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Development of Criteria for Fine Sediment in the Northern Rockies Ecoregion

Final Report

DEVELOPMENT OF CRITERIA FOR FINE SEDIMENT
IN THE
NORTHERN ROCKIES ECOREGION

by

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CONTENTS

I. INTRODUCTION

Early work on fine sediment and fish ecology began with Harrison (1923), who reported low survival of sockeye salmon in gravels with high percentages of fines. Hobbs (1937) conducted field studies of sediment effects on salmonids in some New Zealand streams, evaluating the relationship between embryo mortality and fines in the substrate. Shapovalov and Berrian (1940) and Shaw and Maga (1943) reported effects of sediment on survival in the redd and effects of mining silt, respectively. Stuart (1953) experimented in the laboratory on effects of silt on early stages of brown trout in Scotland. Campbell (1954) combined laboratory and field exercises by placing rainbow trout embryos in baskets in a stream affected by gold dredging and in a control stream. Shelton (1955), in simulated field conditions, showed that fines reduced chinook salmon emergence success.

These early efforts were soon supplemented by a veritable flood of laboratory and field studies on effects of fines in spawning gravel on salmonid survival (McDonald and Shepard (1955), Wickett (1954), Cooper (1956), Terhune (1958), Alderdice et al. (1958), Cordone and Kelley (1961), Coble (1961), Phillips and Campbell (1962), McNeil (1962), Vaux (1962), Bianchi (1963), Silver et al. (1963), McNeil and Ahnell (1964), Shumway et al. (1964), Cooper (1965), Mason and Chapman (1965), Koski (1966), Mason (1969) and Hall and Lantz (1969)).

These early studies led to consensus that low dissolved oxygen and reduced water exchange in laboratory environments caused reduced survival. It was also apparent that incubation success could decline in the intragravel environment in field situations in which fines accreted. Furthermore, laboratory studies demonstrated that emergence of alevins declined as percentage of fines increased in experimental mixtures of substrate. Field study also demonstrated that emergence was lower in gravels with high percentages of fines.

From 1969 to the present, research on sediment in the redd environment tended toward corroboration and refinement of the relationship between emergence success and percentage of fines Bjornn et al. (1977), Koski (1975, 1981), Sowden and Power (1985), Tagart (1976 and 1984), Phillips et al. (1975), Cederholm et al. (1981), Cederholm and Salo (1979), Tappel and Bjornn (1983), Irving and Bjornn (1984). In addition to percentage-of-fines analyses, embeddedness indices (Klamt 1976, Kelley and Dettman 1980) have been compared to fish abundance (Bjornn et al 1977, Thurow and Burns, unpublished).

Some effort has been devoted to the effects of sediment on other life history stages. Juvenile salmonid density has been correlated with living space reductions caused by sedimentation (Bjornn et al. (1977), Stuehrenberg (1975), Klamt (1976), Cederholm and Reid (1986), Everest et al. (1986)), not because of embeddedness but because of lost pool volume. Chapman and Bjornn (1969), Hartman (1965), Rimmer et al. (1983), and Campbell and Neuner (1985) noted the importance of winter hiding locations for juvenile salmonids within the stream substrate. Hillman et al. (1986) demonstrated that addition of rubble piles to a sedimented stream increased winter density of chinook salmon by several-fold.

Effects of sedimentation on macroinvertebrate density or drift in streams used by juvenile salmonids have been evaluated by Bjornn et al. (1977), Martin (1976), Brusven and Prather (1974), and Konopacky (1984), sometimes with equivocal results, with environmental features other than sedimentation sometimes confounding results.

Some work has addressed the difficult task of defining criteria for healthy and degraded intragravel environments (Bjornn et al. (1977), Shirazi et al. (1981), Stowell et al. (1983), Klamt (1976), Platts and Megahan (1975), and Everest et al. (1986)). Most of the information that underlies these criteria is derived from laboratory situations and, usually, single-factor analyses.

A basic confusion in establishing criteria in ways meaningful to fish ecology has been the difficulty inherent in establishing which environmental variable(s) act as limiting factors. [For example, sedimentation in spawning gravels alone may not reduce populations of adult salmonids if winter hiding space controls carryover of juveniles from one year to the next]. Although we address this problem in our report, we contend that criteria suitable for evaluation of watershed management practices may not necessarily relate directly to limiting factors. That is, a habitat criterion for evaluation of best management practices may serve solely to indicate streambed composition in areas used for salmonid spawning, rearing, or winter hiding. Any criterion that we may suggest should have demonstrable relationships to ecological requirements of salmonids or of the food base for salmonids, but may not necessarily measure a limiting factor.

A major problem in field situations is that of quantifying effects of sedimentation in the face of natural variability and extreme hydrologic or meteorologic events. Another major obstacle to development of meaningful models is the difficulty of, or lack of awareness of need for, sampling within the salmonid egg pocket. In laboratory studies, the principal problem is that of approximate duplication of field conditions.

In spite of these and other difficulties, it is appropriate at this time to critically review sedimentation criteria and progress toward management techniques for instream evaluation of sedimentation. The following review is divided into sections on the environments for reproduction and for rearing and winter ecology, fine sediments and channel morphology, tools for prediction of effects of fines, a discussion section on genetic risk, biological compensation and limiting factors, and a treatment of predictors and management regulation. We also offer some research recommendations.

II. INTRAGRAVEL ENVIRONMENT AND SPAWNING SUCCESS

A. MEASURES OF STREAMBED CHARACTER IN SPAWNING AREAS

Measures of streambed character offer an attractive possible means for assessment of effects of land management practices on habitat. Percentages by weight of particle sizes smaller than some specified level, such as <1 mm in diameter, might serve as useful indices of habitat quality. Visual scoring techniques might prove useful. Geometric mean particle size offers another measure, as do the fredle index and permeability.

A.1. Percentage of fines

Percentages of fines in stream substrata may be examined by means of sieving samples withdrawn from the streambed in frozen cores (Walkotten 1976) or excavated within a cylinder that surrounds a bottom area and core (McNeil and Ahnell 1964). In either case, extracted samples are wet- or dry-sieved through a set of wire meshes and weighed by volume or measured by volume of water displaced.

Adams and Beschta (1980) examined 5 streams in the Oregon Coast Range to assess temporal and spatial variation in streambed composition, as well as factors affecting the amount of fine sediment in the streambed. Adams and Beschta used a freeze-core system (Walkotten 1976), which froze two cores at each sample location to 25 cm in depth. The cores for each location were combined for analysis. These workers sampled at the same sites over time, maintaining records of earlier sample locations to prevent repeat sampling of the same specific location. Records were kept on stream profile to document scour and fill, and stream gages were used to index size and sequence of storms.

Large particles (>50.8 mm) were removed from samples and from the analysis of percentage of fines, in order to reduce variance. Although Adams and Beschta justify this on the basis that other workers have excluded large rocks from analysis (McNeil and Ahnell 1964, Wendling 1978), the subsequent treatment is artificial to an unknown degree. Chapman et al. (1986) rejected use of the freeze-core method for a spawning area on the mid-Columbia River because the relatively small-diameter freeze cores (obtained with single-probes) were excessively influenced by presence or absence of large particles. They adopted use of samples excavated within a cylinder 50 cm in diameter.

Ringler (1970) reported that freeze-core and McNeil samplers yielded somewhat different results, but was unable to explain the differences. Ringler (1970) compared freeze core samples with 15 cm core samples from redds in Drift Creek, an Alsea River tributary. He found that the freeze core underestimated the fines smaller than 0.83 mm and 3.3 mm.

Shirazi et al. (1981) tested freeze-core samples with single probe against a McNeil sampler in Berry Creek, Oregon, and found that in this coarse-substrate stream, a single probe tended to produce data with a smaller geometric mean than did the 30 cm McNeil core sampler (Table A.1). They also compared results from

Table A.1. (From Shirazi et al. 1981). Comparison of results from freezecore and McNeil samples.

Sample #	$d_g$mm Freezecore	 12" Core
1	9.7	32.7
2	42	45.5
3	42	45.0
4	33.9	27.0
5	37	66
Mean	32.9	42.4

(should be 43.2)

a 3-tube freeze core sampler with those from a 30 cm McNeil core sampler. Although the mean d_g of 10 such tests was only about 10% higher for the 30 cm core, there were considerable differences between specific samples (Table A.2).

Table A.2. (From Shirazi et al. 1981). Comparison of tri-tube freezecore and 12-inch (30 cm) manual core samples taken from Rogue River, Oregon.

Sample ID		d_g mm	
		Tri-core	12" core
Bridge Hole	B	30.4	30.9
	C	24.0	17.3
Hatchery Site	A	42.1	21.8
	B	18.0	18.6
	C	69.6	48.4
Sand Hole	A	34.2	58.7
	B	22.6	58.8
	C	46.0	65.3
Big Butte	A	15.6	22.9
	C	19.3	19.5
Mean		32.1	35.0

Shirazi et al. (1981) concluded, based on case studies, that by combining the analysis of many single freeze core samples from a spawning site having relatively fine textured substrate, one can obtain a reasonable estimate of the mean composition of that site. They also stated that single freeze cores, particularly from a coarse substrate with a single tube, may not be a good representation of gravel composition, but that a 3-tube system provides a good representation of a gravel patch over the range of grain sizes up to 100 mm. We note that diameters of particles in many substrata used by adult chinook salmon and steelhead often exceed 100 mm. The egg pocket often contains these larger particles. Platts et al (1979) found that about 18% of the particles "in" a chinook salmon egg pocket consisted of particles larger than 100 mm. These workers used a definition of the egg pocket somewhat broader than that used elsewhere in our review.

The principal finding of Adams and Beschta (1980) in their five-stream study was that the fraction of particles smaller than 1 mm was varied greatly in time and space. During a 19-month sampling period, flushing of fines from gravels during high flows caused temporal variability. Percentage of fines varied between streams, between locations in the same stream, and between locations within the same riffle. Even in streams with a relatively high sediment content, channel roughness features such large organic debris, boulder elements, and channel constrictions can sort gravels and create "islands" of clean gravel (Everest et al. 1986).

If percentage of fines (or any other physical measure of substrate quality) serve to gauge stream quality, the time of sampling is important (Adams and Beschta 1980). Freshets and spawning fish can clean fines from the stream bed, and freshets must be accompanied by disturbance of the gravel bed. In other words, flushing will not occur in interstices of the substrate unless that substrate moves (Beschta and Jackson 1979). On the other hand, reduction of fines does not always result from a movement of streambed. The net cleaning of fines from any location during a storm event depends on both disturbance of the bed and on re-intrusion of fines when the bed stabilizes.

Adams and Beschta (1980) recommend that if the investigator can sample a stream only once, this should occur during low flow when beds have stabilized. They suggest that if fines serve to index stream quality for fish, the bed should be sampled during the period when eggs of fish lie in the substrate. Following this line further, we conclude that one should sample in redd egg pockets during the period when embryos are incubating within the pockets, in order to evaluate survival and gravels in a pertinent time stratum. The investigator must decide whether he or she should evaluate fines midway through the incubation period or at the conclusion of emergence.

In addition to the 5-stream study, Adams and Beschta (1980) obtained liquid nitrogen cores from riffle substrata in a total of 21 streams in the Coast Range in both disturbed and undisturbed drainages. Fines content averaged 19.4% (range of 10.6 to 49.3%). In 5 undisturbed streams, fines ranged from 10.6 to 29.4%. In about 75% of all comparisons between plots within the same stream, the percentages of fines differed significantly ($p = .05$). Fines content parallel and normal to flow differed significantly ($p = .05$).

In the 21 streams examined by Adams and Beschta (1980), fines varied with depth in the substrate. In 59 cores, the top 10 cm had significantly ($p = .05$) less fines than the 10-25 and 25-40 cm zones. Fines for the 0-10, 10-25, and 25-40 cm respective depths averaged 17.4, 22.3, and 22.2%. The authors suggest that surface armoring (Milhous and Klingeman 1973) may have reduced fines in the shallowest stratum.

The authors noted that this spatial variability in bed composition may prohibit a simple characterization of gravel bed quality within a given area or an individual channel. They state that the large number of samples needed would also prohibit precise estimates of fines content, although the meaning of this statement is not clear, for one should expect more precise estimates with increased sample size.

Table A.3, which is Table 3 from Adams and Beschta, provides regressions, developed from various data on 21 streams, and that relate fines to slope, area, relief, and land use ($r^2 = 0.66$). In an undisturbed drainage (Flynn Creek) fines were related to sinuosity and bank-full stage ($r^2 = 0.820$, and to sinuosity alone ($r^2 = 0.74$).

Table A.3. (From Adams and Beschta 1980). Regressions of fines content (PF) in percent by weight for streambed cores frozen with liquid nitrogen. * indicates significance at p = 0.05 after application of correlation tests of linearity (t-test) and multiple linearity (F test).

Model	No. observations	Regression equation	*t*	*F*	R^2
1	21	PF = −1.23 (Average watershed, slope, %)	*	*	0.66
		+0.03 (Watershed area, ha)	*		
		+68.89 (Watershed relief ratio, m/m)	*		
		+0.06 (Land-use factor, %)	*		
		+41.94 (Constant, %)	*		
2	7	PF = +27.02 (Sinuosity, m/m)		*	0.82
		+35.22 (Bank-full stage, m)			
		−31.04 (Constant, %)			
3	7	PF = +38.83 (Sinuosity, m/m)	*	*	0.74
		−24.94 (Constant, %)			

Adams and Beschta (1980) warn that temporal variations in percentage of fines may obscure effects of land use, and that more knowledge of in-stream processes that change gravel composition is needed.

A.2. Geometric mean particle size

Platts et al. (1979) adapted several works to propose use of geometric mean particle diameter as a companion measurement to "percent fines" for a more complete analysis of sediments. They suggest that geometric mean particle size is a statistic more amenable to statistical analysis than percent fines. They defined geometric mean diameter as:

$d_g = (d_{16}d_{84})^{1/2}$ where

d_{16} = particle diameter corresponding to the 16th percentile,

d_{84} = particle diameter corresponding to the 84th percentile.

