EFFECTS OF SEDIMENTATION ON SALMONID STREAM LIFE

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WEST VANCOUVER, B.C.

JUNE 1980

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INTRODUCTION

This paper will outline the effects of sediment on the aquatic life present in British Columbia salmonid streams. Since the group of fishes referred to as salmonids includes the grayling, whitefishes, trout, and salmon, the following considerations will apply to most streams in British Columbia. However, the reader should not consider this article to be a complete literature review on the topic; for such the reader should refer to the excellent article by Cordone and Kelley (1961). More recent articles by Phillips (1970), Gammon (1970), and Gibbons and Salo (1973) also provide good reviews of the subject. In addition, a bibliograpy of selected references has been included in this review.

Sediment is considered as inorganic, undissolved matter ranging in size from the fine colloidal clays (particles less than 0.004 mm in diameter) to larger particles commonly referred to as fine pebbles (particles 2 - 4 mm in diameter). This class of particles is commonly referred to as fines by salmonid biologists concerned with stream gravel quality. It should be noted that silt is a particle size class (0.004 - 0.062 mm in diameter) within the size range considered as sediment in this paper.

Sediments have always been present in British Columbia streams and since the last ice age have played an important role in the development of streams and stream life. Large amounts of sediments are presently carried by natural processes into many of our streams. This process is of course very active in watersheds that are geologically young, whereas the more stabilized watersheds have streams that are relatively sediment free during all or at least a portion of each year.

In streams characterized by stable sediments regimes, one will find forms of plant and animal life which have selected by natural processes and are therefore tolerant of certain sediment levels. Each species may be able to compensate for variations in sediment levels from stream to stream or from one day to the next but it cannot physiologically and morphologically adapt to survive very different sediment regimes from one stream to another or from one generation to the next. Therefore any change in the watershed that will cause a significant increase over natural sediment levels will generally have some detrimental effect on aquatic life. Usually the greater the increase in sediment levels in a salmonid stream, the greater will be the adverse effects on the animal and plant life present in that stream.

Sediment is a subtle, ubiquitous water pollutant which has shaped stream life in the past and has become a threat to present stream communities because of man's activities. Poor land use practices, construction and mining activities have been responsible for an accelerated movement of sediment into most salmonid streams in this province. The role sediments play in reducing production in salmonid streams has been difficult to document and for this reason its severity has been overlooked in the water quality management of this province until the last decade.

Available data indicates that sediment can affect all forms of stream life. This paper attempts to review these known effects as they relate to the primary producers, the invertebrates and the production of salmonid fishes in our streams.

EFFECTS OF SEDIMENT ON PRIMARY PRODUCERS

Primary producers in streams are mainly represented by algae which are attached to the stream bottom. This encrusting growth of green plant material is often referred to as periphyton and is the basis of the conversion of sunlight to energy within the stream. In certain sections of streams higher aquatic plants or macrophytes may also act as primary producers.

Sediment has a profound effect in determining the types and amounts of primary producers that exist in a stream. The nature of its effects may in fact allow it to be the limiting parameter in many streams (Cordon and Kelley 1961). Additions of sediment to a stream increases turbidity, causes scouring, smothers periphyton and in large quantities will produce a highly mobile substrate. Any of these conditions will have an adverse impact on primary production thereby reducing or eliminating the conversion of solar radiation into forms of energy usable by the next trophic level.

Turbidity Effects

Since most plants in salmonid streams are found on the stream bottom, the light must be transmitted through the water column before it can be converted into usable energy. Under normal condition, reflection, scattering and absorption of light in the water column prevents much of the total incident light at the stream surface from reaching the stream bottom. Corfitzen (1939) documented suspended sediments as causing the greatest loss of light in the water column. Any increase in the suspended solids or turbidity in the stream will absorb additional light rays and reduce the total amount of photsynthetic activity (Phinney 1959). This principle applies to algae as well as macrophytes which will be found growing in the more sluggish sections of streams.

In addition to the magnitude of the release, the duration of the release is very important. Short-term turbidity increases will depress photosynthetic activity; however, if the turbidity persists, the entire plant community may be significantly reduced or partially eliminated. A Canadian working group on water quality has indicated that aquatic plants cannot be expected to survive if exposed to less than five percent of the light incident on the water surface over periods exceeding seven consecutive days (Anon 1972). Approximately twice that amount of light will reach the bottom through six feet of clear water (Tarzwell 1957).

