CAL. FISH + GAME, 1961, 47(2) 189-228

THE INFLUENCES OF INORGANIC SEDIMENT ON THE AQUATIC LIFE OF STREAMS[1]

ALMO J. CORDONE and DON W. KELLEY
Inland Fisheries Branch
California Department of Fish and Game

TABLE OF CONTENTS

INTRODUCTION

California's tremendous population increase since World War II has created serious problems for those charged with the conservation of its natural resources. Fisheries resources dependent upon the maintenance of natural conditions are threatened with significant damage—if not complete destruction—by the construction of dams, by pollution, and by erosion. These problems are neither new nor unique. Valuable stream fisheries have been lost before to these three horsemen of civilization.

Erosion is probably the most insidious of the three, for it is often unspectacular and goes unnoticed from one year to the next. The damage is often widespread and permanent. Aitken (1936) recorded changes in fish fauna of Iowa streams. Streams supporting trout, smallmouth bass, and other clean-water forms were transformed to streams containing rough fish or mud-loving forms. This change was attributed to erosion which transformed cold, clear streams to warm, turbid streams. Ellis (1931a) states that the outstanding factor producing changes in the Mississippi River fauna seems to be that of erosion silt.

In summarizing man-made influences on the fish fauna of Ohio for the period 1750 to 1950, Trautman (1957, p. 29) states:

---

[1] Submitted July, 1960.

> "These drastic modifications have considerably modified the fish fauna, changing it from a species complex, dominated by fishes requiring clear and/or vegetated waters to one dominated by those species tolerant of much turbidity of water and of bottoms composed of clayey silts. There has been a shift from large fishes of great food value to smaller species unfit as human food, or larger fishes of inferior quality as human food."

Concerning the role of silt pollution in the disappearance of Atlantic salmon from many of its native haunts, Wolf (1950) declares:

> "And now we have come to the problem of the silting down of the spawning grounds and its effect on the salmon production. This silting down is certainly an important factor. Wherever such a thing happens, it is hardly necessary to look for any other reasons for the total disappearance of the salmon. A very great part of the region around the former salmon rivers flowing to Lake Ontario was cultivated during the course of the last century. Already in the beginning of this article, it has been mentioned how the natural cover of vegetation continually diminished as cultivation went on and how the lands slowly lost their protection against the forces of erosion. As a consequence, the soil was washed down into the rivers, where it became silt. . . ."
>
> "As a summary, we could say that, although many factors contributed to diminish the power of resistance of the salmon stock, the real reason for its extinction has been the silting down caused by the uncontrolled cultivation. Again it must be emphasized that this cultivation had very little value for the future. During a relatively short period, it gave a good yield but later had to be given up. The result to-day seems to be only negative. The value of the region for forestry has declined, and an abundance of salmon has been lost. This bitter experience has perhaps had one good effect: it is possible that it may teach us to control cultivation and prevent a repetition of this wasteful process."

Californians and especially those charged with land or resource management must realize that their state is not immune.

SCOPE

This report is essentially a review of investigations made of the effects of inorganic sediment on the aquatic life of streams.

It is not a complete literature review but rather a summary of most of the pertinent investigations that we believe will assist the fisheries worker faced with sediment problems. No references are included on studies of any type of chemical pollutants even though the waste material contained large amounts of sediment, such as when tailings from heavy-metal mining operations are discharged to waterways. In such cases, the physical influence of inorganic sediment on aquatic life cannot readily be separated from damage done by toxic heavy metals in solution. This is true also for chemicals used in floatation processes during mineral extraction.

Of fundamental importance in comprehending the modes by which sediment modifies the aquatic habitat is knowledge of the physical nature of sediment and its movements in flowing waters. Sediment arises from a multitude of soil types, varies greatly in shape, size and density, and enters flowing waters which vary in velocity, temperature, flow, and turbulence. The complex problems involved here are studied by the geologist, the soil scientist, and the hydraulic engineer. Fisheries biologists working on sedimentation problems should be aware of this work and familiar with the basic concepts of erosion and sedimentation, but a review of the literature on this subject was beyond the scope of this report. We mention it here only to mark its extreme importance.

For comprehensive reviews of the problems created by sediment in our waterways which confront land and water uses other than aquatic life, see Einstein and Johnson (1956) and Gleason (1958). See Cordone (1956) for a review of the literature on the effects of logging on fish production.

Detailed physical descriptions of how rainfall and runoff erode soil were presented by Osborn (1955) and Gottschalk and Jones (1955). These reports are helpful in understanding the factors governing sediment movement into or within a streambed.

DIRECT EFFECT OF SEDIMENT UPON FISHES

Fisheries workers seeking an answer to the question, "Are fish directly harmed by inorganic sediment?", have achieved a variety of replies. This is not surprising, considering the variations in sediment types and sizes, in environmental conditions, and in the fishes themselves. Unfortunately, all of the factors that influence the reactions of the fish can seldom be measured in the field, and carefully controlled experiments subjecting fish to sediment are rare.

The work of Wallen (1951) is an exception. He conducted controlled aquarium investigations on the direct effect of turbidity on warmwater fishes. Turbidity was induced by use of silt and montmorillonite clay. Particle size ranged from coarse silt to very fine clay. No salmonids were included in the tests. The results of this study are of sufficient import to bear repeating:

"1. Tests were made to determine the direct effect of montmorillonite clay turbidity on 380 fishes involving 16 species.

"2. Observable behavioral reactions that appeared as a turbidity effect did not develop until concentrations of turbidity neared 20,000 ppm., and in one species reactions did not appear until turbidities reached 100,000 ppm.

"3. Behavioral reactions were governed by concentrations of turbidity and followed a definite pattern from inception to death. The reactions included (1) momentary swimming at the surface and gulping air and water, (2) leaning toward one side or the other while remaining at the surface for several minutes, (3) floating on one side for up to 30 minutes with an occasional swimming movement and (4) floating with only occasional, feeble, opercular and pectoral fin movements until terminated by death of the fishes.

"4. Most individuals of all species used endured exposures to more than 100,000 ppm. of turbidity for a week or longer, but these same fishes finally died at turbidities of 175,000 to 225,000 ppm.

"5. Lethal turbidities caused the death of fishes within 15 minutes to two hours after the onset of exposure.

"6. Fishes that succumbed to turbidity had opercular cavities and gill filaments clogged with silty clay particles from the water.

"7. Important conditions enabling fishes to avoid clogging of gills in sublethally turbid waters were (1) maintenance of movements and (2) aeration of the water.

"8. The results of this work indicate that the direct effect of montmorillonite clay turbidity is not a lethal condition in the life of juvenile to adult fishes at turbidities found in nature."

Wallen found no evidence of gill injury even though the gills were blanketed with a layer of silt and the opercular cavities matted with the material. All organs appeared normal. Arteries and veins were not congested, and no unusual amount of mucus was secreted by the gills.

Ellis (1937) also examined fishes whose gills were coated with sediment. His description (page 401) of the coating responsible for death agrees with that observed by Wallen, ". . . the precipitate coated the gill filaments and filled the filament interspaces so that the water pumped through the mouth and onto the gills for the aeration of the blood could not reach the cells of the gill filaments. Consequently, the aeration of the blood with its accompanying gas exchanges was prevented, and sooner or later death followed from a combination of anoxemia and carbon-dioxide retention." It appears that coating of gills by silt impairs the functions of circulation, respiration, excretion, and probably salt balance. In our review of the literature, we turned up no reports of equally comprehensive tests on salmonids.

Griffin (1938) conducted laboratory tests with young cutthroat trout and king salmon in connection with H. B. Ward's famous investigation (1938a and 1938b) on the effects of placer mining on the Rogue River in Oregon. The tests were made on young cutthroat trout and king salmon held in water recirculated through troughs. Silt from a placer operation was introduced into the troughs. The cutthroat trout test lasted 30 days with a 56 percent survival in the sediment trough, compared to a 10 percent survival in the control. Turbidity reached 3,500 ppm. at daily stirring, but was maintained between 360 and 600 ppm. during the remainder of the day. The experiment with king salmon ended in 28 days with a survival of 88 percent of fish in muddy water, compared to 36 percent for the controls. The maximum load at stirring ranged from 3,100 to 6,500 ppm., and the constant load from 300 to 480 ppm. For a number of reasons, adequate control conditions were not maintained during the experiments. More extensive tests were called for but, as the author indicates, this was impossible due to the limited time and apparatus available.

Griffin concludes, "The results of the experiments indicate that young trout and salmon are not directly injured by living for considerable periods of time in water which carries so much soil sediment that it is made extremely muddy and opaque. They also indicate that cutthroat trout and salmon fingerlings can feed and grow apparently well in very muddy water."

Before the significance of these conclusions can be appreciated, it must be remembered that the duration of the tests were 20 and 28 days and that no attempt was made to compare or analyze growth or condition of the test fish.

Some of the statements in this report have been misinterpreted, and Smith (1940) has clarified the matter.

> "Griffin, in Appendix B to Ward's report (1938a), gave the results of an experiment which seems to prove, according to the *California Mining Journal*, October, 1938, that 'young fish thrive on mud.' In those experiments, cutthroat trout and chinook salmon fingerlings were held in hatchery troughs, some containing clear water and others muddy water. In both species, the survival was greater in muddy than in clear water. However, in each of the two tanks of clear water, the heaviest loss occurred during the first four days of the experiment. Griffin attributed the heavy loss to the fact that the fish in clear water were able to see better and were so frightened by activity near the tanks that they dashed against the walls and injured themselves. Whatever the cause, a mortality as large as forty-six out of seventy-five salmon fingerlings in four days must be attributed to some unusual factor which would not affect wild fish. In fact, ten out of the forty-six fingerlings died because they leaped out of the tank. Consequently it would be better to compare survivals after the fourth day. When this is done it appears that the salmon mortality was higher in muddy water, 12.2 per cent, than in clear water, 6.9 per cent. Results of the experiments with the cutthroat trout were the reverse; mortality was 42.9 per cent in muddy water and 85.7 per cent in clear water, disregarding losses during the first four days. Both percentages of mortality for cutthroat trout are so abnormally high and the number of fish used in the experiment so small (fifty and forty at the start) that the difference between the percentages has no significance. The only conclusion that may be drawn from the two experiments is that salmon and trout fingerlings can survive and take food for a few weeks in muddy water. Griffin himself stated practically the same thing, but unfortunately he presented his data in such a way that they can be misinterpreted easily. Incidentally, the fact that fish can find artificial food in muddy water would not help them much in streams where silt has smothered the natural food organisms."

A field experiment on the direct effect of turbidity on cutthroat trout was conducted by Bachmann (1959). Two enclosed 30-foot study sections were established on Silver Creek, Idaho, with six fish placed in the lower section and five in the upper. The lower section was subjected to artificially created silt turbidities for two hours. Average maximum turbidity was 35 ppm. Fish in the turbid section showed no distress and suffered no mortality. However, the control fish fed actively throughout the study period, while the test fish ceased feeding and moved to cover.

Another field experiment on the survival of trout when exposed to higher turbidity created by a gold dredge on the Powder River was carried out by Campbell (1954). Rainbow trout fingerlings were used in the tests. The control was located in an unpolluted tributary with the test fish placed one and one-half miles below the dredge. Turbidity ranged from 1,000 to 2,500 ppm. Losses of trout in the silty area reached 57 percent within a 20-day period compared to 9.5 percent in the control. The presence of bottom fauna, though drastically reduced, during dredge operation indicated the absence of toxic substances.

Pautzke (1938) conducted live car experiments with steelhead trout in Cedar River and cutthroat trout in Squalicum Creek, and they revealed that the combined action of sand, slate, and coal particles carried in suspension were lethal to all test fish in two and one-half hours and one-half hour, respectively. "Examination of the dead fish disclosed heavy secretions of mucus covering the fish and the gills. Solid masses of coal dust and slate particles adhered to the mucus." The material is discharged to the streams during coal washing operations. The coal chiefly mined was semi-bituminous in type, low in sulphur content, and high in waste materials such as slate and sand. Fish were kept overnight in water pumped from the mine to determine if it was causing the mortality, but no losses occurred.

We have found many statements in the literature that silt is directly harmful to fishes by interference with normal gill functions.

Ellis (1944, p. 12) in a report setting down water purity standards for freshwater fishes summarized the results of a series of experiments conducted by the U. S. Bureau of Fisheries:

> ". . . Particulate matter of a hardness greater than one if held in suspension by current action or otherwise will injure the gills and other delicate exposed structures of fishes, molluscs and insects if the particles be large enough. A large series of experiments at the Columbia laboratories have demonstrated that rock powders, blast-furnace slags, cinder particles, and even coal washings will cut and injure both fish gills and the mantle and gills of unionid molluscs if the particles be larger than those which will pass through a 1,000-mesh (to the inch) screen. In the actual tests the larger the particles, and the greater their hardness and angularity, the greater the possibility of injury to gill structures. These abrasive injuries not only cut the gills but provide entrance for disease organisms. Even erosion silt which will pass through a 1,000-mesh screen produces copious flows of mucous from bivalve molluscs and increases the secretion of slime by fish gills if the quantity in suspension be great enough."

