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TRANSPORT OF GRANITIC SEDIMENT IN STREAMS AND ITS EFFECTS ON INSECTS AND FISH

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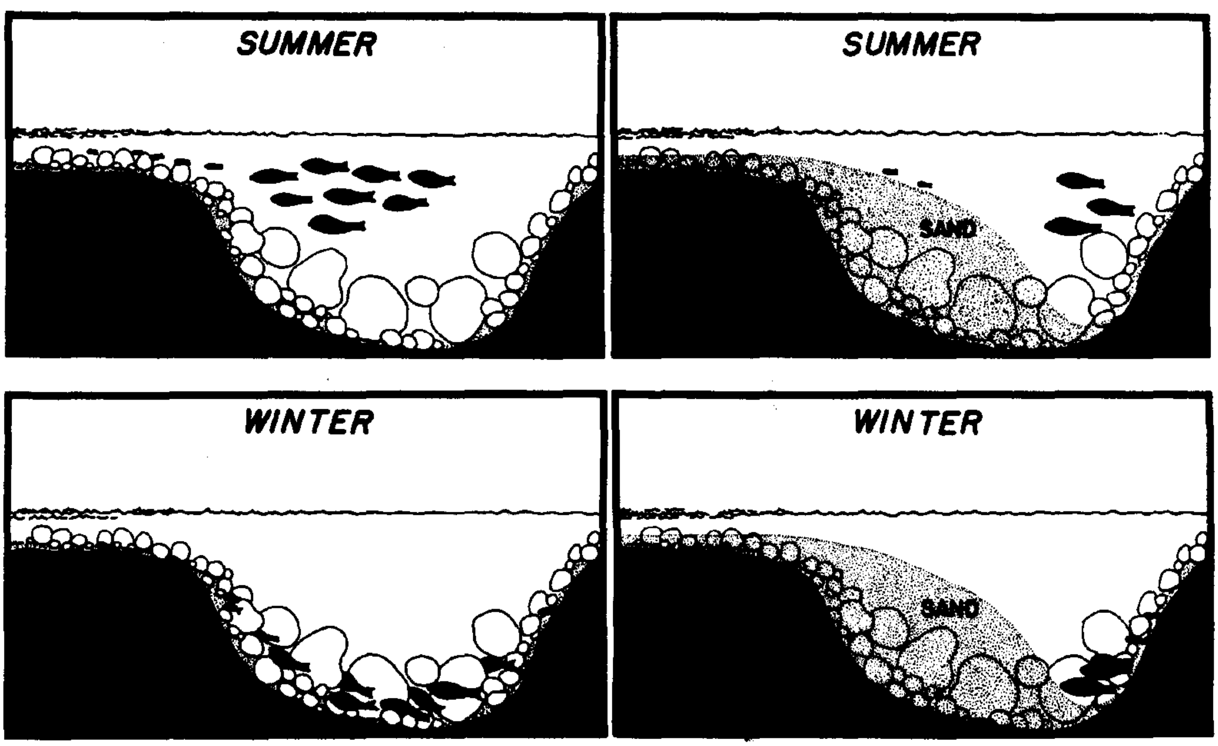

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Transport of Granitic Sediment in Streams and Its Effects on Insects and Fish

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ABSTRACT

We assessed the transport of granitic bedload sediment (<6.35 mm diameter) in streams flowing through central Idaho mountain valleys and the effects of the sediment on juvenile salmonids and aquatic insects. We measured bedload sediment transported in the streams during the spring snowmelt runoff and the summer low-flow periods for 2 years, to test the applicability of the Meyer-Peter, Müller equation for estimating such transport. In both years the streams transported all the sediment available, including that under the armor layer of the stream bottom in the first year. The modified Meyer-Peter, Müller equation proved accurate in estimating the transport capacity of such streams using measurements of slope, hydraulic radius and mean diameter of streambed material.

In artificial stream channels, benthic insect density in fully sedimented riffles (>2/3 cobble imbeddedness) was one-half that in unsedimented riffles, but the abundance of drifting insects in the sedimented channels was not significantly smaller. In a natural stream riffle, benthic insects were 1.5 times more abundant in a plot cleaned of sediment, with mayflies and stoneflies 4 and 8 times more abundant, respectively. Riffle beetles (Elmidae) were more abundant in the uncleaned plot.

During both summer and winter, fewer fish remained in the artificial stream channels where sediment was added to the pools. The interstices between the large rocks in the pools provided essential cover necessary to maintain large densities of fish. Fish in sedimented channels exhibited hierarchical behavior, while those in unsedimented channels were territorial in behavior. In small natural pools (100 to 200 m^2), a loss in pool volume or in area deeper than 0.3 m from additions of sediment resulted in a proportional decrease in fish numbers. We did not, however, find significant correlations between riffle sedimentation and fish density in the two natural streams we studied. Fish abundance was significantly correlated with insect drift abundance in one stream, but not in the other. The amounts of sediment in the two streams studied did not have an obvious adverse effect on the abundance of fish or the insect drift on which they feed.

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In 1972 we initiated studies to determine the amounts of fine sediment (<6.35 mm in diameter) in streams which had detrimental impacts on aquatic insects and juvenile fish and to assess the ability of streams to transport such sediment. We did not concern ourselves with how the sediment got into the streams; that is the province of the hydrologist and the watershed specialist. In a comprehensive review paper, Cordone and Kelley (1961) summarized the evidence indicating that fine sediment is detrimental to aquatic life in streams, but they concluded that the question, "How much sediment is harmful?" had not been answered. Since then researchers have determined the amounts of fine sediment which reduce the survival of salmonid embryos in the gravel or prevent them from emerging successfully as fry (Bjornn 1969, Phillips et al. 1975, Hausle and Coble 1976). Researchers have had less success in providing a quantitative answer to the question of how much fine sediment is harmful to aquatic insects and juvenile fish residing in streams.

In addition to its detrimental effects on fish embryos, fine sediment could reduce the capacity of rearing areas by covering or filling the stream bottom with sand, decreasing the amount of fish habitat and the abundance of aquatic insects, thereby decreasing the growth and/or density of fish in the stream. We report herein our work to quantify the impacts of given amounts of fine sediment on aquatic insects and juvenile salmonids, and to determine the capacity of streams to transport bedload sediment of the type present in the central Idaho batholith.

The central Idaho batholith is a 16,000 square mile expanse of intrusive, acid, igneous rock (Fig. 1). Various granitic rocks are found in the batholith; however, quartz monzonite predominates. The granite base rock decomposes into a coarse sand that is easily eroded from the steep, relatively unstable slopes in many of the drainages (Platts 1975). Megahan (1972) found that sediment production varied over a range of one order of magnitude in small undisturbed watersheds in central Idaho. Natural and man-caused disturbances have resulted in substantial depositions of fine sediment in some stream channels of the batholith. Construction and maintenance of roads for logging, recreation, mining and other uses has been the main source of fine sediment in the streams.

The fine sediment found in most streams of the batholith and referred to throughout this report was primarily a coarse sand. Megahan (1975) analyzed 61 samples collected from sediment retention reservoirs in small streams and found the composition shown in Table 1. In our studies we designated all particles less than 6.35 mm in diameter as fine sediment. Megahan also analyzed for organic matter and found an average of 5.1 percent by volume-weight in 90 samples.

Table 1. Composition of 61 sediment samples collected from retention reservoirs in the central Idaho batholith (Megahan 1975).

Description of sediment	Particle diameter (mm)	Composition (% by weight)
Gravel and larger	>7.900	3.4
Gravel	4.750-7.900	5.3
Gravel	2.000-4.750	25.5
Sand	1.000-2.000	22.7
Sand	0.500-1.000	16.0
Sand	0.250-0.500	11.8
Sand	0.075-0.250	12.6
Sand	0.050-0.075	1.0
Silt and clay	<0.050	1.7

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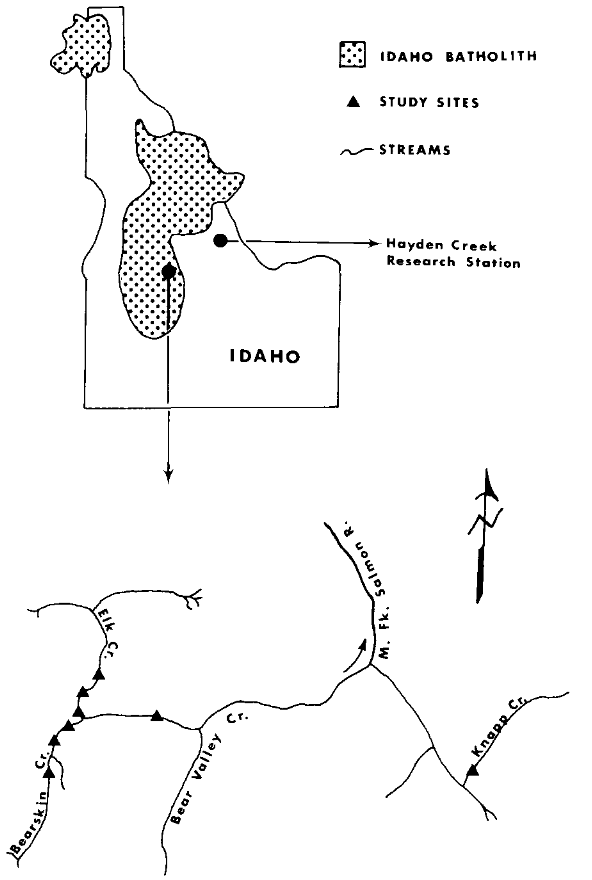

Fig. 1. Locations of study areas for 1974 and 1975 in the central Idaho batholith.

In the streams we studied, the percentage of fine sediment in core samples taken from riffles ranged from 20 to 75 percent. This agrees closely with Corley's findings (1976) of 19 to 77 percent bedload sediment in core samples collected in spawning riffles of the South Fork of the Salmon River. In general, riffles with no more than 20 percent fine sediment were relatively clean, while riffles with over 30 percent fine sediment usually appeared as fully imbedded with fine sediment.

First-Phase Studies

The first phase of our studies (1972-1974) was reported by Bjornn et al. (1974) and resulted in three theses (Stuehrenberg 1975, Sandine 1974, Neilson 1974). During this phase we looked at the effects of sediment in streams in three ways:

1. In three natural streams in the Idaho batholith we measured the amount of fine sediment in the substrate of riffles and correlated this with sediment movement, standing crop of insects, numbers of drifting insects and the distribution and abundance of juvenile chinook salmon (*Onchorhynchus tshawytscha* Walbaum) and steelhead trout (*Salmo gairdneri* Richardson).
2. We constructed laboratory stream channels to control some of the environmental variables so that we could assess experimentally the effects of various levels of riffle sedimentation on the distribution and abundance of insects and fish.
3. We added fine sediment to both pools and riffles in a batholith stream to assess the effects of large amounts of fine sediment added to a stream that normally had small amounts of sediment. We measured the physical characteristics of the stream and monitored the fish and insect populations before, immediately after, and 3 weeks after the sediment was added.

At the conclusion of the first-phase studies, we had determined the following:

1. Negligible amounts of sediment moved in the study streams during the summer.
2. Based on the physical characteristics of the streams we studied and a review of bedload discharge formulas, the Meyer-Peter, Müller formula appeared to be the equation most applicable for estimation of sediment transport capacities of the broad mountain valley streams we were studying. We now needed to field-test the formula during a spring runoff with flows capable of transporting the sediment.
3. Natural streams with the largest amounts of fine sediment had fewer insects, but the density and size of fish were equal to those in streams with smaller amounts of sediment. We did not find evidence of a detrimental impact on fish during the summer rearing period from excessive amounts of fine sediment in riffles.
4. When we added fine sediment to pools in the small test stream, the abundance of fish decreased proportionately to the decrease of pool volume or area. This was evidence of a direct impact on fish from fine sediment in a stream during the summer. We now needed to repeat the test to improve our confidence in the results.
5. Sediment added to riffles in our laboratory stream channels reduced the winter carrying capacity for small age 0 trout and salmon. We also needed to add sediment to the deeper pool and run habitat in streams to see if this reduced the winter capacity for larger fish.

6. Insect abundance was not decreased by adding sediment to riffles in our laboratory stream channels nor by adding sediment to a short section of riffle in a natural stream. Species diversity decreased temporarily in both the channels and the natural stream, but there was no measurable effect on the density of benthic insects nor the abundance of drifting insects following the addition of sediment. These findings were in conflict with our sampling in natural streams, so we needed to repeat these tests and take a closer look at the changes in species composition and insect microhabitat.

Second-Phase Goals

The second phase of our studies began in 1974, with field work during the 1974 and 1975 field seasons, and will also result in three theses (Klamt 1976; C. Schaye, in preparation; E. Chacho, in preparation). Based in part on our findings in the first-phase studies, we formulated the following goals for the second phase:

1. Measure the transport of bedload sediment in study streams and evaluate the applicability of the Meyer-Peter, Müller formula for prediction of bedload sediment transport.

2. Repeat the test conducted during the first phase in which we added fine sediment to riffles and pools in a natural stream.

3. Compare the benthic insect composition and density in cleaned and uncleaned portions of a natural stream riffle with large percentages of fine sediment.

4. Add large rocks to the pools and cobbles to the riffles in the laboratory stream channels to provide insect and fish habitat different from that of the first phase. Then add sediment to both pools and riffles, and monitor the effects on insects and fish during summer and winter periods.

5. In two streams with variable amounts of sediment in their riffles, measure the amount of sediment in riffles, the abundance of insect drift and the density of fish in connecting pools at numerous pool-riffle sites to see if there is a correlation between naturally-occurring fine sediment in streams and the abundance of fish and insects.

TRANSPORT OF SEDIMENT

In the first phase (1972-1974) of the sediment transport portion of the project, Neilson (1974) concluded that, of the numerous bedload transport equations in existence, the Meyer-Peter, Müller equation was the best suited for use on broad valley streams in the Idaho batholith. This conclusion was based on the derivation of the equation for graded bed material and on the fact that the authors recognized that an armor layer appears in many streambeds. The Meyer-Peter, Müller (MPM) equation has received wide acceptance and is often used in either the original or modified form in watershed or sediment routing models (e.g., Simons et al. 1974).

Neilson favored the use of the generalized form of the equation, converted to English units by Sheppard (1960). The equation developed by Sheppard was for use in U.S. Bureau of Reclamation water development projects having a wide areal distribution and varied hydrologic conditions. Also, it appears that the equation in Sheppard's form was to be used in canals constructed in earth where the channel parameters could be easily measured and controlled. Sheppard's generalized form of the MPM equation could not be applied easily to natural streams where measurements of the required stream parameters would be difficult. Particular difficulty is encountered in measurement of the roughness coefficient.

Neilson was unable to verify that the MPM equation was indeed applicable to Idaho batholith streams, because runoff flow rates were not sufficient to move sediment during his study.

The objectives of the second phase (1974-1976) of the sediment transport study were to collect actual field data to validate the application of the MPM equation to Idaho batholith streams and to determine what modifications of the equation might make it better adapted and more easily applied by watershed managers. Since 1974 was an unusual runoff year with record maximum discharges throughout the Salmon River drainage, the 1974 data were useful primarily for observing general trends of sediment transportation rates in the study streams and for planning the 1975 data collection program. The 1975 data provided good information for testing the applicability of the equation and also provided the basis for modification to adapt it for relatively easy and reliable use in typical batholith streams.

Data Collected During 1974 and 1975

During 1974, measurements were taken on three streams at six locations. Only two sampling stations yielded results which could be used to verify the applicability of the MPM equation. Of the four stations rejected, three had boundary effects in the measurements and the fourth was located on a stream which failed to form an armor layer and thus was not suitable for either the method of sediment measurement or the predictive equation being tested.

Bedload transport was measured with the Helley-Smith sampler (Helley and Smith 1971), designed for use on streams with gravel beds. During the 1974 snowmelt runoff season, samples were taken at stream locations where a bridge crossed the stream. This limited the number of streams, the number of sampling sites and the channel types which could be sampled. The streams which were sampled were too deep and too swift for wading during the runoff season.

During 1974 the bedload measurements were taken at intervals of change of stage in the stream, on both the rising and falling phases of the hydrograph. This criterion for measurement was based on the assumption that bedload transport is a function of discharge (or of depth) and that changes in transport rate would follow changes in discharge. While this seemed to be a valid assumption, it was found that it can be applied to measured transport rates only when the supply of sediment in the stream is sufficient to provide for transport at full capacity.

We found that neither Cape Horn Creek nor Knapp Creek carried sediment at full capacity during the 1974 runoff season. In fact, due to the extraordinarily large runoff, the capacity of the streams to transport sediment was much larger than the available sediment supply (Fig. 2). The measured rate of sediment transport in Cape Horn Creek increased during the rising phase of the hydrograph, as expected, but declined just before the peak discharge, then increased again on the falling limb of the hydrograph.

We believe the drop in transport rate near the peak of the hydrograph was due to the lack of sediment available for transport. The stream discharge was such that the critical tractive force required to begin sediment movement was exceeded early in the melt season, before June 11 (Fig. 2). The drop in the measured transport rate on June 15 was not due to a drop in tractive force, which in fact increased, but to a lack of sediment to transport. We theorize that prior to June 15 the stream had been scouring the sediment deposited over the previous year, or during the time since the last critical level of discharge and tractive force was reached, and had cleansed itself of "transportable" sediment. Transportable sediment refers to that sediment deposited above the armor layer rather than the supply of sediment beneath the protective covering of the amor layer. We do not believe the tractive force in Cape Horn Creek was sufficiently large to dislodge the armor layer during the 1974 runoff.

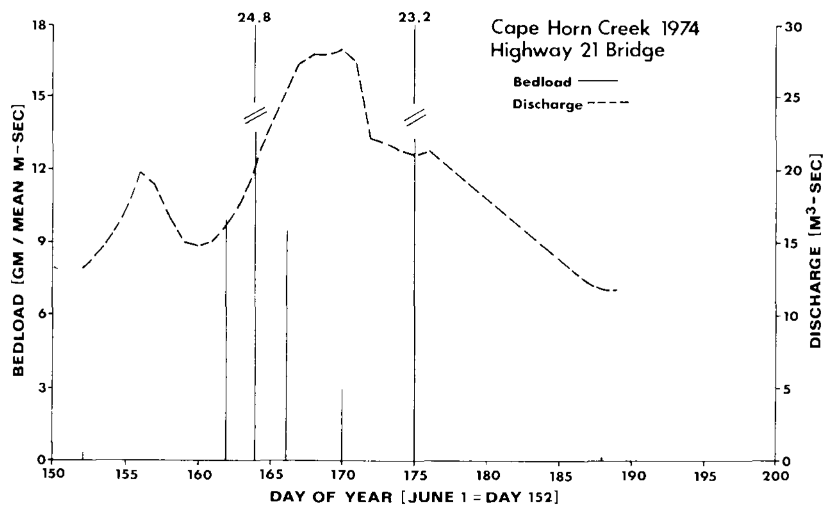

Fig. 2. Runoff hydrograph and sediment discharge for Cape Horn Creek, 1974.

The increased sediment transport rate with decreased flow measured on June 24 (Fig. 2) was apparently due to a disturbance upstream that introduced a large amount of sediment into the stream (i.e., landslide, mudflow, etc.). The water changed suddenly from relatively clear to very muddy. By July 7 the bedload sediment transport rate was near zero and the stream discharge had decreased.

The same basic phenomenon occurred in Knapp Creek in 1974 (Fig. 3). During the first stages of the spring runoff, the rate of sediment transport declined even though discharge increased, as in Cape Horn Creek. However, in Knapp Creek the increase in transport rate near the peak discharge on June 16 may not have been due to introduction of sediment from an outside source, since it was not accompanied by a muddying of the water. The discharge may have reached the point at which the tractive force was sufficient to dislodge the armor layer. Evidence supporting this possibility was found later in the season, when it was observed that riffles had moved from their locations of the previous year and were less compacted. Once the discharge rate dropped below that required to transport the larger material of the armor layer, the sediment transport rate dropped quickly (June 21), and by July 7 the transport rate was nearly zero (Fig. 3).

The objectives of the field work conducted during 1975 were generally the same as in 1974, but in addition, an attempt was made to gather data to help distinguish between the transport rates over riffles and through pools. Additional sampling sites were therefore established and a more intensive sampling program was followed.

As a result of our experience in the field during 1974, we based the bedload measurements taken during 1975 on time intervals rather than on stage-change intervals. The same stations sampled on Knapp Creek and Cape Horn Creek during 1974 were sampled in 1975 on a daily basis, using the same sampling techniques.

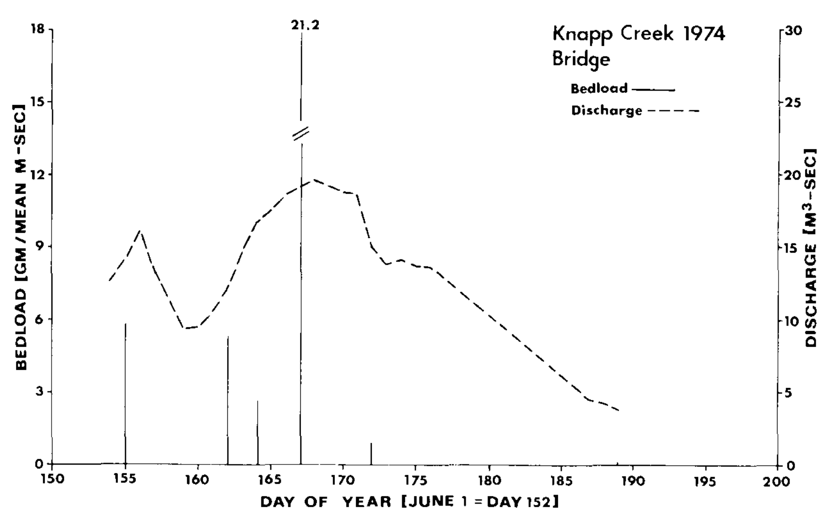

Fig. 3. Runoff hydrograph and sediment discharge for Knapp Creek, 1974.

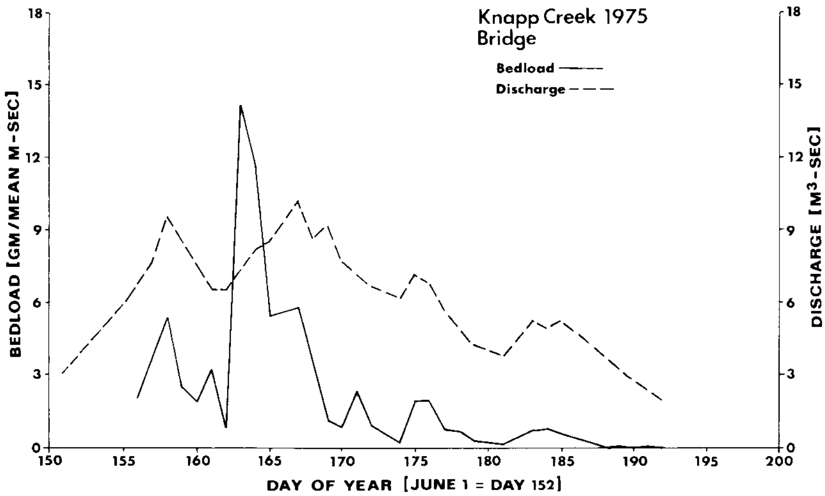

Fig. 4. Runoff hydrograph and sediment discharge for Knapp Creek, 1975.

In 1975, the sediment transport rates were large early in the year and diminished with time, even though stream discharge increased as in 1974 (Figs. 4 and 5). Our earlier conclusion that the available sediment supply limits the rate of sediment transport during most of the season was reinforced by the 1975 data. The tractive force available with observed discharges was more than enough to move the amounts of sediment measured in 1974 and 1975. The maximum rates of sediment transport measured may approach the maximum capacity of the stream to transport bedload sediment.

In both streams, sediment transport rates did not increase late in the runoff season of 1975 as they did in 1974. The snowpack in 1975 was near the long-term average, and although the melt season was delayed about 2 weeks, the runoff hydrographs should be representative of those expected for an average year. We believe the sediment transport rates we measured in 1975 are indicative of the sediment transported during an average runoff year. Apparently, in a near-average discharge year such as 1975, the tractive forces are not sufficient to dislodge the armor layer of the riffles, as occurred during the large discharge in 1974.