Substrate Effects

The larger sediments, which may appear as suspended solids or bed-load movement in the stream, will have a streambed scouring effect thereby damaging and dislodging the attached macrophytes and periphyton. Sediment particles with greater angularities will have a more abrasive effect on this plant life than well rounded particles. For instance, crushed rock particles would have a more abrasive effect on periphyton than most natural alluvial sediments.

When a stream's hydraulic energy cannot maintain the sediment load in suspension, blanketing of the streambed occurs and most primary producers will be eliminated. The sediment will smother the periphyton and cover the firm substrate upon which the algae must attach. The situation becomes more critical when the sediment covering is of such quantity that it forms a mobile substrate thereby making it impossible for any plant life to attach to the stream bottom. However, primary production is usually totally reduced by turbidity and scouring well before this critical condition occurs.

EFFECTS OF SEDIMENTS ON BENTHIC INVERTEBRATES

One of the more obvious effects sediment releases have on stream invertebrate populations of course relates to the effect it has on the primary producers. Many stream invertebrates depend on the periphyton for food and are termed grazers or secondary producers. These and other invertebrates also depend on periphyton growths and macrophytes to provide living areas and protection. Any reduction in these plants by methods outlined in the previous section will have a detrimental effect on such invertebrate populations.

Scouring will also play havoc with invertebrate species that live in exposed locations such as on the upper sides of rocks. Larger sediment particles can dislodge invertebrates from their substrate attachments and move them downstream as drift where they may be preyed upon in excessive numbers. Abrasive particles will have an abrading effect on exposed organs such as the gills of mayfly nymphs.

Many invertebrates are not grazers and feed by means of filtering organic detritus out of the water column. For example, certain mayflies and blackflies have bristles on their bodies while certain caddisflies spin saliva nets to strain the food out of the flowing water (Hynes 1972). An abnormal level of inorganic sediments will cause clogging of such feeding apparatus and cause the invertebrate to starve.

When an abnormal amount of sediment is deposited on the stream bottom the impact on the benthic invertebrates is more pronounced. A large percentage of invertebrates that serve as trout food are produced in riffle areas characterized by a clean gravel substrate. Sediment deposition in such stream areas smothers and forces stoneflies, mayflies and caddisflies out of their living area in the interstitial spaces in the gravel. These invertebrates require clean gravel so as water can percolate through the gravel to supply them with food, dissolved oxygen and remove body wastes. Gravel conditions should be similar to those required for the incubation of salmonid eggs which will be discussed the in next section.

Sediment deposition can cover deposits of leaves and other organic detritus which serves as an important source of food for a wide range of invertebrates (Hynes 1972). Such food deposits are thus made inaccessible and they can subsequently undergo anaerobic decomposition, thereby degrading surrounding subgravel water quality.

It must be mentioned that where the clean-water invertebrates (e.g. stoneflies, mayflies and caddisflies) cannot survive due to high sediment levels, chironomids, Tubificidae and Naididae may replace them and do rather well (Hynes 1966). However, these latter invertebrates cannot replace the clean-water species in the salmonid food chain and when the sediment deposition is prolonged, they will also disappear.

EFFECTS OF SEDIMENT ON FISH LIFE

Indirect Effects on Fish

Previous discussion has outlined how sediment can reduce plant and invertebrate populations in salmonid streams. Since these lower trophic levels produce most of the food required for salmonid production, any decrease in their quantity and/or quality will affect fish growth and survival. This consideration will include forage fish (i.e. minnows) which may feed on plants and invertebrates as well as the salmonid species which may feed on the invertebrates and the forage fish. The blanketing of leaves and organic detritus also affects certain fish such as minnows and suckers which directly feed on such organic materials.

Reduction of food will reduce fish growth rates and condition, increase competition and lower the fishes' ability to avoid predation and deal with other stresses such as disease. The overall population biomass will be reduced and the individuals that do survive may be smaller, of poorer quality and may not be capable of completing the life cycle.