Kemp (1949) stated that mud or silt in suspension will clog or cut the gills of many fish and mollusks and he considered 3,000 ppm. dangerous, if maintained for a period of ten days. As an example, he cited a flood in 1936 which created a turbidity of 6,000 ppm. in the Potomac River and lasted 15 days. The fish kill was large and the oyster beds were severely damaged.

Trautman (1933) maintained that gravel pit washings and soil washings from corn fields, ". . . clog or cover the gills of fishes and so prevent respiration that death results; . . ."

Reliable as these and other observations may be, the fact remains that little data are available to support any universal answer on whether or not sediment is directly harmful to fish. The fisheries worker investigating this problem must be prepared to look very carefully at all conditions before he blames the sediment itself for direct damage to fishes.

The presence of toxic water complicates the picture. Ellis (1937) pointed out that healthy and uninjured fish can move through very muddy water since the continuous secretion of mucus washes away the sediment particles. However, when toxic chemicals injure the gills or alter the flow of mucus, the addition of suspended silt may aggravate gill damage through increased abrasive or matting action.

We observed an example of this in 1957 when a holding pond for a clay products plant washed away into the Mokelumne River near Camanche, California. The same rains which washed away the pond dike caused highly toxic water containing copper and zinc to flow into the river from an abandoned mine five miles upstream. Observations by local wardens suggested that the concentration of clay in the river was killing fish, but subsequent bioassays showed only that the fish died more rapidly when exposed to the suspended clay and the toxic water than they did in the toxic water alone.

The fisheries worker is usually presented with less dramatic cases than this. Our literature review and experience suggests that the question, "Is the sediment directly harmful to fish?", cannot really be answered without knowing more than usually is known. In most cases, indirect damage to the fish population through destruction of the food supply, eggs or alevins, or changes in the habitat probably occur long before the adult fish are directly harmed. Unless he is prepared to conduct exhaustive tests, the fisheries worker would do well to leave the question unanswered and base his actions on the indirect effects of sediment and subsequent changes in the fish population.

Of course, the fish do not have to be killed to be directly influenced. Sumner and Smith (1939) and Smith (1940) reported that king salmon avoided the muddy water of the Yuba River, California, in preference for the clear water of a relatively small tributary, containing about 1/25 of the flow of the Yuba. Salmon occurred in such concentrations that previously constructed redds were torn up. Where clear seepage flow created a clear streak along one side of the Yuba River, salmon again were attracted in more conspicuous numbers than to nearby spawning areas in the main river.

These two reports also mentioned the behavior of salmon in streams of Bristol Bay, Alaska, which carry a load of glacial silt. Salmon will swim through this silt, but always spawn in the clear side tributaries. Cooper (1956) noted that sockeye salmon migrate through the Fraser River during high turbidities but spawn in tributaries where turbidities are low.

The Washington Department of Fisheries (1959, p. 57) reported that the king salmon run in the Columbia River was deterred by excessive silting below Bonneville Dam with near disastrous results because the fish were held up in an area where they were subject to unusual harvest.

The fact that king salmon adults react to turbid waters seems clear. The difficulty of making observations of fish in turbid water has prevented very exact definition of just what the reactions are.

INFLUENCES OF SEDIMENT UPON EGGS AND ALEVINS

Sediment deposition in streams has for years been thought to be damaging to fish eggs buried there. The problem has been investigated rather extensively.

One of the earliest published experiments in the hatching of fish eggs in gravel was reported by Harrison (1923). He described the results of tests conducted in British Columbia with eyed eggs of the sockeye salmon as follows:

Number planted	*Description of nest*	*Number hatched*
500	Gravel from size of pea to hickory nut, some clean sand	350
500	Same as above with top coating of silt, ½ inch deep	325
500	Fine gravel, sand, and small amount of clay in sand	200
500	Fine gravel and much clay or mud in sand	170
500	Gravel from size of hickory nut to walnut, very little sand, no clay or top covering of silt	420

Hobbs (1937) conducted a pioneering study of natural reproduction of king salmon, and brown and rainbow trout in several New Zealand streams. His observations on mortality of eggs in the gravel, led him to state (page 75) that, "The bulk of losses which, irrespective of species of fish, occur in varying intensity in different streams and in different redds of the same streams are attributed to a common factor [sediment] . . . where redds are very clean losses are very slight. Where redds are very dirty losses are heavy."

Hobbs sampled the sediment in redds and directly correlated mortality with amounts of material that would pass through a 0.03-inch screen. Differences of only a few percent appeared to greatly affect mortality. Relatively small amounts (four percent) were damaging. He states (page 75), "There is sufficient evidence to show that where permeability is low there is a greater loss than where, other conditions being equal, the redd material is more permeable."

While Hobbs carefully explained the probability that the losses were directly due to reduction in amounts of oxygen reaching the eggs, he honestly states that his data do not furnish evidence of this. He was able to define the bulk of the losses as occurring before eyeing, when the egg was between 10 and 20 percent of its way toward completing development. Silt deposition during the eyed stage resulted in lower metabolic rates. Hobbs states that it is quite common for a crust of silt to be formed over the top of a redd. This did little harm unless floods with turbid waters increased the penetration of fine material into the egg pocket of the redd.

Hobbs found that king salmon eggs, buried at twice the depth of brown trout eggs, were less affected by silt. Not only were they protected from the silt because they were buried deeper, but they completed pre-eyed development before the worst floods. Rainbow trout spawned after the floods and they cleared silt from the streambed in the process of redd construction.

Sediment in these New Zealand streams was introduced by natural causes, mostly flooding, and in certain observed cases was sufficient to cause unusual mortalities of eggs. In most cases the success of natural reproduction was excellent.

Although the experiments by Shapovalov (1937) were not designed to test the influence of silt on steelhead eggs, natural siltation entering the hatchery water supply provided such an opportunity. Two experiments were conducted comparing survival of eggs placed in gravel in a hatchery trough with eggs in the standard wire hatching basket in aquariums. During the first trial, heavy rains caused the water to become muddy for nine days. Percentage survival to time of emergence during the first trial was 29.8 percent for the eggs buried in gravel and 80 percent for the control lot held in a standard hatchery basket. Clear water conditions existed during the second trial and the egg survival was 79.9 percent in the basket and 81.7 percent in the gravel. The author states, "The exact effect [of silt] on the eggs in the gravel cannot be told, except by inference from the survival data, but it was observed that there was a heavy coating of silt on top of the gravel and down the sides of the aquarium, reaching the eggs. . . It may be significant that in the control lot the largest number of dead eggs was removed during the three days following the period of muddy water." In the summary, Shapovalov maintained that under good conditions in nature the percentage of eggs which are fertilized, hatch, and emerge from the gravel is rather high but may be quite low under adverse conditions such as silting caused by flooding, as here, or mining.

Shapovalov and Berrian (1940), as a follow-up to the 1937 tests, conducted controlled experiments on the hatching of silver salmon eggs. The experimental lot was buried in gravel in a hatchery trough, with the control lot placed in a standard wire hatching basket in a similar trough. Survival to emergence was about 10 percent from the gravel and 50 percent from the control. Concerning this poor survival, the authors state, "In the present experiment some of the worst floods ever experienced occurred while the eggs were in the gravel (especially just after the eyed stage was reached), and the water in the hatchery troughs was laden with silt . . ., when the experiment was concluded, the gravel was removed by hand and a considerable amount of silt was found throughout it. A large number of eggs that had developed partially was found also. There is every reason to believe that they were smothered by the large quantities of silt that had settled around them."

Shapovalov and Taft (1954) presented the results of extensive studies on Waddell Creek, California. They stated (page 274), "As in the case of the silver salmon, silting occurring between fertilization and hatching is probably the principal cause of pre-hatching losses."

Among the investigations on the effect of mining silt on the yield of fry from salmon spawning beds is that by Shaw and Maga (1943). Silver salmon were used in the tests which were conducted at the Brookdale Fish Hatchery, Santa Cruz County, California. The summary and conclusions of this report are repeated below:

> "1. Salmon eggs hatched in the usual manner by placing a basket of eggs in the flowing water of a hatchery trough produced a yield of 79.9% fry with 733 temperature units.

> “2. Salmon eggs placed in prepared gravel beds constructed in a hatchery trough and receiving only normal hatchery water produced a maximum yield of 25.4% and an average of 16.2% fry. Occasional silting of the water supply due to storms may have lowered the yield. To first emergence from the gravel 992 temperature units were required.
>
> “3. Salmon eggs in prepared gravel beds that received mining silt for intervals of 2 to 72 days beginning with the initial stages of incubation produced a maximum yield of 2.4% and an average yield of only 1.16% fry. A total of 1385 temperature units were required to first emergence from the gravel. Many of the undeveloped eggs remaining in the gravel were preserved with a coating of silt. Fry that died or failed to emerge outnumbered those that worked through the gravel.
>
> “4. Salmon eggs in prepared gravel beds that only received mining silt during the emergence period produced a yield of 13.4% fry but earlier silt additions extending back into the incubation period produced progressively lower yields which reached zero with silting at the beginning of the incubation period. In this series the number of undeveloped eggs that were coated and preserved with silt increased steadily with earlier and longer periods of silt addition. Very few fish that hatched failed to emerge but many fry apparently worked forward through a screen rather than upward through the gravel and deposited silt.
>
> “From the data presented in this paper it is evident that the yield of fry from eggs hatched in gravel beds supplied with normal hatchery water is far below that attained by the usual procedure of basket hatching in flowing water. The experiments further show that mine silt deposited on gravel spawning beds during either the early or later stages of incubation results in negligible yields of fry and is therefore a serious menace to natural propogation.
>
> “From a practical standpoint this damage to spawning beds would occur when mining silt enters a stream at times other than storm periods when the water velocity is insufficient to carry the sediment in suspension. It is a well-known fact that the velocities necessary to dislodge deposited particles are far greater than the velocities required to carry the same particles in suspension. For this reason natural stream turbidity is largely limited to those periods when storm water causes erosion. During these periods stream flows in areas suitable for steelhead, trout, or salmon spawning are sufficient to prevent bottom deposits of natural erosion silt and damage to eggs in the gravel is minimized. Thus, while mining silt may be natural material, its presence in waterways during nonerosion periods results in bottom deposition which is unnatural and damaging.”

In 1952 several careful studies were made by the Washington Department of Fisheries of the effects of a large clay slide near Hatterman, Washington, on the North Fork of the Stillaguamish River. The studies were reported by Heg (1952) and Hertzog (1953). The slide consisted mostly of fine material about 90 percent of which was small enough to pass through a number 200-mesh sieve. It was calculated to have increased turbidity of the stream by about 35 ppm. Experiments indicated that less than 15 percent of the introduced material settled out in quiescent areas of the stream.

Steelhead eggs were deposited in plastic mesh bags at various distances below the slide. The silting from the slide reduced successful development of eggs and fry for a distance of less than one mile downstream. In that area, sediment deposits caused losses of 50 to 100 percent of the eggs observed.

The U.S. Fish and Wildlife Service has been conducting survival studies on the eggs of king salmon in Mill Creek, California (Gangmark and Broad, 1955 and 1956). Eggs were placed in containers and buried in spawning riffles. The most obvious factor affecting egg survival in the experiments was flooding. A close correlation exists between egg losses and severe freshets. Since turbidity and siltation occurred simultaneously with flooding, it would seem difficult to separate the effect of each; however, actual physical destruction of the spawning beds by scouring appeared to be the most important factor. Comments on the significance of silt in egg mortality appeared in both reports. Examinations of eggs found after a severe flood during the first test revealed that none of the embryos had survived the floods. "The shifting of the channel and the eroding and smothering action of silt and sand apparently caused a complete kill of the developing young salmon." In the second study a controlled flow area was included as a control not subject to severe scouring floods. "Eggs in the controlled flow area suffered mortalities from silt deposition only."

In the most recent report on their work at Mill Creek, California, Gangmark and Bakkala (1960) presented data to show a direct relationship between the velocity of seepage in gravel adjacent to planted king salmon eggs and the survival of those eggs. They measured the velocity of seepage water through the gravel with plastic standpipes, and the mortality of eggs by burying them in plastic containers in simulated redds 12 to 14 inches under the streambed. At velocities of more than 3.5 feet per second, between 5.8 and 2.9 percent of the eggs died. At velocities between 1.5 to 3.5, mortality ranged from 10.1 to 13.0 percent. At velocities of 0.5 to 1.5, mortality rates ranged from 24 to 40 percent.

The authors studied salmon production in an old streambed through which a channel was bulldozed and from which silt had been flushed. They compared production with that of Mill Creek itself:

> "Production of salmon in the Sacramento River area is limited by a variety of complex factors affecting the incubation of eggs, principal of which is the silt deposit left by heavy runoff of water that is typical of streams in this area. The means for alleviating damage resulting from heavy stream runoff appears to be control of the natural stream. In the assessment of factors that caused the superior production of salmon in the experimental controlled stream, the most impressive relationship in 1958 was the one associated with seepage rate in the gravel . . ."
>
> "Mortality to fry stage was 98.3 percent in the 1957-58 Mill Creek plants. This high mortality was obviously associated with reduced seepage in the gravel, which averaged only 0.3 foot per hour during most of the incubation season. In the controlled-flow area,

> with seepage rates in the gravel averaging 3.5 feet per hour, survivals were either very good or very poor. Seventy-two percent of the samples averaged 75 percent production of salmon and were associated with good seepages. In the other extreme, 22 percent of the 100-egg samples were all dead—a result of poor seepages that were not always detected by the standpipes.''