Although the 1975 sediment transport curves for both streams are variable (Figs. 4 and 5), the peaks and depressions on the curves for the two streams occurred at nearly the same time in the runoff season. The cause and significance of this similarity are not clear to us at this time. The streams were different with respect to depth, slope, size of bed material and reach of stream sampled. Further investigaton of the relationships among these variables and the actual transport rates may lead to prediction of a generalized transport curve as a function of given stream parameters.

The comparison of bedload sediment transport through pools versus transport over riffles yielded preliminary results in 1975. The transport rate through two pools in Knapp Creek (measured at A-7, Fig. 6) was negligible for most of the season (Fig. 7). The small rate of sediment transport through the pools we measured does not seem realistic because larger amounts of sediment

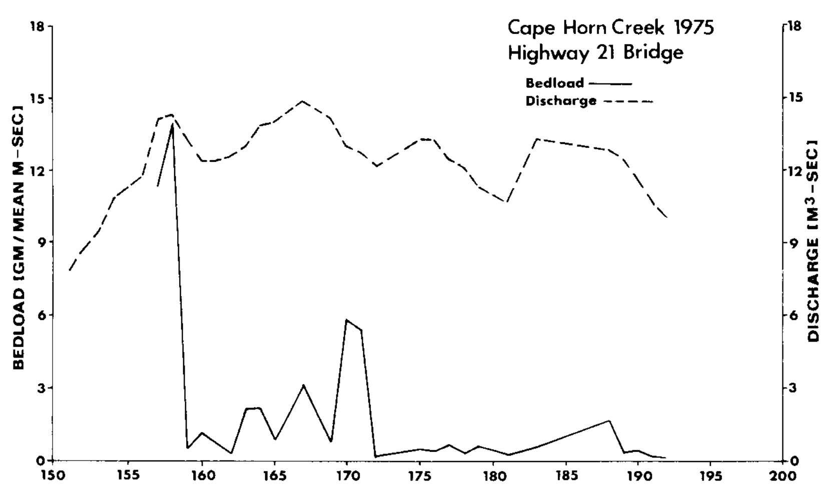

Fig. 5. Runoff hydrograph and sediment discharge for Cape Horn Creek, 1975.

were transported through the total section of stream that contained the pools.

Measurements of sediment transport across riffles were taken at the upstream and downstream ends of riffles. Transects A-2 and A-6 were at the downstream ends of riffles and transect A-1 was at the upstream end of the uppermost riffle (Fig. 6). The cumulative volume of sediment transported at the downstream ends of the riffles at transects A-2 and A-6 was less than the volume measured at the upstream end of the first riffle (transect A-1, Fig. 8). Since more sediment entered the test section (transect A-1) than left (transects A-2 and A-6), we might conclude that the balance of the sediment was deposited in the test section. This conclusion was not supported by visual observations, nor by core samples. We did not take enough core samples to statistically test the amount of sediment in riffles before and after the runoff, but there was no obvious increase. The discrepancy in sediment volumes between transect A-1 and the sum of transects A-2 and A-6 may be the result of the faster velocity at the downstream ends of the riffles, which might have transported the sediment as suspended particles rather than as bedload, as was the case at the top of the riffles.

Analysis of the Meyer-Peter, Müller Equation

A general form of the Meyer-Peter, Müller equation can be expressed as

$$g_s = \{(g/\gamma)^{1/3} \left(\frac{1}{0.25}\right) [\gamma R_H S (N_e)^{3/2} - 0.047(\gamma_s - \gamma) D_m]\}^{3/2} \quad [1]$$

where g_s = bedload transport rate per unit width of flow, weighed underwater (metric tons per meter of width per second),

g = acceleration due to gravity (m/sec^2),

γ = specific weight of water (metric tons/m^3),

γ_s = specific weight of dry sediment in air (metric tons/m^3),

R_H = hydraulic radius (m),

S = slope of the energy grade line (approximated by slope of the water surface),

D_m = effective mean diameter of bed material (m),

N_e = effective roughness (ratio of grain resistance to total channel resistance), and

the constants 0.25 and 0.047 are dimensionless.

In this form of the equation, comparison between measured data and calculated data cannot be made easily. By rearranging the terms in equation 1, the MPM equation takes the form reported by Graf (1971):

$$\frac{\gamma R_H (N_e)^{3/2} S}{D_m (\gamma_s - \gamma)} = \frac{0.25\, (\rho)^{1/3} (g_s)^{2/3}}{D_m (\gamma_s - \gamma)} + 0.047 \quad [2]$$

where ρ = density of water and $\rho = \frac{\gamma}{g}$.

The equation is now dimensionless and in the form of the equation of a straight line:

$$YY = mXX + b \quad [3]$$

where m = 0.25,

b = 0.047,

$$YY = \frac{\gamma R_H (N_e)^{3/2} S}{D_m (\gamma_s - \gamma)} \quad \text{and}$$

$$XX = \frac{\rho^{1/3} (g_s)^{2/3}}{D_m (\gamma_s - \gamma)}$$

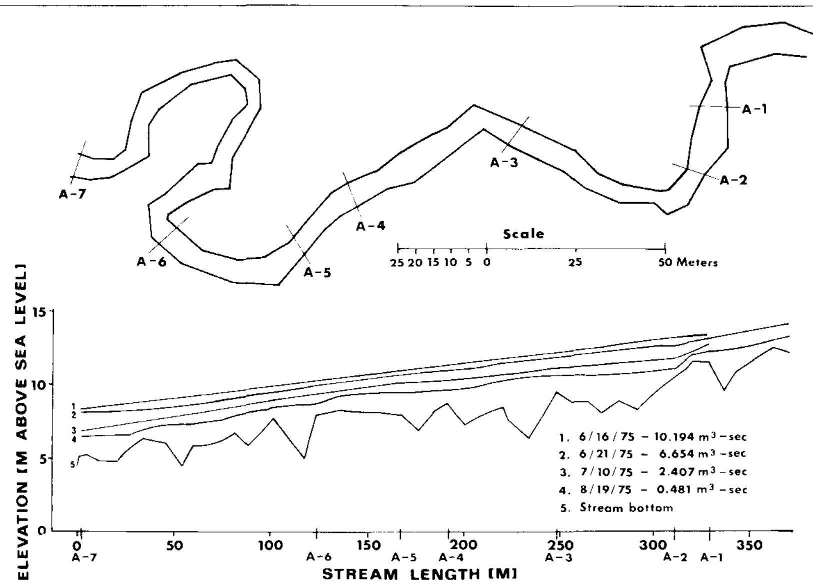

Fig. 6. Location of sediment measuring stations on Knapp Creek, 1975, and corresponding water surface slopes as function of discharge. Station A-O (bridge) is upstream out of figure.

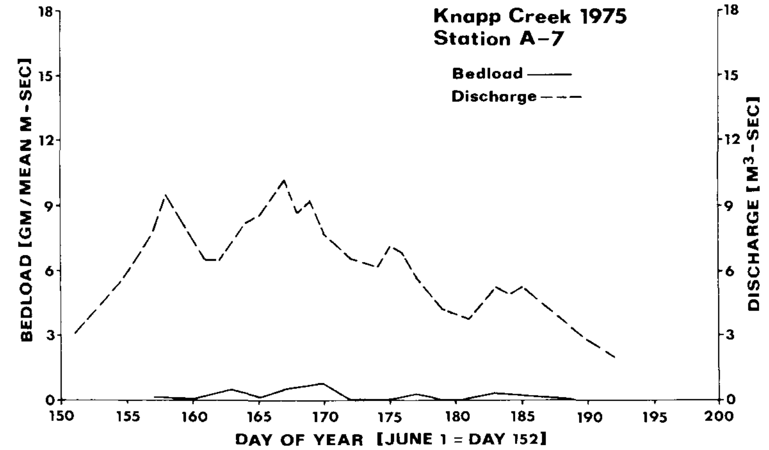

Fig. 7. Runoff hydrograph and sediment discharge for Knapp Creek, 1975, pool section.

The term YY is a function of the stream parameters and represents the total tractive force available for bedload transport and the term XX is a function of the bedload transport. All of the variables in the above expressions can be measured in the field, with the exception of the effective roughness, N_e. The determination of the value of N_e is difficult, especially for natural streams. According to Graf (1971),

$$N_e = \frac{n'}{n} \qquad [4]$$

where n' = Manning's roughness due to grain resistance, and

n = Manning's roughness due to total resistance of the channel.

Graf further reports that Müller proposed that the roughness due to grain resistance, n', be calculated from the relationship

$$n' = D_{90}^{1/6}/26 \; (\mathrm{m}^{1/3}/\mathrm{sec})^{-1} \qquad [5]$$

where D_{90} = diameter of bed material at which 90 percent is finer (m).

The use of D_{90} is reasonable because in armored streambeds the larger material composes the top layer exposed to the flow.

The value of the total roughness of the channel, n, can be calculated from Manning's equation as

$$n = \frac{1}{Q} A (R_H)^{2/3} (S)^{1/2} \qquad [6]$$

where Q = discharge (m^3/sec), and

A = stream cross-sectional area (m^2).

Therefore, by combining equations 4 and 5,

$$N_e = \frac{D_{90}^{1/6}}{26n} \qquad [7]$$

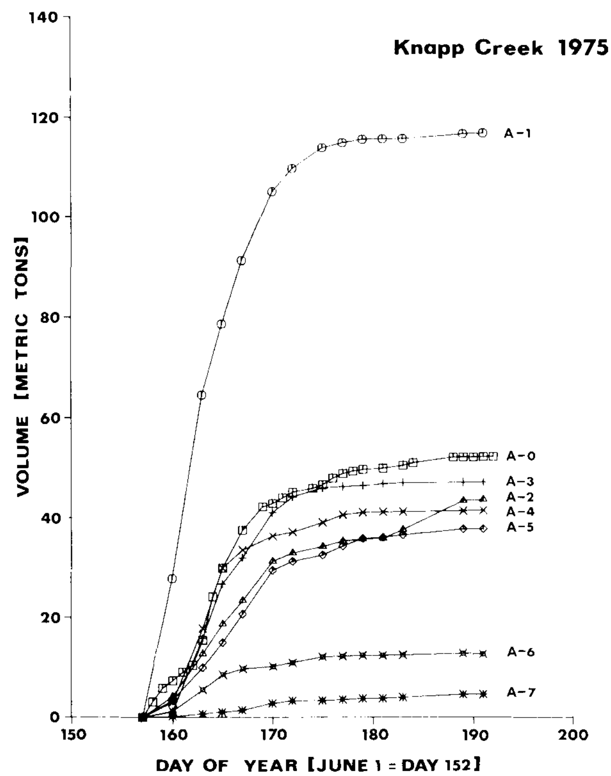

Fig. 8. Cumulative volume of sediment discharge for 8 stations on Knapp Creek, 1975. (For location of stations see Fig. 6.)

This is the form of equation 4 proposed by Neilson (1974). However, the determination of n (from equation 6) requires detailed stream measurements which are not practical for field applications of the bedload transport relationship. Values of n computed from Manning's equation (equation 6) for a station on Knapp Creek during 1975 ranged from 0.022 to 0.029 during the period of measured transport. Using an average of n = 0.0255 and the measured D_{90} for that section of Knapp Creek, the computed value of N_e using equation 7 is 0.98.

Graf (1971) reports that Zeller found the value of N_e to vary between 0.5 for streams with strong bedforms and 1.0 for streams with no bedforms. Based on analysis of Froude number and size of bed material in Knapp Creek, the study stream should never have bedforms present. Therefore it is assumed that the armored streams in this study area would always have a value for N_e very nearly equal to 1.0. This assumption agrees with the computation in the preceding paragraph.

In applying the MPM equation to the 1975 data, the data were plotted as individual stations at each sampling point, rather than combining all transect data for a single cross-section. Thus, the hydraulic radius can be reduced to the depth at each sampling point, since, as shown in Fig. 9,

$$R_H = \frac{A}{P} = \frac{wd}{w} = d \qquad [8]$$

where P = wetted perimeter (m),

w = width of sampler (m),

d = depth of water (m).

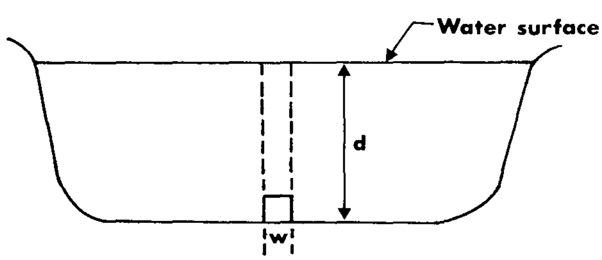

Fig. 9. Schematic representation of parameters required for determination of hydraulic radius of sampling point.

The plot of YY vs. XX (equation 2) for Knapp Creek 1975 data (depth, water surface slope, effective mean diameter, measured bedload transport and N_e = 1.0) is shown in Fig. 10. The critical tractive force – the force required to initiate sediment movement – is shown in the figure at YY = 0.047. At values of YY less than 0.047, no transport of bedload should take place.

Note that the majority of the points lie near the YY axis because of the small rates of bedload transport at most of the sites sampled. The points that lie near the line predicted by the MPM equation were the peak bedload transport measurements and should correspond to the maximum stream transport capacity. The points above the line represent measurements taken when the stream was transporting sediment below its maximum capacity. On the basis of this analysis, we conclude that the MPM equation does reliably predict the maximum bedload transport capacity for Idaho batholith streams.

Predicting Sediment Transport Capacity

For field application of the MPM equation to predict bedload transport capacity in a stream, only a minimum number of measurements are required: R_H, S and D_m.

The value for the slope, S, is approximated by using the water surface slope. If actual water surface slope is known as a function of discharge, then this value can be used. In most cases, however, this relationship is not available and an approximation must be used. The water surface profile changes with discharge; at peak flow the profile is nearly uniform (Fig. 6). Since it is assumed that the measurement of stream parameters will be done during the low-flow period, the best approximation for the slope of the water surface for the entire melt season would be the average of the slopes at high water and at low flow. The low-flow water surface slope can be measured easily with a surveyor's level during the summer months. The water surface slope for high-water conditions can be measured at the same time using the high water marks left during the runoff season, or if no high water marks are visible, the slope of the water surface at high flow can be approximated by the slope of the flood plain (Neilson 1974).

The value for the hydraulic radius, R_H, can be found as a function of the depth (equation 8) by measurement of the cross-section of the stream channel. While this value will range from 0.9 to 1.0 times the depth of flow for these streams, no approximation should be required, except in cases where no field measurements can be taken. Then the value of R_H can be approximated as 0.95 times the depth (Neilson 1974).

The value for the effective mean diameter of the streambed material, D_m, must be found by core sampling the channel bottom and doing a sieve analysis. A technique for relating the D_m to a visual classification system, described by Neilson (1974), was tested but was not adequate (best R^2 = 0.55).

To predict bedload transport, the MPM equation can be simplified using the measured values of the stream parameters that remain constant. From the original form of the equation (equation 2)

$$\frac{\gamma R_H (N_e)^{3/2} S}{D_m (\gamma_s - \gamma)} = 0.25 \frac{(\rho)^{1/3} (g_s)^{2/3}}{D_m (\gamma_s - \gamma)} + 0.047$$

we can derive

$$\frac{\gamma R_H (N_e)^{3/2} S}{\rho^{1/3}} = 0.25 (g_s)^{2/3} + \frac{0.047 D_m (\gamma_s - \gamma)}{\rho^{1/3}} \qquad [9]$$

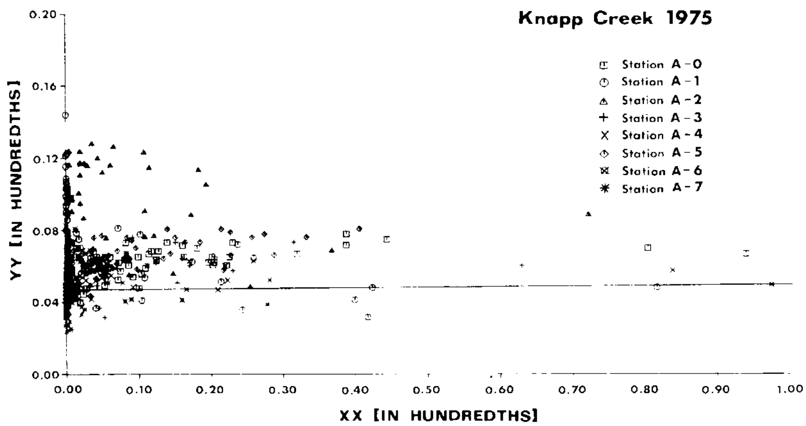

Fig. 10. The Meyer-Peter, Müller predictive equation and measured sediment discharge data for 8 stations on Knapp Creek, 1975, plotted as YY vs. XX (see equations 2 and 3).

For streams of the Idaho batholith where

$$\gamma_s = 2.55 \text{ metric tons/m}^3,$$

$$N_e = 1.0,$$

$$\rho = \gamma / g = 1.00/9.81$$

equation 9 is reduced to

$$2.14\, R_H S = 0.25\, (g_s)^{2/3} + 0.157\, D_m \qquad [10]$$

for R_H and D_m in meters and g_s in metric tons/m-sec weighed underwater. Defining g_s' as the dry bedload transport rate per unit time and width, then

$$g'_s = g_s \left(\frac{\gamma_s}{\gamma_s - \gamma}\right) = g_s \left(\frac{2.55}{1.55}\right) = 1.645\, g_s \qquad [11]$$

Thus equation 10 becomes

$$1.535\, R_H S = 0.25\, (g'_s)^{2/3} + 0.113\, D_m \qquad [12]$$

In English units equation 12 becomes

$$35.90\, R_H S = 0.25 (g'_s)^{2/3} + 2.616\, D_m \qquad [13]$$

where R_H = hydraulic radius in feet,

S = slope (dimensionless),

g'_s = dry bedload transport rate in tons per foot per second,

D_m = effective mean diameter of material in feet.

These equations (equations 12 and 13) apply to armored streams of the Idaho batholith. They would be applied to any specific stream by substituting the specific value for D_m. For Knapp Creek D_m was 0.031 m. Equation 12 for Knapp Creek then becomes

$$1.535\, R_H S = 0.25 (g'_s)^{2/3} + 0.0035 \qquad [14]$$

Equation 14 can be used to compute bedload transport capacity at a stream section on Knapp Creek by substituting measurements of hydraulic radius (R_H) and water surface slope (S).

The value of $(g'_s)^{2/3}$ can also be read directly from a modified YY vs. XX graph. Note that equation 14 has the form of a straight line, $y = mx + b$, where $m = 0.25$ and $b = 0.0035$, so that when $y = 1.535\, R_H S$ is plotted against $x = (g'_s)^{2/3}$ as in Fig. 11, the predicted bedload transport capacity (g'_s in units of metric tons/m-sec) is the x-value read from the graph, taken to the 3/2 power.

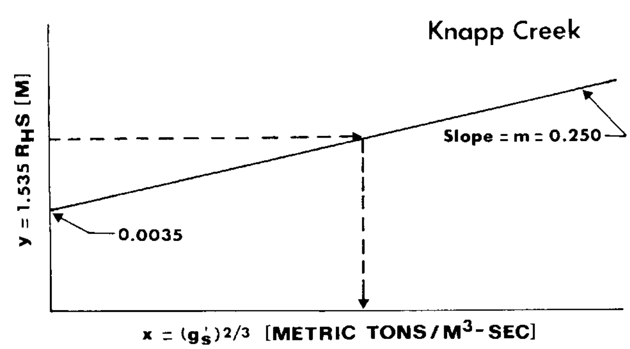

Fig. 11. Unit dry bedload transport capacity of Knapp Creek, as predicted by the Meyer-Peter, Muller equation.

EFFECTS OF SEDIMENT ON INSECTS

We conducted studies in laboratory stream channels and in Idaho batholith streams to test benthic insect community tolerances for different levels of sediment pollution and to develop criteria for describing the habitat quality of Idaho batholith streams. Substrate characteristics such as level of cobble imbeddedness, predominant substrate and size of substrate surrounding cobble were correlated with species-specific and community changes.

Laboratory Stream Channels

In the artificial stream channels at the Hayden Creek Research Station (56 km south of Salmon, Idaho), we assessed the density of benthic insects and insect drift in channels with and without sediment and with and without fish during the summer of 1974.

Methods

The stream channels we used were 45.0 m long, 1.21 m wide and 0.6 m deep. We supplied insects to both channels via a 15.2 cm plastic gravity-flow pipe with a 0.3 m by 1.2 m funnel inserted into Hayden Creek. A headbox at the upper end of the channels allowed the mixing of insects and water and controlled the discharge into the channels (Fig. 12).

Each channel was divided into upper and lower sections of nearly equal length. The upper sections served as control sections (without sediment) and the lower sections as test sections (with sediment). The right-hand channel (looking upstream) contained fish and the left-hand channel had no fish. Each section contained an identical configuration of alternating pools and riffles (Fig. 12). The pools were approximately 5.7 m long and 0.5 m deep, with boulders 0.3 m in diameter placed on the bottom. Riffles were 3.05 m long by 1.21 m wide, and water depth over the riffles was approximately 0.08 m. Each riffle contained a layer of cobbles 6.35 to 12.60 cm in diameter over a 0.4 m layer of gravel. The upstream and downstream 0.3 m of each riffle served as buffer zones and were not sampled.

We allowed insects to colonize the channels 15 days prior to initiation of the tests. Four bottom samples (0.093 m^2 each) were taken randomly from each riffle for each imbeddedness level studied (0, 1/3, 2/3 and fully imbedded), using a sampler similar to that described by Waters and Knapp (1961). Sediment (<6.35 mm diameter) was added to the test sections at 7-day intervals starting August 9, 1974. Riffles were not sampled for benthos until 6 days after each addition of sediment, to allow the insect community to adjust to the respective sediment levels.

Insect drift was sampled with 0.30 by 0.61-m drift nets with a pore size of 0.8 mm. Six days following each addition of sediment, drift nets were placed at the head of each control section to measure recruitment into the channels, and at the bottoms of the control and test sections (Fig. 12). One-hour drift samples were taken 0.5 and 2.5 hours after sunset.

Aquatic insects obtained in bottom samples were identified to species or morphospecies when possible, using keys by Edmonson (1959), Peterson (1962), Jensen (1966), Smith (1968) and Usinger (1968). Chironomid midges were identified only to family because of the taxonomic uncertainty of this group. All Ephemeroptera were characterized as early, middle or late instar on the basis of wing pad development. Aquatic insects obtained in drift were counted for total numbers, total mayflies and total numbers for the mayfly genus *Baetis*. Three species—*B. bicaudatus, B. tricaudatus* and *B. parvus*—were collectively grouped under this genus for graphic analysis and interpretation because damage or loss of the key characteristic (caudal filaments) during collection frequently made separation of these species impossible.

Results and Discussion

Standing Crop in Riffles: When cobbles in the test riffles were fully imbedded with sediment, benthic insect density decreased to less than one-half the density found in the control riffles without sediment (Table 2, Fig. 13A). The test riffles supported a slightly larger insect population than did the control riffles through the first three levels of cobble imbeddedness (0, 1/3, 2/3). The slight to moderate layer of sediment (1.58 mm - 25.40 mm) around stream-bottom cobbles represents a more natural and often more favorable benthic insect habitat than the unnaturally clean cobbles in the riffles without sediment.

Table 2. Standing crop of benthic insects per 0.093-m^2 bottom sample in riffles without (control) and with (test) sediment, at four levels of cobble imbeddedness.

