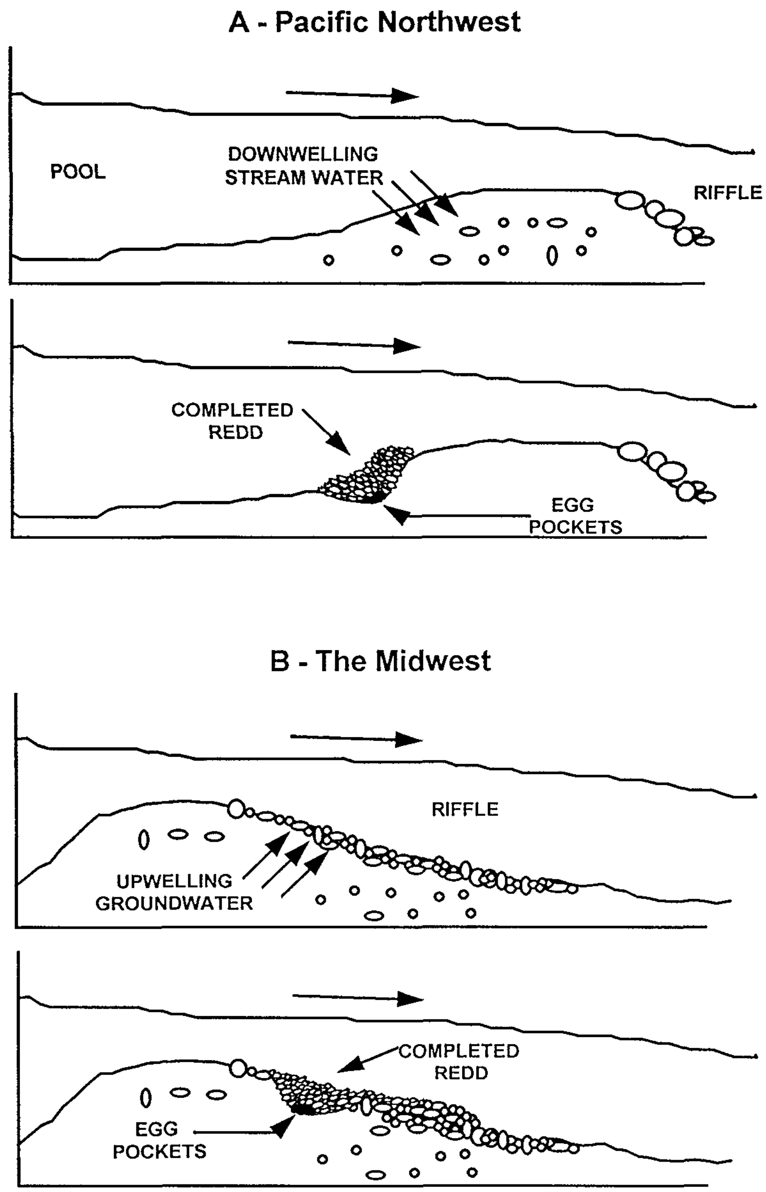
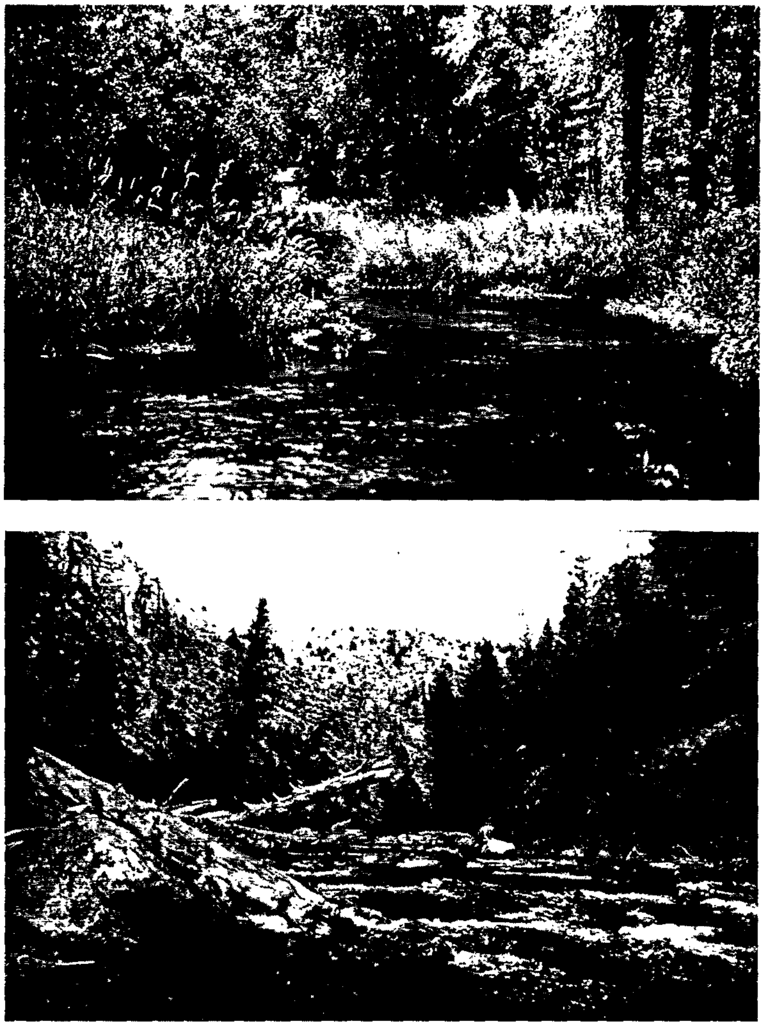


FIGURE 17.—Salmonid redd construction. (A) Downwelling stream water carrying sediment (Pacific Northwest). (B) Upwelling clean groundwater (Midwest). (A is from Phillips 1971.)



Differences in sources of cool water—required in summer for salmonid fisheries—may account for differences in reproductive success. Top: Sandy midwestern streams with cool upwelling groundwater have high reproductive success despite relatively slow currents and sand- or silt-covered streambeds because of sediment-free upwelling water in redds. Crystal Brook, Wisconsin. Bottom: Rocky, steep streams at high mountain altitudes may depend on cool surface runoff for salmonid fisheries where silt-laden stream water, downwelling into salmonid redds, cause mortality to incubating eggs and emerging fry. Bitch Creek, Idaho.

was not related to stream sediment levels; rather, it was attributed to a constant and high rate of upwelling water flow. Such results, of course, may occur only in those natural redds with a source of oxygenated groundwater.

In Lawrence Creek, Wisconsin, a productive but sandy brook trout stream, Hausle and Coble (1976) compared viable eggs and larvae in redds with various percentages of sand, conducted experiments with planted eggs in artificial redds, and observed emergence of embryos in laboratory troughs with various mixtures of sand (<2 mm) and gravel. They found that although hatching and emergence were lower in redd gravels with the higher percentages of sand, successful emergence ran as high as 82% even with the highest sand proportion (25%). These results suggested that brook trout reproduction in sandy midwestern streams may be less susceptible to failure from heavy sand deposition than salmon and trout reproduction in the Pacific Northwest.

In an extensive study of brown trout reproduction in southeastern Minnesota streams, Anderson (1983) concluded that the scouring effect of floods, rather than siltation, was the major factor causing frequent failures of reproduction. The author found evidence of a groundwater source in redds; he suggested that groundwater percolating through the redd would account for reproductive success even when stream waters were silty.

However, not all experiences with eastern species have been similar. For example, experimental studies conducted on Atlantic salmon eggs by Peterson and Metcalfe (1981), in which varying sand proportions were applied to experimental containers, indicated that this species responded with greater survival to emergence with a lower percentage of sand—a response similar to that of western salmonid species. It may be inferred that the differences in reproductive success observed between the two species groups in natural streams is therefore related to differences in redd water source, rather than to differences in species.