Further evidence on the adverse influences of silt upon eggs in redds was uncovered by Neave (1947). He conducted an experiment on the efficiency of natural propagation of chum salmon in Nile Creek, British Columbia. A count of downstream migrant fry indicated high mortalities. He concluded that, ''Samples of eggs exhumed and examined during the winter of 1945-46 showed heavy mortality, most of which had occurred before the eggs had undergone any recognizable degree of development. Much of this loss could be attributed to silting of the bottom during periods of higher water, with resultant reduction of water circulation in the gravel.''

Williams Creek in British Columbia was the subject of an investigation of sockeye fry production by McDonald and Shepard (1955). Examination of redds in a newly silted section showed high mortality, probably due to suffocation. Following a stream improvement program which increased water flows and flushed out much of the silt, production of fry more than doubled.

An evaluation of the spawning of cutthroat trout in tributaries to Trappers Lake, Colorado, was made by Snyder (1959). One phase of the study was to establish quality standards for spawning sites. It was observed that, ''Areas of silt were frequently passed over by the spawning fish, even if the silt was covered by a thin layer of gravel. Fish were observed to dig through the thin gravel covering and stirring up the silt ladened substrate. When the silt was encountered by the fish, digging would continue forward as far as three feet, but eventually the site would be abandoned.''

Stuart (1953b and 1954) investigated factors which caused brown trout and Atlantic salmon to choose certain gravel beds for spawning in preference to others. Beds selected were found to be permeable to water. Consolidated gravels were avoided. The detailed characteristics of water currents were studied in the laboratory and their existence demonstrated in the field. The currents were found to run obliquely downward through the gravel, at right angles to the surface of the gravel bank. These currents enable the female to detect areas of suitable gravel. The downwardly directed currents are sufficiently strong to enable the fish to rest on the gravel surface without effort. The laboratory model demonstrated that the currents through the gravel are dependent chiefly on the gradient, and not the velocity, from pool to pool. The strongest currents exist below the apex of the gravel mound and decrease towards the middle of the pool where they cease.

Stuart (1953a) told of raking clean of silt the top 3 to 4 inches of gravel in an area which then was indistinguishable from a nearby known spawning bed. Nevertheless, it was still passed over by the spawning trout. He demonstrated the passage of water currents through the tails of pools, which were the favorite spawning sites, by the use of dyes. Trout appear to use this current, which can be quite strong, to hold their position against the main current. This type of gravel is easy for the fish to excavate.

He also conducted laboratory experiments on the effects of silt on ova and alevins of brown trout in Scotland. This study was prompted by field investigations which revealed high mortality of ova in redds exposed to silting. Tests were made first with natural sediments and later with particles of carmine powder and finely divided carbon. Each material gave similar results.

It was found that the chorion lost its smooth and glossy exterior by attracting the finer silt particles and soon became completely covered by a dark coat of sediment. All early ova in this condition died without hatching. Eyed ova placed in turbid waters survived short exposure to these conditions (about 48 hours). Unlike the ova, newly-hatched alevins repelled suspended particles. This was accomplished through pectoral fin action and intermittent tail flexions. About 24 hours after hatching, the mouth and gills of the alevin began functioning to create a new hazard. Survival of the alevins at this stage depended primarily on the timing of the silt additions. The continuous addition of fresh sediment resulted in serious inflammation of the gill membranes which eventually caused death. Intermittent additions did not cause death. Older alevins were slightly more resistant. Alevins are, in general, better able to cope with siltation as they grow and move out of the gravel. Stuart concludes, as follows (page 35):

> "As we have seen, silt is not very dangerous in the normal stream if excess occurs only at intervals. The character of such normal streams can however be altered drastically by allowing the washings of quarries, gravel pits, mines, etc. to flow into streams untreated. In many cases the quantities allowed to enter the streams may be small and the material in suspension may in itself be of a non-toxic character, but as has been shown above, continuous application of small quantities over the redds may be much more detrimental to the welfare of the alevins than sudden flushes of large quantities."

Cooper (1956) conducted a thorough investigation of a probable damage to sockeye salmon runs in the Horsefly River, British Columbia, from proposed placer mining. The study was rather unique in that Cooper determined which materials would be deposited on the spawning beds, and then in the laboratory determined their probable effects upon the success of sockeye salmon egg and alevin survival. He:

1. Measured velocity, discharge, cross sections, slope, suspended sediment, and bottom sediments in the stream.
2. Determined that sediments transported in suspension were 0.3 mm. or less in diameter, and those transported as bed load were 32 mm. or less.
3. Estimated that with bed tractive force exhibited at low flows during the spawning periods, particles of 0.149 mm. or larger would accumulate on the spawning beds below the proposed mining operation.
4. Measured the particle size of sediment produced by a pilot placer mine.

5. Estimated that up to 9.7 percent of the material was small enough to pass as suspended sediment and that up to 57.7 percent was of a size capable of being transported as bed load through existing or potential salmon spawning areas downstream.
6. Tested the effects of sediment on rates of flow through river gravel and found that the reduction in such rates varies inversly with the particle size, the smaller particles being more effective in reducing velocity than the large ones. Silt and fine sand were very effective in clogging the gravel even in minor quantities.
7. Conducted experiments on the effects of sediment on survival of freshly fertilized sockeye salmon eggs buried in the gravel under controlled conditions. The application of sediment, particularly the fine materials, greatly reduced the percentage survival of the eggs.

Some significant statements from Cooper's work are quoted below: The first paragraph was taken from page 28, the second paragraph from page 52, and the third from page 54:

> "In the normal course of events the principal source of sediment in streams in British Columbia is the spring freshet passing down the stream, with consequent bank wash and bed scour. As the freshet passes, the availability of transportable sediment decreases rapidly and in river reaches where the scour action is great, the bed is left relatively free of fine sediments and the water becomes relatively clear. This annual cycle is considered to be an essential characteristic of rivers in which the best salmon spawning grounds are located. However, if this normal pattern is altered by the artificial introduction of sediment during the period of declining discharge when such sediments would not normally be available to the river, some deposition of sediment will take place in the interstices of the bed materials, particularly near the river banks. It is not possible to estimate the bed material composition that will result from a given discharge and concentration of given particle sizes. In regions of large scour the amount of deposition of fine materials probably would be small, but it is a fair assumption that in order to preserve the stream bed in its normal condition, normal relationships between discharge and sediment size and concentration should be maintained."
>
> "It may be concluded from this experiment that the deposition of sediment on gravel spawning beds would cause reduction in survival rates of eggs and alevins in proportion to the reduction in flow of water through the gravel. For a given type of gravel a certain apparent velocity is necessary to supply sufficient oxygen to all parts of the gravel to obtain maximum survival. Where this velocity is not obtained, through deposition of sediment or for any other reason, the supply of oxygen to some or even all parts of the gravel will be too low to permit survival."
>
> "Deposition of sediments on sockeye spawning grounds can reduce the survival rate of eggs and alevins being reared in the gravel. The reduction in survival is in proportion to the reduction of flow of water through the gravel, which in turn varies with the

> concentration of sediment and the sediment particle sizes. For a given concentration of sediment the finer particles in the size range tested were more effective in reducing percolation than the coarser particles. Reductions in survival are caused by insufficient supply of oxygen and by smothering of eggs with sediment. Depositions of sediment early in the incubation of eggs can be more injurious to survival than depositions close to the hatching period. This is believed to be due principally to the ability of alevins to improve or change their environment by body movements.''

Campbell (1954) planted 100 eggs in gravel in a hatching basket in the Powder River, Oregon, below a gold dredging operation. Another 100-egg lot was planted in a clear tributary. Turbidity in the Powder River ranged from 1,000 to 2,500 ppm. All the eggs in the silty river died within a 6-day period, while total mortality in the 20-day test period in the clean tributary totaled but six percent.

What at first appeared to be an exception to the well-established fact that large quantities of silt are destructive to eggs in gravel was reported by Foskett (1958). Both the Shumahalt and Machmell rivers, British Columbia, contain large runs of sockeye salmon and yet carry heavy loads of glacial silt. Analysis of the situation, however, revealed that spawning occurs during heavy rainfall which reduces the concentration of silt and flushes out the spawning gravels. In addition, the fry emerge from the redds in the spring before the glaciers begin melting and deposit silt.

In recent years Canadian fisheries biologists at the Nanaimo Biological Station, British Columbia, have shed much light on some of the problems of sediment and egg survival. Wickett (1954) reviewed the early work on the subject of the requirements and consumption of oxygen by fish eggs and conducted experiments on the dissolved oxygen consumption of chum salmon eggs under controlled conditions. He concluded that the amount of dissolved oxygen supplied to the eggs in water depends upon both the volume of water flowing over the eggs in a given time and upon the dissolved oxygen content of that water.

Wickett found low dissolved oxygen values beneath consolidated and silted gravel of a side channel of Nile Creek, British Columbia. Washing the streambed by hosing increased both dissolved oxygen content and velocity of the water through the gravel.

Alderdice, Wickett, and Brett (1958) conducted further experiments on the dissolved oxygen requirements of chum salmon eggs and showed that critical levels of dissolved oxygen range from about one part per million in the early developmental stages to over seven parts per million shortly before hatching. Alderdice and Wickett (1958) experimented with the effect of carbon dioxide upon the ability of chum salmon eggs to utilize dissolved oxygen and found that as carbon dioxide concentrations were increased, oxygen utilization by the eggs declined. ''Mortality (of eggs) appears to be a function of the inhibition of oxygen uptake by carbon dioxide, resulting in a deceleration of metabolic rate which ultimately is lethal if the inhibiting influence is prolonged.''

Presumably, carbon dioxide build-up may occur outside of the egg capsule when sediment deposits on the bottom of a stream reduce the rate of subsurface flow in the redd to the point where waste products of the egg are not carried away as fast as they are being produced.

The Canadians have designed tools to measure the rate of water flow and dissolved oxygen concentrations within the spawning gravels (Wickett, 1954; Terhune, 1958; and Pollard, 1955). A similar device has been developed by the U. S. Fish and Wildlife Service (Gangmark and Bakkala, 1958). These are invaluable tools to those investigating the effects of sediment upon eggs or the gravel.

The general conclusion we reach from reviewing the considerable efforts of a number of competent investigators is that the effects of sediment upon alevins and especially eggs of salmonids can be and probably often is disastrous. Even moderate deposition is detrimental. Sedimentation is probably one of the most important factors limiting the natural reproduction of salmonids in streams, and certainly every effort must be made to prevent it.

INFLUENCES OF SEDIMENT UPON BOTTOM ORGANISMS

A tremendous number and variety of living organisms inhabit the bottoms of streams and rivers. Bacteria, algae, protozoa, and other lower forms thrive there and are basic components of the ecological community. They play important roles in the food chains converting inorganic nutrients to fish populations utilized by man. Quantitative studies of the effects of inorganic sediment upon the entire stream community were not apparent during our review of the literature. Most investigators have directed their attention toward certain groups of recognized importance.

Ellis (1931a, p. 17), reporting on investigations in the upper Mississippi River, stated that:

> "... Soil experts of the Department of Agriculture have shown recently that the silt now carried by the Mississippi River greatly exceeds in volume that which was carried by this same river only a few years ago, ... The silting-in overwhelms the bottom fauna faster than it is able to adjust itself, with a result that many species are being eliminated or greatly reduced in numbers. As a complicating factor the erosion-silt suspension, which is almost collodial in nature, carries down with it when settling out partly decomposed organic waste which has reached the river through municipal sewage and other sources."

In a later report of the mussel situation on the Mississippi, Tennessee, and Ohio rivers, Ellis (1931b, p. 10) reported that:

> "Erosion silt is destroying a large portion of the mussel population in various streams by directly smothering the animals in localities where a thick deposit of mud is formed; by smothering young mussels even where the adults can maintain themselves; and by blanketing the sewage and other organic material which in turn produces an oxygen want that lowers the oxygen content of the water to the detriment of those species requiring well-aerated water ..."

Sumner and Smith (1939), during an investigation of the effects of hydraulic mining on aquatic life of the Yuba and American rivers in California, collected a series of bottom samples in tributaries with different amounts of silt on the bottom. These authors report (page 27) that ". . . production in silted areas in Yuba tributaries is but 63 percent of that in the clean, while silted American River tributaries produce only 41 per cent as much as the unsilted areas." A summary of the data is presented.