Everest et al. (1981) defined d_g as:

$d_g = (d_1^{w_1} \times d_2^{w_2} \times \ldots\ldots. d_n^{w_n})$, where

d_n = mid-point diameter of particles retained on the n^{th} sieve,

w_n = decimal fraction by weight of particles retained on the n^{th} sieve.

Platts et al. (1979) related sediment porosity to d_g by using Cooper's (1965) data (Figure A.1). They also compared d_g for several areas of the South Fork Salmon River, and found that those in upper reaches had a higher d_g than those in lower reaches (Table A.4), but were unable to determine if this was a result of availability of sediments or preferences of fish.

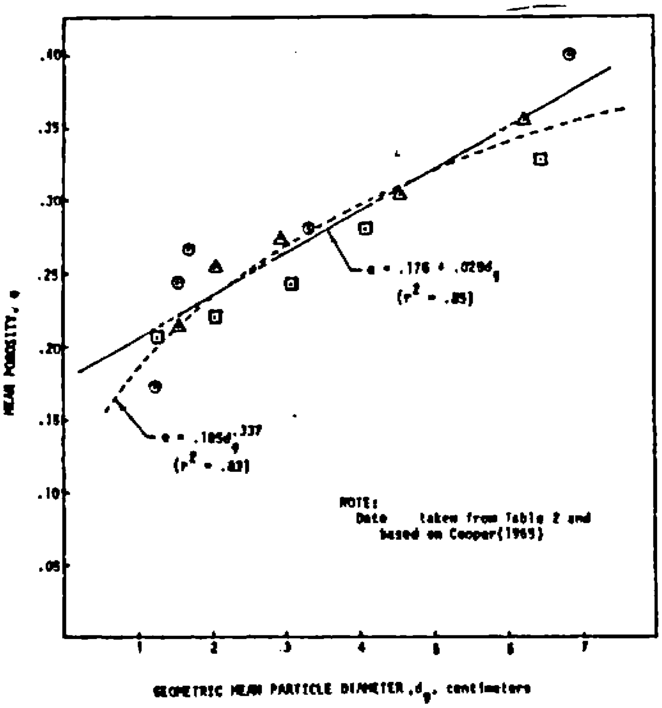


Figure A.1. (From Platts et al. 1979). Relationship between sediment porosity and d_g.

Platts et al. (1979) lifted a complete egg pocket from a chinook salmon redd by using multiple freeze-cores, and measured the d_g of the strata in the pocket as 39.2, 20.1, and 35.2 mm for the top to 15 cm, 15-30 cm, and 30-45 cm respective strata. These data constitute the only available information on composition of the egg pocket.

Table A.4. (From Platts et al. 1979). Variation of geometric mean diameter of spawning sediments collected from channel reaches in the South Fork Salmon River in 1976.

Site		d_g(mm)	
Downstream reaches:			
Glory Hole	9.6		
Oxbow Area	8.5	Average =	8.8
Poverty Flat Area	8.4		
Upstream reaches:			
Dollar Creek Area	13.5	Average =	14.7
Stolle Meadow Area	15.8		

Platts et al. (1979) list advantages of using d_g as:

1. It is a conventional statistical measure used in sedimentary petrology and engineering to describe sediment composition.

2. It is a convenient standard measure that enables comparison of sediment sample results between two studies.

3. It may be calculated from d_{84} and d_{16}, two parameters that may also serve for calculation of the standard deviation.

4. It relates to permeability and porosity of channel sediments at least as well as percentage of fines.

5. It is a more complete description of total sediment composition than percentage of fines and sediment composition evaluations in many cases involve less sampling error using d_g.

6. Because it relates to porosity and permeability, it is potentially a suitable unifying measure of channel substrate condition as it affects embryo survival.

Shirazi et al. (1981) related percentage embryo survival to substrate composition as expressed in d_g (Figures A.2 and A.3).

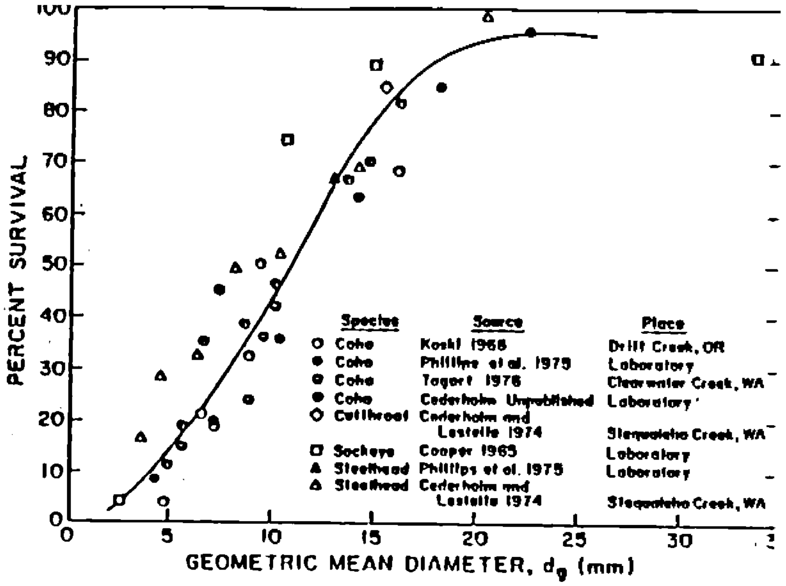


Figure A.2. (From Shirazi et al. 1981). Relationship between embryo survival and substrate composition expressed as d_g.

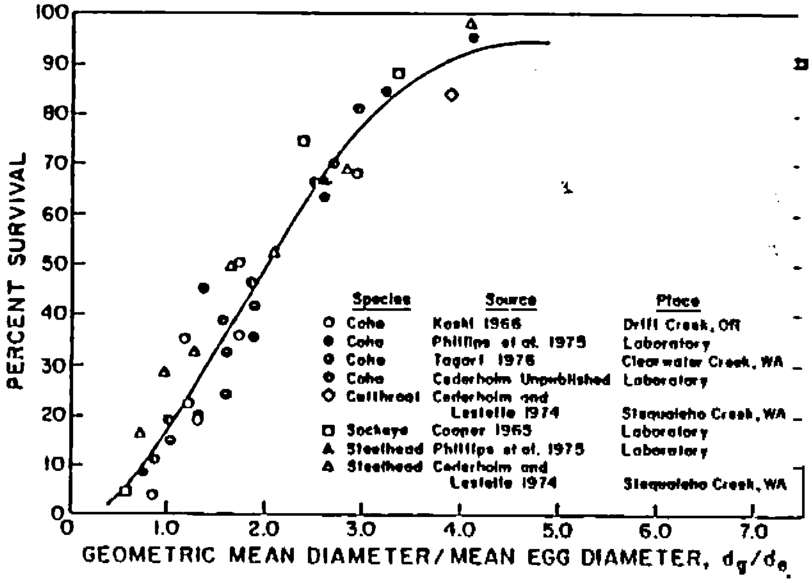


Figure A.3. (From Shirazi et al. 1981). Relationship between percent embryo survival and substrate composition in multiples of egg diameter.

We consider it of the greatest importance in our report to note that the relationships in Figure A.1 and A.2 are based on d_g <u>in the spawning area</u>, or <u>in laboratory troughs</u>, or <u>in the "redd"</u>, but <u>not in the egg pocket</u>. We clarify this point later.

We note that Platts et al. (1979) reported d_g equaled 23 mm for a chinook salmon egg pocket that had been frozen in place and extracted for laboratory analysis. We used their gravel composition data to calculate a d_g of 31.2 mm. We think the 23 mm calculation is a typographic inversion, and are strengthened in this by the authors' calculations of d_g for 6-inch strata that show a d_g of 39.2, 20.1, and 35.2 mm for the 18-inch deep sample.

A d_g of 32 mm falls at the extreme upper end of the model in Figure A.2. The authors noted that this d_g was somewhat large compared with similar measurements taken by other means both in 1978 and previously. They attributed the difference to coarsening of the substrate by the spawning fish, relative to the surrounding substrate, and of course this is true. Average d_g in the Poverty area of the South Fork Salmon River was reported by Platts et al. (1979) as 8.4 mm without correction for water on the samples, and 11.9 mm with the correction, which they note would be a correction of 42%. The d_g of the egg pocket was well over twice that of the Poverty substrate. The egg pocket, as withdrawn intact, also included the large particles at the centrum of the pocket.

Even the egg pocket data of Platts et al. probably incorporated portions of the redd outside the actual egg pocket, and the pocket itself would likely have a makeup different from that of the sample. We will repeatedly note in this report that egg pockets differ greatly from the surrounding substrate in gravel composition.

The data in Figure A.2 show fairly conclusively that high survivals tend to occur in association with high d_g. However, Tappel and Bjornn (1983) concluded that the usefulness of the d_g is limited because gravel mixtures with the same geometric mean can have different size compositions. Lotspeich and Everest

(1981) also noted that d_g may not differ in gravels of vastly different makeup. Tappel and Bjornn noted, after an analysis of 100 samples of spawning gravels from the South Fork Salmon River, that some samples had substantial deviations from lognormality and were not accurately represented by the regressions. These deviate samples curved upward in the upper end of cumulative distribution plots (Figure A.4). The correlation improved if particles larger than 25.4 mm were deleted from the plot.

A much more serious problem with the data in figures A.2-A.4 is that d_g for the cited studies was calculated for McNeil corings that may or may not have included egg pockets, even though taken on redds. Another procedural problem is that McNeil corings may, in redds or in "spawning gravels" either extend too deeply, into consolidated substrate, or too shallowly, missing

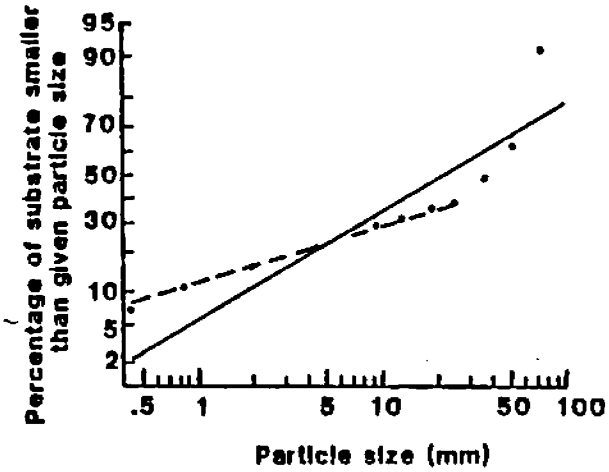


Figure A.4. (From Tappel and Bjornn 1983). Typical deviation from lognormal particle size distribution in gravels from the South Fork Salmon River. Note upper end of the cumulative distribution plot. Solid line is for all particle sizes (r_2 = 0.89); broken line is for material smaller than 25.4 mm in diameter (r^2 = 0.97).

the lowest portion of gravels that make up the environment of salmonid embryos. Use of triple-probe freeze cores would probably minimize this problem in samples within redds because the field worker can visually examine the frozen core to determine whether it probed the relatively consolidated materials at depth, or failed to reach the bottom of an egg pocket.

A.3. Stratified analysis of sieved samples

Tappel and Bjornn also analyzed data from 126 salmon spawning areas sampled by Cederholm et al. (1977) in the Clearwater River drainage in Washington, finding r^2 values for these of 0.97 when particles larger than 26.9 mm were eliminated from the samples.

Tappel and Bjornn (1983) proposed a regression equation for particle sizes smaller than 25.4 mm as:

$\text{PERCENT} = C + K \log_e \text{SIZE}$ where

PERCENT = inverse probability transformation of % of substrate smaller than a given sieve size,
C = intercept of regression line,
K = coefficient of variable $\log_e$SIZE,
SIZE = sieve size in mm.

Tappel and Bjornn (1983) state that because the distribution of particles less than 25.4 mm in diameter can be represented with a regression with r^2 close to 1.0, lines passing through data points for two sieve sizes closely approximate lines determined by the least squares regression procedure. They showed that the line passing through data points for the 9.5 and 0.85 mm particle sizes closely approximated the line from regression procedures.

Plots of gravel samples from the South Fork Salmon River and from the Clearwater River (Washington) were prepared (Figure A.5). Points A and B represent two different spawning gravel samples. The vertical line through A and B represents a

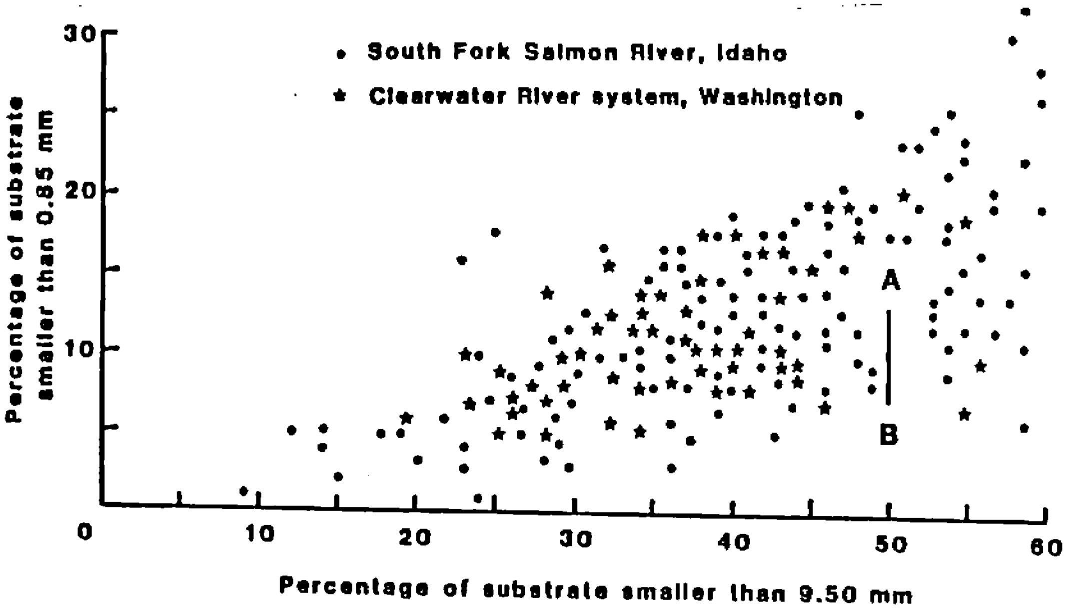


Figure A.5. (From Tappel and Bjornn 1983). Range of spawning gravel sizes for samples from two river systems. Line AB represents mixtures with the same percent fines (50% smaller than 9.5 mm) and d_g but different size compositions.

continuum of gravel size compositions, all with 50% of the substrate less than 9.5 mm in diameter. If particles less than 9.5 mm are termed "fines", any data points on the line AB represent samples of spawning gravel with the same percent fines but different particle size distributions.