Using laboratory incubators with upwelling water, Witzel and MacCrimmon (1981, 1983a) experimented with rainbow trout eggs (homogeneous gravel mixtures) and brook and brown trout eggs (homogeneous gravel and sand-gravel mixtures). Their results were similar to those from western localities and species: survival was low (0–30%) when sand and finer particles constituted 20–30% or more, but higher survival (80–95%) when sand and fines were 0–20%.

Therefore it would be premature to generalize that the difference is due either to species or to continental locales, although the evidence for greater embryo survival in redds with clean groundwater is convincing. Certainly in the trout streams of the upper Midwest (Minnesota, Wisconsin, and Michigan), groundwater sources may well contribute to the great success of both the native brook trout and introduced brown trout, despite the often sandy streambeds of this region.

The question arises: Why is groundwater apparently less available in the West than in the Midwest and East?

One suggestion is that influent streams are common in mountainous terrain and effluent streams are more common in flatter topography. It seems unlikely, however, that influent streams are always the case even in steep-gradient streams. Downwelling water in salmonid redds does not necessarily imply an influent stream. Downwelling in the redd may occur as the result of streambed morphology (i.e., with greater hydraulic pressure just upstream from an elevated riffle). Possibly this type of morphology occurs more commonly in streams with higher gradient.

Such spawning conditions in the Appalachian Mountains, with their steep terrains, may be similar to western conditions: similar sources of stream water and sediment to salmonid redds, with all the attending problems caused by suspended sediment in streams. The work of West et al. (1982) in North Carolina streams suggested that hydrological conditions in streams of the southern Appalachians were more similar to western mountain streams with a stream water supply to salmonid redds.

In streams located at high altitudes (or latitudes) climatic conditions may result in cool runoff in summer, which would favor the salmonid stream with stream water as the source for redds. In the lower altitude of Midwest streams with high runoff temperatures, only those with copious groundwater sources may be cool enough in summer to be suitable for trout or salmon.

The problems of water supply to redds—and salmonid reproductive success relative to sediment—portray an important difference in potential fisheries management between different regions. This question relating to water supply to the salmonid redd is intended as a hypothesis, and it clearly requires further research.

The Holistic Approach to Watershed Management and Salmonid Reproduction

The most recent summaries of the influence of sediment on salmonid reproductive success, particularly those of Everest et al. (1987), Chapman (1988), and Bjornn and Reiser (1991), appeared to signal that the time has come to pause and take stock of salmonid reproduction research for now and proceed further with improved sediment control within the larger scope of salmonid fisheries management.

Some authors have already pointed out the need to proceed beyond the point of ascertaining causes of low egg survival, to determine population effects in the stream, in the ocean stage, and in adult returns. Stowell et al. (1983), using data from the South Fork Salmon River project and other studies, presented a guide for estimating salmonid response from sediment data, including smolt production and adult spawning populations of chinook salmon. Hartman and Scrivener (1990) also made a strong beginning in presenting some preliminary estimates of overwinter survival of fry and juveniles, numbers surviving to the smolt stage and emigration, and marine survival to adult returns. They made a plea for integrating studies of sedimentation (and other forest management impacts) within a broader context of the ecosystem—the holistic view.

In their extensive review, Everest et al. (1987) also urged a holistic approach. As they pointed out, effects of forestry management practices are many and varied. Streams in unforested watersheds also store sediment but still may be favorable for salmon and trout production. The effects of sediment should be studied now in context with other factors, such as water quality and temperature, cover, invertebrate food productivity, large organic debris and other "roughness" elements. Research into sedimentation should expand beyond the study of survival and fry emergence, to assist in developing broader management strategies aimed at maintenance of productive populations, whether resident trout fisheries or adult salmon returns.

Conclusions

The greatest research effort on the relationship between sediment and salmonid reproduction has been applied to anadromous salmon and steelhead trout in the Pacific Northwest and western Canada. In these studies, many researchers have concluded that most reductions in egg-hatching success resulted when fine sediment particles of approximately 0.8 mm and smaller occurred in redds in proportions of about 15–20% or higher (McNeil and Ahnell 1964, and many subsequent authors). Entombment of fry attempting to emerge from redds, another major source of mortality, occurs mainly under high concentrations of larger sediment particles—about 3–6 mm in size—in overlying strata (Hall and Lantz 1969). Subsequent studies suggested that the geometric mean diameter of substrate particles is more precise in predicting hatching success than a simple percentage of fines (Platts et al. 1979). The further development of the fredle index gave additional predictive capability (Lotspeich and Everest 1981; Beschta 1982). The development of freeze-core techniques in sampling redd composition (Walkotten 1973; Lotspeich and Reid 1980) greatly facilitated the analysis of sediment by vertical distribution of sediment in the redd. The freeze-core technique also permitted study of sediments in the redd centrum containing the egg pockets, enabling a "finer scale of resolution" that showed survival closely related to conditions immediately around and among the developing embryos (Chapman 1988).

In the high-gradient streams of the Pacific Northwest, the immediate source of sediment in salmonid redds has been identified as downwelling stream water that carries suspended sediment. Perhaps the same conditions occur in streams of the southern Appalachian Mountains. However, in low-gradient streams of the Midwest and East, upwelling clean groundwater in redds appears to make salmonid spawning more successful than where stream water carrying suspended sediment is the source of water to redds.

With the apparently definitive accomplishments in studies of redd composition and egg-to-fry survival rates, more concern has been expressed recently for the broader view of total watershed management. In addition to production of viable, free-living fry, it is also necessary to discern effects on other life history elements, such as cover and food availability, growth, survival to smolting, and adult return, all of which contribute to attaining the goals of management programs. Such a holistic view has been strongly urged by several authors, including Stowell et al. (1983), Everest et al. (1987), and Hartman and Scrivener (1990).

EFFECTS ON REPRODUCTIVE SUCCESS OF WARMWATER FISHES

The effect of sediment upon reproductive success of warmwater fishes is not well known. Early reports of declines or losses in warmwater populations were broadly correlated with sedimented streams (Trautman 1933; Aitkin 1936; Larimore and Smith 1963; Smith 1971). Sometimes reproductive failures were inferred, but no explicit experimental study has been reported for freshwater stream species.

The major publication on this subject is a comprehensive U.S. Environmental Protection Agency review on the effects of sediment on reproduction and early life of warmwater fishes (Muncy et al. 1979). The majority of papers cited in this report were for lentic species; however, for both lentic and lotic fishes, little explicit research had been done up to the time the review was published. The report functioned mostly as a perspective on the problem, and as a detailed plan for the kinds of research that are needed.

Sediment influences upon reproductive success vary with reproductive guilds, that is, groups of fishes within which reproductive behavior is similar, but between which behavior is distinct (Balon 1975). For example, the guilds for which deposited sediment would be expected to be most important include most of the lithophils (dependent upon clean stony substrate) and speleophils (dependent upon interstitial spaces in the stream substrate). Reproductive guilds most tolerant to sediment include the pelagophils (floating eggs) and those lithophils among which the adults clean and guard nests in stony substrates.

Muncy et al. (1979) also reviewed early reported associations between fish populations and sediment. They concluded, however, that reproductive failure due to suspended solids and sedimentation was mainly inferred. Literature that documented specific effects of sediment was scarce or nonexistent.

Reproductive success should be assessed according to all phases of the reproductive cycle. Muncy et al. (1979) considered five reproductive phases: gonad maturation and fecundity, reproductive behavior, embryonic development, larval development, and the juvenile period. The general conclusions on each of these phases were: (1) limited circumstantial evidence exists that sediment limits gonad development; (2) substantial evidence exists that turbidity and sedimentation variously affect time and phase of spawning, which may be negatively correlated with timing of floods and turbidity; (3) egg incubation is particularly susceptible to smothering by sediment; (4) larval stages are more susceptible to suspended sediment than either eggs or adults; and (5) juvenile fish can be directly affected when suspended sediment reduces sight-feeding and respiratory efficiency (discussed in a previous section). Consequently, Muncy et al. (1979) postulated that those species most dependent upon the bottom substrate would be the most susceptible to negative effects of sedimentation.