Level of cobble imbeddedness	Mean insect density: Without sediment	Mean insect density: With sediment
0	21.2	28.9
1/3	53.8	62.9
2/3	72.1	84.8
Full	64.9	25.1

Not all insect species responded similarly to the different sediment levels. Several species were monitored for their species-specific responses. Except for Chironomidae, each species monitored (*Epeorus albertae* McDunnough, *Cinygmula* sp., *Ephemerella tibialis* McDunnough, *Baetis bicaudatus* Dodds, *Simulium* sp. larvae

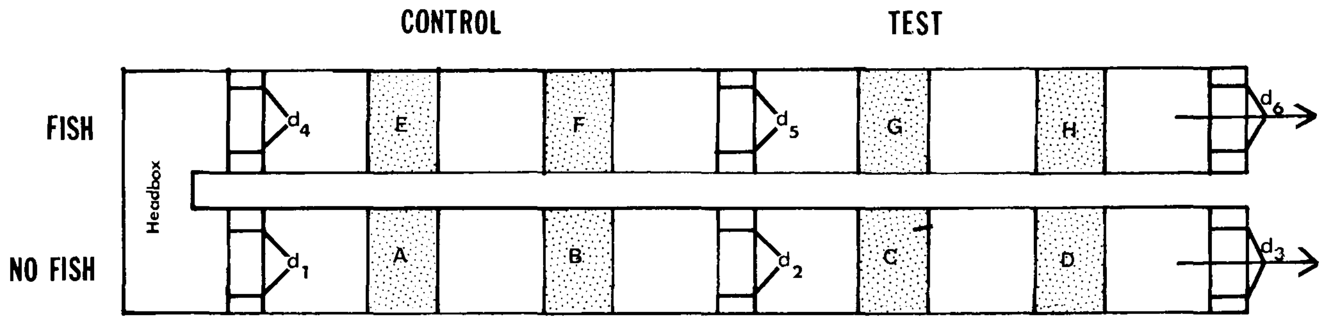

Fig. 12. Experimental stream channel configuration at Hayden Creek. Riffles A and B were in section without sediment or fish; riffles C and D were in section with sediment but no fish; riffles E and F were in section without sediment but with fish; and riffles G and H were in section with sediment and fish. Symbols d_1 to d_6 designate insect drift sampling locations. Shaded areas indicate riffles; unshaded areas pools.

and pupae) decreased significantly in density in the fully imbedded sedimented riffles as compared with their densities when cobbles were two-thirds imbedded (Figs. 13B, 14A-B and 15A-B; Table 3).

The mayfly, *Epeorus albertae* McDunnough, is an important link in the food chain of the aquatic community. As an herbivore, *Epeorus* transforms plant material into animal tissue and is in turn preyed upon by other aquatic insects and fish. Largely defenseless against most forms of predation, this species maintains itself through abundant numbers, protective coloration and secretive habits. The nymph is characterized by having the anterior pair of gills enlarged and overlapping under the abdomen, to function as a suction disc to prevent dislodgment by the current.

Epeorus albertae was an abundant member of the benthic community in the laboratory channels and was intolerant to increased levels of sediment pollution. This species had consistently smaller densities in riffles with sediment than in riffles without sediment. When cobbles were fully imbedded, the average number of *E. albertae* in the test riffles declined to 3 per 0.093 m^2, from 24 per 0.093 m^2 when cobbles were two-thirds imbedded (Fig. 13B).

Baetis bicaudatus Dodds was another abundant member of the channel's benthic fauna. Favored because of its fusiform shape, *B. bicaudatus* is commonly found on the tops and sides of cobbles facing into the current, anchored by its tarsal claws and using its long cerci as

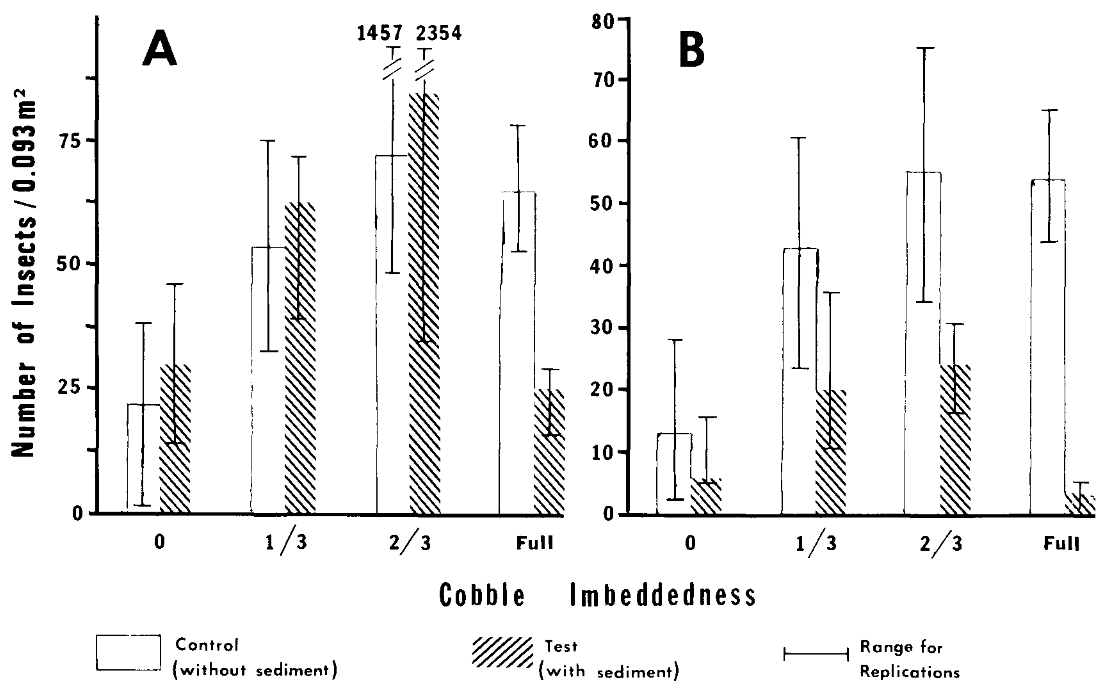

Fig. 13. Density response of benthic insects to four levels of cobble imbeddedness at Hayden Creek. A = total insects, B = *Epeorus albertae*.

Table 3. Comparison of mean insect densities (number/0.093m^2) in test (sediment added) and control (no sediment) riffles at Hayden Creek, 1974.

	Riffle sampled	Level of cobble imbeddedness: 0	1/3	2/3	Full
Total insects	Control	21.2	53.8	72.1	64.9
	Test	28.9	62.9	84.8	25.1*
Total of species listed below	Control	10.0	15.7	13.0	18.0
	Test	9.0	13.2	12.5	17.0
Epeorus albertae	Control	13.5	43.0	55.8	54.1
	Test	6.1	20.6*	24.0*	3.1*
Cinygmula sp.	Control	5.1	7.6	9.1	6.9
	Test	2.3	6.1	10.4	0.5*
Ephemerella tibialis	Control	0.2	2.3	4.0	4.9
	Test	0.1	1.7*	3.6	2.2
Baetis bicaudatus	Control	6.2	18.0	23.7	30.2
	Test	17.0*	20.7	19.7	14.5*
Simulium sp. (larvae)	Control	40.4	59.4	92.0	64.7
	Test	44.7	116.0	206.0	3.9†
Simulium sp. (pupae)	Control	1.8	33.4	23.3	11.4
	Test	2.4	29.7	12.4	1.7*
Chironomidae	Control	13.6	42.9	55.4	58.3
	Test	39.8*	49.1	52.5	44.8

* = significant difference at 5% level.
† = significant difference at 5% level for natural log transformation.

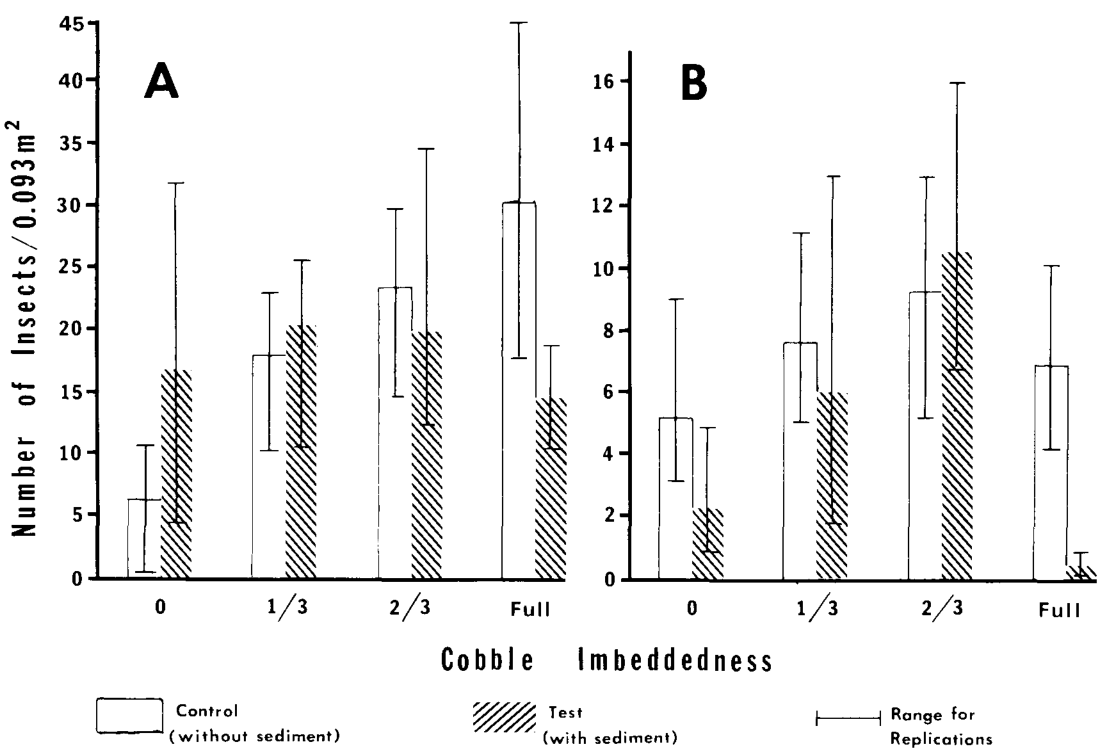

Fig. 14. Density response of benthic insects to four levels of cobble imbeddedness at Hayden Creek. A = *Baetis bicaudatus*; B = *Cinygmula* sp. Control channels without sediment and test channels with sediment.

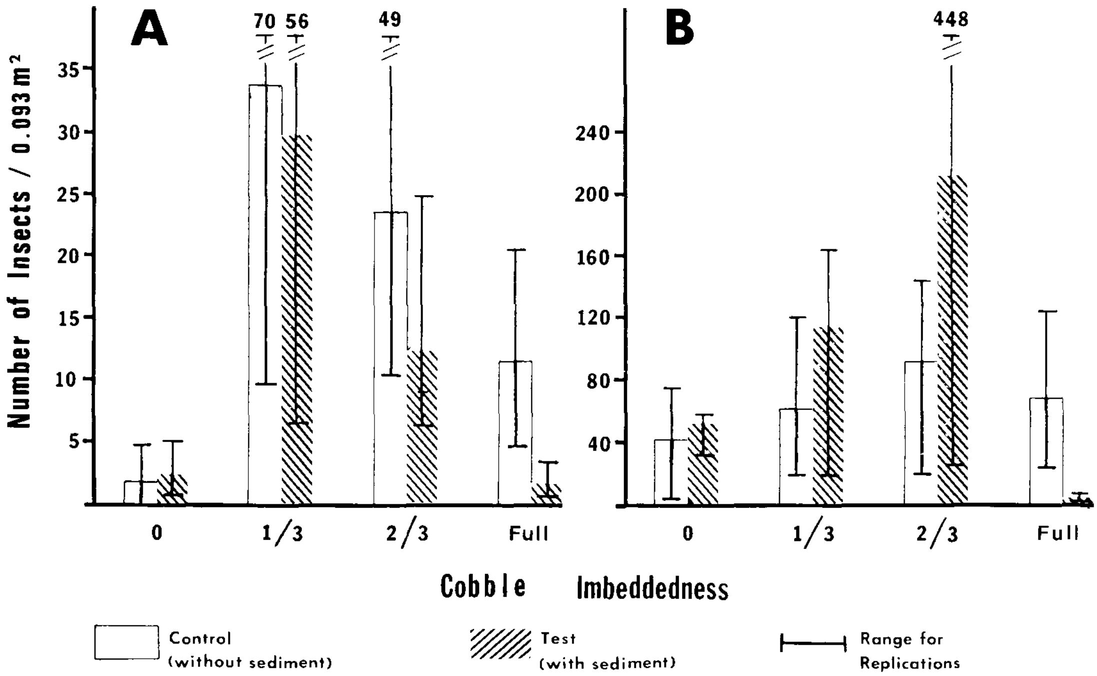

Fig. 15. Density response of benthic insects to four levels of cobble imbeddedness at Hayden Creek. A = *Simulium* sp. pupae; B = *Simulium* sp. larvae. Control channels without sediment and test channels with sediment.

rudders. We expected that *B. bicaudatus* would not be seriously affected by sediment pollution until the tops of the cobbles were imbedded, removing the points of attachment for anchoring the tarsal claws. The results at Hayden Creek confirmed this hypothesis. The density of *B. bicaudatus* in the test riffles did not differ significantly from that in the controls until the test cobbles were fully imbedded (Fig. 14A). The number of *B. bicaudatus* in test riffles D and G, which had consistently larger densities than their respective control riffles B and E for the first three levels of cobble imbeddedness, decreased dramatically when the riffles were fully imbedded with sediment (Fig. 16A-B).

The larval and pupal stages of the blackfly, *Simulium* sp., were monitored for their respective sediment tolerances. *Simulium* larvae tended to favor high-velocity riffles. They were usually found in a clumped distribution (accounting for the wide range in their numbers) on the upper surfaces of cobbles (Fig. 15B).

According to Hynes (1972), the larvae of *Simulium* are among the best adapted of all animals to life in rapidly running water. The larva secretes a silken mat on the substratum, to which it can attach itself by hooks on its highly modified fore and rear prolegs. If disturbed, the blackfly larva will attach itself to the silken mat and lower its body out of the force of the current into the "boundary layer" just above the substrate, where the current is very slow. As a last resort, the larva attaches a silk safety line to the substrate so that in case of dislodgment it can readily climb back up the thread to its original position.

In our channel tests, *Simulium* larvae survived the immediate impact of sediment introduction, but were not able to find suitable places to spin their silken mats when the cobbles were fully imbedded. Larval densities in the sedimented riffles increased through the first three levels of cobble imbeddedness (Fig. 15B). We believe the population was continuing to colonize the channels during these intermediate imbeddedness tests. Larval density was apparently not seriously affected by the sediment levels as long as some areas of the cobbles remained exposed for colonization; however, when cobbles in the test riffles were fully imbedded the numbers of simuliid larvae decreased dramatically, while the density in the control riffles remained stable (Fig. 15B).

The presence of fish in the stream channels did not have a measurable impact on the densities of the four benthic insect species monitored (Figs. 16A-B, 17A-B, 18A-B and 19A-B).

Abundance of Drift: Aquatic insect drift is an important component of stream biology. Many species of fish feed primarily on drift organisms. Müller (1954) and Waters (1961) have shown that insect drift permits rapid recolonization of an area that has been decimated of its benthic fauna.

Insect drift, measured before and 6 days following each introduction of sediment, was not appreciably affected by the increasing levels of cobble imbeddedness (Figs. 20A-E and 21A-E). For any given level of imbeddedness the number of insects collected in drift nets at the end of the sedimented sections was as large as the number collected at the end of the unsedimented sections. We did not try to quantify the immediate impact of sediment introduction on insect drift.

Batholith Streams

In both 1974 and 1975, insect densities in test and control riffles in Knapp Creek were sampled to assess the impacts of sediment added to a stream with small amounts of naturally-occurring sediment. In 1975 we also conducted tests in riffles of Elk Creek which contained large amounts of sediment, to validate some of the results obtained in the laboratory channels at Hayden Creek.

Methods

Streambottom Substrate and Cobble Imbeddedness: During our studies, we took core samples from riffles in the study streams and also classified the surface of the stream substrate according to the imbeddedness of the dominant material in the sediment (Table 4). All benthic insect bottom sample sites were described according to this surface sediment rank classification system.

Knapp Creek: During the summer of 1974 we added 34.5 m^3 of sediment (<6.35 mm diameter) to a portion of a Knapp Creek riffle to simulate a bank slumpage. Using a 0.093-m^2 bottom sampler (previously referred to), we sampled the riffle for benthic insects 2 days before the sediment dump and 1, 3, 14 and 23 days following the addition of sediment, to determine the immediate and longer-term impacts of the sediment. We used a random block method of selecting sampling sites. One-third of the samples were taken in near-shore areas, two-thirds in the thallweg. A minimum of 6 and a maximum of 11 bottom samples were analyzed for each sampling date; the variation in numbers of samples was due to the breakage of some samples during transport to the laboratory. Because of the nature of the correlation used, which did not differentiate between sampling dates, this discrepancy did not affect the statistical tests run.

A control riffle located upstream was sampled simultaneously. Twelve random block bottom samples were taken on the first sampling date and six on each of the following sampling dates.

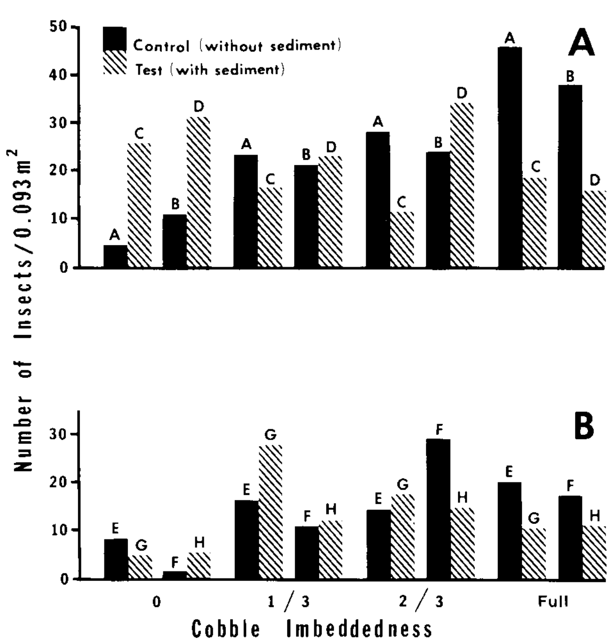

Fig. 16. Density response relationship of *Baetis bicaudatus* to four levels of cobble imbeddedness in riffles in laboratory channels (A through H) at Hayden Creek, 1974. Fish were present in the channels of group B, not present in those of group A.

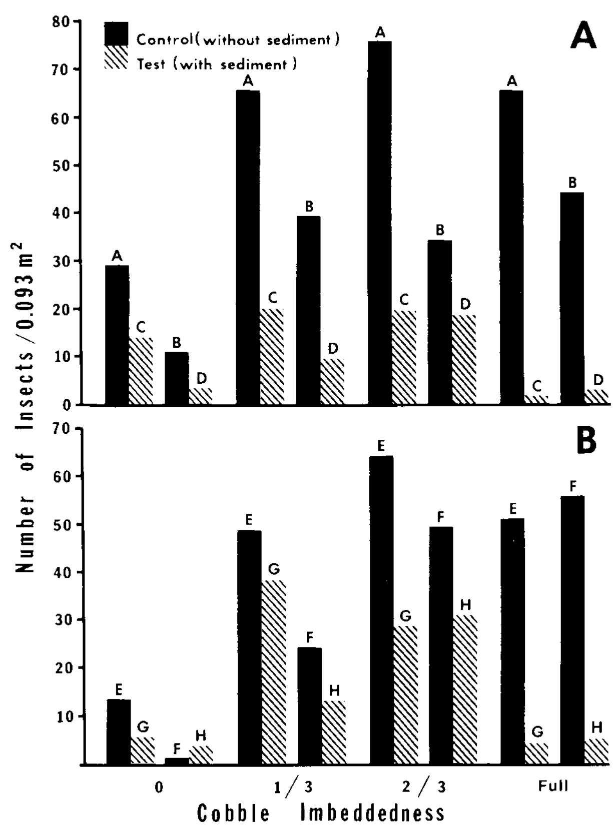

Fig. 17. Density response relationship of *Epeorus albertae* to four levels of cobble imbeddedness in riffles in laboratory channels (A through H) at Hayden Creek, 1974. Fish were present in the channels of group B, not present in those of group A.

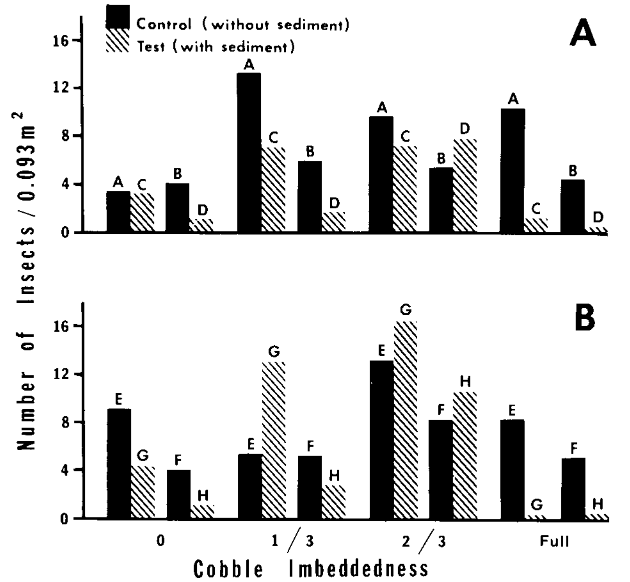

Fig. 18. Density response relationship of *Cinygmula* sp. to four levels of cobble imbeddedness in riffles in laboratory channels (A through H) at Hayden Creek, 1974. Fish were present in the channels of group B, not present in those of group A.

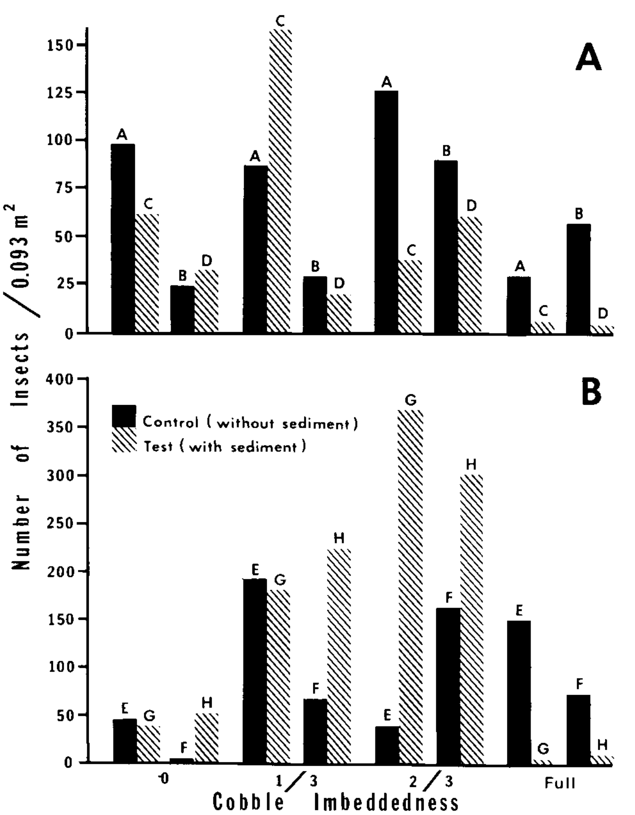

Fig. 19. Density response relationship of *Simulium* sp. (larvae + pupae) to four levels of cobble imbeddedness in riffles in laboratory channels (A through H) at Hayden Creek, 1974. Fish were present in the channels of group B, not present in those of group A.

During the summer of 1975 the benthic insects in test and control riffles were resampled at 3-week intervals. A moderate-gradient riffle in the middle reach of Knapp Creek was also sampled to provide data on spatial relationships with the test site. Six random block bottom samples were taken at each site per sampling date.

For both years, we correlated the abundance of insects in the bottom samples (total and specific species) with level of cobble imbeddedness, predominant substrate and size of sediment surrounding the cobbles.

Elk Creek: A riffle in lower Elk Creek was sampled during the summer of 1975 to validate Hayden Creek results. Two adjacent plots imbedded with sediment (average level of cobble imbeddedness = 3/4) were selected, each plot measuring 3.05 m by 1.52 m. A series of 0.093 m^2 bottom samples was taken from each plot prior to substrate alteration (August 3). One plot was then manually cleaned of sediment, and small cobbles were added to make the plot resemble an unimbedded, healthy riffle. Each plot was subsequently sampled at 3-week intervals (August 23 and September 17).

A riffle in upper Elk Creek was also sampled to assess spatial differences in the insect community within that creek and to illustrate the normal fauna in a riffle with small amounts of sediment.

Results and Discussion

Streambottom Substrate and Cobble Imbeddedness: In most riffles sampled, the predominant material was gravel and pebbles ranging from 6.00 to 75.00 mm in diameter. Substrates that we classified as two-thirds to fully imbedded would correspond to core samples containing 30 percent or more sediment, a situation in which all of the interstitial spaces in the gravel are filled with sediment.