Tebo (1955 and 1957) reported on one phase of the watershed studies being done on the Coweeta Experimental Forest in North Carolina. During a 9-month period, 109 square-foot bottom samples were collected from Shope Creek, immediately above and below the mouth of a tributary draining a logged watershed. Data were analyzed statistically. During the period of sand and silt accumulation in the affected section, there was a statistically significant reduction of bottom organisms below the mouth of the logged watershed. Flooding removed the accumulation of sand and silt, and further reduced the bottom organisms in the silted area to 7.3 per square foot, as compared with 25.5 per square foot at the unsilted station. The bottom fauna rapidly recovered after the flood had exposed clean gravel and rubble.

Some preliminary figures on the effects of a placer mining operation on the physical, chemical, and biological features of Seigel Creek, Idaho, were presented by Casey (1959). A pre-dredging study showed that the bottom fauna population was approximately equal in all three study sections: above, in, and below the area to be dredged. Twelve bottom samples were taken in each of the three sections. Dredging started in May, 1958; by July of the same year the stream section at the dredge site and for about one-quarter mile below was completely silted over and almost devoid of aquatic organisms. Several samples contained no organisms. The section about one mile below the dredge showed over a 50 percent reduction. There was no obvious or consistent evidence that any one type of aquatic organism was more intolerant of siltation than any other type.

A similar reduction of bottom fauna was caused by waste water from a gravel washing operation entering the South Fork Chehalis River, Washington (Ziebell, 1957). A sample above the gravel operation contained 173 organisms per square foot. Only 32 and 4 per square foot were found in two samples 100 yards below the discharge. The 32 represented the best existing bottom condition in a "flushed-out" portion of the stream. A sample four -miles downstream, where siltation was less evident, showed 113 per square foot. Improved conditions were found six and one-half miles downstream, revealing a total of 177 fish food organisms per square foot.

Ziebell and Knox (1957) investigated the effects of another gravel washing operation on aquatic life; this time the Wynooche River, Washington. Results of bottom samples collected below the gravel operation revealed reductions of 75 percent at points 200 yards and 0.3 miles downstream, and 85 percent at a station 1.7 miles below the discharge.

Silt from a gravel washing plant drastically reduced bottom organisms of Cold Creek and the Truckee River, California, according to Cordone and Pennoyer (1960). Reductions of over 90 percent occurred immediately below the outfall, and a reduction of over 75 percent was noted more than ten miles downstream.

Bachmann (1958) found a statistically significant decrease in volume of bottom fauna in an Idaho trout stream receiving silt from logging road construction. Wustenberg (1954) found that silting in small Oregon trout streams from logging operations seriously reduced trout food organisms.

During an information-gathering survey of the Klamath River, California, and its tributaries, Taft and Shapovalov (1935) collected a series of bottom samples to obtain some idea of the relative quantity of bottom foods produced by the different streams. Forty-eight square-foot samples were taken. In a discussion of mining silt pollution, they concluded (page 16), "Whenever a series of quantitive bottom samples was taken in one stream or in a series of similar streams during the summer, the average number of food organisms in the one square-foot samples was *always* less in mined areas than in non-mined areas." Data are presented for the East Fork Scott River, where above a source of silt discharge the mean of three samples showed 249 bottom organisms in comparison with that of 36 for three samples in the affected area.

During the winter of 1957, silt from a hard-rock mining operation for molybdenum polluted Moore Creek in California. Bottom organisms from six square feet were collected both above and below the discharge point. A total of 434 bottom organisms was found in the clear water compared to only 32 collected from the silted area.

As reported by Wilson (1957), "Bartsch and Schilpp (1953) reported on sand processing wastes from a glass sand corporation in West Virginia as affecting a small tributary of the Potomac River. They concluded that the differences in production of plants and animals in affected and unaffected parts of the river are due principally to increased turbidity and solids deposition."

Reports published by the Oregon State Game Commission, *et al.* (1955) and Wilson (1957) summarized the results of extensive collections of bottom organisms above and below gold dredge operations on the Powder River. During siltation, production of fish-food organisms dropped to almost nil in the zone of heaviest pollution. Between 15 and 20 miles of the river were heavily silted. In about one year after the dredge closed operations, there was a remarkable recovery of bottom life. Silt was flushed from the pools and riffles by freshets and bottom organisms increased eight- to ten-fold in weight per unit of bottom area.

The effects of silt from the construction of Granby Dam on the Colorado River, Colorado, were reported by Eustis and Hillen (1954). They observed that flows below the dam from September, 1949, to April, 1952, were not sufficient to dislodge and carry away sediment in the streambed.

> "Stream-bottom samples were taken in 1949, 1950, and 1951. These revealed that a marked change in species of insects present occurred as a result of the deposition and accumulation of sediment. Aquatic insects, typical of the clean rubble bottom formerly existing, became much less prevalent; sediment-loving, burrowing organisms increased in number. This represented a distinct loss in trout foods. The caddisfly larvae and nymphs of several species of stoneflies and Mayflies which tended to disappear were to be preferred, because of their greater size and their accessibility, to the tiny midge larvae or 'bloodworms' which replaced them."

In summary, we can only conclude that there is overwhelming evidence that the deposition of sediment in streams can and often has destroyed insect and mussel populations. Much of the available information has been gathered during pollution investigations and is limited because of the small number of samples taken. It would appear, however, that those who report on the problem are unanimously in agreement that it is a serious one.

Significance of Substrate Type

A knowledge of the ecology of stream insects is helpful in understanding how silt influences production of bottom fauna. One of the more detailed ecological studies was made by Sprules (1947) in Algonquin Park, Ontario. Certain of his conclusions (pages 72 and 73) are pertinent to an understanding of silt and bottom fauna interrelationships:

> "The insect population [of streams] was reduced in areas where the bottom was scoured by a severe freshet. The reduction resulted from the loss of individuals which were dislodged and swept downstream by the current and the elimination of others through molar action. The effect of the freshet was minimized in areas where the bottom was relatively stable and composed of large particles which afforded shelter."
>
> "A variation in the number of species and number of individuals was found associated with different types of bottom in a restricted section of the stream. Rocky riffles were the most productive, followed in order by gravel, muck, and sand bottoms. The diversity of the fauna found on any particular type of bottom was related to the variety of utilizable microhabitats associated with the bottom type. It has been suggested that the number of insects present in any area is related to the habitable surface area of bottom particles exposed to the water."
>
> "The quantitative and qualitative distribution of insects observed in streams results from the complex interaction of many environmental factors, of which temperature, nature and configuration of the bottom particles, and rate of flow are of fundamental importance."

The importance of bottom materials to production of aquatic invertebrates is described by Smith and Moyle (1944, p 145):

> "The most important single factor affecting the bottom fauna production of streams is the physical nature of the bottom. Rubble is the most productive type. Such a bottom is fairly stable, has an abundance of small interstices to provide shelter for bottom organizms, and presents a large surface for the growth of microscopic plants that are the basic food of most smaller aquatic animals. Food production decreases as the particles become larger or smaller than rubble size and is poorest on bedrock and fine sand . . . Muck, being an organic soil, tends to be more fertile than fine-grained inorganic soils and may in some instances exceed the production on rubble."

Many studies have been made on the productivity of the various stream bottom types. In general, these have shown that insect production is higher in rubble and decreases as the substrate becomes composed of finer materials. Organic silt often contains tremendous numbers of organisms many of which are not readily available as trout foods. One such study on a Colorado trout stream was conducted by Pennak and Van Gerpen (1947). They refer to a number of other such studies in their report. No attempt was made to review these publications, with the exception of one by Tarzwell (1937).

During a stream improvement experiment on several Michigan trout streams, Tarzwell collected a series of 447 bottom samples. He compared the production of different bottom types and found that, "The data show that the sand areas produce the fewest organisms. If sand is given the population rating on 1, the relative productivity of the other bottom types was found to be as follows: marl, 6; fine gravel, 9; sand and silt, 10.5; gravel and sand, 12; sand, silt and debris, 13; gravel and silt, 14; *Chara* and silt, 27; *Potamogeton pectinatus*, 28; rubble, 29; coarse gravel, 32; *Chara*, 35; mucky areas, 35; medium gravel, 36; *Potamogeton filiformis*, 43; gravel and rubble, 53; sand and gravel with plants, 67; muck, sand and plants, 67; moss on fine gravel, 89; moss on coarse gravel, 111; moss on gravel and rubble, 140; *Vallisneria*, 159; *Ranunculus*, 194; Watercress, 301; and Elodea, 452."

The fact that insects are less abundant on sand bottoms than on gravel and less abundant on gravel than on rubble, has been adequately reported. The processes of erosion greatly increase the relative proportion of finer materials in stream bottom, and of course the deposition of mining debris or gravel plant waste accomplishes the same thing in a more startling and accelerated fashion. To us, there would appear to be adequate evidence that increasing the amount of fine material in the bottom of streams will eventually result in declining bottom fauna.

Sampling Problems

Most evaluations of the effects of silt pollution on bottom fauna have entailed the use of the Surber square-foot sampler as the collecting device. The advantages and disadvantages of this sampler have been described by Leonard (1939), Usinger and Needham (1954), and Needham and Usinger (1956). Using this tool, it was demonstrated conclusively that large numbers of samples are required to provide significant figures on total numbers and weights.

To attain such significant figures at the 95 percent level of confidence, Needham and Usinger determined that 194 samples were required for an estimation of total wet weight, and 73 samples needed for an estimation of total numbers of bottom organisms. However, only two or three samples were needed, again at the 95 percent level of confidence, to insure that at least one member of each of the commonest genera of bottom insects would be present. A comparison was made of samples taken with the Surber sampler with samples collected alongside in a buried tray on an intermittent stream. It was found that the Surber sampler captured about one-fourth of the total numbers of organisms and three-fourths of the different kinds of bottom organisms.

In a study of the Logan River, Utah, Hales and Sigler (1954) found that from 21 to 715 samples were required to estimate mean number, and 8 to 1,068 for mean volume of bottom organisms in a series of stream sections with 95 percent confidence of being right two-thirds of the time.

Many of the results of silt pollution studies are based on relatively few samples taken usually at a station above the silt source and a series taken at progressive downstream stations. The only studies we have reviewed that were evaluated statistically were those by Tebo (1955) and Bachmann (1958). The question arises, what reliance can be placed on the usual small number of bottom samples taken in a silt pollution survey?

Gaufin, Harris, and Walter (1956) presented a statistical criterion for evaluating the efficiency of different sampling devices currently in use. Random collections were made with a special long-handled dip strainer in marginal areas, with the Ekman dredge in the pools, and with the Surber sampler in the riffle areas. Three samples contained, on the average, at least half and in some cases two-thirds of the species observed in ten samples, and an average set of five samples yielded over eighty percent of all species observed. As many as 10 to 15 percent of species were not collected until at least eight samples were taken. Bottom forms are far from randomly distributed, and the authors suggest that bottom types to be sampled must be carefully selected if a small number of samples are expected to present a comprehensive picture of the fauna.

Allen (1959) presented a clear and valuable analysis of the factors affecting the distribution of stream bottom animals in New Zealand streams. After analysis of stream bottom samples Allen concludes, ''A much smaller range of variation between samples occurs when a series is taken at places selected by eye to be as similar as possible . . . The coefficient of variation (standard deviation as a proportion of the mean) in a series of samples selected for uniformity is generally found to be about 0.2, while in gridded or randomized series within a fairly uniform area it is about 0.4 to 0.5. This increased variability is clearly due to environmental features.''

It appears to us that the biologist faced with even a normal amount of pollution work cannot often collect and sort enough samples to make very accurate estimates of the standing crops of bottom organisms in the stream. This does not mean that he should give up bottom sampling, but rather that he probably will have to select his samples from areas that, before the pollution, were as similar as possible. Depth, velocity, and substrate type appear to be the significant features. This was done by Cordone and Pennoyer (1960) on Cold Creek and the Truckee River, California, and is the method used to some degree by most pollution investigators. Random sampling has achieved more respect than it deserves in this situation.

In selecting sample sites, care must be taken to select not only those that are similar, but also to not limit sampling to the areas where water velocity is great enough to prevent sediment deposition or wash it away once it has been deposited. If this is not done, the tests will minimize the effects of sediment. Transects across similar riffles above and below the sediment source are suggested. Sampling devices must of course, be the most efficient available for the particular habitat sampled.

Importance of Bottom Organisms

There is no doubt that substantial quantities of inorganic sediment entering a flowing stream can seriously reduce the abundance of bottom-dwelling invertebrates; but, what effect does this have on fish production?

Trout food habit studies in stream situations have consistently shown the dependence of trout on aquatic invertebrates, particularly insects. At times terrestrial organisms play a significant role in trout diet, but under normal circumstances the bulk of the trout's diet consists of aquatic forms. Maciolek and Needham (1952) and other workers have established that trout feed on aquatic invertebrates year around, even during winter months at high elevations.

Poor production, growth, and condition of trout populations have been ascribed to poor food supply by many investigators. Most of the statements are of a general nature based on field experience and unpublished data. Leonard (1948), writing of conditions in Michigan, states, ''The food supply is, more frequently than any other, the limiting factor in our waters. We have unmistakable evidence, acquired over many years and from a wide variety of lakes and streams, that an inadequate food supply is the most common cause of poor fishing quality, in lakes and streams alike.''