Muncy et al. (1979) noted that most publications on warmwater fish reproduction were from north-central agricultural regions. Little had been published from western or southern areas.

The authors concluded by identifying several research needs, suggesting three general areas of study: (1) experimental laboratory research on lethal and sublethal effects, in all reproductive phases, at elevated levels of sediment; (2) long-term experimental studies on replicated streams (and ponds) to test modes of sediment action; and (3) use of monitored watersheds to study natural runoff and fish reproduction and to differentiate the effects between sediment and other factors related to agricultural practice, such as pesticide use.

Unfortunately, in the decade and a half since the Muncy et al. (1979) paper, little further research has been accomplished. More study has been applied to marine and estuarine species than to freshwater species, for example, the work of Morgan et al. (1983), who studied the effect of sediment on reproductive success of white perch and striped bass in the Chesapeake and Delaware Canal area.

The only paper specifically on reproductive success of warmwater stream species was that by Berkman and Rabeni (1987), who measured population densities of several fish guilds relative to bottom type in streams of northeastern Missouri. They found that with increased siltation, the abundance of a lithophi-

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lous guild with simple spawning (i.e., requiring clean stony or gravel substrate, but with no site preparation or parental care) decreased significantly. These fishes included the golden redhorse, white sucker, central stoneroller, and several other cyprinids. No other guild was affected. Berkman and Rabeni's (1989) paper is an example of the research needed in sediment problems in warmwater streams.

The volume on guidelines for evaluation of human influences on warmwater streams edited by Bryan and Rutherford (1993) contains many individual papers that summarize the effects of anthropogenic sources of pollutants, including sediment. Although biological effects of sedimentation are not included in detail, these papers provide an excellent introduction to stream problems with emphasis on warmwater stream fish habitat. Many problems needing research are identified. Chapter subjects that deal with sedimentation or sediment-related topics include channelization, dredging, sand and gravel extraction, mining, road and bridge construction, timber harvest, and agricultural practice.

In view of the increased concern for fisheries in warmwater streams, especially in the agricultural regions, a heavy commitment to research on sediment and warmwater fish reproduction is obviously called for. Experimental research on the specific phases of reproduction, as outlined by Muncy et al. (1979), would have great potential value in warmwater fisheries management.

EFFECTS OF DEPOSITED SEDIMENT ON FISH HABITAT

Beyond the problems of successful reproduction and sufficient food resources for growth, both of which are susceptible to the deleterious effects of sediment, is the problem of deposited sediment effects on physical habitat—space of adequate quantity and quality to provide for fish needs. These needs include roughness elements on the streambed to provide winter protection for fry against aquatic predators, foraging territories, and sufficient water depths to provide overhead cover for juveniles and adults. Stream features affording these elements constitute rearing habitat; all are subject to severe reductions caused by deposited sediment.

The rearing habitat for juveniles is the most critical. It is well known that the greatest mortality of a given year class or cohort occurs in young stages, and that the strength of a year-class is most often set in some early critical phase (Elliott 1989). Consequently, the sedimentation of juvenile rearing habitat is decisive in its capability to ultimately damage adult fish populations.

Literature Overview

The literature on the subject of deposited sediment and fish habitat has concentrated on rearing habitat. Two major areas of concern have been investigated: (1) winter survival of fry in the interstitial spaces of riffle gravel and cobbles, and (2) depth of pools providing summer cover during growth stages. Like other aspects of this review, the greatest research emphasis within the subject of deposited sediment and fish habitat has been on salmonids.

The overwinter survival of salmonid fry, which requires clean riffles, has been of primary concern because at low water temperatures (<5°C), salmonid fry seek the greater protection of interstitial space in riffles (Chapman and Bjornn

A plunge-pool dam on a small trout stream creates a deep pool for fish habitat. Center notch in the dam assures the sediment-free depth. Forestville Creek, Minnesota.

1969). However, rearing habitat is not as important to those species in which the early fry descend directly to the sea, such as pink salmon and chum salmon.

For most salmonids, rearing habitat remains critically susceptible to deposited sediment. A few investigators have addressed problems with warmwater species, but these have not included the intensity or the detail of experimental research that salmonid research has embodied. Research (and subsequent publication) on physical habitat has not been nearly so extensive as on fish reproduction or invertebrate production but probably ranks third in order of importance.

Early Observations

The early warnings about fisheries in streams affected by sediment applied generally to soil erosion and the consequent silting of streams (Needham 1928; Trautman 1933; Aitkin 1936; Ellis 1936). These investigators did not differentiate between suspended and deposited sediment, their causes, or specific effects. Observations of muddy water or silted streambeds were visually correlated with loss or reduction of fish populations, changes in species from sport to nongame fishes, or decreases in angling success. Often, little effort was made to distinguish among the specific causes of a fishery decline—whether reproductive failure, loss of invertebrate foods, or decrease in physical habitat.

The deleterious effects of bottom accumulations of silt and sand upon fish habitat have been slowly recognized, and in the 1950s some sediment sources

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were identified. Eschmeyer's (1954) urgent plea to control erosion and sedimentation included mention of southeastern Minnesota's Whitewater River watershed. Severe erosion and excessive sedimentation in the 1930s caused this watershed to lose 90 mi of trout streams (out of an original 150 mi), and the deterioration to "poor condition" of the remaining 60 mi.

Cordone and Penoyer (1960) provided an extensive report on "silt pollution" effects on aquatic life in California's Truckee River and its tributaries. The source of silt was primarily a gravel-washing plant, which caused great turbidity and "striking" silt deposits on stream bottoms. Algae, bottom fauna, and fish were all adversely affected.

The classic paper on this subject was by McCrimmon (1954), whose experimental studies on factors affecting stocked Atlantic salmon fry have stood for many years as landmark research in the ecology of young salmonids. Although McCrimmon included many factors such as temperature and food, the factor that had the greatest deleterious effect upon survival of fry was bottom sedimentation, or deposited sediment. High mortality of the stocked fish occurred as the result of loss of shelter in gravel and riffle spaces, due to filling by sediment and consequent heavy predation by other fishes. Fry survival—particularly winter survival of salmonid fry—in the interstitial spaces of gravel and cobble riffles, so susceptible to loss through sedimentation, remains of major concern.

In their review, Cordone and Kelley (1961) examined the contemporary literature (mostly as informal reports) on deposited sediment. All of those reports suggested serious degradation of available physical habitat by sedimentation. Habitat was lost through filling in of riffle spaces used by small fish, filling of pools occupied by larger fish, and even complete blanketing of stream bottoms with thick deposits. Cordone and Kelley (1961) reviewed early reports such as those by Aitkin (1936) and Trautman (1933), which attributed changes and losses from the midwestern fish fauna generally to erosion and streambed sedimentation. The nine papers quoted began an early distinction between suspended sediment and deposited sediment, and attributed fish mortality to specific effects of deposited sediment. Cordone and Kelley (1961) included in detail the work of McCrimmon (1954) on factors affecting the survival of Atlantic salmon fry.

Fry Survival in Riffles

The need of fry for interstitial space in riffles was emphatically delineated in work on mountain streams in Idaho by Bjornn et al. (1974, 1977). Their research concerned the effect of cobble embeddedness by sediment (<6.35 mm) on the density and distribution of juvenile salmonids (as well as on invertebrates, discussed earlier in this volume). The study involved three parts: (1) experimental additions of sediment to laboratory streams, (2) experimental additions of sediment to a natural stream, and (3) correlative studies of sediment occurrence and fish density among several natural streams. Except for the experimental work of McCrimmon (1954) on stocked fry nearly 20 years previously, this work appeared to be the first to relate experimentally the degree of embeddedness to survival of fry. Their results clearly showed that embedding of cobbles by sediment reduced the physical habitat of juvenile salmonids (mostly chinook salmon and steelhead trout) and consequently the holding capacity of riffle areas for age-0 fish. The decrease in fish density in riffles was greater in winter when fry moved into interstitial spaces, below water temperatures of about 5°C (Chapman and Bjornn 1969; Bjornn 1971). Reductions in fry density were linearly related to the degree of cobble embeddedness. In summer, the greatest effect of excess sedimentation occurred in pools, where decreases in area and depth caused decreases in summer rearing capacity for juveniles.