Knapp Creek: Except for a low correlation between insect density and level of cobble imbeddedness for mayflies and the caddisfly, *Brachycentrus* sp. (Table 5), the artificially introduced sediment did not have a statistically significant immediate or long-term impact on the benthic insect community in the Knapp Creek test riffle. The water velocity over the Knapp Creek riffle was sufficient to displace most of the fine particles immediately after sediment was introduced, and the remaining sediment, consisting largely of coarse sand and pebbles 1.58 mm to 25.40 mm in diameter, did not imbed the cobble except in the near-shore areas. The surface and interstices of the substrate remained available for continued colonization by the majority of the insects.

There was no statistically significant correlation between the substrate parameters and the abundance of individual insect species for the Knapp Creek intensive-study site; however, the "extreme" ranges in substrate

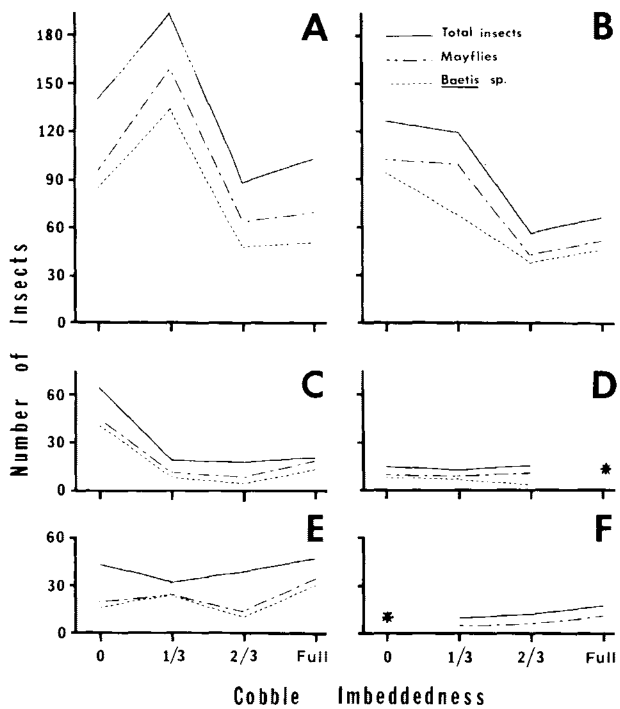

Fig. 20. Insect drift at Hayden Creek 0.5 hour after sunset at six net locations. A, C, E = nets 1, 2, 3, respectively; B, D, F = nets 4, 5, 6, respectively, as illustrated in Fig. 12. Nets A, B = recruitment into channels; nets C, D = drift out of sections without sediment; nets E, F = drift out of test sections subjected to four levels of cobble imbeddedness; * = data not available.

Table 4. Ranking scheme used to classify streambottom substrate in batholith streams for insect studies.

	Predominant Substrate Classification
Rank	Substrate size
1	organic cover (over 50% surface bottom fraction organic debris)
2	1.58 mm diameter
3	1.58 to 6.35 mm diameter
4	6.35 to 25.40 mm diameter
5	25.40 to 63.50 mm diameter
6	63.50 to 127.00 mm diameter
7	127.00 to 254.00 mm diameter
8	boulder
	5-Rank Cobble Imbeddedness Classification
Rank	Imbeddedness
1	completely or nearly completely imbedded (heavy)
2	3/4 imbedded (moderate)
3	1/2 imbedded (intermediate)
4	1/4 imbedded (light)
5	unimbedded

parameters were not always present under our test conditions (i.e., cobble fully imbedded in sand). Therefore, the results for Knapp Creek are more restricted in applicability than those for Hayden and Elk creeks.

Elk Creek: Lower Elk Creek, a low-velocity meandering stream, contained large amounts of fine sediment in its riffles. We used adjacent manually cleaned and uncleaned riffles to validate laboratory results. By the last of three sampling dates (September 17) the cleaned section was again approximately one-fourth imbedded by sand and provided a more "natural" habitat for benthic insects.

On the final sampling date the total number of insects per 0.093 m^2 collected from the cleaned plot was 1.5 times the number collected from the uncleaned plot (Fig. 22A) and the number of species collected from the cleaned plots was approximately 1.3 times the number collected from the uncleaned plots (Fig. 22B). The orders Ephemeroptera (mayflies) and Plecoptera (stoneflies) constituted more than one-half the insects collected from the cleaned plot. There were approximately four times

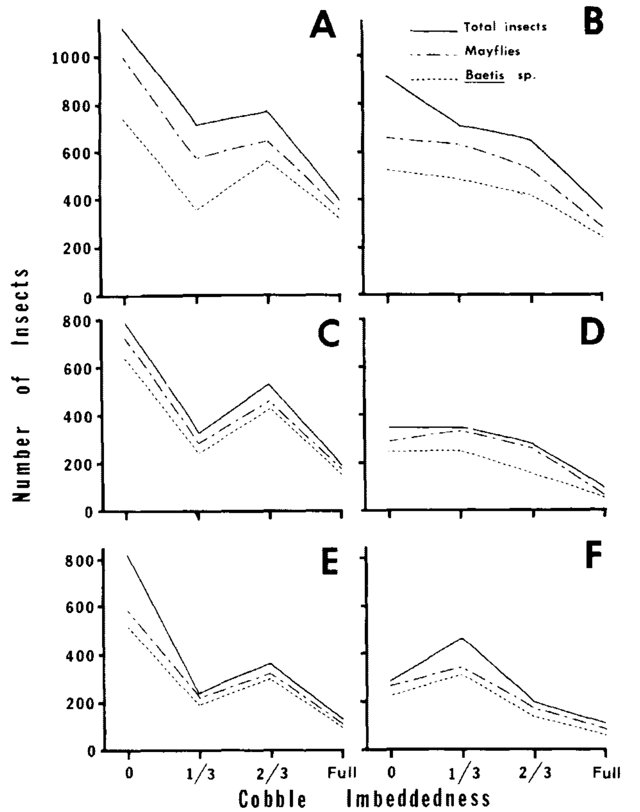

Fig. 21. Insect drift at Hayden Creek 2.5 hours after sunset from six net locations. A, C, E = nets 1, 2, 3, respectively; B, D, F = nets 4, 5, 6, respectively, as illustrated in Fig. 12. Nets A, B = recruitment into channels; nets C, D = drift out of sections without sediment; nets E, F = drift out of test sections subjected to four levels of cobble imbeddedness.

Table 5. Correlation coefficients for the abundance of benthic insect species versus the level of cobble imbeddedness at Knapp Creek, 1974-75. Cobbles were ranked as unimbedded, 1/4, 1/2, 3/4 or fully imbedded.

	Riffles sampled 1974		Riffles sampled 1975	
	Control	Test	Control	Test
Total insects	.125	.261	.146	-.060
Total species	.086	.287*	-.087	-.390
Ephemeroptera (total)	.085	.293*	.203	-.079
Baetis sp.	.030	.246	-.150	.00
Emphemerella tibialis	.228	.250	-.242	-.182
Cinygmula sp.	-.262	-.093	-.063	-.834*
Epeorus longimanus	-.282	.115	.325	-.332
Rhithrogena robusta	.421	.186	.344	.280
Trichoptera	NC	NC	NC	NC
Brachycentrus sp.	-.068	.311*	-.538*	-.464*
Arctopsyche sp.	NC	NC	NC	NC

* = significant difference at 5% level.
NC = no correlation.

more mayflies and eight times more *Alloperla* sp. (the predominant stonefly) in the cleaned plot than in the uncleaned plot on the final sampling date (Figs. 23A and C).

All the mayflies monitored (i.e., *Ameletus sparsatus* McDunnough, *Paraleptophlebia heteronea* McDunnough, *Ephemerella inermis* Eaton-*infrequens* McDunnough, and *Rhithrogena robusta* Dodds) had greater densities in the cleaned plot than in the heavily-sedimented uncleaned plot (Figs. 22C-D and 23A-D). Present as an early instar nymph on the final sampling date, *R. robusta* was a prominent member of the mayfly community and was ten times more abundant in the cleaned plot than in the uncleaned plot (Fig. 23B).

Ameletus sparsatus, which favors slow-moving streams, was found in approximately equal numbers in both plots on the first sampling date (August 3), before the test plot was cleaned. On the second sampling date (August 23), 3 weeks after the test plot was cleaned, this species was six times more abundant in the cleaned plot than in the uncleaned plot (Fig. 22C).

Neophylax sp., a small caddisfly member of the family Limnephilidae, was a prominent component of the insect community at the lower Elk Creek site. *Neophylax* makes its case out of fine sand grains. On the second sampling date, it was more numerous in the uncleaned plot, which apparently offered the fine sand grains necessary for its casebuilding and as background for protective concealment. By the third sampling date the cleaned plot was one-fourth imbedded with sand and *Neophylax* was more abundant in the cleaned plot (Fig. 24C), which suggests that it prefers a cleaner substrate than that offered by the uncleaned plot.

Riffle beetles (Elmidae) were a surprisingly abundant component in the insect community. Two prevalent species (*Optioservus* sp. and *Heterlimnius corpulentus* LeConte) were numerically combined because of similarities in response to sedimented conditions. The riffle beetle larvae clearly favored the uncleaned plot over the cleaned plot, as they were five times more numerous in the uncleaned plot on the final sampling date (Figs. 24B and D). Elmid adults were not present in large enough numbers for us to identify significant statistical trends with regard to substrate preference.

A burrowing larva of the cranefly family (Tipulidae), *Hexatoma* sp., was four times more numerous in the uncleaned plot than in the clean plot (Fig. 24A).

A riffle in upper Elk Creek with only small amounts of sediment had similar species density and composition to the cleaned plot in lower Elk Creek. The mean number of individuals per 0.093 m^2 for each species was similar at both sites, an indication that the manually cleaned site in lower Elk Creek duplicated a riffle with small amounts of sediment. Elmid larval density in the upper Elk Creek riffle was approximately one-half that in the uncleaned lower Elk Creek plot.

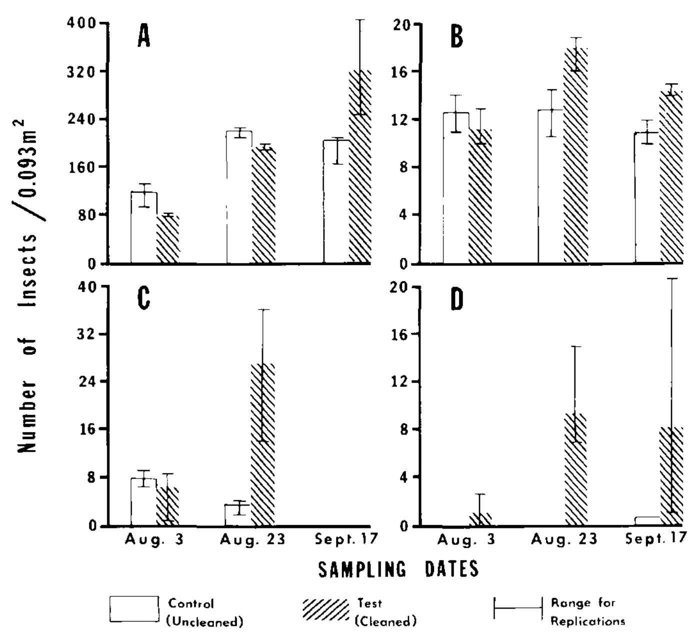

Fig. 22. Density response of benthic insects to cleaned (test) and uncleaned (control) sections in Elk Creek riffle substrate. A = total insects; B = number of species; C = *Ameletus sparsatus*; D = *Paraleptophlebia heteronea*.

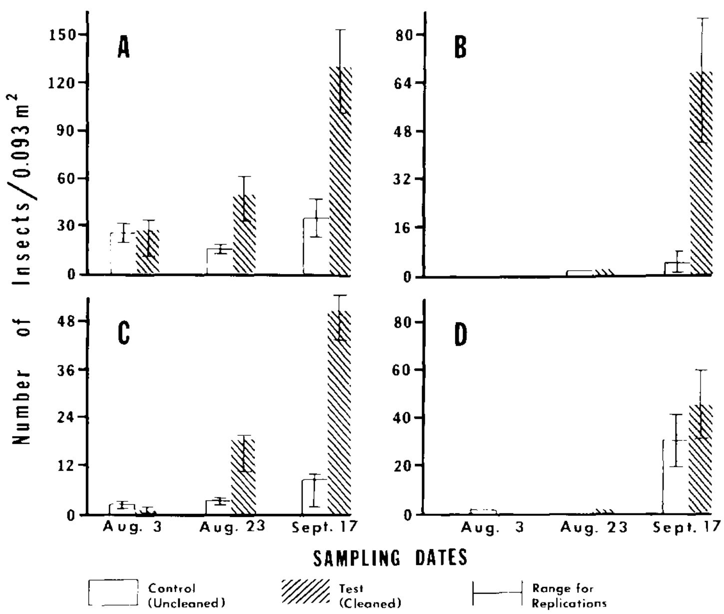

Fig. 23. Density response of benthic insects to cleaned (test) and uncleaned (control) sections in Elk Creek riffle substrate. A = Ephemeroptera; B = *Rhithrogena robusta*; C = *Alloperla* sp.; D = *Ephemerella inermis-infrequens* complex.

The only species found in large numbers at the upper Elk Creek riffle but not found at the lower Elk Creek cleaned site was the larval blackfly (*Simulium* sp.). The low velocity and low gradient of lower Elk Creek seemingly did not provide an optimum habitat for *Simulium* sp. in that, as a filter feeder, its food gathering ability was apparently inhibited.

Streambed Habitat Criteria for Evaluating Benthic Insects—An Overview

The substrate parameters 1) predominant substrate, 2) level of cobble imbeddedness and 3) size of sediment surrounding cobble are useful criteria for physically evaluating benthic insect habitat in Idaho batholith streams. Laboratory tests in the Hayden Creek channels, coupled with field validation studies, confirmed or moderated preconceived notions we had about the relationship between stream habitat quality and insect community dynamics. The *in situ* substrate conditions that prevail in batholith streams following spring runoff are largely the result of natural or man-caused watershed disturbances, geology, stream gradient and the annual hydrologic cycle.

The density and diversity of the benthic insect community in the batholith streams we studied were adversely affected when large amounts of sediment were present in the riffles (i.e.,> 2/3 cobble imbeddedness, as at Elk Creek). The predominant sediment imbedding the cobble was fine sand (<6.35 mm in diameter). In Knapp Creek, where extreme levels of cobble imbeddedness were encountered only in low-velocity near-shore areas after sediment was artificially introduced, the insect community at large was not affected by the introduced sediment, but specific species were adversely affected.

Predominant substrate proved to be a useful indicator of benthic insect density in lower Elk Creek, where the cleaned plot with exposed cobble supported a more dense and diverse insect community than did the uncleaned plot with large amounts of sand.

The size of the sediment surrounding cobble adversely affected the benthic insect community when the extreme condition of fine sand surrounding or fully imbedding cobble was encountered, as was the case at lower Elk Creek and in the laboratory channels at Hayden Creek. Similar findings have been reported by Brusven and Prather (1974).

The surface substrate parameters are interactive and must be considered together. Sedimented streambeds with cobbles more than two-thirds imbedded in sand adversely affect the benthic insect community, since sand tends to restrict subsurface habitation by many benthic insects and reduces streambed permeability. Cobbles imbedded in coarser sediments (e.g., pebble) generally support a richly diverse insect community. Large surface pebbles and small cobbles (6.40 to 12.70 cm in diameter) unimbedded or partially imbedded in a heterogeneous mixture of sediment provide good riffle habitat for insects in batholith streams.

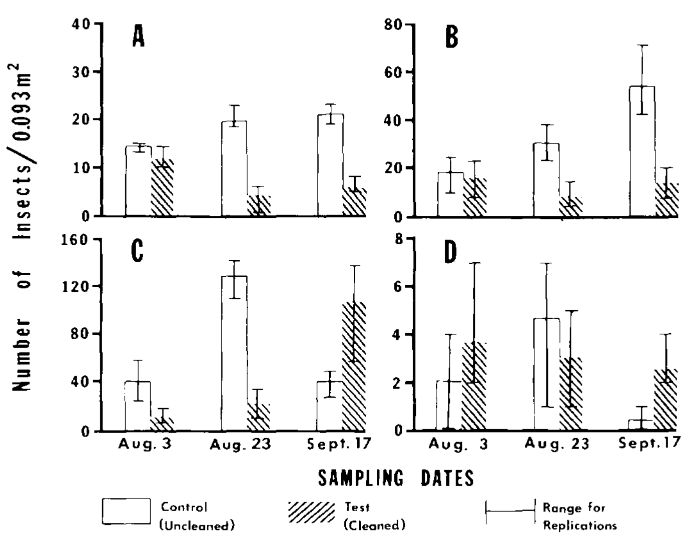

Fig. 24. Density response of benthic insects to cleaned (test) and uncleaned (control) sections in Elk Creek riffle substrate. A = *Hexatoma* sp.; B = Elmidae larvae; C = *Neophylax* sp.; D = Elmidae adults.

In interpreting the utility of a surface sediment classification for describing habitat quality, it should be pointed out that the substrate parameters previously discusssed must be considered in conjunction with the biological and hydrological phenomena of the stream. With insects, species composition and age class distribution are important considerations because of the differential impact of sediment pollution on species and developmental stages of insects. While the results reported herein are for the larval and nymphal stages, the egg stage (uninvestigated in this study) may be equally sensitive to environmental stress by sediment.

EFFECTS OF SEDIMENT ON FISH

We assessed the effects of fine granitic sediment (<6.35 mm) on the density, distribution, behavior, growth and food habits of juvenile chinook salmon (*Onchorhynchus tshawytscha* Walbaum) and steelhead and cutthroat trout (*Salmo gairdneri* Richardson and *Salmo clarki* Richardson) and on the abundance of the insect organisms used as food by the fish. The project contained three major segments: 1) laboratory stream studies in which we introduced fine sediment into laboratory stream channels and monitored the effects on fish and insect abundance; 2) the Knapp Creek study in which we introduced fine sediment into a natural stream channel and monitored the effects on fish and insect populations; and 3) correlational stream surveys on Elk and Bearskin creeks in which we correlated natural physical parameters with fish and insect distribution and abundance.

Laboratory Stream Studies

Methods

We used laboratory stream channels located at the Hayden Creek Research Station (Fig. 1) to determine the effects of granitic sediment on the summer and winter holding capacities of the channels for fish and on the winter hibernating behavior of the fish.

We evaluated the effects of fine sediment added to pools by assessing the number of fish which would remain in channels without sediment versus the number remaining in channels with varying amounts of sediment. Each of the four artificial stream channels was 21.6 to 23.4 m long, 1.21 m wide and 0.60 m deep (Fig. 25). We observed the fish in the channels through plexiglass windows located every 2.4 m. Screens of parachute cloth draped along the sides of the channels reduced disturbance of the fish by people moving around the channels. The pool and riffle configurations were identical in all the channels. Cobble averaging 0.15 m in diameter covered the riffles, and water depth was 0.08 m (Fig. 26). The pools contained a zigzag pattern of boulders (0.30 m average diameter) which afforded cover and hiding places for fish (Fig. 27). Traps at the downstream ends of the channels collected fish moving out of the channels in that direction. Drum screens at the upstream ends of the channels prevented fish from entering or leaving at the head ends.

In the 1974 tests, the four channels contained fish and sediment as follows: channel 1–no fish, no sediment; channel 2–no fish, sediment; channel 3–fish, no sediment; and channel 4–fish, sediment (Fig. 28). Channel 1 served as a control for channel 2, and channel 3 served as a control for channel 4. In 1975 we ran two replicates for most of the tests, using channels 1 and 3 as controls (fish, no sediment) for channels 2 and 4 (fish, sediment), respectively (Fig. 28).

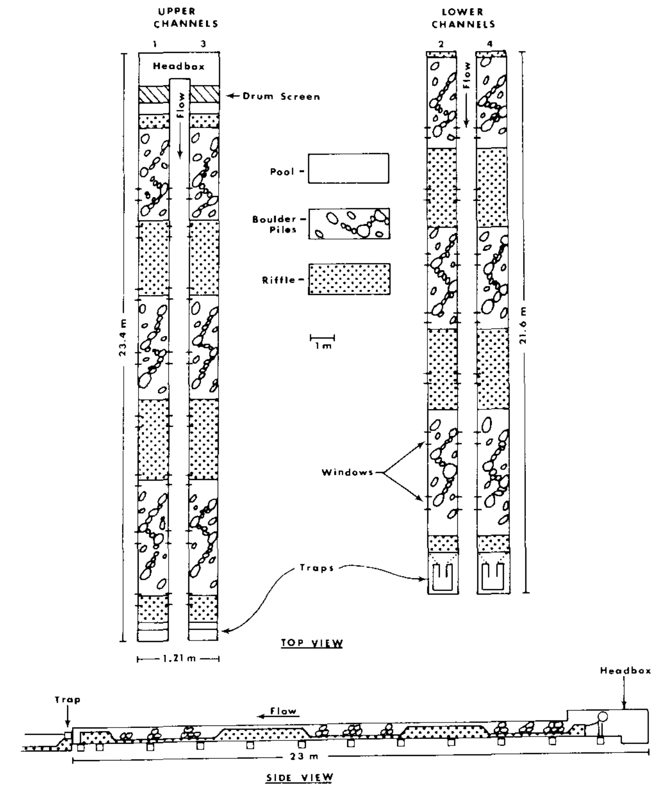

Fig. 25. Artificial stream channels at Hayden Creek Research Station used in summer and winter holding capacity tests for fish.

In 1974 we added sediment to the test channels in three levels of imbeddedness: one-third, two-thirds and full. In 1975 we used two levels of imbeddedness: one-half and full. Imbeddedness was defined as the level to which a key rock was surrounded by smaller size material, in this case granitic sediment less than 6.35 mm in diameter (Fig. 29). Either a predetermined size of rock was used as a key (when imbedding the pools), or the dominant size on the site was used (as in imbedding the riffles). We added more sediment to the pools than to the riffles, due to the larger size of the rocks in the pools, in order to achieve similar imbeddedness in pools and riffles.

In 1974, we introduced insects from Hayden Creek into the headbox through a collecting funnel and pipe. In 1975, insect production within the channels and drift in the normal water supply from Hayden Creek supported the densities of fish used in the tests.

The procedure for each test followed this schedule: 1) sampling of insect drift at 1 hour before sunset until sunset, 2) introduction of the desired amount of sediment into the test (lower) channels, 3) sampling of insect drift and benthos, 4) introduction of test fish into the channels within 24 hours, 5) monitoring of fish emigration and behavior for 5 days, and 6) removal of remaining fish from the channels by electroshocking. We observed behavior

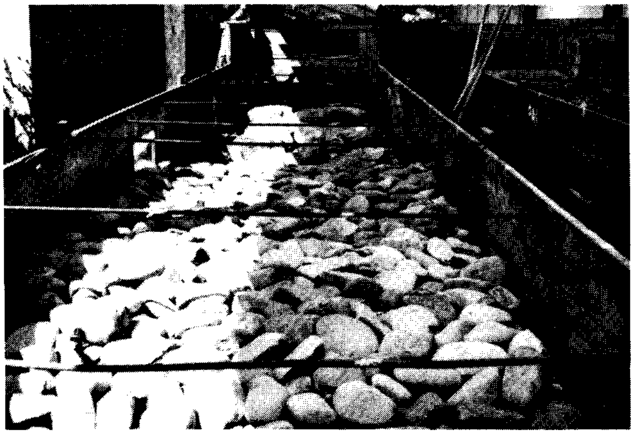

Fig. 26. A typical riffle in the artificial stream channels at Hayden Creek Research Station, 1974 and 1975.

of the fish in the morning, at mid-day, and in the evening just before twilight, and we measured length of fish used in the tests at the start and end of each test. We measured the abundance of the insect benthos in the riffles in 1974, but not in 1975. We recorded water temperatures throughout each test with a minimum-maximum thermometer located in one channel.

We studied feeding habits and food availability by taking stomach samples from fish and by collecting all the insect drift with 1.21 m-wide nets at three locations in each set of channels: 1) at the inlet to the upper channel, 2) at the downstream end of the upper channel, and 3) at the downstream end of the lower channel.