A number of investigators have substantiated in the literature correlations among fish growth, condition, and abundance of bottom organisms. Only a few are mentioned here.

Ellis and Gowing (1957) studied bottom fauna production and the food habits and coefficient of condition of brown trout in Houghton Creek, Michigan. The abstract of this report is as follows:

> ''Field study revealed great differences in the biological productivity of two adjacent areas of a Michigan trout stream resultng from the entrance of domestic sewage into the stream between the two areas. Monthly samples were collected from the two areas to determine the seasonal cycles in abundance of bottom fauna, feeding habits of the trout, and coefficient of condition of the brown trout. In the less productive area upstream, a paucity of food of aquatic origin caused a sharp decline in condition of the fish, a reduction in the quantity of food per stomach, and a shift to a diet containing a considerable portion of terrestrial organisms. In the more productive area downstream (which, throughout the year, had a greater volume of bottom fauna than the unproductive area) trout maintained a significantly higher and much less variable coefficient of condition, their stomachs contained more food in midsummer and did not show the increase in terrestrial foods.''

Cooper (1953) found an apparent correlation between high condition factor and growth of eastern brook trout in three Michigan streams. In one stream he found indications that a low population of bottom organisms was a contributing factor in slow growth of the trout. Temperature data were also correlated with growth and condition, but did not explain the differences in growth noted in the one stream.

Brown (1946) found that brown trout exhibited an annual cycle of growth directly proportional to condition when reared in a laboratory under constant conditions of food, light, and temperature. Cooper and Benson (1951) demonstrated this cycle for brown and eastern brook trout, and Went and Frost (1942) also demonstrated it for brown trout.

Benson (1954) investigated the eastern brook trout of the Pigeon River, Michigan, and collected data which suggested a close relationship among periodicity of growth, condition, and mean volume of stomach contents. His work led him to suggest that growth rate depends upon optimum temperatures and on the abundance of food during the period of optimum temperatures. Allen (1940) found a close correspondence between the amount of bottom organisms in the stomach and the rate at which the fish is growing. Powell (1958), in a comparison of conditions above and below a power reservoir, found a correlation between the weight of bottom fauna and weight of brown trout stomach contents.

Allen (1951) found a close correlation between growth of brown trout and weight of food content in stomachs. He also found (pages 217 and 218) that, "Comparison between the zones [of the Horokiwi stream] suggests that the food supply tends to limit the production of trout, since as the pressure on the food supply increases the actual density of the bottom fauna decreases, and the proportion of the food drawn from it and suitable for growth also decreases." Decreases in the growth rate of trout following floods were attributable to destruction of bottom fauna.

A brief summary of this section can be made in three statements. First, there is abundant evidence that deposition of inorganic sediment will damage and reduce bottom fauna. Second, such reduction will in many cases deleteriously affect salmonid populations. Third, with care such reduction can be measured. These facts lead us to the conclusion that investigation of the bottom fauna is probably one of the most significant approaches that can be made in the detection and measurement of sediment problems.

INFLUENCES OF SEDIMENT UPON AQUATIC PLANTS

All natural-flowing waters are thought to contain at least some algae. The amounts vary tremendously with conditions. Lackey (1944, p. 236) found enough blue-green and green algae to support a large population of lower animals in the bottom of a rivulet six feet from its source; a spring in the side of a clay bank. Algae is commonly considered as the very basis of the food chain, and there can be no doubt that the effects of sediment upon it are of critical importance to the entire stream community.

Sediment is believed to destroy algae by molar action, by simply covering the bottom of the stream with a blanket of silt or by shutting off the light needed for photosynthesis. The effects are probably combined and therefore obscured. Inorganic sediment may occasionally carry nutrient materials, which further complicates the picture because these can be directly used by plants provided the turbidity itself does not destroy them.

Tarzwell and Gaufin (1953, pp. 6-7) have this to say about such situations:

> "Eroded materials also cause turbidity which affects productivity and water uses. Turbidity decreases light penetration and thereby limits the growth of phytoplankton and other aquatic plants which are of outstanding importance as a basic food for aquatic animals and as a producer of oxygen by photosynthesis. The photosynthetic activity of aquatic plants plays an important part in stream reaeration and in the natural purification process. Although turbidity prevents or limits algal growth, it does not eliminate the bacterial action which breaks down organic wastes. Thus, turbid waters may transport the by-products of bacterial action on organic wastes and the effluents of sewage treatment plants considerable distances before they are utilized. When the water clears due to impoundment or other causes so that the phytoplankton can grow, these fertilizing materials are utilized and may produce troublesome blooms, or taste and odor problems far from the source of pollution.
>
> "Soil washings from eroded areas are usually infertile and generally reduce productivity by choking or covering densely populated rubble gravel riffles, and covering rich bottom deposits. Washings, from fertile areas, where accelerated erosion is just beginning, or from rich well-fertilized agricultural areas, carry a great deal of nutrient materials into lakes and streams and increase productivity. This fertilizing effect may be so great that nuisance blooms of algae may develop each year such as those that occur in many Iowa lakes. These blooms become especially troublesome when domestic sewage is also added to the water. Further, in some areas, blooms of toxic algae are frequent and severe."

One perplexing problem has been to determine the effects on aquatic plants of turbidity caused by sediment in streams. Corfitzen (1939) studied the interaction of silt, light, and plant growth. He noticed an absence of algae in silt-carrying canals and attributed this to lack of sunlight rather than erosive action of the silt.

A literature search by Corfitzen revealed that in green plants the greatest absorption of light takes place when light wave length is less than 5,000 Angstrom units. Absorption increases as wave length decreases. Green leaves also utilize light in a small band in the red end of the spectrum between 6,500 and 6,700 Angstrom units.

Passing a light beam through a glass tube with suspended silt resulted in turbidity measurements. A photoelectric cell and microammeter registered the intensity. Greatest loss in intensity was due to light absorption by silt, with some additional loss by reflection and refraction.

It was found that blue light and other colors with wave lengths shorter than 0.00004912 cm. promote the growth of green plants. Thus, any silt concentration which absorbs blue light completely, absorbs all rays promoting plant growth. Based on the data collected, a curve was constructed which permitted a determination of the amount of silt required to completely destroy all green plant growth at any given depth.

Ellis (1936) made over 5,000 determinations of water carrying erosion silt, and found that the penetration of light into inland streams and rivers was being reduced at an alarming rate.

Phinney (1959) explored two general statements often used to describe the relationship between turbidity and sediment to photosynthesis. First—that as turbidity increases, the rate of photosynthesis decreases. Second—that sedimentation will reduce the photosynthetic rate of aquatic plants, because the sediment acts as a physical barrier preventing the free exchange of gases necessary for their survival. Phinney pointed out that, while these generalizations were true, they do not help much in solving our problems. Most research being done on the subject will result in the same general conclusions, unless biologists are careful to control and measure all the factors that affect the photosynthetic process.

During experimental work on photosynthesis—temperature, carbon dioxide concentration, and other factors must be controlled or carefully measured. The measurement of light reaching the plant chlorophyll is in itself a very difficult problem because of the scattering and diffusion of the light waves after they once enter the water. Phinney was critical of the methods now in use. He made a plea for sound research that will determine not just that turbidity decreases photosynthetic rate but rather the mechanics of how, why, to what degree, and under what circumstances this happens. He stated that research on the problem must consider (1) the metabolic status of the population (production and use of CO_2 and O_2), (2) the light transmitting qualities of the medium, and (3) the characteristics of the suspensoids and the color-controlling light transmission.

The complexity of measuring the effects of turbidity on aquatic plants should not discourage the biologist investigating the problems, for often the effects are very dramatic. Cordone and Pennoyer (1960) found that an abundant population of algal pads of the genus *Nostoc* was virtually destroyed by sediment discharged into the Truckee River, California.

Storms usually increase the turbidity of streams, and man's activities increase and prolong the period when light penetration is lessened. The question of the effects of relatively short periods of turbidity needs much study. Short-term discharges of sediment may do little visible damage to fishes, bottom fauna, or fish eggs, but may interrupt the entire biological complex through effects on algae.

INFLUENCES OF SEDIMENT UPON CHEMICAL AND PHYSICAL CHARACTERISTICS

Ellis (1936) outlined the important ways in which sediment affects the chemical and physical characteristics of the environment. He described changes in turbidity and light penetration in a number of streams where silt load had increased as a result of erosion. In addition he found that rates of heat transmission and heat radiation in waters carrying erosion silt were essentially the same as those for distilled water when the samples were constantly agitated. If the samples were undisturbed, the stratification of silt interfered with heat transmission and produced a skew lag in the warming and cooling curves. Regarding changes in chemistry, Ellis found, through chemical determinations, that erosion silt does not materially alter the salt complex or the amount of electrolytes in river waters. He found that the specific conductance of river water fell after heavy rains despite great increases in the erosion silt load. Measurements in the Mississippi River demonstrated that available mineral salts, light penetration, and plankton were all reduced after rains or high water.

Ellis found that organic particles and other substances in the river are carried to the bottom as silt settles out. Often these substances are incompletely decomposed, so that large demands are made on the dissolved oxygen concentration of the river and noxious compounds are formed in these mud deposits. Field investigations were verified with laboratory experiments that also demonstrated that disturbances in pH and carbonate balances were also sustained over a much longer period when organic material was carried down by erosion silt than when deposited with sand.

Our review has turned up no work on the subject as extensive as that done by Ellis. Several authors have reported briefly on temperatures, dissolved oxygen, and pH during sediment pollution investigations.

Ziebell and Knox (1957) found no differences between dissolved oxygen and pH values above and below a source of siltation from a gravel washing plant. Casey (1959) also found no change in dissolved oxygen and pH below an active placer dredging operation in Idaho, but did find that water temperatures below the dredged area were one to two degrees higher than in the clear water above the dredge. A number of other silt pollution studies included measurements of dissolved oxygen, and pH above and below a silt discharge. None showed significant changes.

When organic materials enter the stream along with silt, such as is the case with logging debris, then changes in water chemistry, particularly reduced dissolved oxygen, can be expected. This has been recorded on numerous occasions during field investigations of logging pollution in the north-coastal counties of California.

The combination of silt and organic matter in a stream seriously complicates normal aeration processes as pointed out by Dunham (1958). Following field observations on Indian Creek, California, plus a review of Phelps (1944), he outlined the problem as follows:

> "Occasionally in turbid streams there is another very subtle factor called benthal decomposition which helps to significantly reduce the amount of dissolved oxygen at a critical time in the spring and summer months. If large amounts of organic material are brought into a stream during the runoff period, some portion of this material will be deposited in the bottom of pools and other areas of low velocity. During other periods of the year a part of the normal pollutional load carried by a stream will settle out and be deposited on the stream bottom. If these settled materials are accumulated in relatively large amounts they are recognized as sludge beds. If the stream continues to carry silt, it will also be deposited in these areas of low velocity and cover the organic material previously deposited forming a benthal deposit. This organic material will decompose slowly by an anaerobic process—a process which does not require oxygen. The end products of this

> process will decompose farther in the presence of oxygen and actually use dissolved oxygen in the water. As the spring temperatures rise and the flow decreases, the organic material under the silt and sand begins to decompose at an increased rate. The end products of this decomposition, such as hydrogen sulphide, ammonia, iron, methane gas, carbon dioxide, and hydrogen, are soluble in water and gradually diffuse upward through the overlying silt and sand.
>
> "At the surface of this bottom mud, the bacteria living in the water utilize these materials in an aerobic process which takes oxygen from the stream. This oxygen demand on the stream may be present over a long section of stream. It comes at a critical time when temperatures may be high, stream flows low, and when the stream is carrying an existing pollutional load which also demands oxygen. If the stream has a poor ability to recover from low dissolved oxygen conditions, benthal decomposition will make the situation even worse because it usually extends over an appreciable length of stream.
>
> "Decomposition of benthal deposits has its greatest effect on the stream in a limited zone at the surface of the bottom materials. This zone will have the greatest concentration of substances such as hydrogen sulphide, ammonia, and carbon dioxide which are harmful to many organisms, and it will have the lowest concentration of dissolved oxygen. The presence of decomposing benthal deposits may be a limiting factor in some areas which could otherwise produce important food organisms. Consider even a riffle where anaerobic decomposition is taking place under and around the rocks, and suppose the stream has near-critical dissolved oxygen levels at times. The further decomposition of the materials resulting from anaerobic decomposition may take enough oxygen from the micro-habitat under and around rocks to be a significant factor limiting the distribution of aquatic organisms in certain instances."

The recent use of rivers to discharge atomic wastes places the problem in a somewhat different and even more serious light. Lackey, Morgan, and Hart (1959) reported on a series of experiments testing the ability of sediment of different sizes to settle blooms of *Golenkinia* and *Euglena* and to absorb and settle out radioactive substances. Sand, muck, and clay all were quite effective in settling the plankton.

In a stream polluted with atomic wastes, micro-organisms generally concentrate radioactive waste and they, being eaten by higher animals, transfer it along the food chain perhaps to man. The experiments demonstrated that the sediment itself absorbed radioactive ions and settled out.