Similarly, Bustard and Narver (1975) pointed out that salmonid fry overwinter in rubble (cobble) bottoms. In their experiments on British Columbia streams in timber-harvest areas, cutthroat trout showed a strong preference for "clean rubble," as opposed to "silted rubble"; sedimented substrates seriously reduced winter survival of juvenile cutthroat trout. The authors also noted that the problem may be especially important with riffles along stream margins that are dry in summer (and thus may be overlooked in summer surveys). However, the problem may be particularly important to fry in higher winter discharges when they are susceptible to sedimentation effects of timber harvesting in the later season.

Winter survival of fry in sedimented stream bottoms was further studied in Idaho by Hillman et al. (1987), who observed behavior and survival of age-0 chinook salmon in the Red River and its tributaries. They reported that juvenile fish moved away in the fall from heavily sedimented summer habitat in which riffles were 70% embedded and interstitial spaces were filled; experimental additions of cobbles the following year resulted in fivefold increases in winter density of fry. During the following seasons, the added cobbles were removed by scour, sedimented riffles returned, and fry densities fell again in winter to low levels.

Pool Cover as Rearing Habitat

The filling of pools and blanketing of structural cover are two of the most insidious effects of sedimentation. Many streams have been altered to such an extent, and for over so long a time—particularly in midwestern agricultural areas—that little evidence remains with which to make research comparisons. The silted condition may appear to be the pristine condition. Neither does the effect of excess sedimentation appear as simple as the mere covering of the stream substrate. The influence of sediment on channel morphology has been the subject of extensive work in hydrology (e.g., Lisle 1982). Generally, elevated sediment bed loads increase channel width and decrease channel roughness as pools become filled.

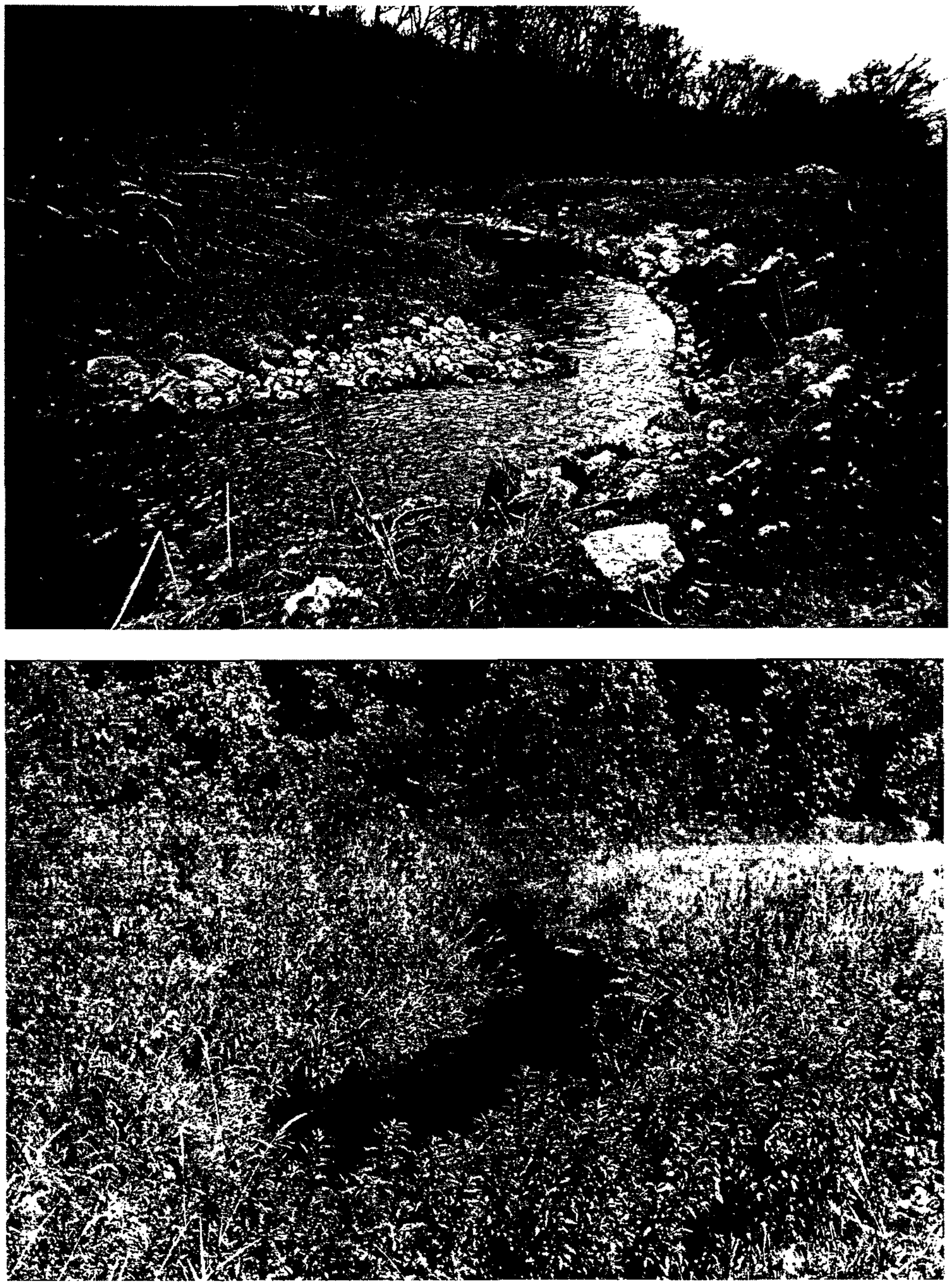
Many field studies have related the loss or reduction of fish populations to sedimentation. Saunders and Smith (1965) studied the effect of heavy siltation in a Prince Edward Island brook trout stream; they reported 70% declines in trout populations, in both age-0 and older fish, due to loss of cover by sediment deposits. Brown trout in a Montana stream decreased with increased sedimentation from agricultural sources (Peters 1967). Elwood and Waters (1969) observed drastic declines in a Minnesota brook trout population after catastrophic spring floods that left stream bottoms covered by shifting sand. Scouring apparently also destroyed the eggs or fry of the new year-class. The flood itself did not immediately reduce numbers of the older trout; subsequent decreases that ultimately decimated the trout population were attributed to the total loss of cover caused by the sand deposits.

Other field reports of population declines and species losses included Barton (1977), who observed a decline in total fish standing stock from 24 to 10 kg/ha owing to sedimentation downstream from a bridge construction on an Ontario brook trout stream. However, fish populations returned to former levels after the bridge was completed. In interior Alaska streams, LaPerriere et al. (1983) reported that streams receiving gold mining wastes had degraded spawning and rearing habitats for Arctic grayling. Interstitial gravel spaces were filled, and cement-like substrates were formed. Along with deleterious effects on algae and benthic invertebrates, mined streams were empty of fish, whereas unmined streams in the same area contained healthy populations of Arctic grayling. In British Columbia, Tripp and Poulin (1986) pointed out the deleterious effects of mass soil movements associated with timber-harvest practices resulting in filled stream pools that reduced juvenile fish habitat.

Few papers discuss management attempts to correct problems of habitat loss by deposited sediment. The gradual reduction of the extraordinary sedimentation in the South Fork Salmon River, Idaho, was accomplished mainly by the cessation of logging activity in combination with normal storms and high flows (Platts and Megahan 1975). With short-term operations such as bridge building, sediment deposits tend to be removed quickly and invertebrates and fish are restored, provided that a source of recolonization in nearby populations is present (e.g., Barton 1977).