Stream turbidity can also have chronic effects on fish life. Most salmonids lead a predaceous mode of life and depend on sight for capturing prey. A reduction in the clarity of water causes fish to stop feeding (Hynes 1966). Lantz (1971) indicates that salmon and trout quit feeding once turbidity exceeds 25 JTU as indicated by a drop in angling success. Noggle (1977) has shown that sediment levels of 100 mg/l can significantly reduce the feeding efficiency of coho fry and levels of 200-200 mg/l can effectively eliminate feeding.

Sediment deposition can also affect fish by obliterating their hiding and living areas. Young fry spend much of their time hiding in the interstitial spaces of gravel and between boulders. This phenomemon is especially practiced by salmon fry during daylight hours. During the day the fry hide and at night they emerge to migrate downstream. Severe sedimentation of the streambed will reduce these hiding areas and force a larger percentage of the population to be exposed to stream currents and/or possible predation (McCrimmon 1954).

Sediment deposition severe enough to fill pools will have a similar effect on larger salmonids. The pools in a stream serve as living areas that provide proper holding velocities, feeding areas and protection. Filling them will ruin this rearing area and resident salmonids will be displaced to marginal living areas which will not be able to support as large a population. The displacement of fish from pools by sedimentation has been documented by Gammon (1970). However, by the time fish will have been so affected, their populations will have been degraded by the more subtle effects of sediments on their food and eggs.

Direct Effects on Eggs, Alevins and Fry Emergence

The factor that most often causes the greatest mortality of salmonids is the destruction of their eggs by sedimentation of the spawning grounds. Other major causes of egg mortality are gravel scouring during floods, ice formation on the spawning gravel, and gravel dehydration.

Adult salmonid spawners deposit their eggs in nests or redds which are formed in the clean gravel riffle areas of streams. The eggs, buried in 4 - 16 inches of gravel, will remain there for up to five months or until they hatch into a larval salmonid called an alevin. The alevin will remain in the gravel until it has developed into a fry. To successfully complete these initial stages of its development, the salmon must totally depend on the physical (temperature, gravel porosity, water percolation, etc.) and chemical (pH, dissolved oxygen, ammonia, etc.) conditions in the subgravel environment.

Sedimentation can affect these parameters to such a degree that viable salmonid populations cannot survive in a stream due to the reduction of the egg to fry survivals. Since this paper will not consider the detailed physical effects of sediment on redds, the reader should refer to the works of Vaux (1962, 1968) and Cooper (1965) to obtain a better appreciation of this topic.

Once the eggs have been deposited in the redd they must depend on a flow of subgravel or intragravel water to supply them with adequate dissolved oxygen for respiration and to remove metabolic waste products such as ammonia and carbon dioxide. If the metabolic waste products reach high enough concentrations, they will be toxic to the eggs. However, a low level of dissolved oxygen is more critical to survival than the possible build-up of toxic metabolic wastes (Phillips 1970).

Generally the greater the subgravel flow and the higher the dissolved oxygen concentrations in the redd, the greater will be the egg to fry survival (Wickett 1954, 1958, 1962; Coble 1961; Phillips and Campbell 1962; Shumway, Warren and Doudoroff 1964). The addition of sediments interstitial gravel spaces thereby reducing the permeability of the to the spawning gravels or redds results in deposition and clogging of gravel and the supply of oxygenated water to the eggs (Wickett 1959; McNeil and Ahnell 1964; Cooper 1965). This reduction of permeability and dissolved oxygen can result in the formation of inferior fry (Alderdice, Wickett and Brett 1958) and cause high egg to fry mortality.

The fact that sedimentation of the spawning grounds causes high mortality is well documented (Gibbons and Salo 1973). Harrison(1923) first showed that eggs subjected to gravel mixtures with large amounts of fines resulted in higher mortality than those exposed to clean gravel. McNeil and Ahnell (1964) documented that the most productive pink salmon streams have the most permeable gravel and this permeability is directly related to the amount of fines in the gravel. Low permeability and low survival was shown to occur when spawning gravel contained more that 15 percent by volume of silt and sand. Five percent or less volume of such fines had a relatively insignificant effect on permeability and egg survival.

The work of McNeil and Ahnell (1964) and Cooper (1965) shows that a small increase of sediment in well cleaned gravel will only slightly reduce egg survival. However, as the percentage of fines in the gravel increases the permeability and egg survival decreases at an alarming rate. For instance, five percent composition of silt and sand in the gravel had a minimal effect whereas a 10 percent composition of these fines in the gravel reduced survival of eggs by up to 50 percent. Since many normal streams can have approximately 15 percent sands and silts in their spawning gravels, any increase in these fines can have disastrous effects on egg survivals.