We conducted five summer tests in 1974, four summer tests in 1975 and seven winter tests in 1975 (Table 6). We tested the effects of sediment on summer holding capacity for wild age I steelhead (tests 1, 2 and 3), wild age 0 steelhead (test 4), hatchery age 0 steelhead (tests 5, 6 and 9), wild age 0 chinook salmon (test 8), and hatchery age 0 chinook salmon (test 7). Growth differences were observed in test 9 by extending the test to 35 days and noting differences in the length, weight and condition of fish in channels with and without sediment. We tested the effects of sediment on the winter holding capacity of the channels for hatchery age 0 steelhead (tests 11, 13 and 16), wild age 0 chinook salmon (tests 10, 12 and 13), wild age I and II cutthroat trout (test 15), and hatchery age 0 cutthroat trout (test 14). Test 13 was run with chinook salmon and steelhead together–wild steelhead and chinook from the Hayden Creek Research Station and wild chinook salmon from the Lemhi River. The hatchery cutthroat trout (Henry's Lake stock) used in the tests came from the Mackay Hatchery and the wild cutthroat from the St. Joe River.

Results

The immediate effects of adding sediment to the channels were a reduction in available habitat (shallower pools and fewer interstices in boulder piles and cobble) and an increase in the turbidity of the water. The turbidity decreased within minutes after the additions of sediment. The reduction in cover for fish (mainly in the pools) and habitat for insects (in the riffles) affected both organisms.

Summer Tests – Fish: We released more fish into each channel than would remain, to insure that the fish densities would be at carrying capacity of the channels. Fish densities in the channels stabilized within 3 to 4 days after the traps were opened (Fig. 30).

In the summer holding capacity tests fewer fish remained in the channels with fine sediment than in those without sediment (Table 7, Fig. 31). The numbers of wild age I steelhead remaining in the pools with one-half, two-thirds and full sediment imbeddedness were 86, 40 and 11 percent, respectively, of the numbers staying in the channels without sediment (tests 1, 2 and 3). Fewer wild age 0 steelhead remained in the fully sedimented channel than in the unsedimented channel (test 4), but the reduction was not as large as for wild age I steelhead (test 3).

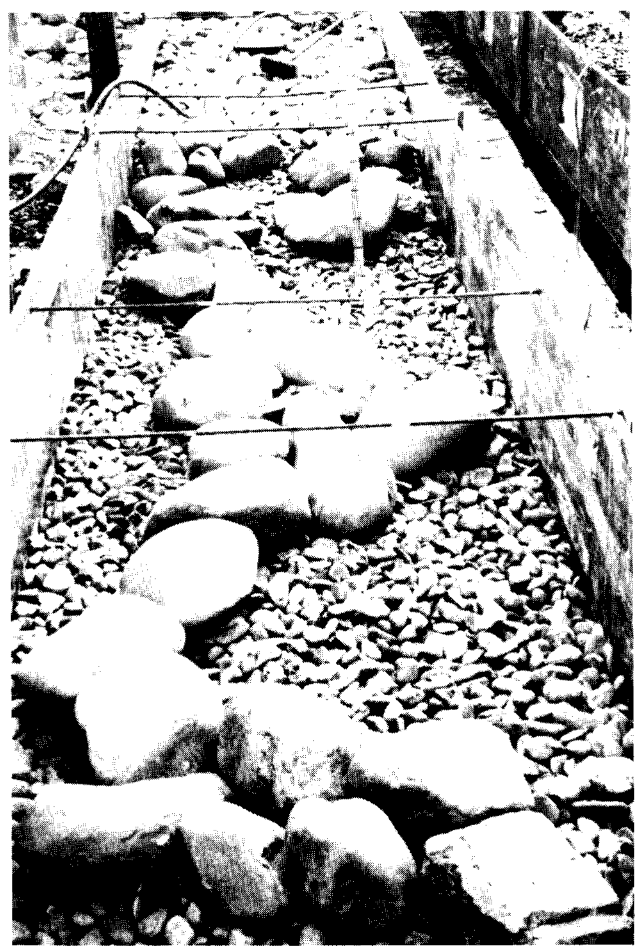

Fig. 27. A typical pool in the artificial stream channels at Hayden Creek Research Station, 1974 and 1975.

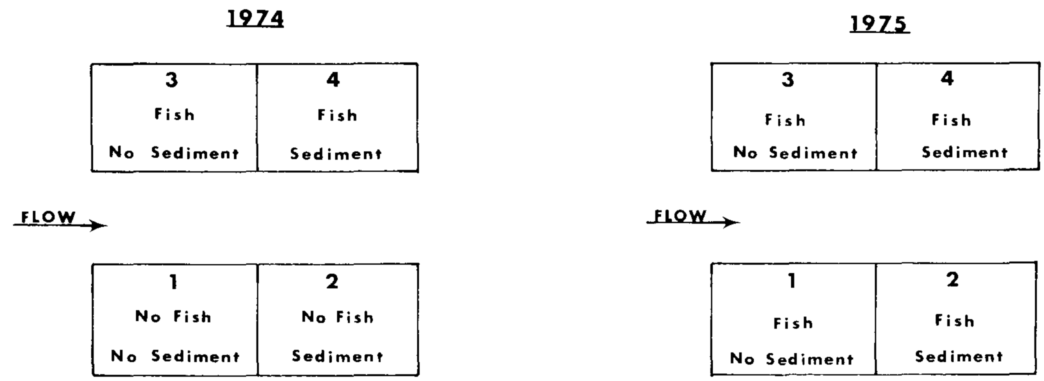

Fig. 28. Schematic representation of the experimental arrangement of the Hayden Creek artificial stream channels during the tests of 1974 and 1975.

At one-half and full imbeddedness in the test pools, densities of hatchery age 0 steelhead in the channels with fine sediment were 94 and 32 percent, respectively, of those in unsedimented channels (tests 6 and 5). Fewer hatchery age 0 steelhead (test 5) remained in the channels with fully sedimented rocks in the pools than did wild age 0 steelhead (test 4).

The density of age 0 hatchery chinook in the one-half imbedded channel was 39 percent of the density in the unsedimented channel (test 7). We did not have time to test age 0 hatchery chinook at full imbeddedness. The density of age 0 wild chinook in the fully imbedded channel was only 3 percent of the density in the unsedimented channel (test 8, Fig. 31).

Fish exhibited hierarchical behavior in the channels with two-thirds or fully imbedded pools, but territorial behavior in the channels without fine sediment. As we increased the imbeddedness levels in the channels, the amount of cover decreased in both pools and riffles. The smaller age 0 steelhead utilized the riffles and pools in the control channels and in the test channels with one-third imbeddedness. As we increased the imbeddedness of the riffles, the age 0 steelhead using the riffles moved into the pools. As cover became scarce in the pools, hierarchical behavior predominated. The main holding areas for fish were at the upstream and downstream ends of the pools.

Fish placed in the channels without fine sediment selected holding areas in the pools and riffles within 0.5 hour and maintained these territories essentially throughout the test.

We extended one 5-day test (test 9) to 35 days to monitor the effects of full sediment imbeddedness on the growth of age 0 hatchery steelhead (Fig. 32). Densities of fish in channels either with or without sediment decreased during the test, perhaps a response to fish growth. The density of fish in the fully sedimented channel stabilized at 12 percent of the density in the unsedimented channel after 35 days. Fish in both the sedimented and unsedimented channels grew in length and weight, but at the end of the test fish in the unsedimented channel were longer and weighed more than fish in the sedimented channel. The condition factor ($K = \text{length}^3/\text{weight}$) of fish in the control channels decreased, while the condition factor of fish in the test channel remained unchanged, something we cannot readily explain.

Few of the age I steelhead and age 0 chinook we examined in 1974 had food in their stomachs. This could be a result of acclimatization to the channels or perhaps of the small size of the insects in relation to the size of the fish. In 1975 fish consumed equivalent numbers of Dipterans and Ephemeropterans during tests 6 and 7, but age 0 chinook and steelhead in tests 8 and 9 consumed more Ephemeropterans than Dipterans (Table 8). The longer length of fish in tests 8 and 9 could account for the shift in preference, with larger fish selecting larger food organisms.

Summer Tests – Insects: During the first three channel tests of 1974 we sampled insect drift at sunset

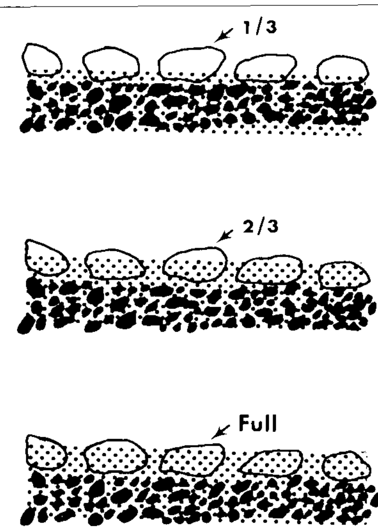

Fig. 29. Diagrammatic representation of three cobble imbeddedness levels, showing key cobble.

Table 6. Tests conducted in the artificial stream channels at Hayden Creek Research Station during the summers of 1974 and 1975 and the fall of 1975.

Test number	Type of test	Date of test	Imbeddedness	Test duration (days)	Replicates	Fish species*	Age group	Average total length of fish (mm)
1	Summer	8/9/74	1/3	5	1	wild SH	I	173
2	Summer	8/15/74	2/3	5	1	wild SH	I	167
3	Summer	8/23/74	Full	5	1	wild SH	I	163
4	Summer	9/1/74	Full	5	1	wild SH	0	71
5	Summer	8/31/74	Full	5	1	hatchery SH	0	61
6	Summer	7/26/75	1/2	5	2	hatchery SH	0	54
7	Summer	8/5/75	1/2	5	2	hatchery CK	0	111
8	Summer	8/14/75	Full	5	2	wild CK	0	96
9	Summer	8/23/75	Full	35	2	hatchery SH	0	53
10	Winter	10/19/75	1/2	5	2	wild CK	0	98
11	Winter	10/26/75	1/2	5	2	hatchery SH	0	116
12	Winter	10/31/75	Full	5	2	wild CK	0	104
13	Winter	11/5/75	Full	5	2	hatchery SH	0	106
						& wild CK	0	122
14	Winter	11/9/75	Full	5	1	hatchery CT	0	59
15	Winter	11/9/75	Full	5	1	wild CT	I, II	134
16	Winter	11/13/75	Full	5	2	hatchery SH	0	119

*SH = steelhead trout (*Salmo gairdneri* Richardson);
CK = chinook salmon (*Onchorhynchus tshawytscha* Walbaum);
CT = cutthroat trout (*Salmo clarki* Richardson).

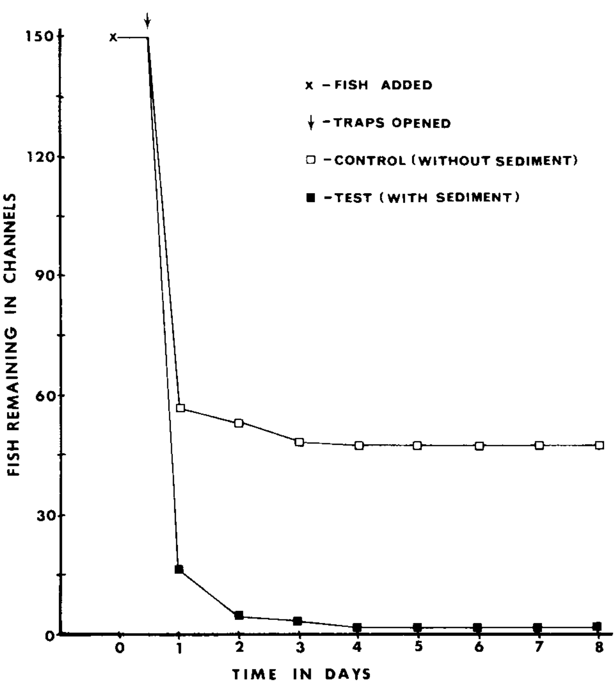

Fig. 30. Changes in fish numbers with time in the Hayden Creek artificial stream channels. Data are for test 8, wild age 0 chinook salmon.

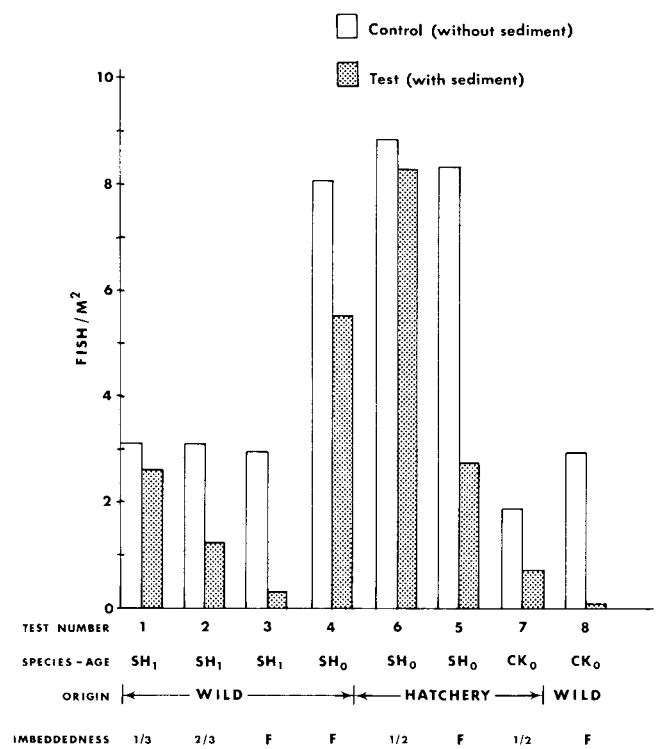

Fig. 31. Densities of fish remaining in the Hayden Creek artificial stream channels after 5 days during the summer tests, 1974 and 1975. SH_1 = age I steelhead; CK_0 = age 0 chinook; 1/3 imbeddedness = key boulders in pools 1/3 imbedded with sediment; F = key boulders in pools fully imbedded.

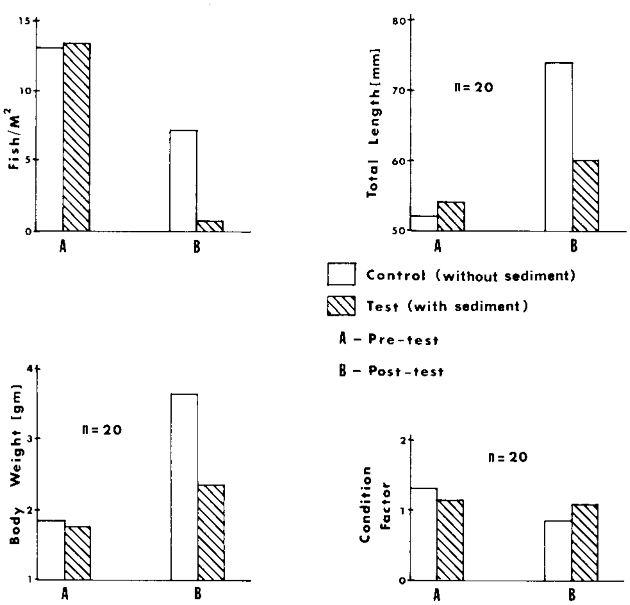

Fig. 32. Results of the 35-day test in the Hayden Creek artificial stream channels at full imbeddedness, using age 0 hatchery steelhead trout, 1975. Condition factor (K) = length^3/weight.

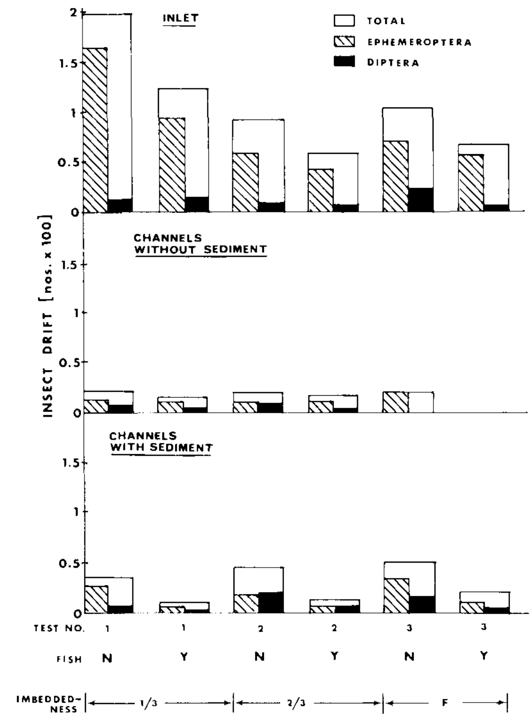

Fig. 33. Insect drift at sunset in the Hayden Creek artificial stream channels during summer tests 1, 2 and 3, 1974. 1/3 = one-third cobble imbeddedness; F = full imbeddedness; Y = fish in channel; N = no fish in channel.

Table 7. Fish in the Hayden Creek artificial stream channels during the summer tests, 1974 and 1975.

			Fish introduced		Fish remaining after 5 days			
Test number	Channel number	Imbeddedness	Species /age	Number	Number	% of fish added	Density (fish/m^2)	Mean density
1	3	0	W,SH/I	60	48	80.0	3.12	3.12-C
	4	1/3	W,SH/I	58	28	48.3	2.63	2.63-T
2	3	0	W,SH/I	60	48	80.0	3.12	3.12-C
	4	2/3	W,SH/I	60	17	28.3	1.15	1.15-T
3	3	0	W,SH/I	60	46	76.7	2.99	2.99-C
	4	Full	W,SH/I	60	5	8.3	0.34	0.34-T
4	3	0	W,SH/0	150	127	84.7	8.10	8.10-C
	4	Full	W,SH/0	150	82	54.7	5.54	5.54-T
5	3	0	H,SH/0	150	126	84.0	8.20	8.20-C
	4	Full	H,SH/0	150	41	27.3	2.77	2.77-T
6	1	0	H,SH/0	225	195	86.7	8.46	8.83-C
	2	1/2	H,SH/0	225	185	82.2	8.11	
	3	0	H,SH/0	225	212	94.2	9.20	8.26-T
	4	1/2	H,SH/0	225	192	85.3	8.42	
7	1	0	H,CK/0	100	26	26.0	1.73	1.90-C
	2	1/2	H,CK/0	100	8	8.0	0.51	
	3	0	H,CK/0	100	31	31.0	2.07	0.77-T
	4	1/2	H,CK/0	100	16	16.0	1.03	
8	1	0	W,CK/0	150	48	32.0	3.20	3.06-C
	2	Full	W,CK/0	150	2	0.1	0.13	
	3	0	W,CK/0	150	44	29.3	2.93	0.06-T
	4	Full	W,CK/0	150	0	0.0	0.00	
9	1	0	H,SH/0	300	300	100.0	13.02	13.02-C
	2	Full	H,SH/0	300	53	17.7	2.32	
	3	0	H,SH/0	300	300	100.0	13.02	1.64-T
	4	Full	H,SH/0	300	22	7.3	0.96	

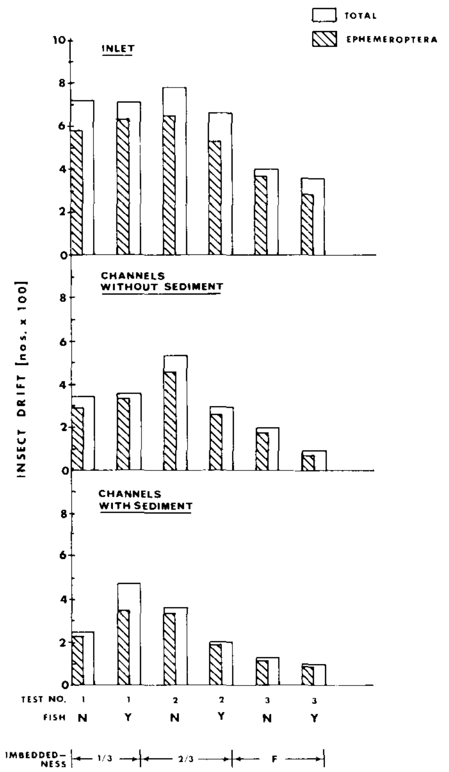

Fig. 34. Insect drift at midnight in the Hayden Creek artificial stream channels during summer tests 1, 2 and 3, 1974. 1/3 = one-third cobble imbeddedness; F = full imbeddedness; Y = fish in channel; N = no fish in channel.

and at midnight. Although we found more insects drifting at midnight than at sunset, we believe insect drift at sunset (or other daylight periods) to be a more relevant index of food available to the fish in this study because the fish species we tested are generally inactive at night (Edmundson et al. 1968). Insect drift at sunset during tests 1, 2 and 3 was not related to imbeddedness level (Fig. 33). Ephemeropterans were the most abundant insects in channels either with or without sediment. The total number of drifting insects was not substantially different in channels with or without sediment.

Insects drifting at midnight during 1974 tests 1, 2 and 3 were mostly Ephemeropterans of the genus *Baetis* (Fig. 34). Midnight insect drift was 6 times more abundant than insect drift at sunset in the inlet water supply and 14 to 16 times more abundant in the channels (Fig. 35). A full moon was present during test 3, which may account for the smaller numbers drifting during that test, since drift of some insects (especially Ephemeroptera) is suppressed by moonlight (Anderson 1966, Holt and Waters 1967). The abundance of insect drift was not decreased by adding sediment to the riffles in 1974.

Our counts of insect drift at sunset in 1975 (Fig. 36) were larger than in 1974 (Fig. 33) because we included adults and pupae in 1975. Ephemeropterans were less abundant than Dipterans in 1975, particularly in the sedimented channels at full imbeddedness (Fig. 36). Because of the large number of Dipterans, there was essentially no difference in insect drift of all species in sedimented and unsedimented channels.

Winter Tests: In the winter tests, the number of fish that remained in the channels, particularly those channels with sediment, was smaller than in the summer tests (Figs. 31 and 37, Table 9). We believe that colder water temperatures caused this difference. At water temperatures below 5°C, the salmonids we tested enter the interstices of the substrate (Everest 1969, Miller 1970, Bjornn 1971, Morrill 1972). As we increased the imbeddedness levels in the channels, the interstices were filled and fish densities decreased, but the differences in fish densities in channels with one-half versus full imbeddedness were less in the winter tests than in the summer tests. Age 0 wild chinook stabilized at a density of 0.45 fish/m^2 in the channels with one-half imbeddedness (test 10) and 0.22 fish/m^2 in the fully imbedded channels (test 12). The difference in densities of fish in the unsedimented channels for tests 10 and 12 was probably caused by colder water temperatures during test 12 (Fig. 38; refer to Table 6 for dates of tests).

Age 0 hatchery steelhead in the channels with one-half and full imbeddedness stabilized at 15.8 and 8.5 percent, respectively, of the fish densities in the channels

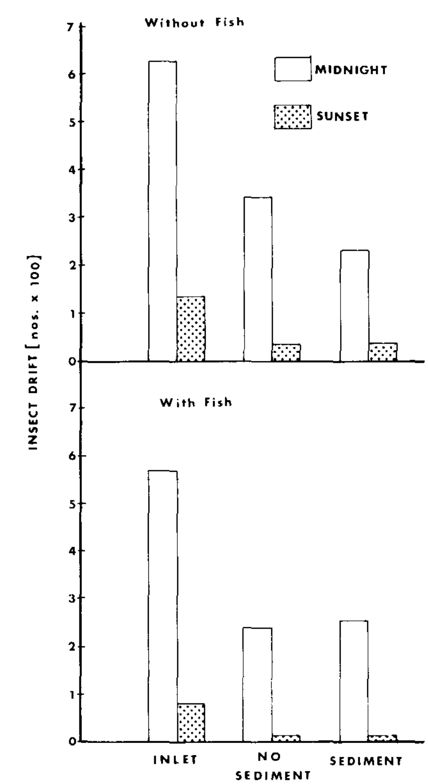

Fig. 35. Average abundance of total insect drift during tests 1, 2 and 3 in the Hayden Creek inlet water supply and the artificial stream channels with and without sediment, 1974.

Table 8. Average numbers and percentages of Diptera, Ephemeroptera, and terrestrial insects found in the stomachs of age 0 chinook salmon and steelhead trout in tests 6, 7, 8 and 9, at the Hayden Creek artificial channels, 1975.