The most extensive and long-term field experiment relating to sedimentation of fish habitat was that of Alexander and Hansen (1986) in Hunt Creek, a small Michigan trout stream. The experiment included (1) 5 years of pre-treatment study of the trout population (and benthos, previously discussed) in both an upstream 1-mi control section and a lower 1-mi treatment section; (2) 5 years of daily sand addition to the treatment section; and (3) 5 years of post-treatment study. A total of 4,223 yd^3 of sand was added over the 5-year period (stream discharge = 20 ft^3/s). The treatment increased the normal sediment bed load by fourfold, widened and shallowed the stream, and filled pools, whereby the channel became a shallow continuous run of shifting sand with no pools or riffles. Abundance of brook trout declined to less than one-half, the result attributed by the authors to lower survival during summer rearing periods (fry to fingerling) as well as to losses in the egg stage. Not until the fifth year of post-treatment study did fish populations return to normal levels.

Habitat alteration projects often include the installation of structures intended to maintain sediment-free cover, such as undercut banks and plunge pools (described in the Control chapter later in this volume). An example of such a successful program is one in Minnesota, where trout streams had undergone heavy damage from agricultural operations, including sedimentation. Trout populations responded favorably to a habitat improvement program that narrowed channels, deepened pools, and increased riffle areas (Thorn 1988). Increases in trout standing stocks were attributed mainly to increased overwinter survival in the altered reaches.



Restoration of a degraded trout stream. Top: A section of stream in an overgrazed pasture was treated with deflector–bank cover installations and riprap. Bottom: The same section 3 years later with narrowed channel, stabilized stream banks and sediment-free pools for fish habitat. A healthy riparian zone now is protected by fencing to exclude grazing livestock. Middle Fork Whitewater River, Minnesota.

Warmwater Fish Habitat

Sediment problems with warmwater fish habitat appear to be equally severe. King and Ball (1964) speculated that sediment from major highway construction in southern Michigan filled pools or decreased their depths such that smallmouth bass might have been eliminated from some reaches of the Red Cedar River, a once-renowned smallmouth bass stream. Branson and Batch (1972) reported the elimination of some species of fish in a Kentucky stream affected by strip-mining activities and attributed the loss to clay deposits that covered the bottom in places to depths of 2–6 in. A gravel-dredging operation in the Brazos River, Texas, discussed previously in relation to changes in the benthos, was responsible for changes in fish habitat and abundance, notably a decrease in sport fishes (spotted bass, largemouth bass, and bluegill) and increases in other species (Forshage and Carter 1974). Paragamian (1981) concluded from his studies of smallmouth bass in the Maquoketa River, Iowa, that stream-bottom areas of cobble and gravel constituted excellent habitat, with high fish density and standing stock. Smallmouth bass populations were lower in other areas with silt and sand substrates—which constituted poor habitat—although the specific factors responsible were not discussed. Matthews (1984) published a strong indictment of agricultural practices that produced excessive sediment in Wisconsin and destroyed many formerly productive smallmouth bass fisheries in that state's southwestern streams. The comprehensive report by Lyons and Courtney (1990) includes an insightful review of warmwater stream problems in the midwestern United States, with many related references and a compendium of improvement projects in midwestern streams, all of which should stimulate further research on this neglected aspect of deposited sediment.

Major Reviews

Several reviews and major discussions of deposited sediment and fish habitat have been published. Included is the review by Reiser and Bjornn (1979), who addressed many aspects of salmonid habitat. They included a brief discussion of sedimentation in their review of forest and rangeland management effects in western North America. Hall (1984a) reviewed some of the papers published since Cordone and Kelley (1961). Sullivan et al. (1987) included a discussion of the physical aspects of sediment input and transport and resulting effects on the formation of pools, riffles, bars, and other components of stream morphology that form fish habitat.

Everest et al. (1987), in their comprehensive treatment of sediment and salmonid production, pointed out the lack of work on sediment and fish habitat relations (in contrast to the numerous studies of effects on reproductive success). They suggested more research on the relationship between sediment and fishing success, an integrative approach. Finally, Heede and Rinne (1990), in an insightful discussion of hydrodynamic and morphological processes in relation to fisheries management, urged the incorporation of sediment factors into the planning of fish habitat management programs.

Conclusions

The two most important effects of deposited sediment upon the physical habitat of fish are (1) filling of interstitial spaces of riffles, which reduces or eliminates those spaces essential to fry, especially in winter when fry retreat to coarse riffle bottoms for overwinter cover; and (2) reductions of water depth in pools, including the complete loss of pools and cover with heaviest sedimentation, which decrease physical carrying capacity for juvenile and adult fish during summer growth periods.

Most research on both of these effects has emphasized salmonid fishes. Few studies have been reported on warmwater fish species in agricultural areas despite early observations of species losses in streams severely affected by heavy sediment deposits. Fortunately, concern is on the increase for warmwater streams degraded by sedimentation. Lyons and Courtney (1990) suggested that the extension of basic stream ecology, as well as our long-accumulated experience with trout streams, be applied to warmwater problems, an approach that could well result in major advances in warmwater systems management.

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SUMMARY

Inorganic fine sediments are naturally present to some extent in all streams. However, in the last half century, excessive sediment of anthropogenic origin has caused enormous damage to streams throughout North America. Most cases that are well-documented by research have been in salmonid streams, particularly in the western United States and Canada. However, most extensive damage to streams has been in the agricultural Midwest and Southeast, where warmwater streams have been severely degraded by excessive sediment. Ironically, it is in these agricultural regions where specific biological effects from sediment has been the least documented.

Quantitatively, sediment has been labeled the most important single pollutant in U.S. streams and rivers. In the latest U.S. Environmental Protection Agency summary of the nation's water quality, siltation tops the list of the foremost 10 pollutants in rivers, half-again higher than the second most important pollutant, nutrients.

Anthropogenic sediment rarely acts alone in its effects on the biological communities in streams. Other factors, such as temperature changes (usually upward), bank slumping and loss of fish habitat, nutrients that cause excessive plant growth, contaminants and chemical pollutants, frequently accompany sedimentation and are often attributable to the same sources or are associated with the same human activities.

SOURCES OF SEDIMENT

Anthropogenic sources of sediment include agriculture (row-crop cultivation, livestock grazing); forestry (timber harvest, logging roads, landslides); mining (spoil piles, tailings dumps, sand and gravel extraction); and urban development (residential, industrial). Road construction for all purposes produces some of the greatest quantities of sediment. Streambank erosion is a natural process in all streams but where it is exacerbated by human activities, destabilized streambanks may deliver great quantities of sediment directly into stream channels.

Agriculture: Row-crop Cultivation

Sedimentation from row-crop cultivation has been overwhelmingly indicted as the major environmental problem in warmwater streams of the Midwest and

Southeast. Reports of the U.S. Environmental Protection Agency list siltation from agriculture as the most important of all river pollutants—more than three times higher than from forestry, mining, or urban development.

Historical reports indicate severe degradation of water quality in many, if not almost all, warmwater streams of the Midwest, with many documented alterations in fish distribution and losses of species. Because such pollution by sediment commenced early along with human settlement in this region, most streams today have few data on pre-cultivation conditions. Surface erosion from poor cultivation practices (up- and downslope plowing, fall plowing, long exposure of disturbed soil), combined with the absence of streambank protection or buffers, has resulted in sediment production in enormous proportions. Particularly indicted is row-crop cultivation on floodplains, where streambanks are severely eroded by floods to deliver sediment directly to stream channels.

Only gross correlations exist between observations of heavily sedimented conditions and apparent loss of fisheries. Specific modes of sediment action on reproductive guilds, feeding guilds, and functional groups related to specific erosional sources have been studied little. Research in these areas is badly needed in order to formulate control and remedial measures.