In 1970, I made a series of basket egg plants of chum salmon eggs in the Coquitlam river which further demonstrates the above point. Eyed eggs were planted in the gravel of a clean tributary as well as upstream and downstream of a known sediment release. Suspended sediments over the plant site and sub-gravel oxygens in the plants were measured on a regular basis (Table 1). The data indicates that a 12 percent increase of suspended solids accounted for a 55 percent decrease in egg survival. A small increase in suspended solids increased gravel sediment levels so as to as to account for a very disproportionate decrease in egg survival.

Table 1. Relationship between eyed egg to alevin survival, dissolved subgravel oxygen and suspended solids in the Coquitlam River.

	Average Suspended Sediments mg/l	Average Dissolved Oxygen mg/l	Average Survival %
Clear Tributary Stream	10	8.5	93.8
Coquitlam Above Sediment Release	97	7.8	23.9
Coquitlam Below	111	4.9	10.7

After hatching the alevin is exposed to the same subgravel conditions as the egg was. However, oxygen requirements are greater at hatching (Hayes, Wilmot and Livingstone 1951) and the alevin has a greater need for space to develop into a fry. Once the yolk sac is absorbed, the fry becomes very active in the subgravel environment and begins an upward movement to the streambed surface in preparation for life in the open stream. Fry can move through clean gravel without difficulty but if the interstitial gravel spaces are clogged with fines, the fry's movement is impeded or made impossible.

The above phenomenon has been well documentd. Bjornn (1968) has shown that the addition of a mixture of sand and pea-sized gravel (0.04 - 0.25 inches) to spawning gravel can reduce chinook salmon and steehead trout survival by inhibiting swim-up. Gravel containing 40 percent of the above fines formed a total block and complete mortality of chinook fry. Similar experiments by Hall and Lantz (1969) on steelhead and coho fry showed that 10 percent composition of fines (1.0 - 3.0 mm) in spawning gravel did not inhibit swim-up greatly. However, increases in the fines beyond this level accounted for substantial mortality.

Direct effects on Juvenile and Adult Fish

Sediment levels in certain cases can have a direct acute effect on fish thereby causing fish mortality. Short term exposures to concentrations in excess of 20,000 mg/l can cause fish mortality (Kemp 1940; Campbell 1954; Hebert and Merkens 1961; Phillips 1970). Usually the more abrasive the sediment, the lower the required concentration and/or exposure time need be to have a direct acute effect on salmonids.

The sediment particles abrade the body surface and the gill tissue of fish. The sediment has its greatest effect on the sensitive gill tissues because the sediment passes through the gills as the fish breathes. The gill tissue responds to the abrasions by secreting a mucus covering for protection, If the sediment levels are high, the sediment particles will stick to the mucus in such large quantities that the gill no longer serves as a respiratory surface and the the fish literally suffocates. In 1970 I observed extensive Rocky Mountain whitefish mortality in the Shuswap River below a B.C. Hydro dam when a sluice gate was opened causing river suspended sediment levels to exceed 10,000 mg/l. The gills of these dead whitefish were totally clogged with mucus and sediment.

In lower sediment concentrations the gills may be able to shed the mucus-sediment mass. However, if this activity is prolonged, the physiological stress may cause mortality. Hebert and Merkens (1971) have shown that ten-day exposures to concentrations of suspended solids from 270 - 810 mg/l caused gill structure damage and mortality of rainbow trout. They noted that such concentrations reduce the trouts' chances of survival by making them more susceptible to other adverse factors in their environment.

Noggle (1977) conducted a series of seasonal bioassays with juvenile coho and documented that this species has a differing seasonal tolerance to natural suspended sediments. In August, the LC_{50} was 1198 mg/l, however, by November the tolerance had increased over

10-fold and the LC_{50} was 35,000 mg/l. The sizes of the fish between the two time periods were very ccmparable so fish size could not be the main factor causing this difference.