Tappel and Bjornn (1983) further showed that although gravels A and B both had a d_g of 9.5 mm, they had very different 16th and 84th percentile diameters. The 16th percentile, for example, was 0.95 mm for gravel A and 2.2 mm for gravel B.

Tappel and Bjornn (1983) proposed to test embryo survivals in relation to gravel mixtures on the basis of two substrate variables; diameters 9.5 and 0.85 mm. They suggested that this technique removed the need to define exactly which gravel sizes harm embryos, and it only requires the assumption that gravel material larger than 25.4 mm is not harmful to incubating embryos. It also requires the assumption that particles larger than 25.4 mm are not beneficial, and this again raises the point that for many salmonids, particularly for anadromous fish, the egg pocket centrum in natural redds is formed of particles much larger than 25.4 mm. We will repeatedly note, later in this report, that laboratory studies simplify of necessity, and that results obtained from them cannot serve to predict conditions in natural egg pockets in quantitative fashion.

Tappel and Bjornn (1983) prepared gravel mixes as shown in Figure A.6 to cover the range of natural spawning substrata shown in Figure A.5. We caution that the range of gravels referred to the spawning area, not to egg pockets. The results of survival tests to emergence for 15 mixtures, each test composed of 2-3 replicates, permitted the development of a model of survival (Figures A.7 and A.8). Isolines of survivals were placed through the test results, and second-order equations of

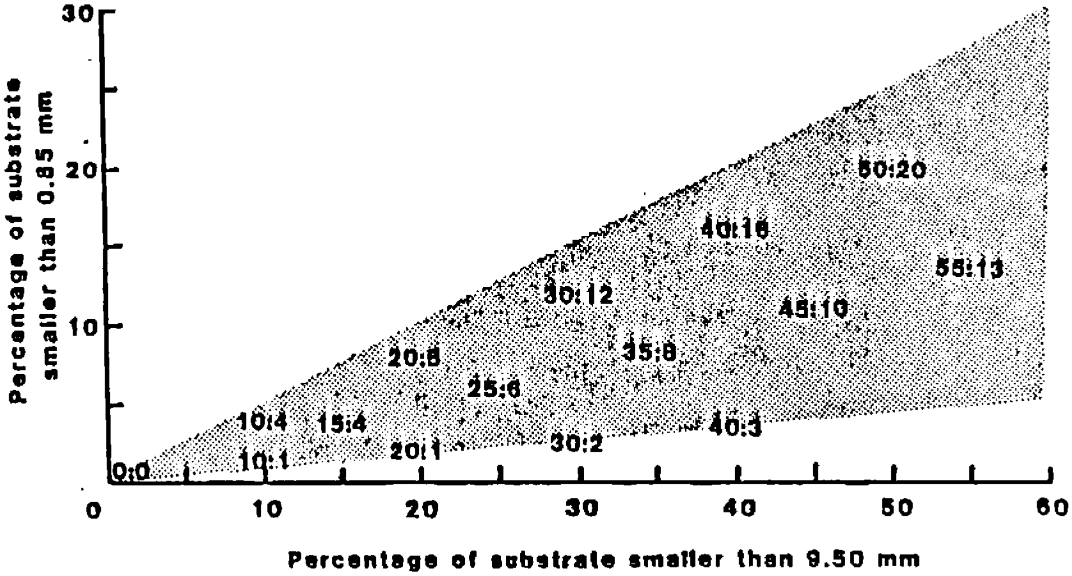


Figure A.6. (From Tappel and Bjornn 1983). Experimental gravel mixes overlying range of natural spawning substrata. Labels correspond to respective gravel compositions.

survival were prepared:

For steelhead,

$$\text{Percent survival} = 94.7 - 0.116 s_{9.5} s_{0.85} + 0.007\, s^2_{9.5}$$

and for chinook salmon,

$$\text{Percent survival} = 93.4 - 0.171 s_{9.5} s_{0.85} + 3.87 s_{0.85}.$$

The equations had r^2 values of 0.90 and 0.93, respectively. The authors noted that green steelhead eggs were used in the tests but that chinook embryos were eyed at the start of the experiment. Therefore, and in accord with data from Bjornn (1969), the survival isolines should be shifted toward the origin for chinook by an unknown amount.

Figure A.9 shows that percent survival to emergence was about 90% when d_g exceeded 10 mm, while Shirazi and Seim (1979) reported survival generally was less than 90% unless d_g exceeded 15 mm. Tappel and Bjornn (1983) showed that in gravels with identical d_g, survivals were higher than those reported by Shirazi and Seim. Tappel and Bjornn thought this was because of

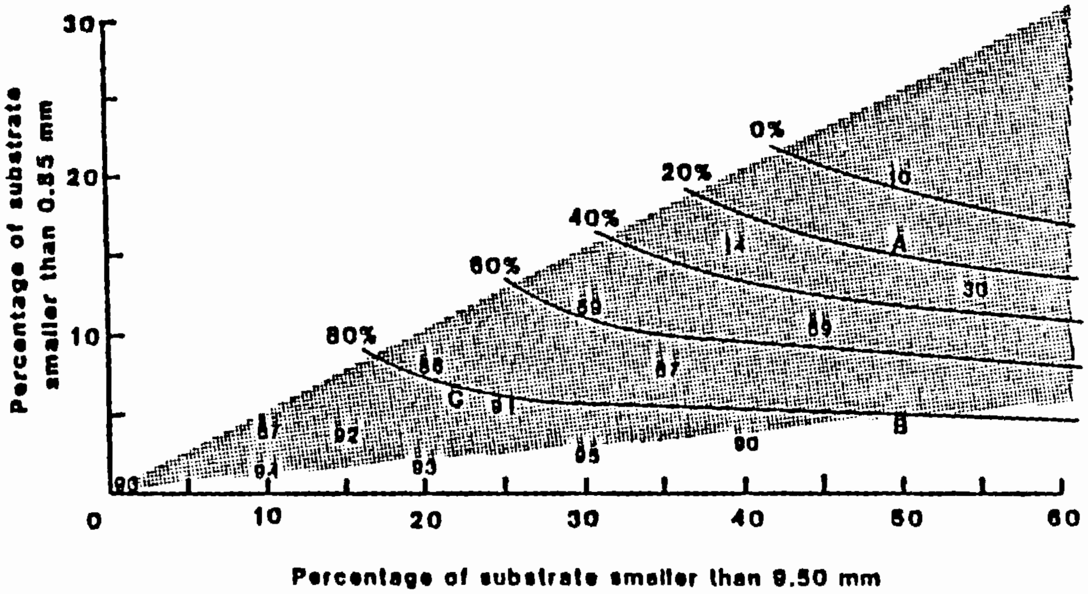


Figure A.7. (From Tappel and Bjornn 1983). Isolines showing survival predictions (0-80%) for steelhead embryos under various gravel combinations. Scattered numbers are empirical results.

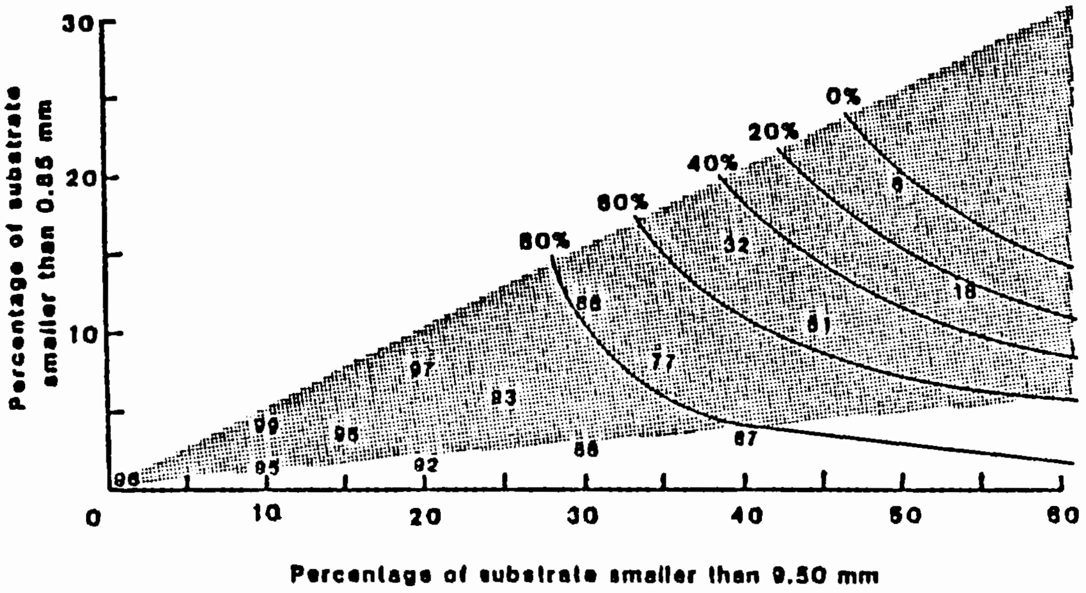


Figure A.8. (From Tappel and Bjornn 1983). Isolines showing survival predictions for chinook salmon embryos under various gravel mixes. Scattered numbers are empirical survivals.

differences in gravel composition not described by d_g alone. We submit that d_g in the Tappel and Bjornn information actually more closely reflected d_g in the laboratory environments in which survivals were obtained. The Shirazi and Seim data reflect d_g of some laboratory cells, but include many samples in the immediate area of the redd or in the redd, not necessarily in the egg pocket.

In spite of the excellent laboratory work done by Tappel and Bjornn (1983), we state that their results cannot serve to predict field survivals of embryos (eg. Talbert 1983, 1985a, 1985b) without field verification of the laboratory results. Such verification should consist of measurements of survival to emergence in egg pockets of natural redds.

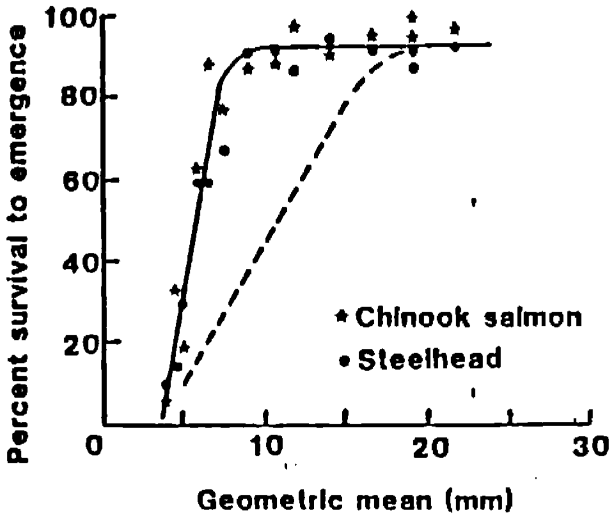


Figure A.9. (From Tappel and Bjornn 1983). Relation between geometric mean of each experimental gravel mixture and steelhead and chinook salmon embryo survival. Solid line fitted by eye to laboratory tests. Broken line is survival curve from Shirazi and Seim (1979).

A.4. <u>The fredle index</u>

A "fredle index" was developed by Lotspeich and Everest (1981). The index, d_g/s_g, where d_g is geometric mean particle size and s_g is geometric standard deviation, is stated to indirectly characterize the pore size and permeability of substrates. The index has been suggested as an integrated measure of substrate suitability for development of embryos. Lotspeich and Everest cautioned that the gravel samples used to develop the fredle index should be taken from locations known as spawning sites and no deeper than the depth of egg deposition. This stratification precaution should be applied to other substrate sampling as well, as noted by Burns (1984). We go one step beyond Lotspeich and Everest by stating that for purposes of predicting survival in natural redds, the fredle index must be developed with data from natural egg pockets, and we discuss the reasons in section II.B.

To date, no evidence from field sampling has been presented to establish utility of the fredle index in a variety of field situations. Sowden and Power (1985) correlated the index with rainbow trout survival in groundwater-fed streams in southwestern Ontario, and found no significant correlation until redds with mean dissolved oxygen lower than 5.3 mg/l and extreme gradients were removed from the analysis. When this was done (Table A.5 and Figure A. 10), correlation improved. The correlations do not include the emergence phase.

Table A.5. (From Sowden and Power 1985).

*Correlation coefficients between percent survival of preemergent rainbow trout embryos (arcsine-transformed) and percentage of fine sediments less than 2.0 mm in diameter (fines), the geometric mean particle size (D_g), fredle indices of substrate quality (D_g/S_g), and permeability for two groupings of redds. DO denotes mean dissolved oxygen concentration and I denotes hydraulic gradient; asterisks denote *P ≤ 0.05; **P ≤ 0.01.*

Redd grouping	Arcsin(% fines)	D_g	D_g/S_g	$\log_e$(permeability)
All redds ($N = 19$)	−0.3175	0.4090	0.3620	0.3604
Redds with mean DO ≥ 5.3 mg/L and $0.08 \leq I \leq 0.12$	−0.7618	0.8457	0.9049*	0.9826**

Perusal of Table A.5 indicates that correlation coefficients equalled -0.76, 0.84, 0.90, and 0.98 for independent variables of percentage of fines < 2.0 mm, geometric mean particle size, the fredle index, and permeability, respectively. The latter two variables provided significant regressions.

Sowden and Power explain the need for stratification by noting that survival in redds was not described by the measures of substrate composition tested because the oxygen content of groundwater varied independently of substrate makeup, and substrate composition accounted for only a limited portion of the variance in groundwater velocities.

Sowden and Power did their work well. Unfortunately, the results do not carry survivals to the emergence phase, and, although a single freeze-core was taken from redds, we have no way to determine if they were extracted from egg pockets.