Agriculture: Livestock Grazing

Sediment sources involving livestock grazing occur mainly in arid, western regions where livestock are attracted to forage and water in the riparian zone. Destabilization of streambanks often results, with large quantities of fine sediments entering the stream. Loss of wildlife habitat in riparian zones, loss of streambank cover for fish, widening and shallowing of the channel, and elevation of water temperatures—all combine to severely degrade both fish and wildlife environments. Salmonid fisheries, largely in the western United States, are affected the most by this source, causing loss of reproductive success in anadromous salmon and steelhead trout fisheries and threatening extirpation of native stocks. Livestock grazing also affects inland trout fisheries in midwestern regions, causing streambank erosion, channel widening, and loss of fish habitat. A large literature exists, both descriptive and experimental, on the effects of overgrazing on sediment production and on stream fisheries. Increasing concern about sedimentation and other damage due to overgrazing has prompted extensive demands for grazing reforms on western rangelands, especially on the vast public lands used for private livestock production.

Forestry

More is known about the potential of sediment from forest management practices than from other sources. Sediment sources are strongly related to the steep hillslopes in western North America and the southern Appalachian Mountains. In such extreme topography (up to 70% gradient) almost any surface disturbance generates potentially damaging sediment. The fisheries affected by excessive sediment in these areas are almost wholly salmonid, including anadromous Pacific salmons and steelhead trout in western regions and inland trout fisheries in the Appalachian region. Potential problems in warmwater fisheries have not been identified or researched relative to potential sediment from forestry practices.

Cutting methods, log skidding and yarding, machinery operation, and site preparation are all important sources of sediment but the overwhelmingly significant source is the logging road. Construction, use, maintenance—even techniques of abandonment—of the logging road have all been strongly indicted.

Two aspects of the logging road problem have been clearly identified: (1) erosion from the roadbed, resulting from overly steep gradients, close proximity to streams, lack of proper drainage, and improper stream crossings; and (2) landslides or mass soil movements that are secondary results of logging road design and placement. Where mass soil movements occur, often unpredictably, the consequent erosion of large areas of the disturbed and exposed soil often contributes the greatest sediment to receiving streams. Sediment, however, is usually not the sole problem generated by landslides; others include debris torrents, destruction of riparian zones and their natural buffering capacity, and clogging of streams with large woody debris, all of which affect stream fisheries.

Several major research programs have been established for experimental study on logging practices: the Alsea Watershed Study in western Oregon; the H. J. Andrews Watershed Study in Oregon; many streams in the granitic batholith in central Idaho, particularly the South Fork Salmon River, an area of highly erodible rock and soils; the Carnation Creek Watershed Project on Vancouver Island, British Columbia; streams of the Olympic Peninsula, Washington; and Coweeta Hydrologic Laboratory, in the southern Appalachian Mountains, North Carolina. All of these intensive, long-term research programs have contributed greatly to identification of sediment sources and the development of control measures.

Mining

Mining operations of several kinds contribute immense quantities of sediment, mainly through erosion of spoil piles, drainage of tailings dumps and ponds, and in sand and gravel extractions. Historically, placer mining—the separation of mineral particles from river-sorted gravels, including streambed deposits—contributed huge quantities of sediment to streams. Although placer mining operations have been curtailed, important gold-mining activity continues in Alaska and northwestern Canada, where inputs of suspended sediment in washwater from ore-treatment operations continue.

Surface mining, both contour strip mining and open-pit, produces large waste piles of overburden. Spoil piles greatly modify whole landscapes and if not regraded and revegetated, can generate enormous quantities of sediment through erosion of exposed spoil surfaces.

Underground mining involves drilling and digging to remove mineral-containing ore and processing to extract the desired mineral, which may be done near the mine site or at processing mills farther away. Processing requires copious amounts of water and results in waste materials or tailings that make up 90% or more of the mined ore. Consequently, tailings are often deposited in ponds, the waters of which may drain away carrying sediment. Unlike most surface-mined spoil piles, processed tailings contain ore particles or solutions that may be toxic to stream organisms.

Sand and gravel mining operations are intimately involved with natural streams, because sand and gravel occur most commonly in alluvial deposits, often in streambeds. Most extractions are in floodplains rather than in the streambed itself, but floodplain operations are closely involved with nearby streams, because gravel and sand washing operations require large quantities of water. Waste water with high concentrations of finer sediment may be returned to the stream. Because sand and gravel extractive mining is the least controlled and regulated—and recorded—of all mining operations, the total extent of these operations is unknown and may be much larger than any other type of mining.

Urban Development

Land-disturbing operations involved in urban construction are varied, including much grading and reshaping of landforms that may expose disturbed soil for extended periods. Specific operations include excavations, soil transport with heavy machinery, drainage during and after construction, channelizing or bridging streams and waterways, temporary storage of soil piles, and road construction. Most published information on municipal sediment sources concerns the large metropolitan complexes around Baltimore, Maryland, and Washington, DC, but some published studies have been conducted in Virginia, North Carolina, and Wisconsin, among others. Sediment contributions from urban areas may be less, on a continental basis, than other major sources. In the smaller, localized areas of municipal construction, however, sediment capable of severe effects on local streams can be generated in extremely high concentrations. Sediment must be treated along with organic pollution, contaminants from industry, and runoff from roads and streets in a comprehensive manner. However, because urban development operations are usually within well-defined boundaries and under potentially strict control from public agencies, sediment control measures may be more effective than in other sources.

Streambank Erosion

Erosion of streambanks is a natural process that results from the tendency of streams to meander. The process may be exacerbated by many human activities that accelerate erosion and generate excessive sediment; the quantities may be large and locally of equal importance to other anthropogenic sources. Two processes are chiefly responsible: (1) entrainment of bank material by high flows, and (2) bank failures that cause slumping of material directly into a stream to be entrained by normal currents. Streambank erosion appears to be a greater problem in warmwater streams of the Midwest, because, historically, settlement and agriculture were attracted to the fertile floodplains of this region. Channelization of streams for any purpose increases streambank erosion potential because the natural tendency of streams is to change straightened channels back to sinuous patterns. Furthermore, straightened channels are shorter with increased gradient and current velocity, which in turn cause further incision and erosion of the streambed.

Miscellaneous Sources

Many other activities can cause erosion of disturbed lands. Road building in any application can have severe erosional effects with consequent sediment generation. Miscellaneous activities that produce sediment include flushing of silted reservoirs, electric transmission and pipeline crossings of streams, bridging and tunneling, habitat alterations in stream fisheries, and any other land- or streambed-disturbing activity. Exposure of disturbed surfaces for long periods extends the duration of erosion potential. Extraordinary storms are a constant threat, exacerbated by past drainage practices, levee construction, and loss of permeable land surface in urban areas. Remedial streamside measures generally have little positive effect on storm-generated sediment production. Not until regional, comprehensive, water-conservation measures are made effective will the disastrous effects of unusual storms be reduced.

BIOLOGICAL EFFECTS OF EXCESS SEDIMENT

Suspended Sediment: Primary Producers

The principal effect of suspended sediment upon primary producers is through turbidity, which reduces light penetration through the water, thus reducing photosynthesis. The ecological effects of sustained, reduced photosynthesis upon higher trophic levels (i.e., invertebrates and fish) is generally unknown. Virtually no experimental research has addressed the effects of sediment-reduced primary production on herbivorous invertebrates.

In some forestry applications, particularly in small headwater streams, light reduction by suspended sediment may be compensated by concurrent canopy removal, which increases sunlight reaching the water surface. The effect of changes in photosynthesis on higher trophic levels presents a difficult problem, because sustained turbidity may have negative effects on invertebrates and fish productivity that may overwhelm effects of photosynthesis variations.

Suspended Sediment: Invertebrates

Much more is known about the effects of suspended sediment on macroinvertebrates. The most common direct effect observed in experiments with fine sediments has been a pronounced increase in downstream drifting. Such increased drift has been attributed primarily to a decrease in light with consequent drift responses similar to behavioral drift in a diel periodicity. Extraordinary drift under prolonged high levels of suspended sediment may deplete benthic invertebrate populations.