SUMMARY AND DISCUSSION

The material presented above indicates that sediment in a salmonid stream can be considered as a very broad-spectrum pollutant affecting all life forms from primary producers to adult fish. However, the effects of sediment on all the different life forms in a particular stream will not necessarily occur simultaneously. The overall impact on the aquatic community is as complex as the inter-relationship between the various organisms in the stream.

The impact of a sediment release on stream production will depend on the organisms present, streambed composition, the season, stream flow, stream velocity, background sediment levels, the volume of the release, the duration of the release and the composition of the sediment. The above paramenters dictate only the degree to which sediment will decrease production or harm stream life. A sediment release will always have some harmful effect regardless of the status of the above parameters.

The obvious effects of sediment of fish production will have greater impact on certain stages of the life cycles. This will, of course, vary from species to species. Probably sediment causes the greatest reduction of salmonid production by causing mortality in the egg and alevin stages of development. Sedimentation of a spawning riffle prior to spawning will cause less mortality of eggs that sedimentation after spawning because the adult salmon cleans the gravel during redd construction. An increase of sediments in the stream during the spring freshet would have minimal impact, providing the sediment carrying capacity of the stream is not surpassed. Once certain salmon species (i.e. pink and chum salmon) have reached the fry stage, they migrate directly to the ocean, thereby avoiding further exposure to the effects of sedimentation. Chinook, coho and trout species must spend part or all of their lives in the stream. Such fish are thus more prone to be affected by abnormal stream sedimentation, especially after the spring freshet. During the summer when stream flow is low, temperatures high, and the stream is filled to capacity with rearing fish, a sediment release can greatly reduce salmonid populations by reducing their food supply.

However, it must be emphasized that one cannot look only at the obvious effects on fish life to gauge the damage sediment can have on a stream. Although sediment affects all stream life, these effects are not exerted equally on primary producers, invertebrates and fish. These life forms are linked together by food chains so any deleterious effect on algae will affect aquatic invertebrates and fish that depend on energy produced in the stream. It is for this reason that one cannot examine the effects of sediment on fish alone. For instance, it is of minor value to be concerned about the level at which stream sediments will clog the gills of fish or reduce their hiding areas. In most cases the entire food chain complex upon which these fish must depend, would have been destroyed well before the fish was directly harmed. If stream life is to be adequately protected from abnormal sediment levels, we must measure and be concerned about the more subtle effects of sediments. Cordone and Kelly (1961) most aptly describe this concern: "short-term discharges of sediment may do little visible damage to fishes, bottom fauna, or fishes' eggs, but may interrupt the entire biological complex through effects on algae." In addition, it must be noted that the greater the sediment release volume and the longer its duration, the greater will be its impact on all life and production in the stream.

OPERATIONAL GUIDELINES

It is impossible to put a number on what is considered to be an acceptable sediment release level. The laws of dilution and assimilation that can be applied to many other pollutants cannot be applied to sediments. Other variables which disallow a simple solution to the problem have already been described. However, for enforcement purposes, control agencies are quoting acceptable sediment release levels for point-source releases. The British Columbia Pollution Control Branch commonly accepts 50 mg/l while Federal Fisheries accepts releases of 25 mg/l or background levels - whichever is greater. The State of Oregon insists that releases match background levels up to 30 Jackson Turbidity Units and when background levels exceed 30 JTU, the release may elevate background levels by 10 percent. Unfortunately, turbidity does not necessarily correlate with the amount of suspended sediment present.

Other standards are available but most of them require involved studies on each watershed and therefore do not relate to sediment contributions from sheet erosion resulting from forest harvesting and similar land-use activities. In such cases the most realistic guideline should not relate to the stream but to the sediment-releasing activity, its time, and location. Common sense must be used with best available technology to keep abnormal sediment releases out of salmonid streams. These techniques relate to actual logging methods as well as to a watershed harvesting policy designed to reduce the size of the cut and reduce stream exposure.

Activities that can cause high localized sediment releases, such as bridge and road construction, should be timed and so conducted so as the silt release will be minimal. For example, roads should be built in the summer as far away from streams as possible, culverts must be properly placed, cuts stabilized and sidecasting discouraged. Unfortunately, these common-sense rules are not practiced in many areas and certain operators make no real attempt to keep sediment out of our salmonid streams. Until they try to do so, it would be rather academic establishing sophisticated stream water quality guidelines because they would require large resource commitments to formulate and would not be effective in reducing the problem.

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