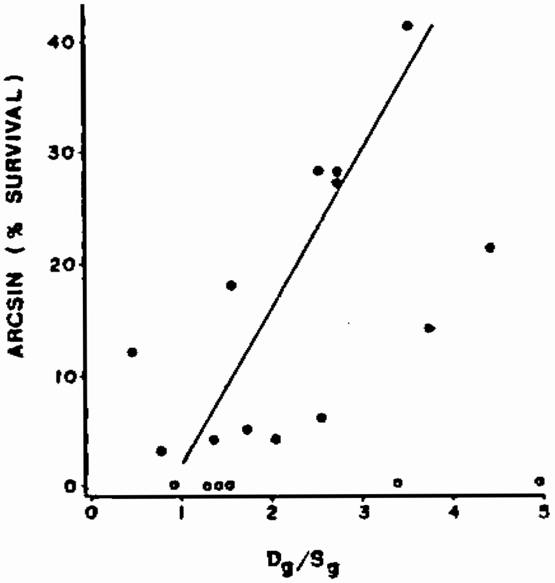


Figure A.10. (From Sowden and Power 1985). Relation between survival of preemergent rainbow trout embryos and the fredle index for redd substrates. Redds for which mean dissolved oxygen content was 5.3 mg/l or greater are noted by dark and split circles. Open circles denote redds in which dissolved oxygen content was less than 5.3 mg/l.

Lotspeich and Everest (1981) calculated fredle indices for laboratory data of Phillips et al. (1975) (Figure A.11). These data included only the intragravel period of "swim-up" fry to emerging fry, the period after "button-up". Figure A.11 must be

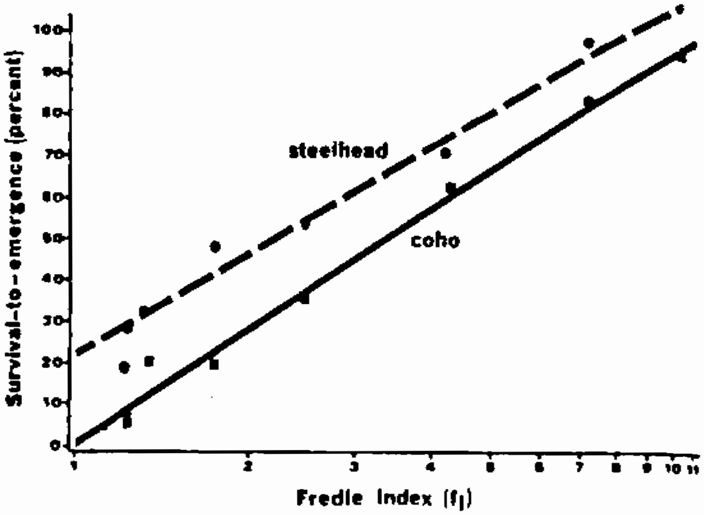


Figure A.11. (From Lotspeich and Everest 1981). Survival from introduction of swim-up fry to emergence from gravel mixtures with various fredle numbers. The underlying data on survivals were those of Phillips et al. (1975).

used with caution. Lotspeich and Everest called the models in Figure A.11 "preliminary", and identified the next task as development of relationships between fredle numbers and survival to emergence in natural gravel mixtures. We go one important step further, stating that the relationships should be between embryo survival to emergence and fredle numbers in egg pockets.

In the absence of field corroboration and correlation of embryo survival to emergence with the fredle index, it appears premature to assess the fredle index, then to predict survival of species of interest as has been done for steelhead in Pete King and Deadman creeks in the Idaho batholith, for example (Talbert 1983, 1985a, 1985b). However desired are tools for survival prediction, an extrapolation of this extent should be avoided. This is not to say that the fredle index does not offer a useful measure of gravel character. But the next step to predictions of survivals is premature without field verification.

A.5. Visual assessment

All of the measurements described in A.1 through A.4 require coring and sieving of substrate samples. Shirazi and Seim (1981) suggested that natural variability of gravels in space and time makes desirable a rapid visual examination of gravel heterogeneity. Such a measure would reduce sampling cost and effort. These authors worked in the field in Oregon and Alaska to test utility of the method. At each sample location, the spawning area was visually divided into three groupings based on apparent composition of surface gravels: coarse, fine, and intermediate. A single 30 cm core sample was collected within each area and field-sieved for analysis.

When mean particle diameters in bed material of neighboring patches differed by about 10%, based on the visual procedure, Shirazi and Seim were able to correctly identify the coarser material 87% of the time. When differences were about 20%, the visual estimation of relatively coarser material was correct 93% of the time.

Shirazi and Seim (1981) proposed to use the visual stratification system as a means of allocating gravel sampling effort, not as a method of characterizing the gravels in detail. It is logical that the surface appearance of gravels may be quite different in watersheds of different hydrologic pattern (eg. coastal rain forests or interior plateau or northern Rockies) with varying degrees of surface armoring, making a unifying visual separation suspect or impossible. However, if the visual stratification is used solely as a means of allocating core samples, risk is minimized.

Use of a visual system for sediment classification requires familiarity with the stream system and some objective means of characterizing surface appearance. Platts and Megahan (1975) assessed long-term trends in sediments in the South Fork Salmon River by using visual classification of the substrate surface into groups as noted in Table A.6.

Table A.6. (from Platts and Megahan 1975). Size classification of riverbed materials in ocular evaluation of substrate.

Particle diameter	Classification
12 inches or over (304.8 mm or over)	Boulder
3 to 11.9 inches (76.1 to 304.7 mm)	Rubble
0.19 to 2.9 inches (4.7 to 76.0 mm)	Gravel
0.18 inch and less (less than 4.7 mm)	Fines (Sand)

They used groups of channel cross-sections within major spawning areas, and evaluated composition of bed materials from waterline to waterline along the sections. They visually projected each 30-cm division of a measuring tape to the bed surface and assigned the observed sediment to one of the 4 sediment classes.

The visual examination of substrate was reported for 9 years of data (figures A.12 and A.13), and showed gradual decreases in fines (and concomitant increases in amounts of larger particles).

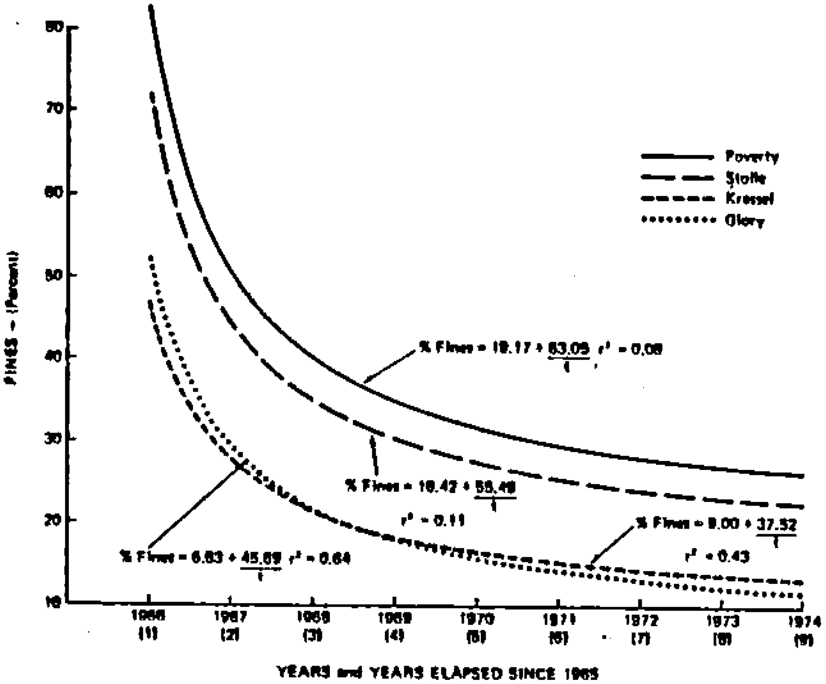


Figure A.12. (From Platts and Megahan 1975). Trends in percent fines in spawning areas of the South Fork Salmon River as determined visually.

Although the error bands for each relationship are wide, as indicated by low coefficients of determination, the fitted regressions are significant (Platts and Megahan 1975).

Although not available for the same time period as the data reported by Platts and Megahan (1975), core samples reported by Corley and Newberry (1982) show a downward trend in proportions of fines (< 6.3 mm) from 1975-1981 in the main South Fork (especially since 1979), but no trends in the Stolle Meadows site in the upper river. These data somewhat loosely support the

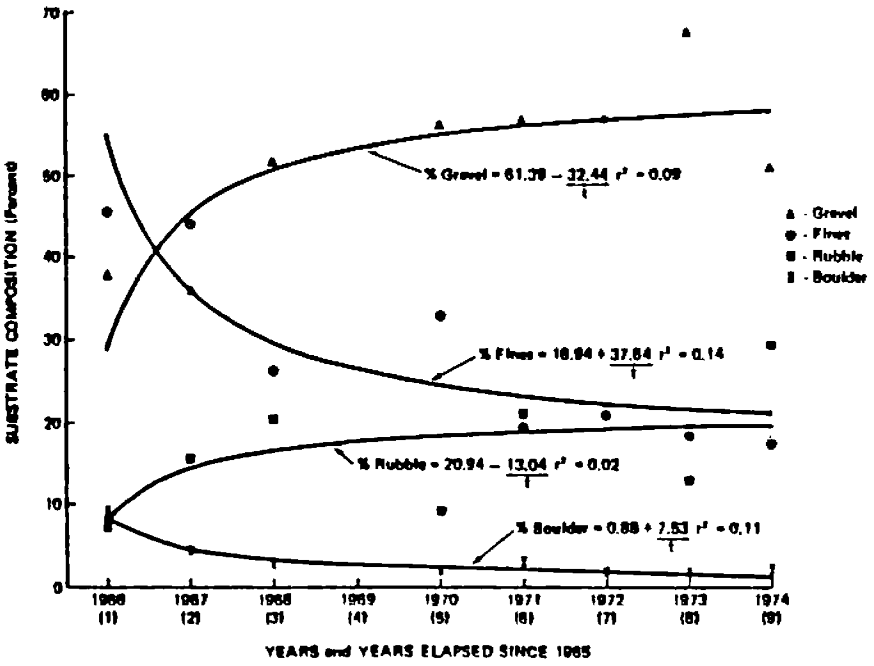


Figure A.13. (From Platts and Megahan 1975). Trends in size composition of the substrate surface in spawning areas of the South Fork Salmon River, as determined by a visual estimation.

visual measurement trends of Platts and Megahan (1975).

Everest et al. (1981), in summarizing techniques of sediment sampling and analysis, objected to use of visual inspections of surface gravels because estimates of quantity and quality of the substrate were typically in error and provided no indication of conditions in the substrate at egg-pocket depth. The "crust" of fines that may form in the surface layers of a cleansed gravel (Hobbs 1937 and Adams and Beschta 1980) could conceivably contribute to error in a visual assessment of substrate as it relates to embryo survival. Armoring would also contribute to error of visual measurement. However, where used as a time-trend indicator (Platts and Megahan 1975) in fixed locations, it appears to offer a reasonable measure of major change.

Burns (1978) compared core samples with a photographic assessment of surface conditions in known spawning areas. An area of stream bottom in a plexiglas grid was photographed with glass marbles of known size on the gravel surface. Fines smaller than 4.75 mm were compared with core samples. The photo method resulted in assessment of a mean of 13.2% fines but failed to distinguish fines of size less than 0.85 mm. The author concluded that the photo method was viable. However, the Payette National Forest has subsequently abandoned photo and visual assessment techniques (D. Burns, personal communication).

Scrivener and Brownlee (1981) analyzed over 1000 gravel cores (freeze cores with dry ice and acetone) from Carnation Creek, Vancouver Island, and found that fines were more abundant deeper in the substrate than at the gravel surface (Figure A.14). They also found evidence of seasonal trends in fines, with fines accumulating in the substrate during low flow periods and being removed by spawning fish or freshets in the higher flow periods. This underscores the importance of timing of sampling in substrate evaluations.

Ringler (1970) reported a variable pattern of vertical stratification of sediments in freeze-cores extracted from coho salmon redds in three tributaries of Drift Creek, an Alsea River drainage. Fines smaller than 0.83 mm and smaller than 3.33 mm tended to be more abundant in the top 1/3 of a 25 cm core segment than in deeper strata in two streams but not in the third.

The disparate findings of Scrivener and Brownlee and of Ringler should, at minimum, be carefully considered by workers seeking to evaluate sediments based on surface conditions. Evaluation of surface character on the same location each year and at the same time would at least reduce variability associated with time and space, although leaving unresolved the fact that surface condition will not accurately or even approximately reflect conditions deeper in the substrate, or differences in depths of intrusions of fines.

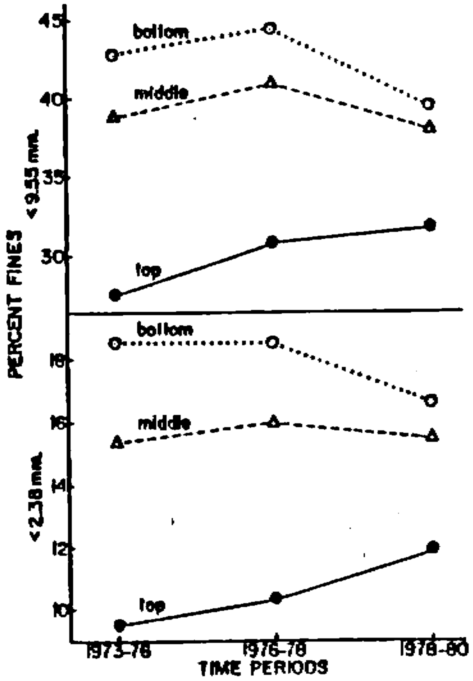


Figure A.14. (From Scrivener and Brownlee 1981). Mean percent of particles smaller than 9.55 and 2.38 mm in top, middle, and bottom layers of gravel cores in Carnation Creek.

A.6. Permeability and apparent velocity

Pollard (1955) described the theory of flow through spawning gravels. He defined porosity as the ratio of volume of voids to the total volume of solids plus voids. Hydraulic gradient is the pressure head drop, or head loss, per unit length of stream, or the slope of the hydraulic grade line. Apparent velocity is the rate of seepage of water expressed as the volume of liquid flow per unit time through a unit area (solids plus voids) normal to flow direction. Apparent velocity is sometimes called the superficial or macroscopic velocity. True velocity, or pore velocity, is the actual velocity of flow through the interstitial spaces, and differs from pore to pore.