Test number	Fish species/age	Channel number	Imbeddedness	Number of fish in sample	Number of fish with food in stomach	Average number of insects in stomach: Diptera	Ephemeroptera	Total	Percentage of total insect numbers in stomach: Diptera	Ephemeroptera	Terrestrial
6	Steelhead	1	0	9	6	7	5	14	50	36	7
	age 0	2	1/2	10	5	3	9	16	19	56	19
		3	0	11	7	7	7	18	39	39	17
		4	1/2	11	8	7	7	20	35	35	25
7	Chinook	1	0	10	5	7	9	27	26	33	18
	age 0	2	1/2	5	2	20	16	42	48	38	10
		3	0	10	5	9	6	19	47	32	20
		4	1/2	11	4	9	9	22	41	41	14
8	Chinook	1	0	10	7	9	19	31	29	61	6
	age 0	2	Full	3	3	8	19	33	24	58	15
		3	0	10	6	12	23	39	31	59	8
		4	Full	0	0						
9	Steelhead	1	0	10	6	4	10	16	25	62	12
	age 0	2	Full	10	5	4	9	17	24	53	21
		3	0	10	5	4	7	14	29	50	18
		4	Full	7	5	5	9	19	26	47	21

Table 9. Fish remaining in the Hayden Creek artificial stream channels during the winter tests, 1975.

Test number	Channel number	Imbeddedness	Fish introduced: Species*/age	Number	Fish remaining after 5 days: Number	% of fish added	Density (fish/m²)	Mean density
10	1	0	W,CK/0	100	59	59.0	3.93	4.10-C
	2	1/2	W,CK/0	100	7	7.0	0.45	
	3	0	W,CK/0	100	64	64.0	4.27	0.45-T
	4	1/2	W,CK/0	100	7	7.0	0.45	
11	1	0	H,SH/0	200	111	55.5	7.40	7.70-C
	2	1/2	H,SH/0	200	17	11.3	1.09	
	3	0	H,SH/0	200	120	60.0	8.00	1.22-T
	4	1/2	H,SH/0	200	21	14.0	1.35	
12	1	0	W,CK/0	100	20	20.0	1.33	1.43-C
	2	Full	W,CK/0	100	0	0.0	0.00	
	3	0	W,CK/0	100	23	23.0	1.53	0.22-T
	4	Full	W,CK/0	100	7	7.0	0.45	
13	1	0	W,CK/0	75	15	20.0	1.00	
			H,SH/0	75	56	74.7	3.73	1.06-CH,C
	2	Full	W,CK/0	75	6	8.0	0.39	3.80-SH,C
			H,SH/0	75	12	16.0	0.77	
	3	0	W,CK/0	75	17	22.7	1.13	0.48-CH,T
			H,SH/0	75	58	77.3	3.87	0.68-SH,T
	4	Full	W,CK/0	75	9	12.0	0.58	
			H,SH/0	75	9	12.0	0.58	
14	1	0	H,CT/0	300	237	79.0	15.80	15.80-C
	2	Full	H,CT/0	200	50	25.0	3.22	3.22-T
15	3	0	W,CT/I,II	48	16	33.3	1.07	1.07-C
	4	Full	W,CT/I,II	15	1	6.7	0.06	0.06-T
16	1	0	H,SH/0	130	108	83.1	7.20	7.20-C
	2	Full	H,SH/0	50	9	18.0	0.58	
	3	0	H,SH/0	130	108	83.1	7.20	0.61-T
	4	Full	H,SH/0	50	10	20.0	0.64	

*SH = steelhead trout;
CH = chinook salmon;
W = wild; H = hatchery;
C = controls; T = tests.

without sediment (Fig. 37). Age 0 hatchery cutthroat trout in the channel with full imbeddedness stabilized at 20.4 percent of the fish density in the channel without sediment (Fig. 37). Age I and II wild cutthroat trout in fully imbedded channels stabilized at 5.6 percent of the fish density in unsedimented channels.

In test 13 we placed both age 0 hatchery steelhead and age 0 wild chinook together in the channels. The combined fish density in the fully imbedded channels stabilized at 24.7 percent of the density in the unsedimented channels, with steelhead at 17.8 percent and chinook at 45.5 percent.

Behavioral observations were not made during the winter test. Upon introduction into the channels, the fish immediately sought out spaces in the substrate. They remained in these spaces until the water temperatures were increased just prior to electroshocking. For this same reason no stomach samples or drift samples were taken during the winter tests.

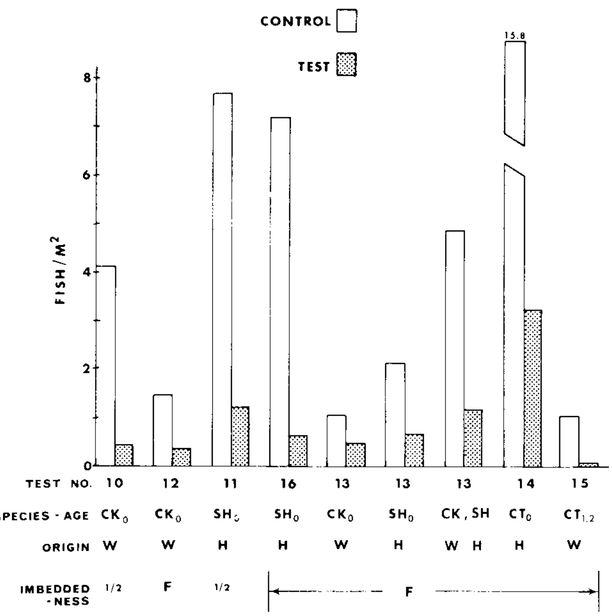

Fig. 37. Densities of fish remaining in the artificial stream channels after 5 days during the winter tests, 1975. W = wild; H = hatchery; 1/2 = boulders in pools 1/2 imbedded with sediment; F = fully imbedded; CK_0 = age 0 chinook salmon, SH_0 = age 0 steelhead trout, CT_0 = age 0 cutthroat trout, $CT_{1,2}$ = Age I, II cutthroat trout.

Knapp Creek Study

Methods

During August of 1974, we introduced 34.5 m^3 of coarse granitic sediment (<6.35 mm diameter) into a test section of Knapp Creek (Fig. 1), as was done in 1973, to assess the effects of sediment on fish and insect distribution and abundance in a section of natural stream where little sediment occurred naturally. Knapp Creek was selected because it contains natural populations of steelhead and chinook salmon, is small enough to be sampled adequately, and is accessible by road.

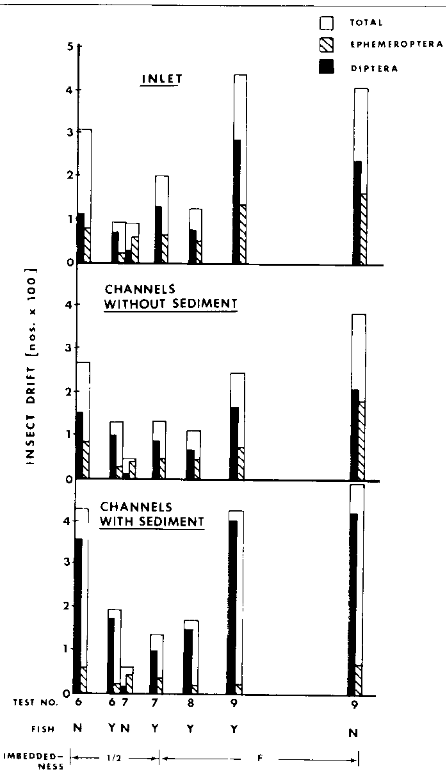

Fig. 36. Insect drift at sunset (average of two channels) in the Hayden Creek artificial stream channels during summer tests 6, 7, 8 and 9, 1975. 1/2 = one-half cobble imbeddedness; F = full imbeddedness; Y = fish in channels; N = no fish in channels. Horizontal scale is temporal.

The section of stream we studied flows through a meadow, has a low gradient, and has a pool-riffle configuration. We mapped the study section and established upper and lower control areas adjacent to the test section (Fig. 39). The surface areas of these sections were as follows: upper control, 506.8 m^2; lower control, 233.4 m^2; test section, 290.8 m^2. The length of the study section was 165 m. We measured water volumes, fish and insect densities, depth contours, and fish and insect distribution in both test and control areas of the study section. We measured fish and insect distribution and abundance prior to and after the addition of sediment in the test area and in control areas upstream and downstream from the affected section of stream.

We added sediment in three steps to the test area and monitored the amount of sediment in the substrate before, during and after the additions. We introduced 19.00 m^3 of sediment to the upper test pool on August 2. On August 5, we introduced 1.00 m^3 to the upper test pool and 4.80 m^3 to the lower test pool. On August 10, the last addition, we introduced 14.50 m^3 into the upper test pool.

Table 10. Ranking scheme used to classify streambottom substrate in batholith streams for fish studies.

Rank	Predominant Substrate Classification Substrate size
1	<than 1.58 mm diameter
2	1.58 to 6.35 mm diameter
3	6.35 to 25.40 mm diameter
4	25.40 to 63.50 mm diameter
5	>63.50 mm diameter

Rank	5-Rank Cobble Imbeddedness Classification Imbeddedness
1	completely or nearly completely imbedded (heavy)
2	3/4 imbedded (moderate)
3	1/2 imbedded (intermediate)
4	1/4 imbedded (light)
5	unimbedded

We took random core samples from the riffle substrate with a modified sampler described by McNeil and Ahnell (1960). We analyzed the samples volumetrically, using 37.50 mm, 18.85 mm, 9.42 mm, 6.35 mm, 4.70 mm and 2.36 mm sieves. We classified the surface of the substrate at each core and benthos sampling location with a modification of Brusven and Prather's (1974) classification (Table 10).

We sampled insect benthos in the test section and in the upper control prior to the first addition of sediment and 1, 3, 14 and 23 days after the last addition. We counted (by snorkeling) the number of fish and noted their location in each section prior to the first addition of sediment, 1 day after the first addition, 1 and 4 days after the second addition and 3 and 13 days after the third addition. The data were plotted on maps of the study sections by a researcher following along the stream bank. Ages of chinook were designated as age 0 and I, and steelhead as age 0 and age I or older.

In August of 1975 we again mapped the study site and measured fish and insect densities in both test and control sections to determine if there were any long-term effects from the 1974 sediment additions.

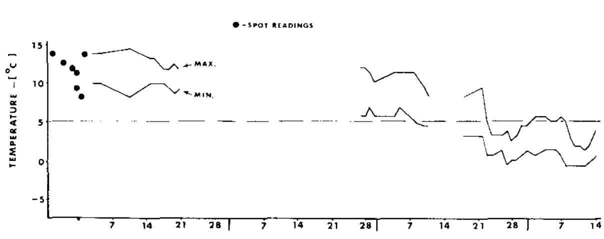

Fig. 38. Water temperatures in the Hayden Creek artificial stream channels during the 1975 tests. 5°C = critical temperature for salmonids studied.

Results

As we introduced fine sediment into the test section of the creek, several changes occurred. The physical characteristics of the stream section were changed in terms of pool volume, available habitat for fish and water velocity. Fish densities in the pools were affected, but insect benthos in the test riffle was relatively unaltered in either abundance or distribution by the sediment additions.

As sediment was introduced onto the riffles and allowed to wash into the pools, the volume of the test pools was reduced and water velocities increased. This increase in velocity tended to spread the sediment over a larger area, until a point of stabilization was reached and the sediment delta stopped its downstream movement in the pools (Figs. 40, 41, 42 and 43).

We observed four species of salmonids in the study section of Knapp Creek: chinook salmon (age 0 and age I), steelhead-rainbow trout (age I and older), brook trout (*Salvelinus fontinalis* Mitchell) and Dolly Varden (*Salvelinus malma* Walbaum). Age 0 chinook comprised the largest percentage of fish present.

As the amount of fine sediment added to the test section increased, the amount of cover for fish decreased and fish densities decreased (Fig. 44 and Table 11), whereas densities in the unsedimented sections remained relatively stable. With the additions of sediment, we decreased the volume of the upper test pool (portion of pool deeper than 0.15 m) to 48 percent of the original volume. Total

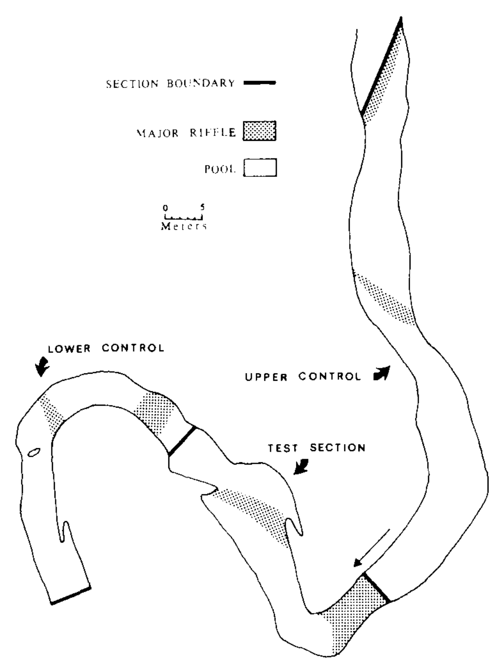

Fig. 39. The Knapp Creek study area. Coarse granitic sediment (<6.35 mm diameter) was introduced into the test section in August 1974.

Table 11. Fish counted in the Knapp Creek study area before sediment was added (8/1), after the first addition (8/3), after the second addition (8/5 and 8/9), after the third addition (8/13 and 8/23), and on 8/15/1975. Sediment added on 8/2, 8/5 and 8/10/1974.

Date of count	Fish species/age*	Number of fish counted: Lower control section	Upper control section	Test section
8/1/74	CK/0	84	314	233
	CK/I	9	17	12
	SH/I+	11	11	29
	EB/I+	15	12	28
	DV/I+	1	0	6
8/3/74	CK/0	126	314	198
	CK/I	4	5	14
	SH/I+	4	3	7
	EB/I+	9	4	22
	DV/I+	2	2	8
8/5/74	CK/0	103	248	149
	CK/I	7	8	9
	SH/I+	5	5	14
	EB/I+	12	8	16
	DV/I+	1	2	5
8/9/74	CK/0	79	204	97
	CK/I	6	5	6
	SH/I+	3	3	10
	EB/I+	8	5	11
	DV/I+	3	2	3
8/13/74	CK/0	80	223	73
	CK/I	7	7	14
	SH/I+	3	7	7
	EB/I+	5	4	14
	DV/I+	1	2	2
8/23/74	CK/0	75	209	53
	CK/I	10	25	12
	SH/I+	1	10	9
	EB/I+	7	12	10
	DV/I+	1	1	2
8/15/75	CK/0	36	49	90
	CK/I	5	9	9
	SH/0	0	32	0
	SH/I+	9	3	19
	EB/I+	4	3	6
	DV/I+	1	1	4

* CK = chinook salmon;
SH = steelhead trout;
EB = brook trout;
DV = Dolly Varden trout;
0 = age 0; I = age I; I+ = age I and older.

fish in the upper test pool decreased to 29 percent of the number prior to the addition of sediment, while age 0 chinook decreased to 25 percent of the original number (Fig. 44 and Table 11). The density of fish expressed as

Fig. 40. The main pool in the Knapp Creek test section (looking downstream) before sediment was introduced into the stream in August 1974.

Fig. 41. The main pool in the Knapp Creek test section (looking downstream) after the second addition of sediment and just prior to the last addition of sediment, 1974.

Fig. 42. The main pool in the Knapp Creek test section (looking downstream) after the last addition of sediment, 1974.

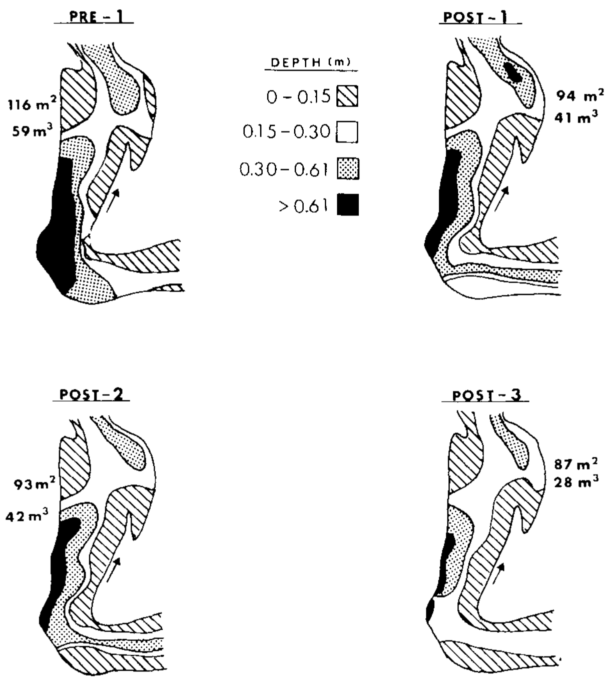

Fig. 43. Depth contours in the Knapp Creek test section during the sediment additions of 1974. Pool areas and volumes for portions of the upstream pool more than 0.15 m deep appear next to each figure. Pre-1 = before first sediment addition (8/1); post-1 = after first addition (8/3); post-2 = after second addition (8/9); post-3 = after third addition (8/13).

fish/m^2 of pool surface area deeper than 0.15 m decreased to 39 percent of the original density; the density of fish expressed as fish/m^3 of pool volume decreased to 38 percent of the original density.

The relationship of fish numbers to percentage pool volume deeper than 0.15 m after each addition of sediment appeared linear (Fig. 45). The fish numbers-percentage volume data for the period after the second addition of sediment were not included in the fitting of the regression line. Fish numbers decreased from 169 after the first addition of sediment to 77 after the second addition, whereas pool volume did not change (41.3 versus 41.5 m^3). The large decrease in fish numbers with no decrease in pool volume resulted when we added 1.0 m^3 of sediment to one area of the pool where large numbers of age 0 chinook were located (Fig. 46). After the first addition of sediment, 67 age 0 chinook were located in a small eddy area at the upstream end of the pool where depth was 0.15 to 0.30 m. The presence of large predator trout and Dolly Varden in the deeper parts of the pool probably influenced the behavior of the age 0 chinook, forcing them to remain mostly in the upstream end of the pool, a habitat not preferred by the chinook prior to the sediment additions. When we added sediment the second time we decreased the depth of this section of the pool to less than 0.15 m without decreasing the total pool volume. The age 0 chinook then moved into the deeper part of the pool or out of the test section entirely (Fig. 46).

The relationship between number of fish in the upper test pool and percentage pool area deeper than 0.15 m was not linear for the full range of 0 to 100 percent pool area (Fig. 47). We decreased the pool area deeper than 0.15 m only to 75 percent of the original area. The depth of 0.15 m may not be the critical depth in the relationship of fish numbers and percentage pool area. When we used the percentage pool area deeper than 0.30 m, the relationship of fish numbers to pool area was again approximately linear (Fig. 48) if in fitting the regression line we did not include the observation after the second addition of sediment. A decrease in the area of the pool deeper than 0.30 m caused a linear decrease in fish numbers in the pool.

Total fish densities in 1975 in the study area were about 50 percent of the pre-sediment densities of 1974 (Fig. 44). The smaller densities in 1975 were probably a result of fewer chinook salmon spawning in 1974 than in 1973. Other streams in the study area also had decreased fish densities in 1975 compared with 1974 (P.T. Sekulich, University of Idaho, personal communication).

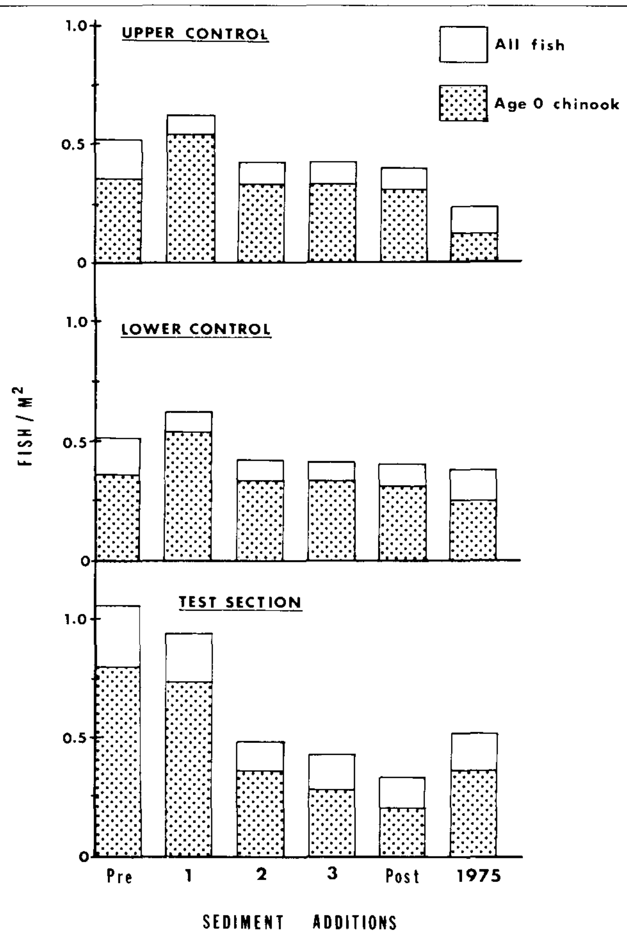

Fig. 44. Total fish and age 0 chinook salmon densities in the control (unsedimented) and test (sedimented) sections of Knapp Creek prior to the first addition of sediment (8/1/74), 1 day after the first addition (8/3), 4 days after the second addition (8/9), 3 and 13 days after the third addition (8/13 & 8/23), and 1 year later (8/15/75).

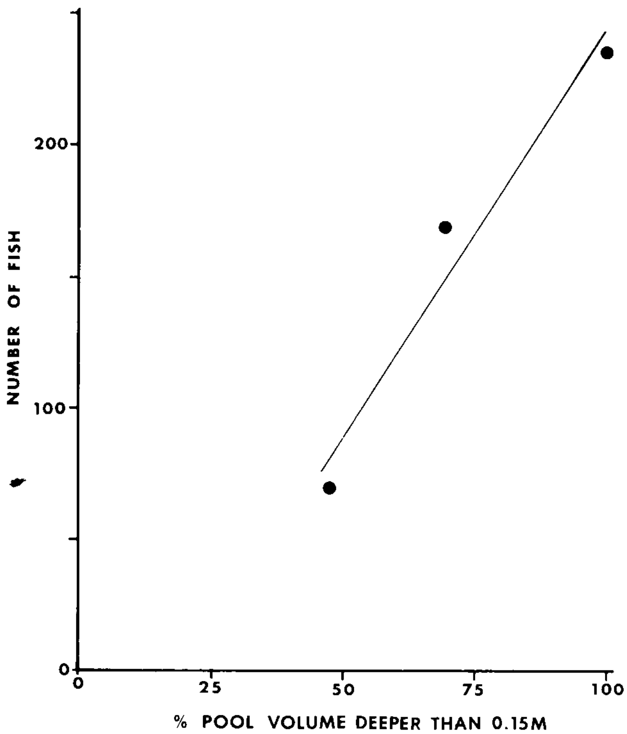

Fig. 45. Number of fish in the upper test pool at Knapp Creek versus the percentage pool volume deeper than 0.15 m during the sediment additions in 1974.

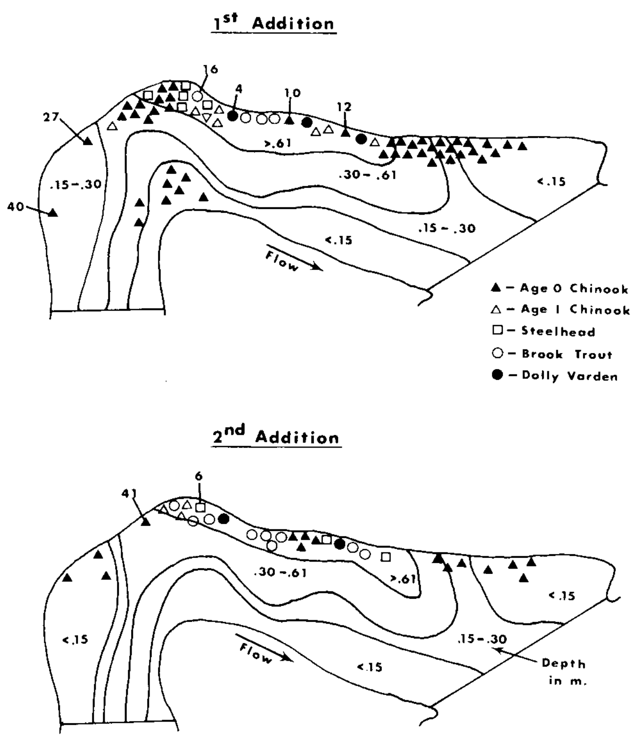

Fig. 46. Distribution and numbers of fish in the upper test pool at Knapp Creek after the first and second additions of sediment into the pool. Each symbol represents one fish, unless otherwise labeled. Decimal fractions indicate depths of outlined portions of pool.