INFLUENCES OF SEDIMENT UPON FISH HABITAT AND FISH POPULATIONS

There can be little doubt that numerous fisheries have been destroyed by erosion and sediment deposition during the periods of rapid development of this country and others. Unfortunately, only a few cases have been analyzed by fisheries workers.

The studies of Aitken (1936) and Trautman (1957) correlating great changes in the fish fauna of the mid-west, with increased erosion and sediment deposition, have been previously mentioned. Both report a change from what are considered game fishes to less desirable types.

Trautman, after reviewing the early Ohioana literature critically, concludes (page 28) that in 1750 there was little erosion in what is now Ohio. "The stream bottoms consisted almost entirely of clean sand, gravels, boulders, bedrock, and muck, peat, and other organic debris. The amount of clayey silt of stream and lake bottoms was negligible." Of the fish fauna he says (page 29), "The population of fishes were very great, especially of large fishes desired as human food." Trautman refers to pikes, walleyes, catfishes, buffalo fishes, suckers, drums, and sturgeons. He blames the decline of this fish population on a number of habitat changes wrought by man, the principal one being the introduction into the waters of large amounts of sediment (page 26):

> "Studies made since 1925 have proved that since then, if not before, soil suspended in water has been the most universal pollutant in Ohio and *the* one which has most drastically affected the fish fauna. Clayey soils, suspended in water, prohibited the proper penetration of light, thereby preventing development of the aquatic vegetation, of the food of fishes, of fish eggs, and of fry . . . Settling over the formerly clean bottoms, silt destroyed the habitat of those fish species requiring bottoms of sand, gravel, boulders, bedrock, or organic debris."

Wolf (1950) blames erosion and sediment deposition for the disappearance of the Atlantic salmon from many of its haunts around Lake Ontario. Eschmeyer (1954) mentioned the Whitewater River drainage in Minnesota, where by 1941 the original 150 miles of good trout stream were reduced to 60 miles by erosion.

Sediment problems in California rivers received some attention during the days of intense hydraulic mining for gold (1850-1900). Sediment loads were so heavy that farm lands in the Sacramento Valley were covered with soil and sand washed into the American and Yuba rivers. King salmon runs were at least temporarily destroyed and many miles of streams rendered unfit for trout (Sumner and Smith, 1939).

Sumner and Smith seined in the muddy sections of two tributaries of Yuba River, California, taking no trout whatsoever. Turbidity was attributed to the washings of pulverized ore from hard-rock gold mines. In one stream there was the possibility of toxicity from a cyanide flotation process. In a stream where muddiness occurred only once a week and lasted but a few hours, trout could still be found. The authors concluded, ". . . this survey, as well as other observations, shows conclusively that very heavy continuous silting will greatly reduce, if not completely eliminate, salmon or trout: In the Yuba River at Washington, to cite one good case, a pool was seen completely filled in with fine silt so that there was no place for a fish to hide. When this happens to long stretches of stream, game fish will be driven out. Shelter is just as important as food."

Dredging and mining continue in the west and have been the subject of considerable investigation. Campbell (1953) described fish population studies on the Powder River, Oregon, in relation to siltation from a gold dredger. Samples were collected with an electroshocker during and following cessation of dredging. Although data were not given, the report states that sport fish did exist prior to operations in the silted zone. "Results of fish population studies in the various zones of pollution in Powder River indicated a complete alteration of the population from sport fish [rainbow trout and whitefish] above all major sources of pollution to rough fish [squawfish, suckers, etc.] in the zone of pollution and recovery. Although the desirable fish-food organisms gradually returned and conditions at North Powder were satisfactory for sport fish at the time of the survey, rough fish persisted. It is probable that under conditions of greater stream flow, the effects of the dredge wastes will persist farther downstream." The silted area was finally rotenoned to remove rough fish and then planted with trout. Creel census indicates that a sport fishery was successfully reestablished (Wilson, 1957).

According to Casey (1959), the fish population of Seigel Creek, Idaho, prior to operation of a placer dredge, was approximately the same in sections above, below, and within the area to be dredged. Fishes present were sculpin, dace, mountain suckers, mountain whitefish, and cutthroat, rainbow, and eastern brook trout. Population studies made at the end of about two months of operation showed no fish in the dredged section and a dominant rough fish population "below." Species composition above the silted area remained about the same.

Studies by Bachmann (1958) showed no changes in trout populations in a silted section of a northern Idaho trout stream. Direct disturbance of the stream was not great, however, and came from installation of culverts at road crossings, rechannelization of 1,000 feet of stream, and some log skidding in the streambed. Sampling difficulties prevented accurate comparisons.

Wustenberg (1954) reported that cutthroat trout populations were eliminated from three small streams crossed by tractor logging. The major source of silt was believed due to road building rather than the actual logged areas. A further note on the status of these trout populations appeared in the Annual Report for 1954 of the Oregon State Game Commission (1955, p. 216):

> "A tributary stream, previously reported as being one in which 'cat logging' eliminated the trout population, was found to again possess fish in the area which was barren a year earlier. Such a finding suggests that practices presently regarded as extremely destructive may be more temporary than heretofore suspected."

Seamans (1959, p. 21) reports that the lower section of the Saco River in New Hampshire supported one of the three best large brook trout fisheries shortly after the turn of the century. His observations suggest that the decline may well have been the result of sedimentation. The bottom of the stream is now shifting sand which has reduced shelter to a minimum.

During the winter of 1957, finely ground rock waste from a molybdenum mine polluted Moore Creek in California. Sampling with an electric shocker revealed a healthy population of native rainbow trout above the pollution, but only three pale-colored, emaciated fingerlings were caught with equal effort in the polluted section.

Cordone and Pennoyer (1960) reported on the extensive sedimentation of the Truckee River and Cold Creek in California by a gravel washing operation. Using similar "above and below" sampling with an electric shocker, they found a reduced trout population in the zone affected by sediment.

An excellent study of the effects of sediment upon the habitat and subsequent survival of planted Atlantic salmon fingerlings was made by McCrimmon (1954). From 1944 to 1949, he studied the survival and distribution of planted Atlantic salmon fry in Duffin Creek, a tributary of Lake Ontario. Fish populations in 19 experimental sections were assessed by use of the "one-man" hand seine.

Various factors which might influence survival were studied quantitatively. These included temperature, turbidity, predation, shelter, bottom sedimentation, shade, abnormal water flow, and food. McCrimmon concluded that the degree of bottom sedimentation determined the amount of shelter offered and this in turn determined the extent of predation. Clearing of woodlands for agriculture had resulted in extensive erosion in the watershed.

Bottom sedimentation was measured by means of small glass collectors placed in riffle areas under standard conditions for two weeks at a time. Material collected was air-dried for 24 hours at 100 degrees C. and then measured. A detailed explanation of mechanisms of sedimentation versus fish was presented (pages 396 and 398):

> "It has been shown in a previous section that the shelter offered by shallow gravelly riffle areas was the only satisfactory habitat for the high survival of planted fry in all streams. In the general description of the relative extent of sedimentation over the stream system, the criterion employed was the degree to which these gravelly riffle areas had become sedimented. Areas typed as "unsedimented" were those in which the spaces around the gravel and rubble were not filled in by sediment and hence offered the shelter required by the planted fry. The degree of bottom sedimentation played an important part in influencing the survival and distribution of the planted salmon.
>
> "As the amount of sedimentation of the stream bottom increased from the 'unsedimented' to 'heavily sedimented' condition, the apertures and spaces around the gravel, rubble and other irregularities even in the riffle areas became filled with sediment, until the protective cover offered to the small frys became low, resulting in a high salmon mortality. Thus the amount of sedimentation in the riffle areas largely determined the survival of salmon over the stream system.
>
> "It was shown that the survival of the small fry in the pools was low, largely because the absence of suitable shelter for the young salmon resulted in predation by certain species of fish. This lack of shelter was directly caused by the deposition of sediment in the pools sufficiently great to cover generally the gravel and rubble, and fill in the spaces around stones, boulders, logs and the like, to an extent that they could not be utilized by the fry.
>
> "From these observations on the correlation of the degree of bottom sedimentation in the gravelly riffle areas with the percentage survival of underyearling salmon, it may be concluded that the

> effect of sedimentation was to destroy the shelter offered by the riffle areas which was needed for the survival of the salmon fry during and following planting. Sedimentation in the pools resulted in a low survival of fry even in stream sections where the riffle areas were free of sediment and provided excellent habitat for young salmon.
>
> "Since the survival studies show that, once the salmon population had become established in the stream as fry and underyearlings, further mortality until the following autumn as yearlings was very low, it would seem that bottom sedimentation did not cause any appreciable mortality of the larger salmon. However, the inability of most of the tributary stream sections with high underyearling survivals to support the same number of salmon in their pools as yearling fish may be attributed largely to sedimentation."

Our own observations in California lead us to believe that shelter may be the factor limiting the numbers of trout growing to catchable size in many small streams. Even though abundant fingerlings are produced and riffle areas are kept clean by current velocity, sediment deposited in pools and runs fills in the spaces between boulders and rubble, reducing shelter for trout to a minimum. Extensive experience in sampling small trout streams on the west slope of the Sierra Nevada leads us to generalize that, all other things being equal, streams with clean rubble bottoms have large trout populations and streams with bottoms containing much sand or decomposed granite contain fewer catchable-sized fish.

SEDIMENT STANDARDS

An important tool in the pollution control programs of recent years has been the setting of "standards" of water quality of streams and rivers receiving waste discharges. Obviously sediment discharge is pollution. It is deleterious and usually caused by the activities of man.

Sediment standards are difficult to set and would be meaningful only if based upon thorough studies that allow accurate prediction of sedimentation rates, turbidities, and subsequent biological effects. Cooper (1956) appears to have done this on the Horsefly River in British Columbia.

Following a very thorough analysis of possible silt pollution from a placer mining operation, he arrived at the following recommendations for protection of sockeye spawning in the Horsefly River, British Columbia:

1. No placer mining operations be permitted in the stream bed or in any tributary stream beds.
2. No placer mining operations be permitted adjacent to the river or any of its tributaries without provision of settling basins to clarify all sediment-carrying waters by sedimentation and, if necessary, by filtration.
3. All suspended sediment in the effluent from such basins should be less than 0.1 mm. in diameter, and during the period July 1 to April 1, the turbidity of the effluent should be less than 25 ppm.

4. Any settled materials removed from the ponds during periodic clean-outs must be disposed of on land where they cannot be washed into the river or its tributaries.

Ellis (1937) suggested that if conditions even approximating those when erosion was checked by forest and grassland are to be restored, ". . . the silt load of these streams should be reduced so that the millionth intensity level would not be less than 5 meters, . . ." The millionth intensity level is the depth at which light is reduced to one millionth of its intensity at the surface.

Ellis (1944) restated this conviction and added to it, in an effort to prevent direct damage to the gills and delicate exposed structure of fishes, mollusks, and insects:

> "From the standpoint of aquatic life therefore all particulate matter introduced by man of a hardness of one or greater should be so finely pulverized that it would pass through a 1,000 mesh screen, and should be so diluted that the resultant turbidity would not reduce the millionth intensity level to less than 5 meters. The quantity should be controlled so that the stream could carry the powder away without blanketing the bottom to the depth of more than one quarter of an inch."

Tarzwell (1957) felt that it was not possible to establish numerical criteria for settleable solids which are applicable over wide areas. He maintained that the amount of damage done will vary with the character of the stream and its substrate. He felt that criteria should be established to protect environmental conditions but they will vary from stream to stream, depending on local conditions. He discussed some tentative criteria based on measures of light penetration (page 253):

> "Turbidity standards must be somewhat local in their application as they will depend on the area and type of stream. It is possible to set up relatively simple turbidity standards which can be readily checked for compliance by field tests. Turbidity standards might state that a certain percentage of the incident light at the surface shall reach a stated depth between 11:00 A.M. and 1:00 P.M. The depth selected would depend on the depth to which the regulatory agency felt the photosynthetic zone should extend. Different types of water differ in their capacities to absorb light. Water transparency is affected by the suspended matter, including the plankton, and by stain or color. In water of the clarity of usual municipal supplies, 9.5 percent of the solar energy present at the surface reaches a depth of 6 feet . . . the limit for growth for the higher aquatic plants lies between 2.5 and 3.5 percent of the total surface energy at bottom depth, but that it rapidly declines below 4 percent where severe etiolation occurs in submerged seed plants. There is some evidence that certain algae can grow at levels of 1 percent of the incident light, but it is not definitely known how much light is required for them to produce more oxygen by photosynthesis than they use in their respiration. While criteria will vary with the area they can be kept relatively simple. For example, a criterion for a particular area might state—under conditions of brilliant sunlight at or near noon 4 percent of surface incident light

> shall reach a depth of 6 feet. Incident light and light at any given depth can be readily read by means of photometer fitted for underwater use.''

Wilson (1957) stated that, ". . . rather than to propose arbitrary criteria either for turbidity or settleable solids, some percentage increase above normal low flow concentrations should be established. This would take into consideration differences in watershed and stream or reservoir characteristics.''