Permeability, which is more properly termed Darcy's coefficient of permeability, is the constant of proportionality, K, in the function below:

$V = KS$, where

V is apparent velocity of groundwater and S is hydraulic gradient. K has the dimension of length (or distance) per unit of time. Permeability is a packing indicator, so that apparent velocity is proportional to packing and gradient. The looser the gravel and the higher the gradient, the faster water will flow through the substrate. Permeability of a gravel can be measured by forcing water through a sample of it.

Pollard (1955), and Terhune (1958) described a standpipe and associated equipment for measurement of apparent velocity and permeability. Apparent velocity measurements required a visual comparison of water samples withdrawn at various time intervals from a standpipe "cell" about 25 cm deep in the substrate. Variability in this technique is often high, and apparent velocity measurements made by the techniques described by Terhune (1958) have utility principally for purposes other than for descriptions of suitability of gravels for spawning (see next major section for applications of apparent velocity measurement).

Gravel permeability indices have been described by Cooper (1965) and Pollard (1955). Cooper shows beta, the gravel permeability, as $\beta = \left(\frac{e}{1-e}\right)\left(\frac{1}{5\sum \frac{p}{d_g}}\right)$, where

e = porosity, and

p = fraction by weight of size d

He defines a permeability function as

$$e^{n}\beta^{3-n} = \phi .$$

Cooper conducted tests with various gravels, demonstrating the relationship between sediment addition, time, and permeability. He showed a reduction in permeability as gravels trapped sediment over time. In general, the rate at which sediment was removed from surface water was directly related to permeability of the gravel. Less permeable gravels trapped more fines. Silt-laden water can deposit fines more readily in the voids, where low velocity permits silt to settle. The egg pocket is more porous and permeable at the conclusion of redd construction than is the case outside the pocket. It will trap fines at a rate different from the retention rate in areas surrounding the redd outside the egg pocket or in the gravels termed by many workers "spawning habitat" or "spawning gravels."

Pollard (1955) showed that permeability declines as porosity declines when gravel is packed more and more tightly (Figure A. 15). Pollard demonstrated the relationship between volume of water pumped from a standpipe well under one-inch suction head and gravel permeability in a laboratory permeameter (Figure A.16). The standpipe, later thoroughly discussed by Terhune (1958), is an artifice for creating, with minimum gravel disturbance, a cavity 25 cm below the surface of a streambed, or roughly at the depth of a salmon egg pocket (Figure A.17). Terhune provided a plot, developed from a laboratory permeameter, of permeability (K) in relation to volume of water pumped per unit of time (Figure A.18).

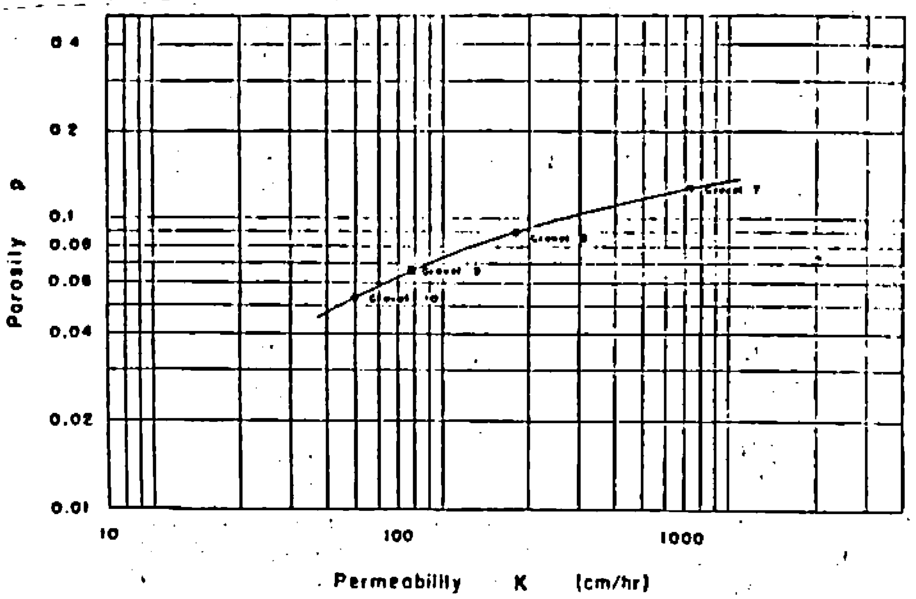


Figure A. 15. (From Pollard 1955). Log-log plot of permeability against porosity for one gravel bed successively compacted.

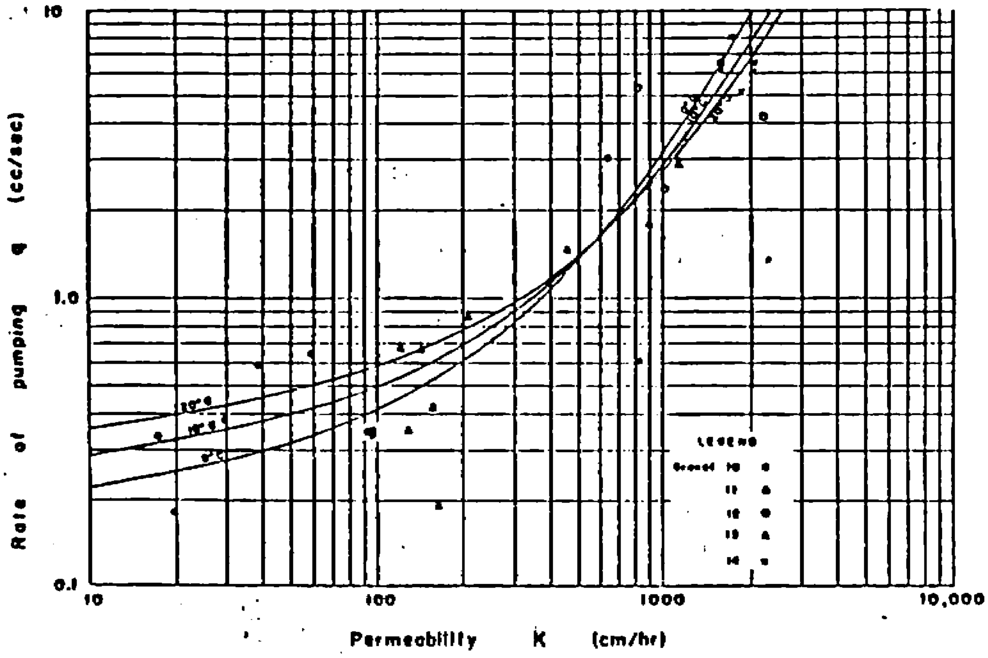


Figure A.16. (From Pollard 1955). Calibration curves of rate of pumping groundwater from standpipe under one-inch suction head against permeability of gravel at temperatures 0, 10, and 20 C.

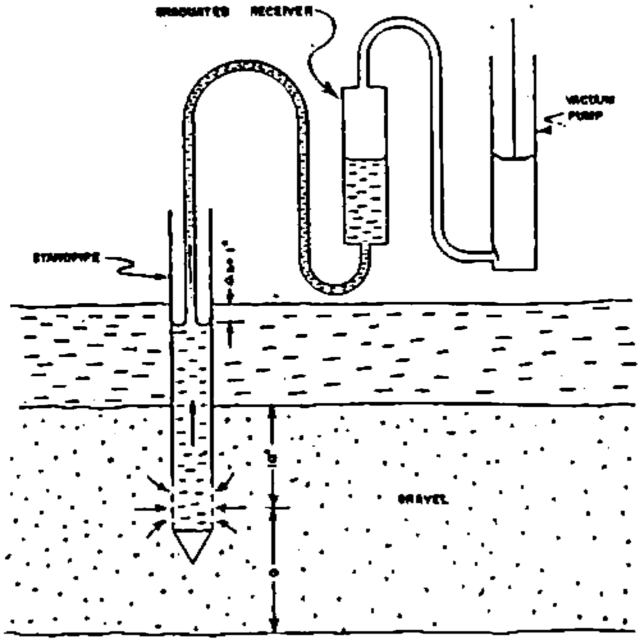


Figure A.17. (From Terhune 1958). Schematic of standpipe and associated apparatus to measure gravel permeability.

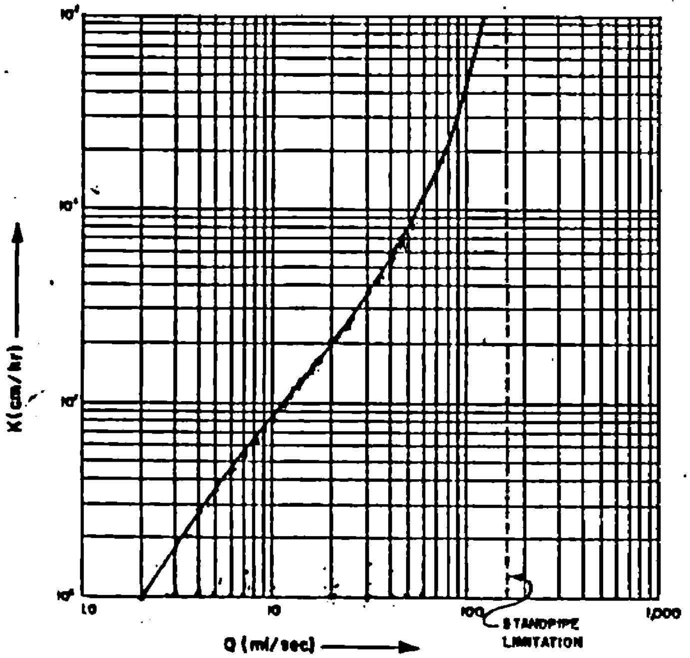


Figure A.18. (From Terhune 1958). Permeability (K) versus rate of inflow (Q) to Mark VI groundwater standpipe at one inch head.

Platts et al. (1979) extracted data from Cooper (1965) to relate permeability and d_g (Figure A.19). Permeability was directly related to d_g with a high (90%) coefficient of determination. Platts et al. used this relationship to help explain why d_g offered a unifying statistic for gravel description. One could also use it in the reverse, to demonstrate that permeability is a measure of gravel composition. We later contend that permeability offers a useful tool for correlations with survival and for assessment of fines intrusions in egg pockets, as well as for evaluation of land mangagement practices.

Beta, the permeability noted on the vertical axis of Figure A.19, differs from the permeability function (K) in Pollard (1955) and Terhune (1958). Beta is defined by porosity, a shape factor, and a sum of fractions of particles by weight of each size class, and has a centimeter dimension, while K lumps several factors and has a dimension of cm/hr.

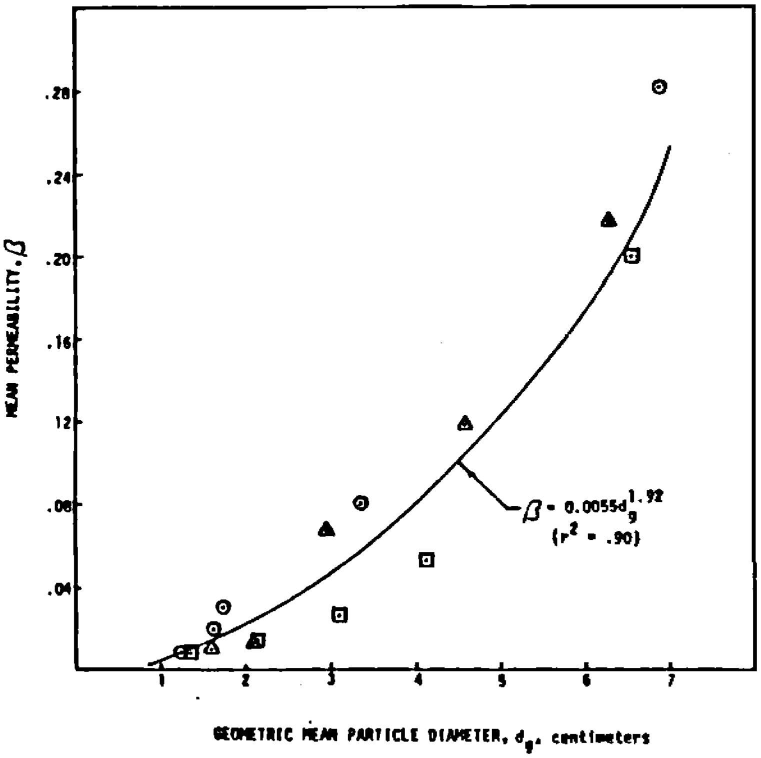


Figure A.19. (From Platts et al. 1979). Permeability as a function of geometric mean particle diameter (d_g).

A.7. Timing and location of samples

Burns (personal communication), in discussing embeddedness (see section III) statistics, made the point that he directed embeddedness samples to a particular stratum, namely to rubble or cobble areas under laminar flow conditions. In a technical sense, true laminar flow would not occur over a rubble substrate, but the point is that selection of smoothly-flowing areas over a particular substrate type narrows sampling focus and reduces variance among embeddedness samples. In evaluations of spawning gravels, it is pointless to sample deep pools with a boulder substrate, as an extreme example.

Cederholm et al. (1977) extended this reasoning in the Clearwater River system in Washington by sampling with a core sampler only in riffles known to be selected by spawning salmonids. This approach automatically reduced scope of sampling and numbers of samples required to estimate parameters of spawning gravels. McNeil and Ahnell (1964) obtained core samples only from spawning beds. Lund (1985) core-sampled only in known spawning areas.

We would carry the stratification process on by noting that if the study objective is to assess conditions in the substrate as they control salmonid incubation and emergence, samples should come only from natural egg pockets. If the objective is to determine overall condition of "spawning gravels" without reference to embryo survival, then a somewhat less-restrictive stratification could suffice.

Whether one uses permeability, coring, or even visual scoring to describe condition of spawning gravels, time of sampling may also have a major impact on results. For spring spawners, gravel conditions present after the peak of the hydrograph probably best represent conditions faced by the female when she selects a redd site and begins excavating. For fall spawners, conditions in September or October are more appropriate.

Condition of gravel before redd construction does not indicate that present during incubation or emergence. The spawning female purges the redd of a fraction of the fines present in undisturbed gravel, as noted in the next major section. Hence, coring or permeability data may or may not correlate with embryonic survival, depending upon when the data were obtained, quite apart from problems associated with failure to sample in the egg pocket.