Deposited Sediment: Invertebrates

Severe damage to benthic invertebrate populations can be caused by heavy sediment deposits. The factor of "embeddedness"—the fraction of substrate surfaces fixed into surrounding sediment—is a major, measurable parameter that affects the living space of those invertebrates inhabiting the interstitial spaces within the streambed. The affected organisms consist mainly of the insect orders Ephemeroptera, Plecoptera, and Trichoptera, (EPT), which generally are the forms most readily available to foraging fish. Virtually no research has been conducted on the effect of sediment on the meiofauna of streambeds, despite increasing appreciation of the ecological importance of these small organisms to fisheries.

The term "habitat reduction" refers to an increasing level of embeddedness by sediment, resulting in a decrease of invertebrate populations and, consequently, in food available to fish. Complete inundation of gravel and cobble substrate by fine sediment is termed "habitat change," that is, from cobble riffles to homogeneous fine sediment deposits. The consequence of such a habitat change is the alteration of invertebrate forms from EPT to burrowers such as chironomids and oligochaetes, which may be numerous but unavailable to foraging fish. In either case, the fish food resource can be drastically reduced.

Many reports indicate a positive relationship between benthic invertebrate productivity and fish productivity, but direct observational or experimental research on this relationship, as affected by sedimentation, has not been done. Long-term research on the effects of anthropogenic sediment on invertebrate production—and its relationship to fish production—is badly needed, especially in warmwater streams.

Sediment and Fish

Most published information on the effects of sediment in streams relates to fish. Four major categories of this relationship are (1) the direct effects of suspended sediment and turbidity, (2) sediment trapped in salmonid redds and its influence on reproductive success, (3) effects on warmwater fish reproduction, and (4) effects of deposited sediment on fish habitat.

Suspended sediment and fish.—Early studies on the direct effect of suspended sediment on fish generally agreed that fish could withstand concentrations up to 100,000 mg/L at least temporarily but that such high levels were unlikely to be encountered in nature. These early conclusions probably were responsible for delaying the needed intensive investigation into the direct effect of suspended sediment on fish "in nature."

Under conditions where fish have more response options than those available in a laboratory environment, some species exhibit lethal or serious sublethal effects from suspended sediment concentrations far less than 100,000 mg/L. Perhaps more important, fish in nature avoid streams or stream reaches with high suspended sediment levels, creating environments just as devoid of fish as if they had been killed. Intensive, long-term research on this subject is called for, especially in warmwater streams of the Midwest, where so many have been severely degraded, and where almost no experimental research results have been acquired.

Reproductive success of salmonids.—The severe effect of sediment upon developing embryos and sac fry in redds has been intensively investigated. A major problem in many circumstances is that the source of oxygen reaching the redd is in the downwelling water of the stream itself. Suspended sediment carried by stream water enters the redd where velocities are slowed in the interstitial spaces and sediment particles settle. Consequent effects include the coating of eggs and embryos and the filling of interstitial spaces in the redd gravel so completely that the flow of water containing oxygen through the redd is impeded or stopped. The salmonid redd thus functions as an effective "sediment trap," and the entry of oxygen required for embryo survival and development is prevented.

The dependence upon downwelling stream water as the oxygen source appears most common in high-elevation or high-latitude regions, where the stream water source is often cool surface runoff. However, in midwestern regions—with low gradients and warmer runoff—salmonid streams are commonly fed by cool groundwater. Here the oxygen source for the redd is upwelling groundwater that contains no sediment. Consequently, embryo development may continue unimpeded even when stream waters contain high levels of suspended sediment, or when redds contain moderately high quantities of sand that is kept in motion by the upwelling.

A second major problem occurs when sedimentation on the streambed or in upper strata of the redd produces a consolidated armor layer through which emerging sac fry cannot penetrate. Even though embryo development and hatching may be successful within the redd, such entombment of fry attempting to emerge from the redd can result in reproductive failure.

Reproductive success of warmwater fishes.—In contrast to salmonid reproduction, warmwater fish reproduction under various conditions of suspended and deposited sediment is little known. Reproductive behavior of warmwater fish species is more complex and less understood than for salmonid species. Historically, observations of gross correlations between fish species distribution and heavy sedimentation in streams strongly suggested cause and effect but only circumstantial evidence is available. The severe degradation of water quality in streams of the agricultural midwestern and southeastern regions is under increasing scrutiny. Badly needed is experimental and explicit research on the effects of both suspended and deposited sediment, at various levels of intensity, on the specific modes of warmwater fish reproduction.

Deposited sediment and fish habitat.—The effect of deposited sediment, most often sand, on fish-rearing habitat has been studied within two major subject areas: mortality to fry by elimination of interstitial space in riffles of gravel and cobbles, and loss of juvenile-rearing and adult habitat by filling of pools. Salmonid fry, particularly, often require the protection of streambed "roughness" conditions for winter survival. Severe reductions in year-class strength occur when a cohort of salmonid fry faces stream riffles heavily embedded by sediment deposits. Presumably, fry of warmwater species require similar habitat for survival of early life stages, but little research has been accomplished on sediment relationships for these fishes.

Although not as extensively documented, the effect of deposited sediment on juvenile rearing habitat in pools has been similarly convincing. When heavy deposits eliminate pool habitat, reduced growth and loss of populations result.

CONTROL OF SEDIMENT

The control of excess sediment is viewed in three phases: (1) prevention, avoiding erosion or retaining eroded sediment on site; (2) interdiction, capture and retention of sediment between the site of origin and a stream; and (3) restoration, removal of excess sediment from a stream or stream reach.

Prevention

The greatest development of methods to prevent erosion has been in row-crop agriculture. Modern procedures (and some older) include contour plowing, strip cropping, terracing, crop rotation, and recently developed techniques of conservation tillage. Research and development applied to reducing soil losses from row-crop fields have yielded excellent control results when the techniques have been rigidly applied. Field implementation on a broad scale, however, has not been forthcoming. The same techniques developed to reduce soil losses also can be used to reduce sediment pollution in receiving water bodies.

Prevention of sediment generation by livestock overgrazing depends almost solely on fencing to keep livestock from the riparian zone and away from streambanks. The overgrazing problem is most apparent in the arid West but fencing all salmonid streams in arid rangelands appears impracticable. More innovative and effective control techniques have been urged. Similar fencing has been used along inland trout streams in midwestern areas to allow water use by livestock at controlled access points; positive results—more stable streambanks and lower temperatures under streamside canopy—have been achieved.

Many effective techniques in preventing erosion in timber-harvest operations have been developed, particularly for logging roads. Erosion from the roadbed itself can be reduced greatly by surfacing roads with gravel or pavement and by providing cross-drainage to the forest floor with water bars, culverts, and, particularly, the broad-based dip. Seeding roadbeds on sides, on cut and fill slopes, and when abandoned also is effective.

Other factors include road placement, length, and gradient; design of cut and fill slopes; design of stream crossings with culverts and bridges; and harvest methods that require few or no roads, such as overhead skyline yarding and helicopter log transport. The design of roads, especially road cuts, can sometimes be modified to reduce the likelihood of mass soil movements.

The principal way to prevent sediment generation from mining operations is to eliminate erosion of mining wastes—both spoil piles from surface mining and tailings dumps and ponds. The major methods are reshaping spoil piles to an approximation of the original landscape, dewatering of tailings ponds with drainage control, and revegetation. The techniques developed to restore mining-disturbed lands to former terrestrial productivity and aesthetic quality can just as well serve to reduce or eliminate excessive sedimentation of streams with valuable fisheries.

Restoring the physical landscape requires blading and shaping with heavy machinery, reducing gradients, allowing for drainage away from slopes, and replacing topsoil. Revegetation materials include grass seed, transplants, and root stock; grasses, forage, bushes, and trees; and preferably the use of native species.

Irrigation and fertilization may be required. Reclamation of tailings, which often contain toxic mineral particles and solutions, requires special treatment to provide nontoxic soil and suitable conditions for plant growth.