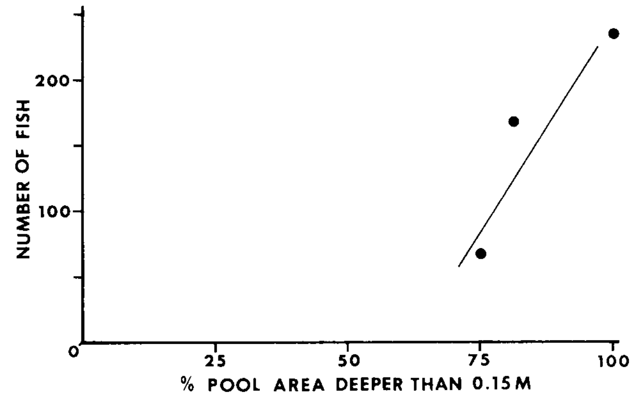

Fig. 47. Number of fish in the upper test pool at Knapp Creek versus the percentage pool area deeper than 0.15 m during the sediment additions in 1974.

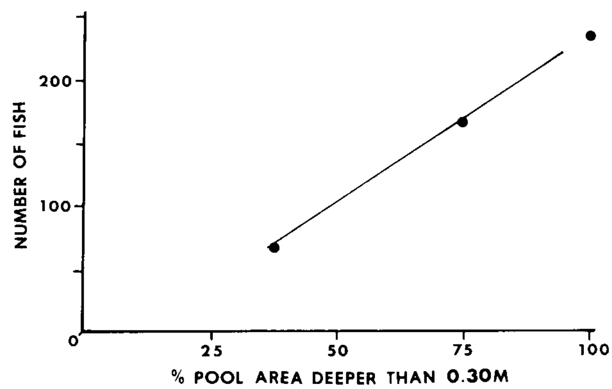

Fig. 48. Number of fish in the upper test pool at Knapp Creek versus the percentage pool area deeper than 0.30 m during the sediment additions in 1974.

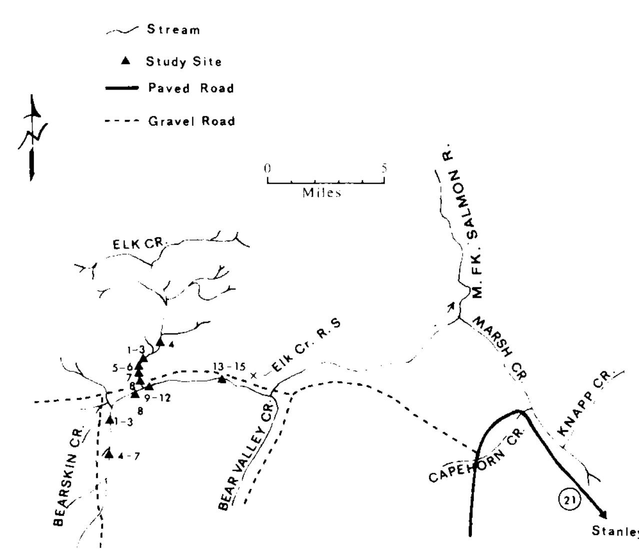

Fig. 49. Correlational survey study sites on Elk and Bearskin creeks in the central Idaho batholith.

Correlational Stream Surveys

Methods

As another approach to determining if fish density is limited by food abundance, which in turn might be limited by the amount of fine sediment in the riffles, we measured the following parameters at 23 pool-riffle sites on Elk and Bearskin creeks in the summer of 1975: riffle length and area, pool length and area, insect drift, percentage sediment (<6.35 mm) in the riffles, average substrate imbeddedness in the pools, percentage cover in the pools, water depth, water temperature, fish densities, and fish lengths and weights (Table 12).

Our aim in this portion of the study was to see if fish densities in August were correlated with the environmental parameters we thought important, particularly sediment concentrations in riffles and insect drift abundance. We wish to emphasize the extensive rather than intensive nature of the data collected. Because of manpower limitations, we could not sample at all sites simultaneously and we had to settle for a less-than-optimum research design. We made the following assumptions:

1) insect drift measured at sunset and in late August is a valid measure of drift food abundance;
2) insect drift at sunset and in late August reflects the effect, if any, of various fine sediment concentrations in riffles;
3) insect drift collected on the first sampled riffles (August 17) is comparable with drift from the last sampled riffles (August 28).

We selected 15 pool-riffle complexes in Elk Creek and 8 such sites in Bearskin Creek (Fig. 49). These creeks have low gradients and meander through meadows. We selected the sites to provide a wide range of sediment concentrations in the riffles. The section of Elk Creek studied was about 18 km long, and the section of Bearskin Creek about 12 km long. Discharges in early September of 1975 were 0.84 m^3-sec for upper Elk Creek and 1.30 m^3-sec for lower Elk Creek. Bearskin Creek had a flow of 0.28 m^3-sec at the mouth.

The creeks contain natural populations of chinook salmon, steelhead trout and mountain whitefish (*Prosopium williamsoni* Girard). We obtained fish densities by snorkeling and counting fish in the areas of preferred habitat (depth >0.15 m).

Samples of insect drift at each site were taken with 0.70 mm mesh nylon drift nets for 1 hour, beginning 1 hour before sunset. Two nets were placed at the downstream end of each riffle and the samples were combined for analysis. One net was positioned on each half of the main flow over the riffle and we measured the volume of flow through each net. Weather conditions and time of sunset were also recorded for each sampling. The samples were preserved in 70 percent ethanol and the insects were keyed to order and analyzed numerically and volumetrically. Drift was expressed as both numbers and volume per cubic meter of flow.

We estimated the percentage of substrate material smaller than 6.35 mm in diameter in each riffle from five random core samples taken from each riffle using techniques described previously in this report. We analysed the samples volumetrically, using the same set of sieves used on Knapp Creek.

We measured the amount of cover in each study site and classified the cover using a two-type system. Surface

Table 12. Ranges and means of the parameters measured during the correlational stream surveys on Elk and Bearskin creeks, August 1975.

Stream section and number of sample sites (n)		Riffle length (m)	Riffle area (m^2)	Pool length (m)	Pool area (m^2)	% Riffle sediment	Pool imbeddedness	Water temperature (°C)	% Surface cover	% Bottom cover	Insect drift (nos./m^3 flow)
Upper Elk Creek											
n = 8	Range	5-14	29-195	14-30	62-269	23-47	1/4-3/4	7.0-13.5	10-60	0-30	.40-1.80
	Mean	9	90	22	154	32	1/2		35	9	0.98
Lower Elk Creek											
n = 7	Range	5-15	13-158	10-38	51-235	38-59	1/2-Full	7.0-13.5	20-60	0-10	.05-3.70
	Mean	9	80	22	129	44	3/4		39	6	1.40
Upper Bearskin Creek											
n = 4	Range	2-8	8-25	7-12	29-52	20-37	1/4-1/2	2.0-11.0	40-50	10-30	.31-0.71
	Mean	4	16	10	39	28	1/2		45	22	0.53
Lower Bearskin Creek											
n = 4	Range	4-8	25-84	9-22	29-133	61-75	Full	4.0-13.0	25-40	0-20	.43-1.60
	Mean	6	52	13	65	66	Full		31	22	1.10

cover (type 1) included overhanging vegetation, undercut banks and surface turbulence. Bottom cover (type 2) included boulders and logs lying in the bottoms of the pools. Both types of cover were expressed as percentages of the total pool area.

We also attempted to increase fish density by adding wild age 0 chinook salmon to pools. The hypothesis tested was *H_0: The addition of fish to pools downstream from riffles with either large or small amounts of fine sediment will not permanently increase the fish density.* Sites with large and with small concentrations of sediment in the riffles were chosen for the test. We counted the fish in the test pools before and 24 hours after the additional fish were introduced, to determine if the densities had changed.

Results

Elk Creek: Elk Creek contained three species of salmonids (chinook salmon, steelhead trout, and mountain whitefish) that we included in the total fish densities. Total densities in the pools ranged from 0.09 to 0.43 fish/m^2. Age 0 chinook comprised the majority of the fish in the pools studied (Table 13).

Table 13. Fish densities (per m^2) in Elk Creek pools during the correlational surveys of August 1975.

Site number	Chinook salmon Age 0	Chinook salmon Age I	Steelhead Age I+	Whitefish	Total fish
1	0.10	0.07	0.004		0.18
2	0.09	0.01	0.010		0.11
3	0.28	0.07		0.020	0.37
4	0.16	0.01		0.004	0.17
5	0.18	0.05	0.040	0.005	0.28
6	0.14	0.06			0.20
7	0.28				0.28
8	0.10	0.02		0.008	0.13
9	0.31	0.10		0.020	0.43
10	0.10	0.02			0.12
11	0.05	0.03		0.020	0.10
12	0.10	0.05			0.15
13	0.03	0.01	0.005	0.040	0.08
14	0.13	0.04	0.010	0.010	0.19
15	0.09	0.03			0.12

Insect drift densities from the riffles in Elk Creek did not correlate significantly with percentage fine sediment in the riffles ($r = 0.126$, Fig. 50). Correlation of fish densities in the Elk Creek pools with insect drift gave an r value of 0.559 (probability that r not significantly different from zero equals <0.028) (Fig. 51), suggesting that a relationship existed between insect drift abundance at sunset and fish density. Fish densities in the pools did not

Table 14. Multiple correlations for Elk Creek in 1975, using the model $Y = a + bX_1 + cX_2$.

Y	X_1	X_2	R
Fish/m^2 in pools	% Riffle sediment	Drift density	0.324
Fish/m^2 in pools	% Riffle sediment	Drift/pool area	0.780*
Fish/m^2 in pools	% Riffle sediment	Bottom cover	0.582
Fish/m^2 in pools	% Bottom cover	Drift density	0.602
Fish/m^2 in pools	% Bottom cover	Drift/pool area	0.767*
Drift density	% Riffle sediment	Riffle area	0.138
Drift density	% Riffle sediment	Riffle length	0.197

* Significant at $\alpha = 0.01$.

correlate significantly with percentage sediment in the riffles ($r = 0.164$, Fig. 52), as we might expect, since insect drift did not correlate with percentage sediment in the riffles.

Cover limits fish density in some cases, so we attempted to correlate fish density with the amount of cover in the pools (Fig. 53). The largest r value obtained was with bottom cover ($r = 0.574$, $p < 0.025$), an indication that cover in the pools may in fact affect the density of fish in Elk Creek.

To see if these parameters in combination affected fish density, we correlated percentage sediment in the riffles, insect drift, bottom cover and the ratio of insect drift to pool area (Table 14). We used the ratio of drift density to pool area on the hypothesis that the amount of available food per unit area of pool could affect fish density. Fish density correlated best with percentage sediment and drift/m^2 of pool area ($R = 0.780$, significant at $\alpha = 0.01$) and with amount of bottom cover and drift/m^2 of pool area ($R = 0.767$, significant at $\alpha = 0.01$). The correlation of fish density with bottom cover and drift density ($R = 0.602$) may be more valid, as artifacts can be produced by using a ratio as a variable in a multiple regression model.

Table 15. Results of Duncan's multiple range test of the means for age 0 chinook length and weight in Elk and Bearskin creeks, August 1975.

Stream section and number of sample sites	Total length (mm) Mean	Total length (mm) Different at $\alpha = 0.01$	Body weight (kg) Mean	Body weight (kg) Different at $\alpha = 0.05$
Upper Elk Creek n = 20	63.0	yes	2.60	yes
Lower Elk Creek n = 20	70.9	no	3.90	no
Bearskin Creek n = 20	72.2	no	4.28	no

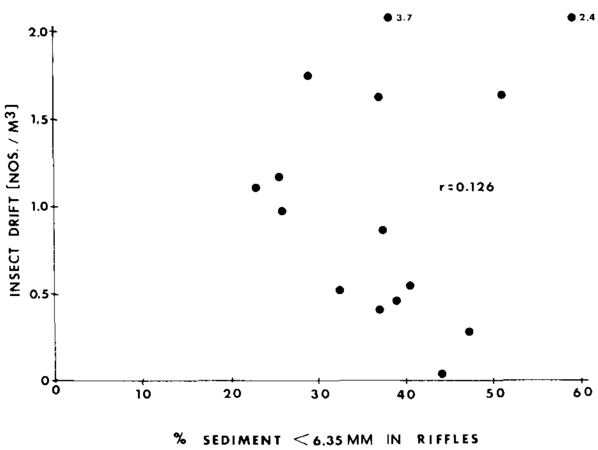

Fig. 50. Insect drift density at sunset versus percentage sediment in riffles in Elk Creek, August 1975.

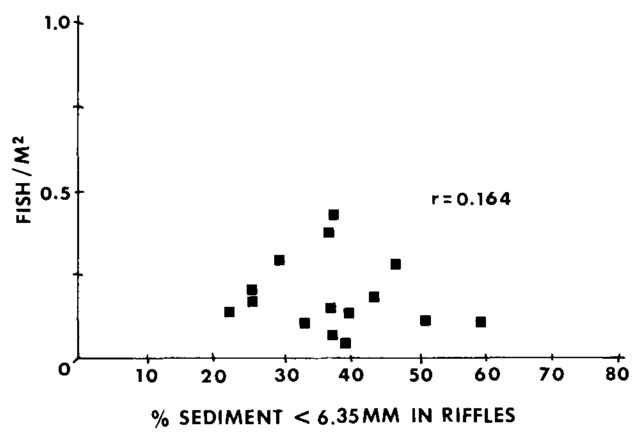

Fig. 52. Fish density in pools versus percentage sediment in riffles in Elk Creek, August 1975.

Lengths and weights of age 0 chinook from upper and lower sections of Elk Creek were significantly different at $\alpha = 0.05$ (Table 15). The larger amount of insect drift in lower Elk Creek (Table 12) may be responsible for the larger sizes of fish there. Water temperatures were the same in both upper and lower Elk Creek sections during the surveys.

We expected that, among other factors, riffle size might affect the density of insect drift (Brusven 1970a). However, the correlation coefficients of insect drift to riffle area (Fig. 54) and riffle length (Fig. 55) were not significant (r = 0 and r = 0.16, respectively). The multiple correlation of insect drift to percentage sediment in the riffles and riffle length had an R value of 0.197 (Table 15).

Bearskin Creek: Bearskin Creek contained the same species of fish as Elk Creek, with age 0 chinook comprising the majority of the fish counted (Table 16). Total fish densities in Bearskin Creek ranged from 0.60 to 1.47 fish/m^2 in the pools, substantially larger densities than in Elk Creek.

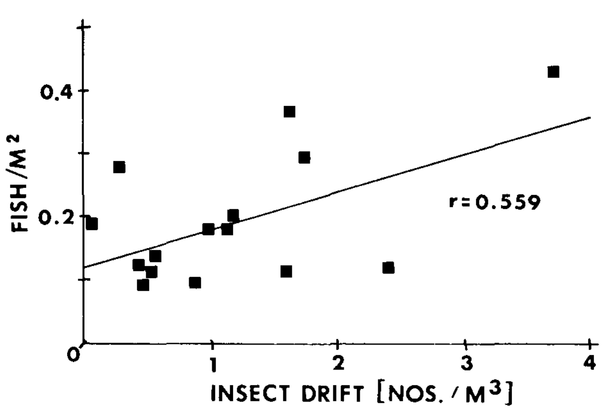

Fig. 51. Fish density in pools versus insect drift in pools in Elk Creek, August 1975.

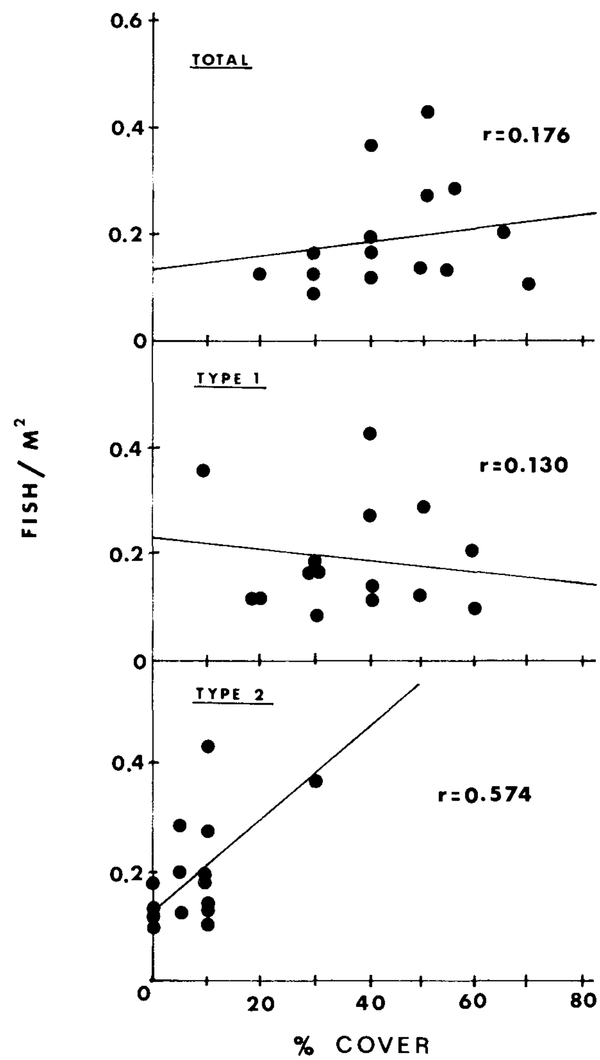

Fig. 53. Fish density in pools versus percentage of pool area with cover in Elk Creek, August 1975. Type 1 = surface cover; type 2 = bottom cover.

Table 16. Fish densities (per m^2) in Bearskin Creek pools during the correlational surveys of August 1975.

Site number	Chinook salmon Age 0	Chinook salmon Age I	Steelhead Age I+	Whitefish	Total fish
1	0.86	0.10		0.03	0.99
2	0.80	0.17			0.97
3	0.82	0.13			0.95
4	0.71	0.06			0.81
5	0.93	0.14	0.05		1.22
6	1.44		0.03		1.47
7	0.54	0.06	0.03		0.63
8	0.45	0.09	0.06		0.60

As we found in Elk Creek, insect drift density was not significantly correlated with percentage fine sediment in the riffles of Bearskin Creek (r = 0.467, Fig. 56). We did find, however, evidence of a community shift to more Dipterans with larger percentages of sediment in the riffles Such a shift was also noted in the 1975 drift samples collected in the artificial stream channels at Hayden Creek.

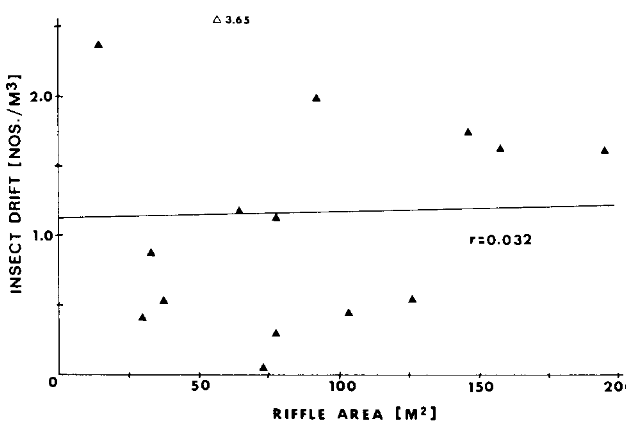

Fig. 54. Insect drift density versus riffle area in Elk Creek, August 1975.

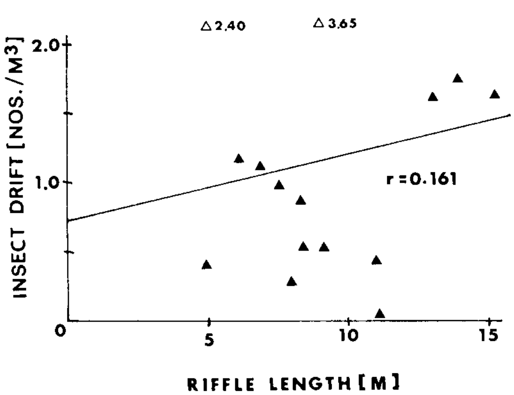

Fig. 55. Insect drift density versus riffle length in Elk Creek, August 1975.

Insect drift density in Bearskin Creek was significantly correlated with riffle area ($r = 0.834$, $p < 0.012$; Fig. 57) and this may explain the large numbers of drifting insects across riffles with large percentages of sediment (Fig. 56), since the sites with large numbers of drifting insects and large percentages of sediment also had the largest riffle areas. The correlation coefficient for riffle length and insect drift, however, was not significantly different from zero ($r = 0.557$, $p < 0.850$; Fig. 58).

Fish density versus insect drift density (Fig. 59) was not linearly correlated ($r = 0.141$). The relationship in Fig. 59 appeared curvilinear, and the r value using the square of the insect drift as the second "X" variable was 0.908 and significant, but as Ricker (1975) warned, beware of using this function lest significance appear where it does not exist; we could not think of any reason why fish density should decrease with larger drift densities.

As in Elk Creek, fish density in the pools of Bearskin Creek was not significantly correlated with percentage sediment in the riffles ($r = 0.420$, Fig. 60). Fish density in Bearskin Creek was not strongly correlated with either bottom cover ($r = 0.404$, $p < 0.15$; Fig. 61) or surface cover ($r = 0.590$, $p < 0.13$; Fig. 61).

The relationship of fish density to insect drift density may be obscured by the effect of cover. Those sites where fish density was small even though insect drift density was large (Fig. 59) had small percentages of cover. Bottom cover was 10, 0 and 0 percent, respectively, for the three sites (sites 1, 2 and 8). By combining drift density and percentage bottom cover (by multiplying the two variables together), a significant correlation with fish density was obtained ($r = 0.758$, $p < 0.025$; Fig. 62).

None of the multiple correlation coefficients of fish density versus percentage sediment in the riffles, insect drift density, bottom cover or the ratio of drift to pool area was significantly different from zero (Table 17). Bottom cover and drift density/m^2 of pool area correlated best with fish density.

Table 17. Multiple correlations for Bearskin Creek in 1975, using the model $Y = a + bX_1 + cX_2$.

Y	X_1	X_2	R
Fish/m^2 in pools	% Riffle sediment	Drift density	0.424
Fish/m^2 in pools	% Riffle sediment	Drift/pool area	0.628
Fish/m^2 in pools	% Riffle sediment	Bottom cover	0.452
Fish/m^2 in pools	% Bottom cover	Drift density	0.431
Fish/m^2 in pools	% Bottom cover	Drift/pool area	0.669
Drift density	% Riffle sediment	Riffle area	0.913*
Drift density	% Riffle sediment	Riffle length	0.653

* Significant at $\alpha = 0.05$.

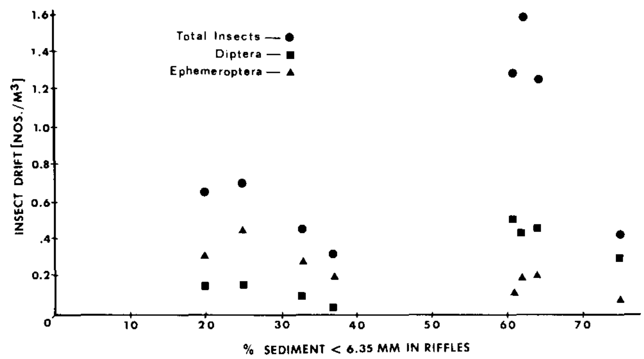

Fig. 56. Insect drift density versus percentage sediment in riffles in Bearskin Creek, August 1975.

Age 0 chinook in Bearskin Creek were the same length and weight as age 0 chinook in lower Elk Creek, but significantly larger in length and weight than fish in upper Elk Creek (Table 15). Water temperatures and insect drift densities were not obvious explanations for the differences in length and weight of salmon from Bearskin Creek and upper Elk Creek.

Insect Drift: The natural variation in insect drift abundance inherent with the temporal and spatial separation of our sampling may have masked some correlations, if present, or created some spurious ones. Although we were able to sample the drift once at each of the 23 sites during a 12-day period (August 17 to 28), there were differences in moon phase and cloud cover during the period. Elliott (1970) illustrated the effects of light intensity on the abundance of insect drift. Correlation of insect drift to moon phase or cloud cover did not, however, help to explain the variability in our data. Brusven (1970a and 1970b) illustrated the variations in drift abundance that also could occur from sampling the same stream on different dates and at different stages of insect development.