B. PHYSICAL ENVIRONMENT IN GRAVELS USED FOR SPAWNING

We see the structure of salmonid redds as critical to the role of fine sediments in affecting survival of incubating embryos and emergence success. We believe that many field and laboratory researchers have failed to understand redd structure, with pervasive effects upon utility of data. The following discussion supports these statements.

B.1. Redd structure

Burner (1951) described the shape and size of redds constructed by Pacific salmon. Figure B.1 shows development of a chinook salmon redd over time and locations of ova.

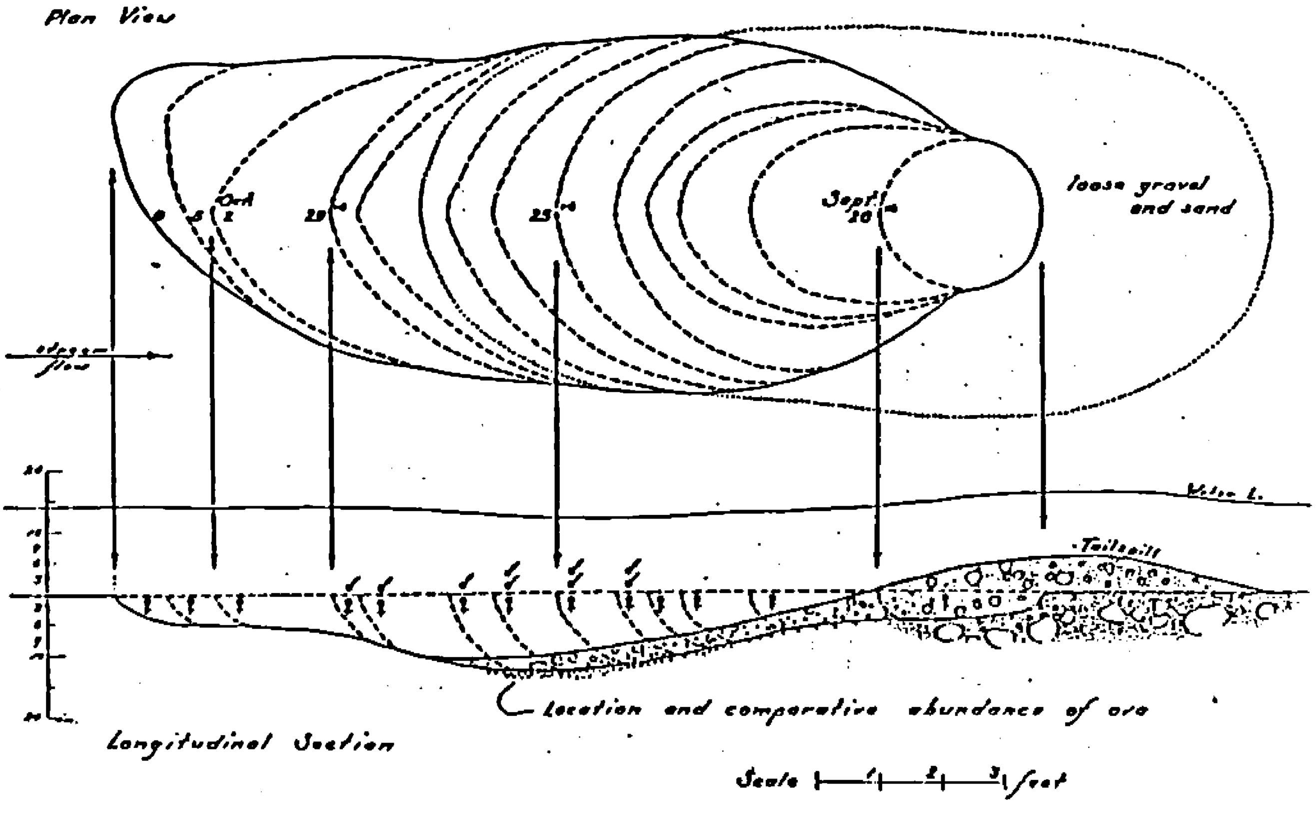


Figure B.1. (From Burner 1951). Diagrammatic views of a fall chinook salmon redd that was measured daily.

Burner's figure shows the position of the ova within the redd. They lie well upstream from the crest of the tailspill.

Hawke (1978) excavated chinook salmon redds in New Zealand. Although his methods section did not explicitly describe the tailspill, his definition of a redd as the total area excavated by a fish, and the area in which ova lie, implicitly means that he did not include the tailspill in the term "redd". His diagrams show that deposited embryos lie not beneath the tailspill crest, but upstream in a series of 5-6 egg pockets within the disturbed area of the substrate (Figure B.2). Observations of Hobbs (1937) support this point.

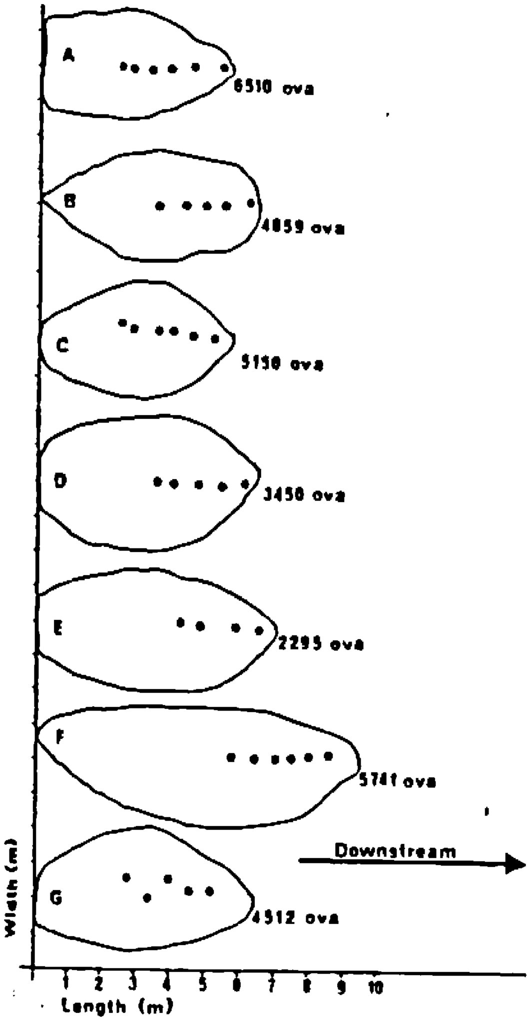


Figure B.2. (From Hawke 1978). Positions of egg pockets in 7 redds of Oncorhynchus tshawytscha in a New Zealand river.

The redd begins as an initial pocket from which the female has removed fine materials by the lifting action created by turning on her side and vigorously flexing her body. Current helps carry the lifted fines downstream; the finest particles travel well downstream and gravels move into a pile or low ridge below the pocket.

The largest particles in the substrate cannot be lifted by the female; these form the clean egg pocket centrum, commonly a grouping of 3 or 4 large gravel or cobble particles. The female deposits the first group of eggs into this centrum and the male simultaneously fertilizes them. The eddying currents within the pocket (Figure B.3) probably help retain sperm in contact with the eggs. The female quickly begins digging upstream from the first pocket, both directly and obliquely upstream. Current again carries the finer materials downstream below the redd, and gravels lifted from this newly-excavated area drop into the first egg pocket or onto the tailspill, depending upon size of the excavated material. The female then prepares a new egg pocket with a centrum of several large particles, cleaned of fine

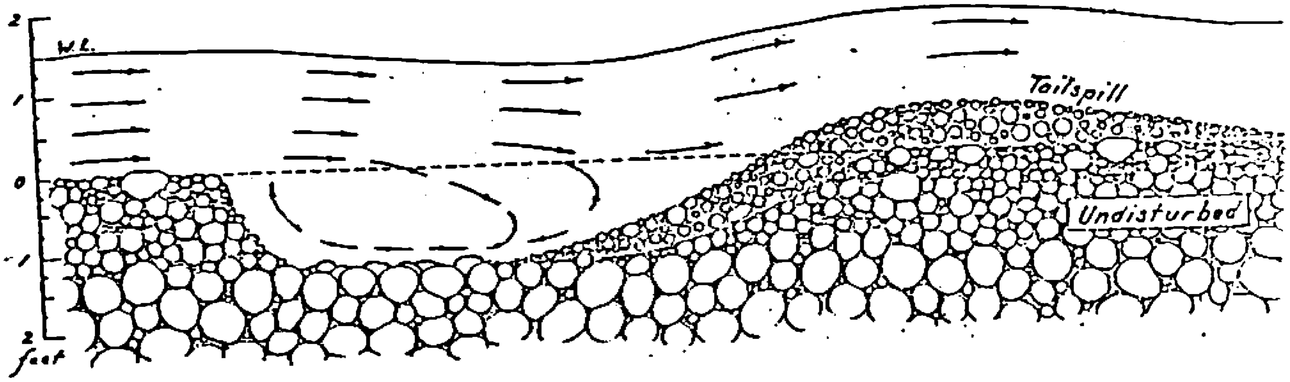


Figure B.3. (From Burner 1951). Drawing of currents within a chinook salmon redd.

materials, and the egg deposition and fertilization process continues.

Vronskiy (1972) confirmed characteristics of the egg pocket centrum by noting: "One interesting structural feature of most chinook redds is the presence of one or two large stones (15-23 cm in diameter) lying on the bottom of the redd; the bulk of the eggs are concentrated around them." He excavated redds to reach this conclusion.

Hawke (1978) showed that pocket placement progresses upstream, but that excavation also extends normal to streamflow and to the pocket line (because of oblique digging to cover the egg centrum). Not all digging in the redd serves to cover earlier egg pockets or even to construct new ones. Females apparently direct some digging at testing the substrate for suitability. Not all initial pockets are used for egg deposition, and females may move to a new area for actual spawning.

When the final, most upstream egg pocket has been prepared, digging upstream covers the pocket, but no identifiable new single pocket is excavated. Rather, several shallow excavations often appear directly and obliquely upstream.

The point of the foregoing description is to clarify that the redd in longitudinal section is a series of pockets, the bottoms (or "floors") of which consist of undisturbed streambed. Several large gravel or rubble particles that the female cannot,. or does not, move form the centrum of the pocket, and small and medium gravels lie among, around, and over the centrum (Hawke 1978).

The female removes fines from an area much wider than the pockets themselves as she obliquely digs to cover deposited eggs and test for the next pocket location. Thus fine particles of silt and sand are substantially decreased in the completed redd. Some sand, probably tending to consist of larger-diameter sands from upstream pocket preparation and final digging, drops back into the redd. One might expect, in theory, that these fines would most likely fall back into the gravel bed in which the downstream egg pockets lie, rather than into the area occupied by the most upstream pockets, but turbulence and eddying within the redd prevent any clear longitudinal stratification. Possibly the waning energy of the spawning female as she deposits and covers the last eggs would lead to reduced movement of larger sands out of the redd, further obscuring stratification. Hawke (1978) notes that the first egg pockets are deeper than later ones, and disturbed gravel from the last pockets tends to depo- sit toward the lower end of the redd. Hobbs (1937) described the "floor" of the redd by noting that the substratum of undisturbed material underlying the redd falls steadily from the upstream end of the redd down to the point where the female commenced work.

Egg pocket depth ranged from 18 to 43 cm for chinook salmon redds excavated by Hawke (1978), and 8-22 cm for brown trout (Hardy 1963). Ova tend to be concentrated at the bottom of the egg pocket (Hawke 1978). Dr. Fred Everest (personal communication) recorded the vertical stratification of ova in freeze-core samples taken from chinook salmon redds in the Rogue River. He found that the eggs lay in a stratum 2-3 cm thick just above the undisturbed streambed at the bottom of the egg pocket. Although stray eggs lay higher in the redd matrix, the bulk of the ova were in the deepest portion of the redd. A photo of an egg pocket in Everest et al. (1986), and Hawke's (1978) photograph and schematic of the photo of a section through an egg pocket support Everest's description (Figure B.4).

Hobbs (1937) stated that chinook (quinnat) salmon eggs within egg pockets were at a depth of about 25 cm beneath the surface of the redd. Chapman et al. (1986) reported that the

Figure B.4. (From Hawke 1978). Typical egg pocket in a redd of Oncorhynchus tshawytscha in section view.

shallowest chinook salmon eggs lay 10 cm beneath the gravel surface in the redd, but that 19 cm was the mean depth at which the first eggs were encountered. In this study of spawning in the main Columbia River, the mean depth of egg pockets was 29 cm (range 19-37 cm).

Hobbs (1937) found that although redds of brown and rainbow trout were smaller than those of chinook salmon, the redd structure was similar. Egg pocket number in brown trout redds ranged from one to four, the number a function of redd size, and most eggs lay 20 cm beneath the gravel surface. Hobbs stated that rainbow trout eggs also lay in well-defined egg pockets at a depth of about 20 cm beneath the gravel surface.

Redds may be constructed in isolation but are frequently adjacent and often overlap. Chapman et al (1986) found that mean redd size with tailspill was about 17 m^2, and 13 m^2 without tailspill. Considerable overlap can occur before egg pockets are disrupted (Chapman et al 1986), as is obvious from Hawke's diagram of egg pocket placement in relation to overall redd shape.

In areas heavily used by spawners, adjacent redds are often constructed in a pattern that creates "dunes" of tailspills lying normal to streamflow (Envirocon 1984). These dunes may persist from year to year, especially in regulated streams, and fish that spawn on the upstream faces inevitably "march" the peak of each dune upstream over time. The dune configuration duplicates the location of redds in runs and tails of pools just above riffles, with a slight tilt downward in an upstream direction. This shape facilitates water movement downward into the redd (Cooper 1965). R. Thurow (personal communication) reported that steelhead (spring spawners) spawned in some identical areas used in fall by chinook salmon in the South Fork Salmon River. Fish spawned in clusters, and Thurow observed dune formation as a result.