The Aquatic Life Advisory Committee of the Ohio River Valley Water Sanitation Commission (1956) did not establish requirements governing settleable solids. The seriousness of the silt pollution problem was presented in detail, but due to a lack of exact information, no valid criteria were formulated.

Waste discharge requirements commonly set on an operation likely to discharge sediment into trout, salmon or steelhead waters tributary to the Central Valley of California usually contain the following clauses adopted by the Central Valley Water Pollution Control Board:

Any waste discharged into the waters of ________ Creek:

1. Shall *not* cause an increase in the natural turbidity during the period from May 1 to November 1 of each year.
2. Shall not contain deleterious substances in amounts which would be toxic or harmful to animal or aquatic life.
3. Shall not produce silt or gravel deposits.
4. Shall not cause the dissolved oxygen content of receiving waters to fall below 7.0 ppm.

Protection of the streams from damage by excess turbidity during the period November 2 to April 31 must depend upon investigations to show that requirement Number 2 was violated. Certainly no standards are by themselves going to prevent damage from sediment; but equipped with a general set like this, a knowledge of what has been learned in the past by others, and some biological investigation on the stream, the biologist should be able to greatly reduce it.

LONG-TERM SILTATION RESEARCH

Among fisheries scientists, there is an increasing awareness of the need for basic, long-term investigations on the influences of erosion and siltation on fish production. To our knowledge, there are at least four such projects now in existence. All of these are concerned with the relationships between logging operations and production of salmon or trout in streams. Siltation is but one, although probably the most important, of the means by which logging and its associated works act to modify the stream habitat.

Four small trout streams in northern Idaho are under investigation by the Idaho Cooperative Wildlife Research Unit of the College of Forestry, University of Idaho. Trout species include both cutthroat and eastern brook. Studies of these streams prior to road construction and actual logging have been completed (Oien, 1957). The second phase of the study covered the influence of logging road construction on the physical, chemical, and biological characters of the disturbed stream

(Bachmann, 1958). The final phase now in progress will cover the effects of actual logging in the area.

Another long-range project designed to critically evaluate the influences of logging is now under way on four salmon streams in Alaska. It was initiated in 1949 by the Alaska Forest Research Center of the U. S. Forest Service and will cover at least a 15-year period. A summary of the program and of the Center's first five years of work prior to logging was published by James (1956) and Anderson and James (1957). Data of great interest on natural changes in stream channel topography, sedimentation, and movements of bottom material are presented in the former paper. The need for biological investigation brought about a cooperative research program starting in 1956 between the Center and the Fisheries Research Institute of the University of Washington under contract to the U. S. Fish and Wildlife Service (Sheridan and McNeil, 1960).

For the past seven years the Department of Zoology of the University of California at Berkeley has studied the fish populations, fish habitat, and related matters on Sagehen Creek, California. These studies will be extended to include the effects of stream flow and sedimentation on fish populations (Anderson, 1958). Evaluations will cover the effects of forest, brushland, and other land treatments on streamflow, sedimentation, and fish habitat and populations. Trout species include brown, rainbow, and eastern brook.

The final, known long-term research project on the influences of logging is proceeding under direction of the Oregon Cooperative Wildlife Research Unit, Oregon State College. The results of preliminary studies were presented by Wustenberg (1954). Current plans call for an extended study of pre-logging conditions on trout streams.

SUMMARY

Almost all of the investigations we have reviewed on the effects of sediment on the aquatic life of flowing waters have been done on streams inhabited by trout and salmon. Only historical changes and the work of Ellis (1931a) are available to evaluate the warm waters.

There is abundant evidence that sediment is detrimental to aquatic life in salmon and trout streams. The adult fishes themselves can apparently stand normal high concentrations without harm, but deposition of sediments on the bottom of the stream will reduce the survival of eggs and alevins, reduce aquatic insect fauna, and destory needed shelter. There can scarcely be any doubt that prolonged turbidity of any great degree is also harmful.

The question, "How much sediment is harmful?" has not yet been answered since most workers have failed to measure the amounts of sediment. The Aquatic Life Advisory Committee of the Ohio River Valley Water Sanitation Commission (1956) reviewed the problem and reached the following conclusion:

> ". . . only a small amount of sand or silt shifting in and around the gravel of the bottom eliminates much of the area suitable for the attachment or hiding of the aquatic insects and drastically reduces the total production of these forms. Small amounts of sand, not discernable by casual inspection but evident only on close ex-

> amination of the bottom materials, can bring about significant changes.
>
> "To the best of our knowledge adequate data are not available on the amounts of inorganic materials which can be added to a stream without significant harm to its productive capacity. . ."

This certainly agrees with our own observations. Field investigations with electric sampling gear in the Sierra Nevada over the past years have led us to develop the maxim, "Clean stream bottoms mean good trout populations." By "clean" we mean lacking much sand.

Many of the sediment problems reported in the literature are the result of large-scale discharges of sediment from gravel washing or mining operations. These are often spectacular but probably less important than the gradual deposition being caused by erosion.

The increasing activity of man on our mountain watersheds in California is resulting in obviously increased erosion and sediment deposition. Our failure to recognize that even small amounts of sediment may be harmful may well result in gradual destruction of the majority of our streams, while we work feverishly to solve more obvious and spectacular problems.

We have been impressed by two facts. *First*, there has been sufficient work done to establish the fact that sediment is harmful to trout and salmon streams; the only references found to the contrary (Ward 1938a and 1938b) have been adequately criticized. *Second*, our experience in the Sierra Nevada indicates that the bulk of the damage there is unnecessary. It can be prevented with known land use methods, often with little or no additional expense. Much of it is the result of carelessness.

More than anything else we need to develop a philosophy of land husbandry that will avoid the creation of untreated and running sores on the earth's surface. Man must acquire a responsibilty to future generations that matches the power he has gained through the development of heavy machinery.

Our observations in the field and our review of the existing literature leads us to the unshakable conclusion that unless this can be done many of our trout streams will be destroyed by the deposition of sediment.

REFERENCES

Aitken, W. W.
1936. The relation of soil erosion to stream improvement and fish life. Jour. Forestry, vol. 34, no. 12, pp. 1059-1061.

Alderdice, D. F., and W. P. Wickett
1958. A note on the response of developing chum salmon eggs to free carbon dioxide in solution. Fish. Res. Bd. Canada, Jour., vol. 15, no. 5, pp. 797-799.

Alderdice, D. F., W. P. Wickett, and J. R. Brett
1958. Some effects of temporary exposure to low dissolved oxygen levels on Pacific salmon eggs. Fish. Res. Bd. Canada, Jour., vol. 15, no. 2, pp. 229-250.

Allen, K. Radway
1940. Studies on the biology of the early stages of salmon *(Salmo salar)*, I. Growth in the River Eden. Jour. Anim. Ecol., vol. 9, no. 1, pp. 1-23.
1951. The Horokiwi stream, a study of a trout population. New Zealand Mar. Dept., Fish. Bull. 10, 231 pp.
1959. The distribution of stream bottom faunas. New Zealand Ecol. Soc., Proc., no. 6, pp. 5-8.

Anderson, Harold E., and George A. James
1957. Watershed management and research on salmon streams of southeast Alaska. Jour. Forestry, vol. 55, no. 1, pp. 14-17.

Anderson, Henry W.
1958. Progress report, 1957-58, California cooperative snow management research. U. S. Forest Serv., Calif. For. and Range Exp. Sta., 56 pp.

Aquatic Life Advisory Committee of the Ohio River Valley Water Sanitation Commission
1956. Aquatic life water quality criteria, second progress report. Sewage and Indus. Wastes, vol. 28, no. 5, pp. 678-690.

Bachman, Roger Werner
1958. The ecology of four north Idaho trout streams with reference to the influence of forest road construction. Master's Thesis, Univ. Idaho, 97 pp. (Typewritten)

Bartsch, A. F., and J. H. Schilpp
1953. Water pollution survey of the Potomac River Hancock-Williamsport Section. A cooperative report by St. of Md. Water Poll. Control Comm.; West Va. St. Water Comm.; and No. Atlantic Drainage Basins Office, Dir. of Water Poll. Control, Publ. Health Serv.

Benson, Norman G.
1954. Seasonal fluctuations in the feeding of brook trout in the Pigeon River, Michigan. Amer. Fish. Soc., Trans., vol. 83 (1953), pp. 76-83.

Brown, Margaret E.
1946. The growth of brown trout *(Salmo trutta* Linn.), II. The growth of two-year-old trout at a constant temperature of 11.5 degrees C. Jour. Exp. Biol., vol. 22, pp. 130-144.

Campbell, H. J.
1953. Report on biological reconnaissance on the effect of gold dredging and mining operations on Powder River, Oregon, September 29-October 1, 1953. Oregon St. Game Comm., 8 pp. (Processed)
1954. The effect of siltation from gold dredging on the survival of rainbow trout and eyed eggs in Powder River, Oregon. Oregon St. Game Comm., 3 pp. (Processed)

Casey, Osborne E.
1959. The effects of placer mining (dredging) on a trout stream. Ann. Prog. Rept., Project F34-R-1, Water Quality Investigations, Federal Aid in Fish Restoration, Idaho Dept. of Fish and Game, pp. 20-27. (Mimeo.)

Cooper, A. C.
1956. A study of the Horsefly River and the effect of placer mining operations on sockeye spawning grounds. Internat. Pac. Salmon Fisheries Comm., Publ. 1956:3, 58 pp. (Processed)

Cooper, Edwin L.
1953. Periodicity of growth and change of condition of brook trout (*Salvelinus fontinalis*) in three Michigan trout streams. Copeia, no. 2, pp. 107-114.

Cooper, Edwin L., and Norman G. Benson
1951. The coefficient of condition of brook, brown, and rainbow trout in the Pigeon River, Otsego County, Michigan. Prog. Fish.-Cult., vol. 13, pp. 181-192.

Cordone, Almo J.
1956. Effects of logging on fish production. Calif. Dept. Fish and Game, Inland Fisheries Admin. Rept. no. 56-7, 98 pp. (Mimeo.)

Cordone, Almo J., and Steve Pennoyer
1960. Notes on silt pollution in the Truckee River drainage. Calif. Dept. Fish and Game, Inland Fisheries Admin. Rept. no. 60-14, 25 pp. (Mimeo.)

Corfitzen, W. E.
1939. A study of the effect of silt on absorbing light which promotes the growth of algae and moss in canals. U. S. Dept. of Interior, Bur. of Reclamation, 14 pp. (Mimeo.)

Dunham, L. R.
1958. Notes on the Indian Creek erosion problem. Report to Calif. Dept. Fish and Game, Region II, Inland Fisheries Branch, 29 pp. (Typewritten)

Einstein, H. A., and J. W. Johnson
1956. Sediment problems in California. Proc. on Confer. on Sediment Problems in California. Sponsored by Hydraulic Lab., Dept. Eng., Univ. Calif., Issued by Committee on Research in Water Resources, 142 pp.

Ellis, M. M.
1931a. A survey of conditions affecting fisheries in the upper Mississippi River. U. S. Dept. Commerce, Bur. Fisheries, Fishery Circ. 5, 18 pp.
1931b. Some factors affecting the replacement of the commercial fresh-water mussels. U. S. Dept. Commerce, Bur. Fisheries, Fishery Circ. 7, 10 pp.
1936. Erosion silt as a factor in aquatic environments. Ecology, vol. 17, no. 1, pp. 29-42.
1937. Detection and measurement of stream pollution. U. S. Dept. of Commerce, Bur. Fisheries, Bull. 22, vol. 48, pp. 365-437.
1944. Water purity standards for fresh-water fishes. U. S. Fish and Wildl. Serv., Spec. Sci. Rept. 2, 18 pp.

Ellis, Robert J., and Howard Gowing
1957. Relationship between food and supply and condition of wild brown trout, *Salmo Trutta* Linnaeus, in a Michigan stream. Jour. Limnology and Oceanography, vol. 2, no. 4, pp. 299-308.

Eschmeyer, R. W.
1954. Erosion—and fishing. Montana Wildlife, vol. 4, no. 2, pp. 21-23.

Eustis, A. B., and R. H. Hillen
1954. Stream sediment removal by controlled reservoir releases. Prog. Fish-Cult., vol. 16, no. 1, pp. 30-35.

Foskett, D. R.
1958. The Rivers Inlet sockeye salmon. Fish. Res. Bd. Canada, Jour., vol. 15, no. 5, pp. 867-889.

Gangmark, Harold A., and Robert D. Broad
1955. Experimental hatching of king salmon in Mill Creek, a tributary of the Sacramento River. Calif. Fish and Game, vol. 41, no. 3, pp. 233-242.
1956. Further observations on stream survival of king salmon spawn. Calif. Fish and Game, vol. 42, no. 1, pp. 37-49.

Gangmark, Harold A., and Richard G. Bakkala
1958. Plastic standpipe for sampling streambed environment of salmon spawn. Spec. Sci. Rept.: Fisheries no. 261, U. S. Fish and Wildl. Serv., 20 pp.
1960. A comparative study of unstable and stable (artificial channel) spawning streams for incubating king salmon at Mill Creek. Calif. Fish and Game, vol. 46, no. 2, pp. 151-164.