Sand and gravel mining is a very widespread activity that may produce more sediment than any other mining operation. Because sand and gravel are often found in alluvial deposits, the association with streams and rivers is common. Erosion-control measures have not been well developed but some general principles have been suggested: (1) avoid excavations in streambeds entirely; (2) do not connect excavations in floodplains directly to streams; (3) filter water used in washing operations before returning it to streams or underground; and (4) avoid the creation of new stream channels and connecting ponds.

The prevention of sediment generation in urban development depends chiefly on containment of soil and disturbed surface materials on the site. Diverting runoff and sediment from entering a site during construction may forestall having to treat additional sediment; such diversions should direct incoming runoff around the site. Sediment-containment practices aimed at the control of surface runoff include: use of hay, straw, or fiber filters; creation of berms or terraces on contours; installation of retention walls and dams; and construction of small sediment traps or larger settling basins. Measures aimed at reducing the duration of disturbed soil exposure include early revegetation, temporary or permanent sodding, and use of mulches. To promote greater infiltration of runoff water, temporary diversions to level spreaders are also employed. Temporary, unpaved roads can be treated with erosion-control measures similar to those applied on logging roads.

Control of streambank erosion primarily involves grading to reduce bank slope and some kind of bank stabilization structure. Riprap of rock, logs, concrete slabs, and other material may be used on the lower bank to reduce or prevent high stream flows from entraining soil. Sloping is often necessary on both lower and upper banks. Sloping back the upper bank (above high water flows) is intended to prevent bank slumping. The degree of slope should be consistent with the cohesive property of the bank material. Finally, revegetation with grass, bushes, and trees can stabilize surfaces against further erosion from runoff.

Interdiction

Intercepting and retaining sediment between the site of its origin and a receiving stream is second-best to preventing erosion. However, because the total prevention of erosion and soil losses is not yet a reality, interdiction remains an important tool in reducing potential damage in streams. Two general means of interdiction have been developed: (1) buffer strips of vegetation placed or left along streamside to collect and retain sediment as a permanent addition to the riparian zone, and (2) sediment traps placed either on land as temporary structures during construction operations or in the streambed itself as permanent installations which require periodic sediment removal.

Use of buffer strips is one of the oldest means of preventing sediment from reaching streams. Beginning with its application in timber-harvest operations, the buffer strip in its simplest form is a corridor of vegetation left uncut along a stream (i.e., leaving the original riparian zone intact). Buffer strips developed by seeding and planting can also be used effectively in other applications, such as reducing runoff from agricultural areas or urban developments. Fencing the riparian zone in livestock grazing areas is a major application of buffer-strip interdiction.

Much research attention has focused on determining the minimum effective width for a buffer strip. Hillslope and land use are the two most important factors, although watershed area, annual precipitation, and the degree of protection already in place are also important. Buffer strips create stable streamflow, stabilize streambanks, reduce suspended sediment and turbidity, lower summer water temperatures, and filter chemical and organic pollution.

A healthy riparian zone also offers benefit to terrestrial wildlife. Regardless of the research effort and development of different types and sizes of buffer strips, the best application of buffer strip technique is the total avoidance of any surface-disturbing activity in riparian zones and floodplains—cultivation, timber harvest, mining, residential development.

The sediment trap operates on the principal that particles moving in stream currents settle when current velocity is reduced. Sediment traps may be installed in many forms: temporary small structures such as brush barriers used on-land in forestry and urban construction operations; instream excavations and reservoirs to collect bedload sediment that require periodic dredging; and permanent dams and reservoirs that collect sediment and create clearer water downstream. Farm ponds—although usually constructed for livestock watering or fish production—function to trap sediment flowing overland.

Instream sediment traps retain sediment such as active bed load. High dams with large sedimentation capacity, especially when designed with a hypolimnetic water-release feature, create productive and popular tailwater trout fisheries. Although these structures may have a design life of many years, the eventual silting in and loss of reservoir capacity is certain.

On a smaller scale, the instream excavation is most effective in low-gradient streams and is sometimes installed in combination with a dam. The installation is usually designed to trap excess sand in salmonid streams in order to protect spawning beds and invertebrate-producing riffles. The reservoir requires periodic, perhaps frequent, dredging to remove sediment accumulated from both normal and storm flows. The small, instream sediment trap represents very intense management, but it can be extremely effective in small, highly-valued stream fisheries.

Restoration

The term "restoration" in this volume is taken to mean the removal of excess sediment from a stream after the sediment has passed through both the phases of erosion prevention and offsite interdiction. In a program with the goal of complete ecosystem restoration, the removal of excess sediment is only a part—although an essential part—of the overall restorative process.

The success of a removal program depends first on elimination of the sediment source. Most removal measures flush sediment downstream which, more correctly, transfer the sediment, rather than remove it. The effects downstream are often not known and usually not evaluated.

Three general approaches have been developed for sediment removal: "flushing flows" below large dams; small instream structures to scour and maintain sediment-free sites; and gravel-cleaning machines.

Flushing flows, employed in the operation of large dams and reservoirs, are most commonly used to scour sediment from downstream reaches. In practice, the calculation of appropriate discharge magnitude, timing, and duration has been extremely difficult; a common approach is to attempt to simulate natural fluctuations in discharge. Other problems have been encountered, such as too much scour on existing spawning or food-producing gravel and riffles, increased streambank erosion due to the greater capacity of clearer water to entrain sediment, and the unevaluated transfer of sediment to downstream reaches. Continuing research is needed to properly evaluate and further develop the flushing flow technique. Caution is advised in the use of flushing flows because of the changes in stream morphology that may take place downstream and the resulting potential increase in sediment generation from scour, destabilized streambanks, and accelerated incision of the streambed.

Small instream devices are frequently used in the fishery management application of habitat alteration, usually in trout streams. These devices, often some form of deflectors or other channel-narrowing devices, divert or focus flows to maintain sediment-free spawning gravels, invertebrate-producing riffles, and pools and overhanging streambanks that provide holding cover for fish. The design of many such structures and their use have been profusely published in the past 50 years but relatively little evaluation has been done. Much early work involved placement of logs, stumps, brush, and cribbing without concern for specific habitat needs or hydraulic factors. The more recent and better approach is the judicious application of hydraulic and biological principles to existing stream conditions. As with flushing flows, but on a smaller scale, stream alteration devices intended to scour sediment only transfer sediment downstream. Such programs have rarely included the evaluation of possible downstream effects.

Several machines have been designed to sift and remove fine sediments from streambed gravels—mainly to clean salmonid spawning beds. Several designs—usually adapting available tractors or similar machines that power air or water jets through gravel—disturb interstitial deposits of fine sediment, collect the fines in filtering devices, and pump the silt-laden slurry to streamside for disposal. This process actually removes sediment as long as the streamside deposits are placed so as to preclude subsequent return to the stream. This technique represents extremely intensive management and appears to be impracticable in natural rivers that include boulders and varying water depths. However, where the application is on a small but productive spawning reach and the source of sediment has been first eliminated, it can be highly effective.

The installation of small sediment traps, especially in a series and where periodic dredging can be done, can effect removal as well as interdiction. The use of hose, pump, and water jets—although not described in the literature—in combination with a series of frequently dredged sediment traps is suggested as a means of removal of sediment from a small stream—after the original sediment source has been eliminated.

POSTSCRIPT

Enough research now has been completed by biologists of many kinds to know the disastrous results of excess sediment to the major stream biota. Sufficient surveys and summaries have been made by pollution-control agencies to comprehend the enormous quantities of sediment polluting North American streams.

It is also known where the major sediment sources are: agriculture, forestry, mining, urban development.

Recently—and relatively quietly—agricultural engineers, foresters, soil scientists, and many others have developed on-site technologies that markedly reduce soil erosion from sites of human activity, in many cases reducing soil losses almost to zero. The same techniques that retain soils on the land also can prevent the degradation of our streams' biological communities—for public recreational use, aesthetics, and protection of water quality for many purposes.

It is now time to vigorously pursue programs of restoration and planning for future conservation of our streams and rivers, their riparian zones, and the upland landscapes that sustain and nourish them with water, the quality of which we deem worth preserving.

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