Where spawners utilize the same areas year after year, they may maintain the area in a coarser condition than surrounding gravels that remain unused. Presence of large numbers of spawners in the same area should lead to a "mass cleaning", as fines removed from one redd may deposit downstream, then be lifted and passed along by females working downstream. Large annual spawning escapements have a major impact on maintenance of high quality spawning habitat. When populations are reduced, the overall quality of spawning habitat can decline because the annual cleaning effect exerted by spawners is diminished (Everest et al. 1986).

McNeil and Ahnell (1964) found that pink salmon significantly reduced the percentage of solids in the substrate that passed through a sieve of 0.833 mm and of 0.104 mm, and a portion of the removed materials consisted of light organic material. Organics in the materials that passed the 0.104 mm sieve amounted to an average of 3.9% of solids retained by a 0.074 mm sieve, and

12.4% of solids that passed a 0.074 mm sieve. Thus, the highest organic fraction was in the smallest size fractions, and would easily be removed by females during redd construction. This should be typical of other salmon and trout redds as well.

Ringler (1970) demonstrated that new redds contained 32% less organic material than old redds (from spawning in the previous year) in Needle Branch, but in Flynn Creek new redds and old redds contained approximately the same amount of organic material. Needle Branch had been logged while Flynn Creek served as a control.

Ringler (1970) also compared gravel composition in new and old (previous year) redds (Figure B.5). His data demonstrate considerable reduction of fines during spawning. Removal of fines from the redd is also demonstrated by Figure B.6 (Everest et al. 1986), which depicts the extent of reductions in fines of

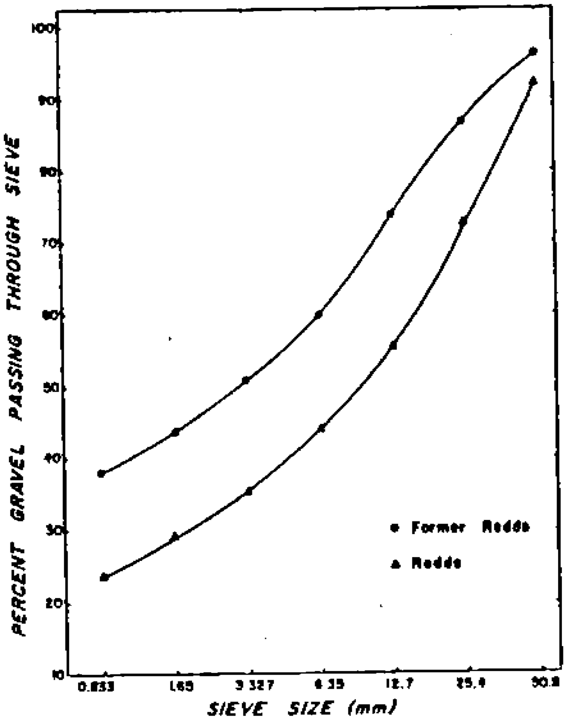


Figure B.5. (From Ringler 1970). Mean size distribution of gravels in new redds and former redds in Needle Branch, an Alsea River tributary.

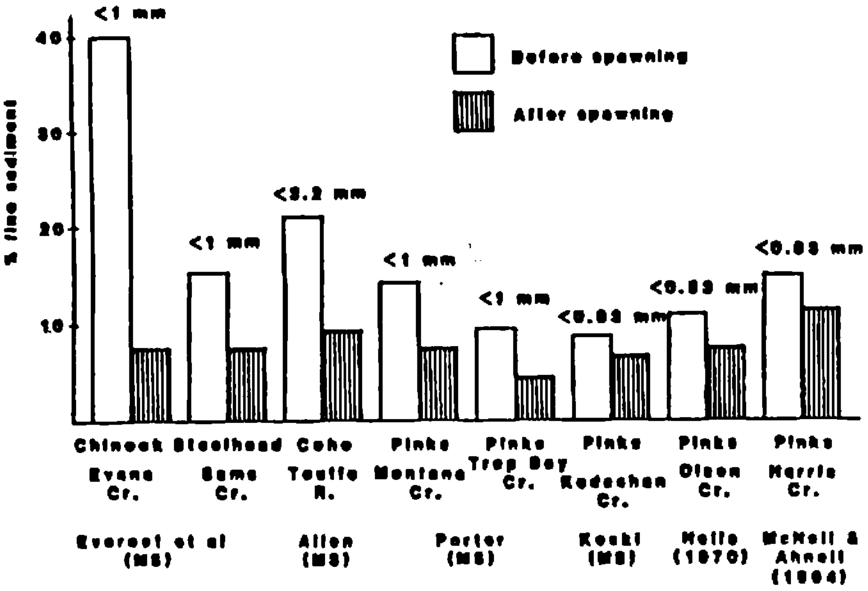


Figure B.6. (From Everest et al. 1986). Percent fine sediment before and after spawning for several species of anadromous salmonids at various sites.

various sizes from the substrate by spawning females. Although the criterion for fines differed among workers, the evidence for substantial cleaning is clear.

B.2. Intrusion of fines into gravel

A photo in Everest et al. (1986) demonstrates that the egg pocket is overlain by relatively clean gravels of lesser size. Hobbs (1937) describes the formation of a "crust" of fines in the surface layer of the redd as time passes. The rate at which fines intrude into clean materials is of great interest.

Beschta and Jackson (1979) tested intrusions of fine sediments (sands with median particle size 0.5 mm) into an initially clean gravel bed (median particle diameter 15 mm). They found that sands were trapped in voids within the upper 10 cm of the bed, forming a barrier to further intrusions. Intrusion amounts varied from 2 to 8% of total bed volume. Once the intrusion "seal" developed, intrusion stopped and additional sands were transported past the bed.

Froude numbers (F_r) help characterize flow conditions. Beschta and Jackson (1979) describe this dimensionless variable, which represents the ratio of inertial to gravitational forces in fluid flow (from Streeter and Wylie 1975):

$F_r = V^2/gy$, where
V = mean velocity, m/s,
g = acceleration due to gravity, 9.8 m/s^2,
y = depth of flow, m.

For subcritical flow ($F_r < 1.0$), conditions consist of relatively deep, slow flow. At a critical flow ($F_r = 1.0$), the specific energy ($E = V^2/2g + y$) is at a minimum. Standing waves in a stream indicate critical flow conditions. Supercritical flow ($F_r > 1.0$) is typical of relatively shallow, rapid streamflow.

At low F_r, the 0.5 mm sands quickly established a sand seal in the upper 5 cm of the clean gravel bed as the larger sand particles bridged the openings between adjacent gravel particles and prevented downward movement of additional sands. At higher F_r, flow characteristics began to alter the sealing process, and most deposition and intrusion occurred within the 5-10 cm depth zone in the bed. Higher velocities (associated with higher F_r) led to greater bed shear and "jiggling" of surface gravels, inhibiting formation of a sand seal near the gravel surface. Hence, the sand seal still formed, but deeper within the bed, and where it would prevent deeper intrusion.

These observations on intrusion of fines parallel those made regarding brown trout redds nearly 50 years earlier by Hobbs (1937), who stated that "Sediment tended to lodge and to cake firstly amongst the surface material of the redds, forming a silt "crust" overlying cleaner material. In some cases, but subsequently, silt penetrated to egg-pockets, virtually restoring the bed to its original state." But he stated that it was unusual for silt to penetrate to the egg pocket while ova or alevins remained in the pocket.

Beschta and Jackson (1979) used 0.2 mm instead of 0.5 mm sands in two tests. They found that the sand seal in the upper level in the bed did not develop. Instead, the finer sands moved down through the gravels by gravity and began to fill the test gravels from the bottom up. Particle size appears to be an important variable that influences depth of intrusion. The amount of intrusion by 0.2 mm sands decreased as F_r increased from 0.6 to 1.1. Beschta and Jackson showed that particle size distribution of 0.5 mm sands 1 cm above the gravel bed was the same as that at the point of sand introduction to the channel, but that intruded sands tended to be smaller (Figure B.7).

Beschta and Jackson noted that flow conditions, sediment transport rates, and sediment particle size all influenced the amount of fines deposited in initially-clean gravels. They state that the quantitative results of their study cannot be directly applied to natural streams, but that their study had several

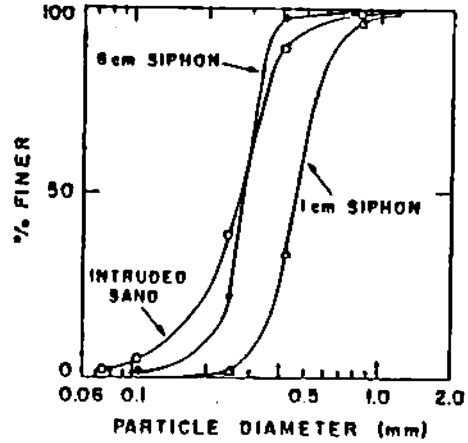


Figure B.7. (From Beschta and Jackson 1979). Size distributions of sands during an intrusion test.

implications. Fine sediments added when the bed is stable will deposit and intrude into initially clean gravels. If the particles are large enough, a bed seal will form, and subsequent deposition will be above the seal. If the fine particles are small enough, they can fill the bed from the bottom up. As long as the bed is stable, addition of fines can only result in intrusion or a blanketing of gravel surface.

Phillips (1971) provided a diagram that showed a typical salmonid redd. It illustrated that hydraulics within the redd should tend to pull surface water through the redd. Vaux (1962) and Cooper (1965) provided the experimental data that showed how surface waters penetrate the substrate. Cooper showed penetration to depths as great as 46 cm, much below the average depth of the "floor" beneath the egg pocket.

Although gravel composition would affect the depth to which surface water circulates, it is clear that the shape of the salmon redd leads to greater surface water penetration than would be the case in a gravel bed with relatively flat surface (Figures B.8 to B.11).

Cooper (1965) studied the effect of this "pulling" on intrusion of fines in gravels in an experimental environment. He confirmed that deposition of silt occurs within the gravel even though surface water velocities are too high to permit deposition on the gravel surface. The intrusion of fines reduced gravel permeability.

The lowest retention occurred in a very coarse gravel, and the greatest in a finer gravel such as that in typical spawning beds. Figure B.12 illustrates this point.

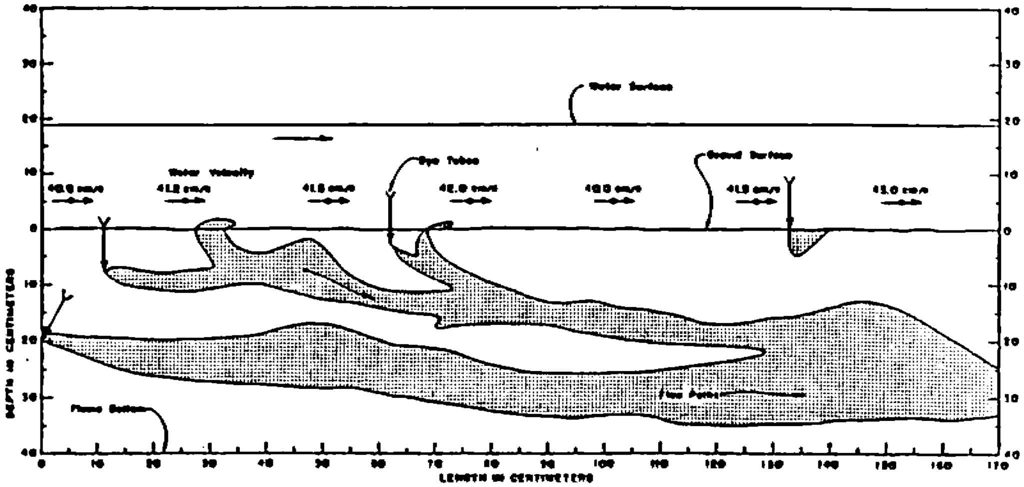


Figure B.8. (From Cooper 1965). Flow through homogeneous gravel with level gravel surface.

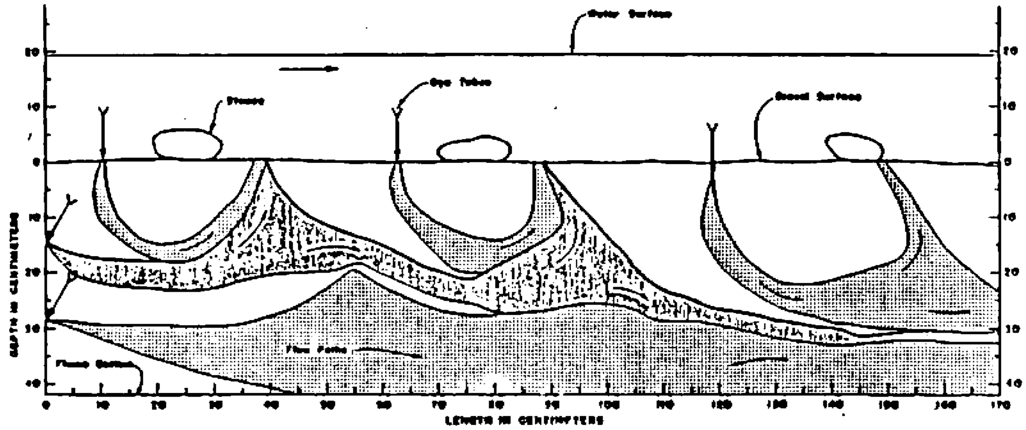


Figure B.9. (From Cooper 1965). Flow through homogeneous gravel with level surface and stones on surface.

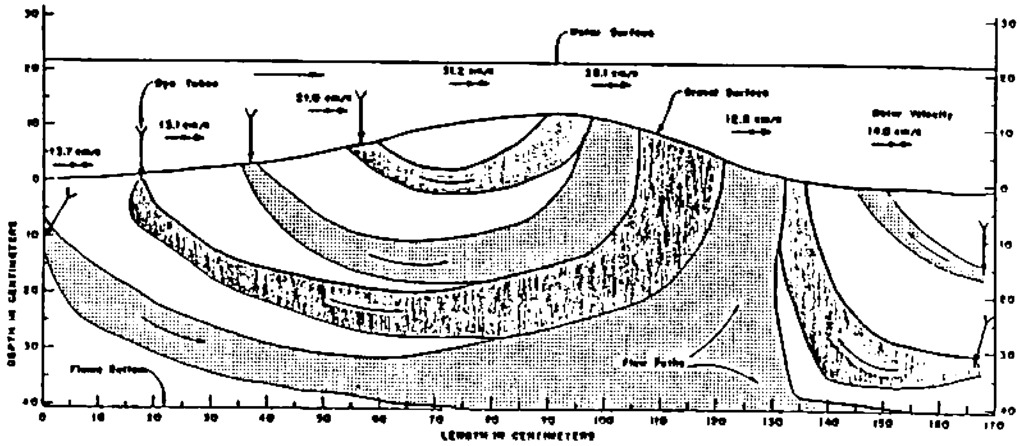


Figure B.10. (From Cooper 1965). Flow through homogeneous gravel with surface similar to a new salmon redd.