Gaufin, Arden R., Eugene K. Harris, and Harold J. Walter
1956. A statistical evaluation of stream bottom sampling data obtained from the three standard samplers. Ecology, vol. 37, no. 4, pp. 643-648.

Gleason, Clark H.
1958. Watershed management—an annotated bibliography of erosion, streamflow, and water yield publications by the California Forest & Range Experiment Station. Calif. For. and Range Exp. Sta., Tech. Paper no. 23, 79 pp.

Gottschalk, L. C., and Victor H. Jones
1955. Valleys and hills, erosion and sedimentation. *In:* Water. Yearbook of Agriculture, 1955, U. S. Dept. of Agric., pp. 135-143.

Griffin, L. E.
1938. Experiments on the tolerance of young trout and salmon for suspended sediment in water. *In:* Placer mining on the Rogue River, Oregon, in its relation to the fish and fishing in that stream, by Henry Baldwin Ward. Oregon Dept. Geology and Mineral Industries, Bull. 10, Appendix B, pp. 28-31.

Hales, Donald C., and William F. Sigler
1954. Evaluation of stream bottom fauna sampling techniques as used on the Logan River. Utah Coop. Wildl. Res. Unit, Quarterly Activity Rept., vol. 19, no. 2, pp. 50-54. (Mimeo.)

Harrison, C. W.
1923. Planting eyed salmon and trout eggs. Amer. Fish. Soc., Trans., vol. 53, pp. 191-200.

Heg, Robert T.
1952. Stillaguamish slide study. Summary of data obtained by research division during 1952. Wash. Dept. Fish., 11 pp. (Typewritten)

Hertzog, Donald E.
1953. Stillaguamish slide study. Wash. Dept. Fish., Feb. 20, 1953, 29 pp. (Typewritten)

Hobbs, Derisley F.
1937. Natural reproduction of quinnat salmon, brown and rainbow trout in certain New Zealand waters. New Zealand Mar. Dept., Fish. Bull. 6, 104 pp.

James, G. A.
1956. The physical effect of logging on salmon streams of southeast Alaska. Alaska Forest Res. Center, U. S. Dept. Agric., U. S. Forest Serv., Sta. Paper 5, 49 pp.

Kemp, Harold A.
1949. Soil pollution in the Potomac River Basin. Amer. Water Works Assoc., Jour., vol. 41, no. 9, pp. 792-796.

Lackey, James B.
1947. Stream microbiology. *In:* Stream sanitation, by Earle B. Phelps, John Wiley and Sons, Inc., New York, pp. 227-265.

Lackey, James B., George B. Morgan, and Oral H. Hart
1959. Turbidity effects in natural waters in relation to organisms and the uptake of radioisotopes. Engin. Progress at the Univ. of Fla., Fla. Engin. and Indust. Exper. Sta., Coll. of Engin., Univ. of Fla., vol. 13, no. 8, Tech. Paper 167, 9 pp.

Leonard, Justin W.
1939. Comments on the adequacy of accepted stream bottom sampling technique. Fourth No. Amer. Wildl. Conf., Trans., pp. 288-295.
1948. Importance of fish food insects in trout management. Michigan Cons., vol. 17, no. 1, pp. 8-9.

Maciolek, John A., and P. R. Needham
1952. Ecological effects of winter conditions on trout and trout foods in Convict Creek, California, 1951. Amer. Fish. Soc., Trans., vol. 81 (1951), pp. 202-217.

McCrimmon, H. R.
1954. Stream studies on planted Atlantic salmon. Fish. Res. Bd. Canada, Jour., vol. 11, no. 4, pp. 362-403.

McDonald, J. G., and M. P. Shepard
1955. Stream conditions and sockeye fry production at Williams Creek, Fish. Res. Bd. Canada, Prog. Repts. on Pac. Coast Sta., no. 104, pp. 34-37.

Neave, Ferris
1947. Natural propagation of chum salmon in a coastal stream. Fish. Res. Bd. Canada, Prog. Repts. of Pac. Coast Sta., no. 70, pp. 20-21.

Needham, Paul R., and Robert L. Usinger
1956. Variability in the macrofauna of a single riffle in Prosser Creek, California, as indicated by the Surber sampler. Hilgardia, vol. 24, no. 14, pp. 383-409.

Oien, Waine E.
1957. A pre-logging inventory of four trout streams in northern Idaho. Master's Thesis, Univ. Idaho, 92 pp. (Typewritten)

Oregon State Game Commission
1955. Annual report, fishery division, 1954. Ore. St. Game Comm., Fishery Div., 239 pp.

Oregon State Game Commission, Oregon State Sanitary Authority, and U. S. Public Health Service
1955. Gold dredge siltation, Powder River, Oregon, 1953-1955. Water Supply and Water Pollution Control Program, 9 pp. (Mimeo.)

Osborn, Ben
1955. How rainfall and runoff erode soil. *In:* Water, Yearbook of Agriculture, 1955, U. S. Dept. of Agric., pp. 126-135.

Pautzke, Clarence F.
1938. Studies on the effect of coal washings on steelhead and cutthroat trout. Amer. Fish. Soc., Trans., vol. 67 (1937), pp. 232-233.

Pennak, Robert W., and Ernest D. Van Gerpen
1947. Bottom fauna production and physical nature of the substrate in a northern Colorado trout stream. Ecology, vol. 28, no. 1, pp. 42-48.

Phelps, Earle B.
1944. Stream sanitation. John Wiley and Sons, Inc., New York, 276 pp.

Phinney, Harry K.
1959. Turbidity, sedimentation and photosynthesis. *In:* Siltation—its sources and effects on the aquatic environment, Fifth Symposium-Pacific Northwest, Dept. Health, Ed., and Welfare, U. S. Public Health Serv., Water Supply and Water Poll. Control Program, Portland, Ore., pp. 4-12. (Mimeo.)

Pollard, R. A.
1955. Measuring seepage through salmon spawning gravel. Fish. Res. Bd. Canada, Jour., vol. 12, no. 5, pp. 706-741.

Powell, Guy C.
1958. Evaluation of the effects of a power dam water release pattern upon the downstream fishery. Colo. Coop. Fish. Res. Unit, Quarterly Rept., vol. 4, pp. 31-37.

Seamans, Richard G., Jr.
1959. Trout stream management investigations of the Saco River watersheds. New Hampshire Fish and Game Dept., Survey Rept. no. 9, 71 pp.

Shapovalov, Leo
1937. Experiments in hatching steelhead eggs in gravel. Calif. Fish and Game, vol. 23, no. 3, pp. 208-214.

Shapovalov, Leo, and William Berrian
1940. An experiment in hatching silver salmon (*Oncorhynchus kisutch*) eggs in gravel. Amer. Fish. Soc., Trans., vol. 69 (1939), pp. 135-140.

Shapovalov, Leo, and Alan C. Taft
1954. The life histories of the steelhead rainbow trout (*Salmo gairdnerii gairdnerii)* and silver salmon *(Oncorhynchus kisutch)*, Calif. Dept. Fish and Game, Fish Bull. 98, 375 pp.

Shaw, Paul A., and John A. Maga
1943. The effect of mining silt on yield of fry from salmon spawning beds, Calif. Fish and Game, vol. 29, no. 1, pp. 29-41.

Sheridan, William L., and William J. McNeil
1960. Effects of logging on the productivity of pink salmon streams in Alaska. *In:* Res. in Fish., 1959, Coll. of Fish., Fish. Res. Inst., Univ. of Wash., Contrib. no. 77, pp. 16-17.

Smith, Loyd L. Jr., and John B. Moyle
1944. A biological survey and fishery management plan for the streams of the Lake Superior north shore watershed. Minn. Dept. of Conservation, Div. of Game and Fish, Tech. Bull. 1, 228 pp.

Smith, Osgood R.
1940. Placer mining silt and its relation to salmon and trout on the Pacific Coast. Amer. Fish. Soc., Trans., vol. 69 (1939), pp. 225-230.

Snyder, George R.
1959. Evaluation of cutthroat trout reproduction in Trappers Lake inlet. Colo. Coop. Fish. Res. Unit, Quarterly Rept., vol. 5, pp. 12-52.

Sprules, Wm. M.
1947. An ecological investigation of stream insects in Algonquin Park, Ontario. Univ. Toronto Studies, Biological Series, no. 56, Publ. Ontario Fish. Res. Lab., no. 69, 81 pp.

Stuart, T. A.
1953a. Spawning migration, reproduction and young stages of loch trout (*Salmo trutta* L.). Scottish Home Dept., Freshwater and Salmon Fisheries Research, no. 5, 39 pp.
1953b. Water currents through permeable gravels and their significance to spawning salmonids, etc. Nature, London, vol. 172, no. 4374, pp. 407-408.
1954. Spawning sites of trout. Nature, London, vol. 173, no. 4399, p. 354.

Sumner, F. H., and Osgood R. Smith
1939. A biological study of the effect of mining debris dams and hydraulic mining on fish life in the Yuba and American Rivers in California. Submitted to the United States District Engineer's office, Sacramento, California; Stanford Univ., Calif. 51 pp. (Mimeo.)

Taft, A. C., and Leo Shapovalov
1935. A biological survey of streams and lakes in the Klamath and Shasta National Forests of California. U. S. Bur. of Fish., 71 pp. (Mimeo.)

Tarzwell, Clarence M.
1937. Experimental evidence on the value of trout stream improvement in Michigan. Amer. Fish. Soc., Trans., vol. 66 (1936), pp. 177-187.
1957. Water quality criteria for aquatic life. *In:* Biological problems in water pollution, U. S. Dept. Health, Educ., and Welfare, Robert A. Taft San. Eng. Center, pp. 246-272.

Tarzwell, Clarence M., and Arden R. Gaufin
1953. Some important biological effects of pollution often disregarded in stream surveys. *Reprinted from:* Purdue Univ. Eng. Bull., Proc. 8th Indus. Waste Conf., 38 pp.

Tebo, L. B., Jr.
1955. Effects of siltation, resulting from improper logging, on the bottom fauna of a small trout stream in the southern Appalachians. Prog. Fish-Cult., vol. 17, no. 2, pp. 64-70.
1957. Effects of siltation on trout streams. Soc. of Amer. Foresters, Proc., 1956 Meeting, pp. 198-202.

Terhune, L. D. B.
1958. The Mark VI groundwater standpipe for measuring seepage through salmon spawning gravel. Fish. Res. Bd. Canada, Jour., vol. 15, no. 5, pp. 1027-1063.

Trautman, Milton B.
1933. The general effects of pollution on Ohio fish life. Amer. Fish. Soc., Trans., vol. 63 (1933), pp. 69-72.
1957. The fishes of Ohio with illustrated keys. Ohio St. Univ. Press, Ohio Div. of Wildl., 683 pp.

Usinger, Robert L., and Paul R. Needham
1954. A plan for the biological phases of the periodic stream sampling program. Calif. Water Poll. Control Bd., 59 pp. (Processed)

Wallen, Eugene I.
1951. The direct effect of turbidity on fishes. Okla. Agric. and Mech. Col., Arts and Sci. Studies, Biol. Series no. 2, vol. 48, no. 2, 27 pp.

Ward, Henry Baldwin
1938a. Placer mining on the Rogue River, Oregon, in its relation to the fish and fishing in that stream. Oregon Dept. Geology and Mineral Industries, no. 10, 31 pp.
1938b. Placer mining and the anadromous fish of the Rogue River. Science, vol. 88, no. 2289, pp. 441-443.

Washington Department of Fisheries
1959. 1958 Annual report. State of Wash., Dept. of Fisheries, 303 pp.

Went, A. E. J., and W. E. Frost
1942. River Liffey survey, V. Growth of brown trout *(Salmo trutta* L.) in alkaline and acid waters. Proc. Royal Irish Acad., vol. 68, sec. B, no. 7, pp. 67-84.

Wickett, W. Percy
1954. The oxygen supply to salmon eggs in spawning beds. Fish. Res. Bd. Canada, Jour., vol. 11, no. 6, pp. 933-953.
1958. Review of certain environmental factors affecting the production of pink and chum salmon. Fish. Res. Bd. Canada, Jour., vol. 15, no. 5, pp. 1103-1126.

Wilson, John N.
1957. Effects of turbidity and silt on aquatic life. *In:* Biological problems in water pollution, U. S. Dept. Health, Educ., and Welfare, Robert A. Taft San. Eng. Center, pp. 235-239.

Wolf, Ph.
1950. American problems and practice, I. Salmon which disappeared. Salmon and Trout Magazine, no. 130, pp. 201-212.

Wustenberg, Donald W.
1954. A preliminary survey of controlled logging on a trout stream in the H. J. Andrews Experimental Forest. Master's Thesis, Oregon St. Coll., 51 pp. (Typewritten)

Ziebell, C. D.
1957. Silt and pollution. Wash. Poll. Control Comm., Information Series 57-1, 4 pp.

Ziebell, C. D., and S. K. Knox
1957. Turbidity and siltation studies, Wynooche River. Report to Washington Poll. Control Comm., 7 pp. (Mimeo.)