If insect drift abundance does regulate fish abundance in the study streams, perhaps the insect drifts in late August and/or at sunset are not the critical portion of the drift. The number of insects drifting throughout the day or at another time during the summer may be the critical drift parameters that regulate fish abundance. Since drift is less abundant during the daytime, we might expect maximum interaction between fish for food during the daytime. In addition, Waters (1969) pointed out that although drifting insects are an important source of food for most salmonids, these fish species also feed on non-drifting bottom insects.

Insect drift from a particular riffle at sunset or in August may not fully reflect the effects, if any, of sediment

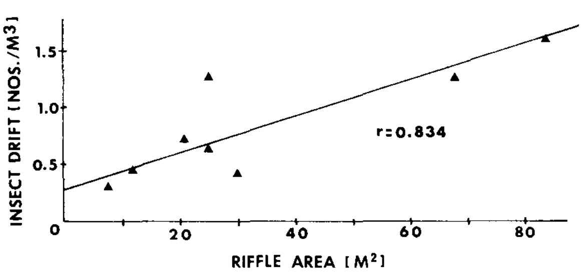

Fig. 57. Insect drift versus riffle area in Bearskin Creek, August 1975.

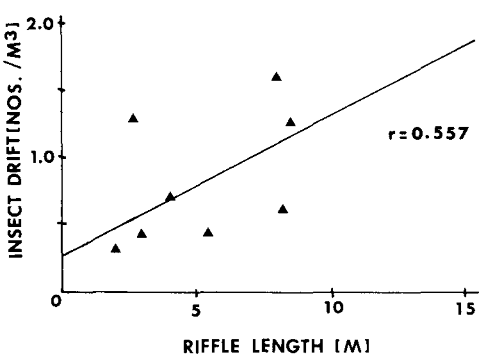

Fig. 58. Insect drift versus riffle length in Bearskin Creek, August 1975.

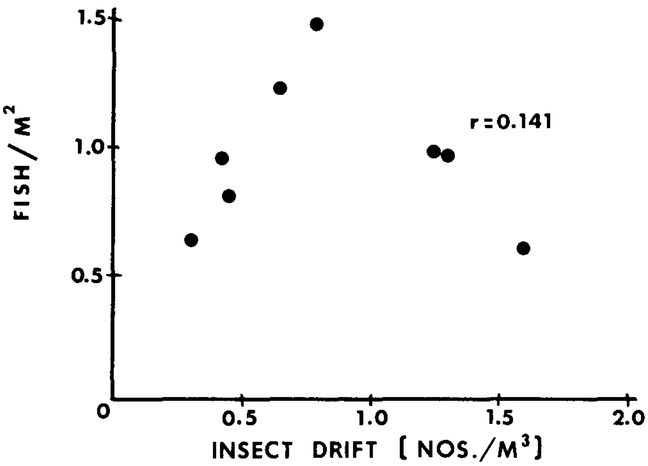

Fig. 59. Fish density in pools versus insect drift density in Bearskin Creek, August 1975.

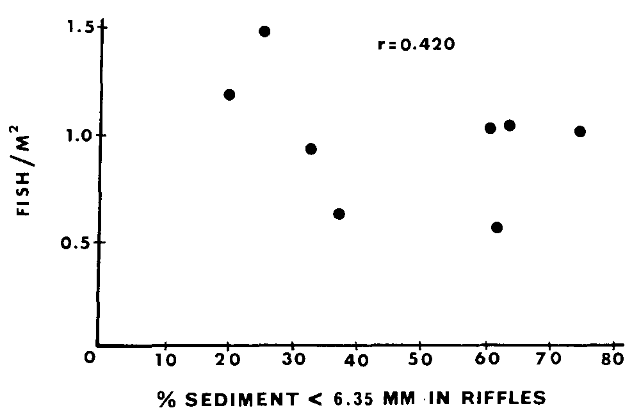

Fig. 60. Fish density in pools versus percentage sediment in riffles in Bearskin Creek, August 1975.

concentrations in that riffle. The drift entering our nets at the downstream end of a riffle may also come from other riffles upstream with lesser concentrations of sediment. Drift at a particular time of day may not reflect a decrease in insect abundance caused by excessive amounts of fine sediment in riffles.

Discussion

In our 1974 and 1975 tests of summer holding capacity in the artificial stream channels, we observed a decrease in fish densities with an increase in fine sediment in the pools for all species tested. Holding capacities of the channels were fish-size related, the smallest fish (age 0 steelhead) stabilizing at the largest densities. Fish densities decreased more than decreases in volume of water in the pools. For example, densities of wild age I steelhead at one-third, two-thirds and full sediment imbeddedness were reduced to 84, 40 and 11 percent of their original densities, respectively, but volumes were reduced during the same tests to 92, 84 and 75 percent, respectively, of the original volumes. Reduction in the amount of cover (large rocks in bottom of pools) for fish was the reason for larger reductions in fish densities than in pool volumes. As we increased fine sediment levels in the channels, we decreased cover for fish more than we decreased volume in the pools.

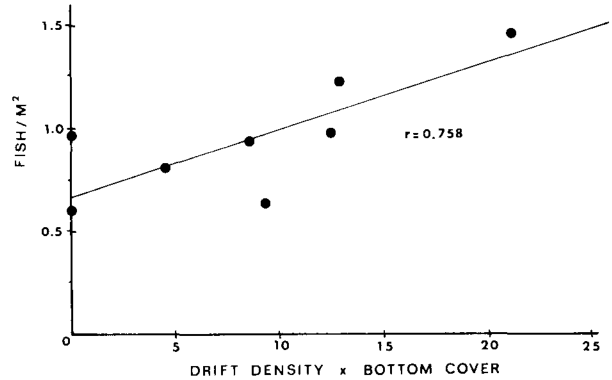

Fig. 62. Fish density in pools versus insect drift times percentage bottom cover in pools in Bearskin Creek, August 1975.

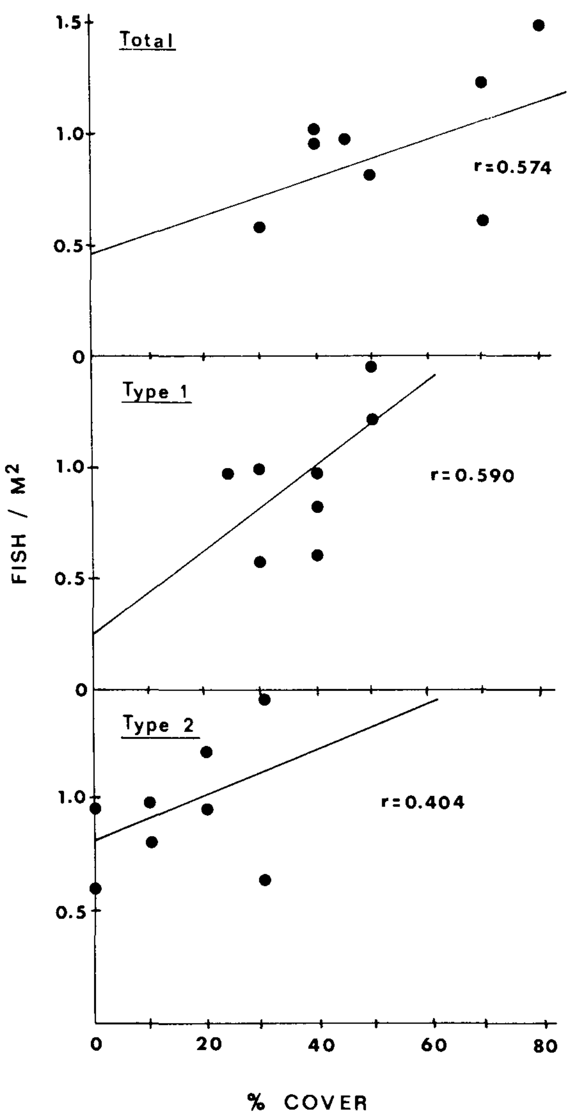

Fig. 61. Fish density in pools versus percentage of pool area with cover in Bearskin Creek, 1975. Type 1 = surface cover; type 2 = bottom cover.

Bjornn et al. (1974) found no decrease in fish densities with the addition of fine sediment to only the riffles in the same artificial stream channels in the summer of 1973. Insect drift was not limited in the 1973 tests with the addition of sediment to the riffles, and cover was not reduced in the pools; thus it was not surprising that fish densities were not affected. In the 1973 tests, the pools did not contain large rocks as cover for fish, and fish densities at the end of each test, although unaffected by sediment added to the riffles, were therefore smaller than in our 1974 and 1975 tests, except for hatchery age 0 steelhead.

The differences in behavior of fish in channels with or without sediment probably resulted from changes in available cover. As cover decreased with increased sediment levels, fish were forced into the open areas of the pools where they could not easily maintain territories. Bjornn et al. (1974) found that age I steelhead set up a hierarchical structure at the downstream end of the pools in both the test and control channels. In our tests, we found a large rate of fish interaction in the pools containing sediment, until the density declined as fish moved out of the channels. In the channels without sediment and in the channels with low levels of sediment imbeddedness, where most of the cover was still available, we observed few hierarchical interactions between fish.

Fish densities decreased more in the winter tests than in the summer tests. In the winter tests interstitial cover provided by the large rocks was important, but the capacity of the large rock substrate as cover was less in winter than in summer. When water temperatures dropped below 5°C the fish entered the interstices in the substrate.

Bjornn et al. (1974) found that fewer age 0 steelhead and chinook remained in the channels containing fine sediment in the riffles than in channels without sediment during the 1973 winter tests. Some of these fish used the riffles for winter cover. As sediment levels were increased in the riffles, the cover was reduced and fewer fish remained in the channels with sediment.

In Knapp Creek, as in the channels, fish densities decreased as fine sediment was added to pools in the test section in 1974. Fish abundance decreased at a faster rate than did pool volume. Observations of the fish in Knapp Creek indicated definite habitat preferences. Age 0 chinook preferred water 0.15 to 1.00 m in depth near the shore areas of the pools. The addition of granitic sediment into the stream decreased the abundance of age 0 chinook by reducing their preferred habitat. The larger steelhead trout, brook trout and Dolly Varden preferred the deeper areas of the pools and the undercut banks. As this habitat was reduced by the addition of sediment, more of these fish left the pool. The reductions in fish abundance in Knapp Creek were due primarily to the reductions in pool volume and areas of preferred depth for the fish. The reductions in fish densities in the artificial stream channels were due primarily to loss of cover, as volume of the pools was not reduced as much as in Knapp Creek.

In their 1973 tests Bjornn et al. (1974) observed little, if any, decrease in fish density in the test section of Knapp Creek as they added sediment. In fact, both number of fish and fish density (fish/m^3) in the upper test pool increased after the first addition of sediment. The researchers concluded that fish density was not at a maximum when the sediment was first added to the test pool in 1973.

In both 1973 and 1974 additions of sediment to the upper test pool in Knapp Creek caused decreases in area and volume of those parts of the pool deeper than 0.30 m and ultimately caused decreases in fish numbers (Fig. 63). The number of fish in the pool prior to the sediment additions was not used in the fitting of the line for 1973 because fish density was not at a maximum and therefore fish numbers in the pool were not affected by the decrease in pool area that occurred during the first sediment addition.

The 1974 observations indicate the same general linear decline in fish abundance with decreased pool area as in 1973 (Fig. 63). The decline in fish numbers after the second addition of sediment was due to loss of a small area of habitat where age 0 chinook were concentrated.

From the Knapp Creek data for 1973 and 1974 we have concluded that a decrease in the area of pools deeper than 0.30 m from the addition of fine sediment will cause a linear decrease in fish abundance in streams the size of Knapp Creek or smaller. Such a direct linear relationship may not hold for large pools (more than 100 to 200 m^2) in larger streams. Our observations in other streams, particularly Elk Creek, lead us to believe that juvenile fish use and need only a fraction of the total area available in large pools.

Elk Creek posed an interesting problem in assessing and quantifying the effects of fine sediment on the fish and aquatic insect populations. Riffles with large and small percentages of sediment occurred throughout most of the stream length. Although riffles with large percentages of sediment were more common in the lower section of Elk Creek, some riffles in the upper reaches also had large percentages of sediment.

Fish density and insect drift density were not significantly correlated with riffle sedimentation in Elk Creek. Fish density was related to insect drift and cover in the pools. Multiple correlations of insect drift, percentage riffle sediment and cover indicated that these factors in combination may affect the fish density in Elk Creek.

In Bearskin Creek none of the simple correlations of insect drift versus sediment, fish density versus sediment, fish density versus insect drift, fish density versus cover or insect drift versus riffle length was signifcant ($\alpha = 0.05$). The only correlation with a coefficient significantly different from zero was insect drift versus riffle area.

In Bearskin Creek fish density was small in three sites with large amounts of insect drift (Fig. 59). Small amounts of cover in these three sites may have been partly responsible for the small densities of fish. With the three sites omitted, the correlation coefficient for the relationship of fish density to insect drift was 0.974. Using insect drift density and percentage bottom cover combined (Fig. 62), we found a significant correlation ($\alpha = 0.05$) with fish density in Bearskin Creek.

From our work in Elk and Bearskin creeks, we concluded that fish densities were not directly regulated by the percentage fine sediment in the riffles (range = 20 to 75 percent). There was some inconclusive evidence that fish densities were regulated, in part, by insect drift abundance and bottom cover in pools. The abundance of insect drift also was not obviously related to the percentage of fine sediment in the riffle sampled. Unless we failed to measure the critical parameters (as discussed earlier), the sediment conditions in Elk and Bearskin creeks did not have an observable adverse effect on fish densities or food available to fish in the form of insect drift.

SUMMARY

In the experimental portions of our studies, we found that excessive amounts of coarse sand and smaller sediments can 1) affect the aquatic insect populations when deposited in riffles, 2) reduce the summer rearing capacity of streams when deposited in pools, and 3) reduce the winter fish capacity of streams when deposited in the larger interstitial spaces of stream substrate. In earlier studies, Bjornn (1969) and more recently McCuddin and Bjornn (unpublished data, Idaho Cooperative Fishery Research Unit) demonstrated that survival and emergence of salmon and steelhead trout embryos were reduced by excessive amounts of fine sediment in spawning riffles. We were unable to consistently correlate insect abundance to riffle sedimentation or fish abundance to either of the above variables in the natural streams, but less-than-full seeding of the rearing areas with salmon fry may have been a reason for the lack of consistent results.

Survival and emergence of salmon and trout embryos in spawning riffles may not limit the abundance of these fish in batholith streams, except in years with small spawning escapements. Summer rearing or winter holding habitat in the stream may be more important than embryo survival in regulating fish abundance in most years.

If we come back to the question, "How much sediment (coarse sand and smaller) is too much?" we find that when the percentage of fine sediment exceeds 20 to 30 percent in spawning riffles, survival and emergence of salmonid embryos begins to decline. When riffles are fully imbedded with fine sediment, insect species composition, if not abundance, changes (Figs. 13 through 19). The abundance of juvenile salmon in pools of small rearing streams declines in almost direct proportion to the amount of pool area or volume lost to fine sediment deposited in the pool (Fig. 63). The number of juvenile salmon and trout a stream can support in winter is much reduced when the interstices in the stream substrate are filled with fine sediment.

To avoid seriously reducing the salmonid production capacity of a batholith stream, fine sediment should not be allowed to fill in the pools or to fully imbed the larger substrate rocks. In years with small spawning escapements, spawning riffles should not have large amounts of fine sediment or the rearing areas will not be fully seeded with fry.

Since it is not practical to determine the sediment budget (input minus deposition + pickup = output) for each stream, we advocate using the percentage of fine sediment in selected riffle areas as the primary index for monitoring the deposition of fine sediment in streams and for determining when too much deposition is occurring in Idaho batholith streams. Monitoring the percentage of fine sediment in riffles is, admittedly, an after-the-fact measurement as far as the riffles are concerned, but may give advance warning of excessive fine sediment inputs that will fill pools and substrate interstices. At the least, if sample sites are properly located, the riffle sedimentation index can be used to help locate sources of excessive amounts of fine sediment.

Our rationale for using the percentage of fine sediment in selected riffles as the primary index for monitoring the "sediment health" of a stream is based on several considerations. The determination of a sediment budget for most streams would not be practical. The measurement of bedload sediment transport during peak discharge is difficult in most streams. Annual accurate measurement of sediment transported throughout the year would be costly. Turbidity of the stream has been used as an index of total sediment transport in some streams but is indirectly, and perhaps poorly, related to the deposition of coarse sand and smaller sediments in Idaho batholith streams. Core sampling of riffle sediments in Idaho batholith streams can be done during the low flow periods of summer. Relatively precise estimates of riffle sediment can be obtained

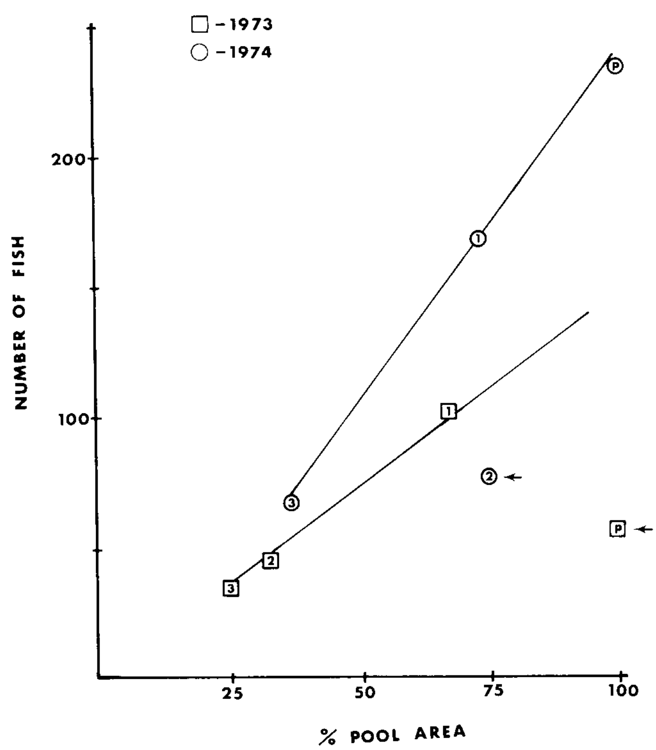

Fig. 63. Fish numbers in upper test pool versus percentage pool area deeper than 0.30 m, during the sediment additions into Knapp Creek, 1973 and 1974. Arrows denote observations not used in fitting the regression line. P = prior to addition of sediment; 1 = after first addition; 2 = after second addition; 3 = after third addition.

if annual sampling sites are restricted to spawning riffles, most of which have gravels of a size which can be handled by core sampling techniques.

The percentage of fine sediment in riffles not only provides a measure of the suitability of the riffles for embryo survival, but also should be an index of the amount of fine sediment being deposited in pools or substrate interstices. If the riffles contain small amounts of fine sediment, then it is not likely that significant amounts of sediment are being deposited in pools or between the boulders of the stream substrate.

Sediment transport and deposition in relation to discharge for given sections of the batholith streams we studied can be generalized as in Fig. 64. For a given section of stream there are critical discharges which will transport the coarse sand and smaller sediment across riffles, out of pools, out of riffles after dislodging the armor layer, and out of the substrate after moving the large boulders (Fig. 64A). In the batholith streams we studied, the snow melt runoff was rarely insufficient to transport sediment out of the pools. An above-average snow melt runoff would be needed to dislodge the armor layer on the riffles so that sediment trapped within the riffles could be removed (Fig. 64B). The amount of coarse sand and smaller sediment that can be transported through a given section of stream is a function of discharge (Fig. 64C).

In a year of above-average runoff with discharge capable of moving the armor layer on the riffles, the fine sediment within the riffles becomes available for transport down the stream. If the stream were to run out of sediment to transport while the discharge is still large enough to move the armor layer on the riffles, the amount of sediment redeposited within the riffles would be minimal (Fig. 64D). If the stream is still transporting fine sediment after the discharge has declined below the quantity which dislodges the armor layer on riffles, then the riffles would be refilled with fine sediment (Fig. 64E). If the stream is still transporting fine sediment after discharge has fallen below the level which removes fine sediment from pools, then the pools would be refilled (Fig. 64F).

Some of the streams we studied, such as Elk Creek, contained large amounts of fine sediment. We believe there is little prospect that such streams can remove excess amounts of fine sediment. Because of their low banks and the broad valleys in which they are situated, the depth in the streams during snow melt runoff seldom reaches the critical level required to completely cleanse the pools, much less remove the armor layer from the riffles so that the riffles can be cleansed of fine sediment. Streams such as Elk Creek may have always contained larger amounts of fine sediment than other streams; it is difficult to determine whether cattle grazing and limited road encroachment have increased the amount of fine sediment in Elk Creek.

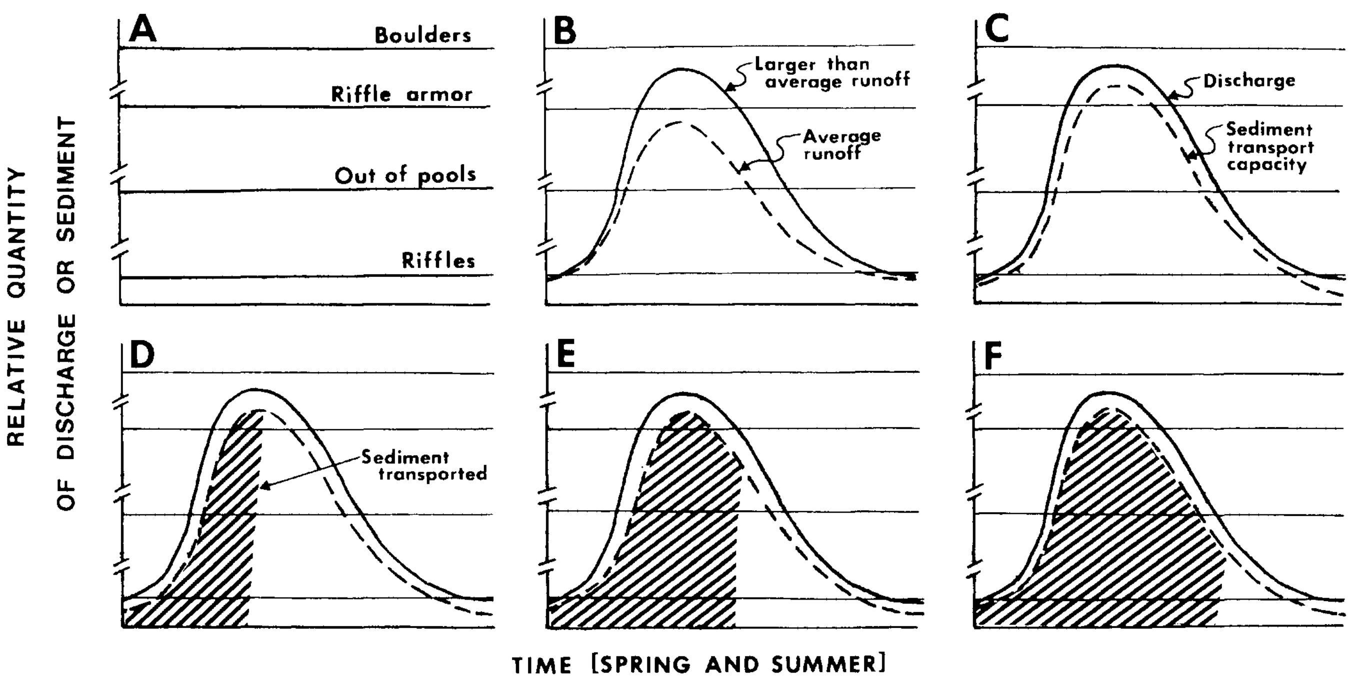

Fig. 64. Relative critical discharges which transport coarse sand and smaller sediment across riffles, out of pools, out of riffles after dislodging the armor layer, and out of the substrate armored by large boulders for a given section of stream (A); discharges observed in study streams relative to critical sediment transporting discharges (B); a rough approximation of the sand and smaller sediment transport capacity of a given stream section relative to discharge (C); a case where the stream has removed all sand and smaller sediment from the channel by the peak of the hydrograph (D); a case where the stream has not removed all the sand and smaller sediment until after the discharge fell below the level which dislodged the riffle area armor layer (E); a case where the stream was still transporting sediment after discharge had fallen below the pool clearing level (F).

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