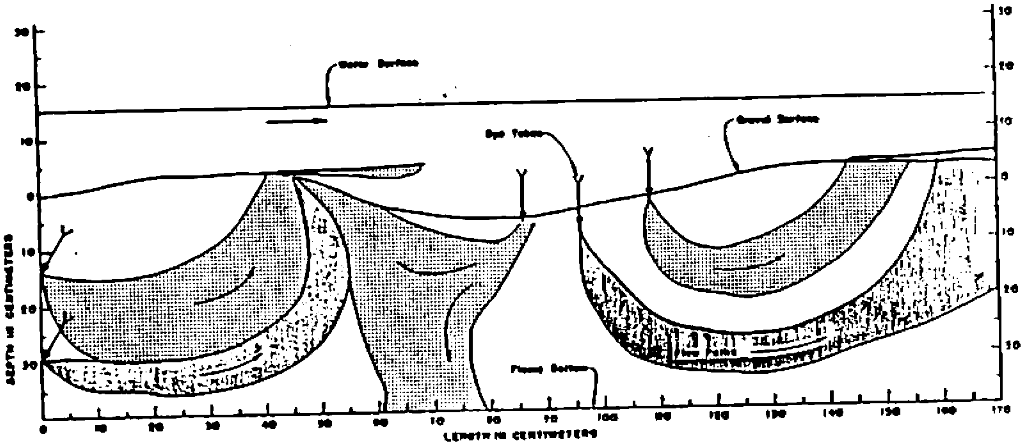


Figure B.11. (From Cooper 1965). Flow through homogeneous gravel with surface similar to a new salmon redd.

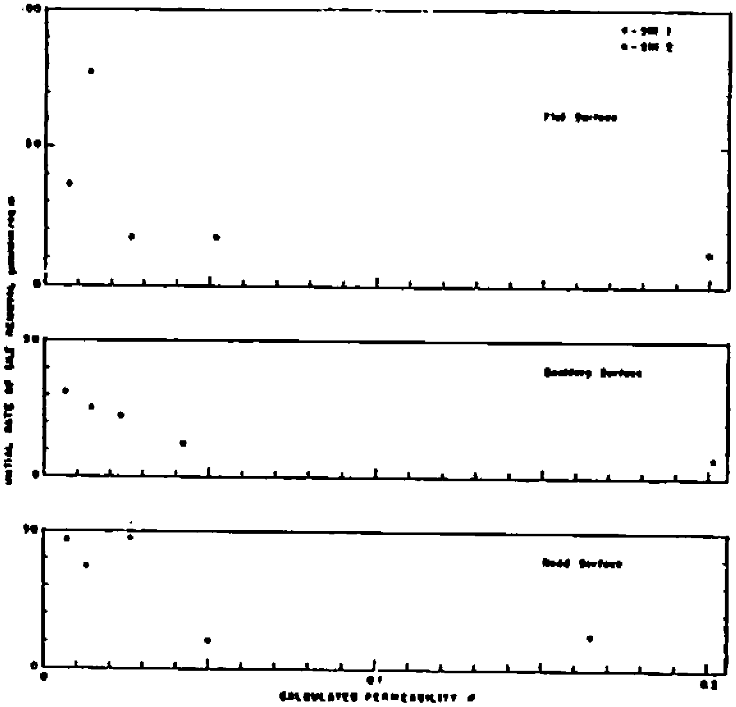


Figure B.12. (From Cooper 1965). Rates of sediment removal from surface waters for different surface conditions, permeability, and silt sizes.

Meehan and Swanston (1977) found that the rate of retention of fines <2 mm that were introduced into flow of an artificial stream channel was greater in test baskets a given distance downstream from the source of sediment for rounded gravels than for angular gravels at very low flows, and that the results reversed at higher flows. The authors attributed these results to presence of more low-velocity areas in rounded gravels at low flows, which permitted fines to intrude and settle. In angular gravels, more tractive force was needed to carry sediments downstream, but more zones of low velocity were present in angular particles at high flows, permitting more accumulation of sediment.

Koski (1975) showed that the percentage of silt (<0.105 mm) retained in gravels in experimental stream channels is related inversely to the amount of sand (particles >0.105 and <3.327 mm). The relationship appears to reflect "space available", in that voids filled with sand cannot fill with silt.

Although it is perilous to project the findings of Cooper (1965) and Jackson and Beschta (1979) to the salmonid redd in detail, some conjecture seems reasonable. From the moment when fertilized eggs fall into the cobble or large gravel centrum of the egg pocket, digging by the female spawner results in a bridging of smaller gravels among egg pocket centrum components, and then a mix of gravels over the centrum. Finally a seal of of finer sediments will develop somewhere in the redd, with the depth and composition of the seal dependent on sediment transport patterns in the surface flow. The seal may develop partly during the completion of the redd.

Hawke (1978) described the gravels above the egg pocket centrum as mainly fine, with a high proportion of coarse sand. In some pockets a loose core of pebbles ran from the egg pocket to the surface (an example of bridging, perhaps). The smaller the spawner, the smaller will be the average particle size in the redd and the smaller should be the average diameter of the "seal" components. Of course, egg and alevin size tend to be directly related to fish size as well. The implications of this in relation to the "seal" will be covered in another report section.

The complex interaction among F_r, freshet events, and sediments in transport during the incubation period for salmonids will strongly influence conditions in the redd during incubation and emergence.

B.3. Porosity, permeability, and water movement

Porosity of gravels is defined as the ratio of the volume of the voids to the total volume of solids plus voids. It can be measured by dividing volume of water in a gravel bed by volume of water plus gravel.

Permeability is a measure of the ability of gravel to pass water per unit of time and is reported as a distance per unit of time. It is a function of hydraulic gradient and apparent velocity and temperature. Gravel porosity is embodied in the apparent velocity variable.

Water movement in the substrate is measured by apparent velocity, the volume of water passing through a unit area of the gravel bed per time unit. It is a function of gravel permeability, hydraulic head, and temperature. The modifier "apparent" is used because true velocity at any micro-point in the substrate, say at a point on the surface of an incubating embryo, varies greatly from point to point. Pollard (1955) describes the relationships among these variables. An excellent body of laboratory research and theory is formed by Pollard and by Cooper (1965). Terhune (1958) and Wickett (1954, 1958) complemented this with work on field measurement of *in situ* intragravel conditions.

Cooper (1965) showed that intrusion of fines in the substrate reduced porosity and permeability. He also demonstrated that gravels with lower permeabilities trapped more sediments than those with higher permeability (Figure B.12).

Sediment intrusion also reduces apparent velocity. Theoretically, blanket deposition of fines on the surface of the gravel might reduce water movement, as reflected in apparent velocity, without reducing permeability of the gravel if the surface seal of fines were precise and complete. However, intrusion would probably occur in cleaner gravels without a seal, such as those in the redd, until a seal develops.

C. INTRAGRAVEL ECOLOGY OF SALMONID EMBRYOS

C.1. Apparent velocity

Cooper (1965) showed that apparent velocity strongly influenced survival of eyed sockeye salmon eggs to emergence (Figure C.1). He also demonstrated that survival declined with increased fractions of particle sizes smaller than 3.36 mm, possibly caused by packing of particles around embryos or by transfer of soil pressure, and possibly with higher uniformity of gravel size (Figure C.2) except perhaps in very coarse gravels.

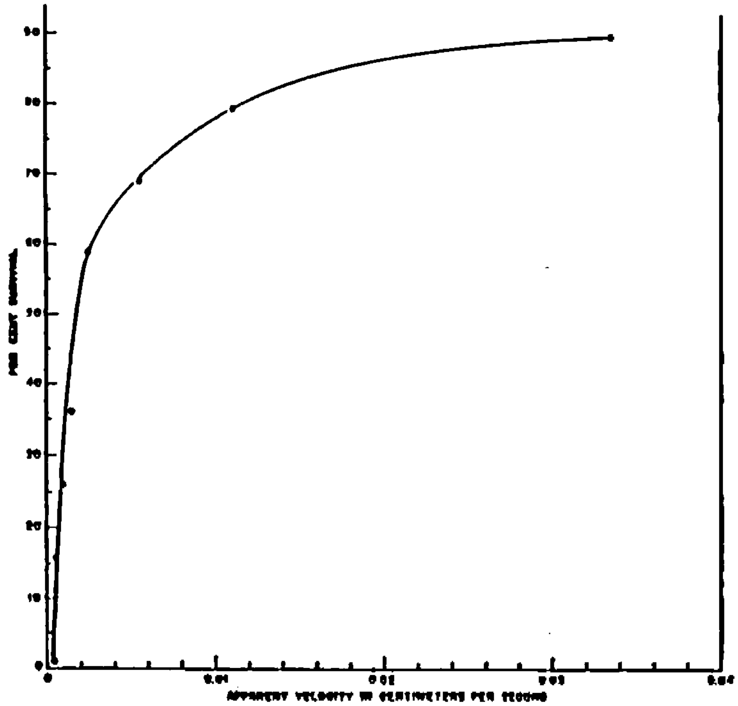


Figure C.1. (From Cooper 1965). Survival of sockeye salmon embryos as a function of apparent velocity in the gravel.

Shumway et al. (1964) established that water velocity past embryos and dissolved oxygen concentration directly affected survival of embryos. But these workers showed that the oxygen requirements of the embryo can be met by very low water velocities when oxygen levels are sufficient. The influence of apparent velocity is slight in comparison to influence of oxygen levels.

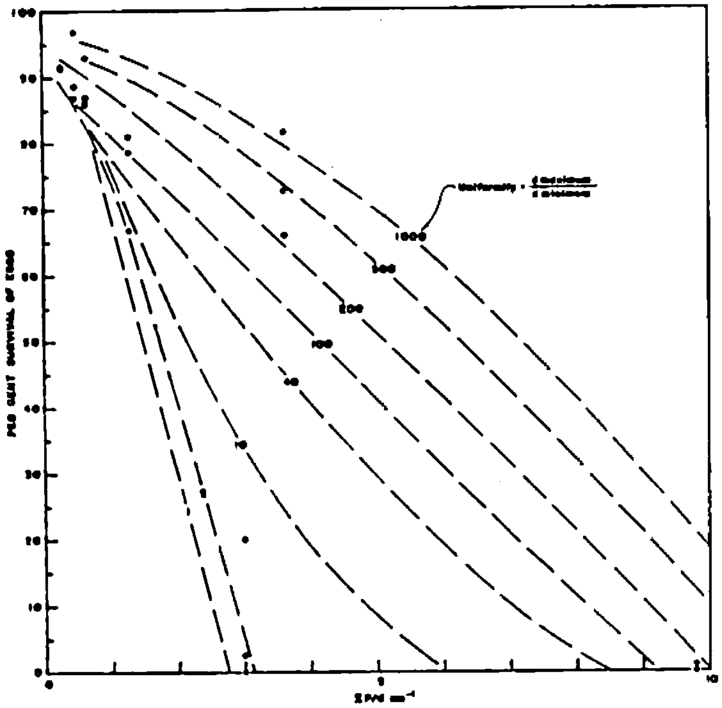


Figure C.2. (From Cooper 1965). The effect of gravel size and uniformity on the survival of sockeye eggs at a flow of 0.0167 cm/s.

Coble (1961) demonstrated that survival of steelhead embryos was directly related to apparent velocity of intragravel water. However, when he adjusted his data to normalize dissolved oxygen level at 6 mg/l, he found that survival was no longer an obvious function of apparent velocity. Coble noted that it is oxygen that is essential to incubating embryos, not velocity, and the function of water movement is mainly to deliver oxygen to the embryo and to carry away waste. He prepared a graph (Figure C.3) to illustrate the relationship between dissolved oxygen and apparent velocity in artificially-dug redds that contained steelhead embryos. This showed that when velocities were low, oxygen concentrations were low; when velocities were high, oxygen concentrations were higher as well. Coble reported that survival of embryos is related to apparent velocity, but indirectly through dissolved oxygen concentrations.

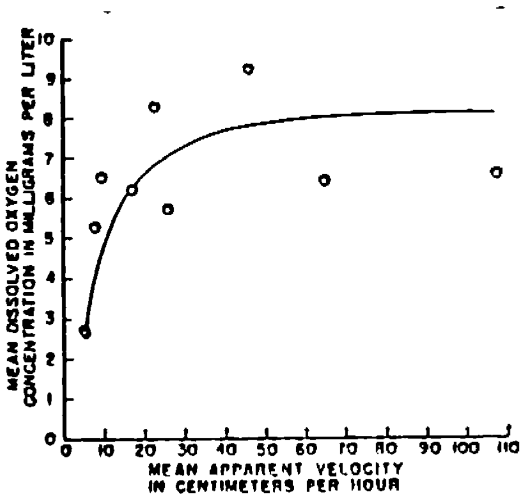


Figure C.3. (From Coble 1961). Relationship of dissolved oxygen to apparent velocity in artificially-dug redds.

C.2. <u>Permeability</u>

Wickett (1958) related percent survival (to emergence) of pink and chum salmon fry to permeability. McNeil and Ahnell (1964) showed that permeability was inversely related to the percentage of substrate particles that passed through a 0.833 mm sieve (Figure C.4), and that the more productive pink salmon spawning streams that they examined had high permeability coefficients. Wells and McNeil (1970) found that the largest embryos of pink salmon in Sashin Creek, Alaska, came from a stream segment with a relatively steep grade and coarse materials in the bed.

We used water volumes measured per unit of time by McCuddin (1977) to calculate permeabilities of gravels that he used for examination of embryo survival to emergence. These data (Figure C.5) indicate that survival of chinook salmon and steelhead trout is positively related to permeability.

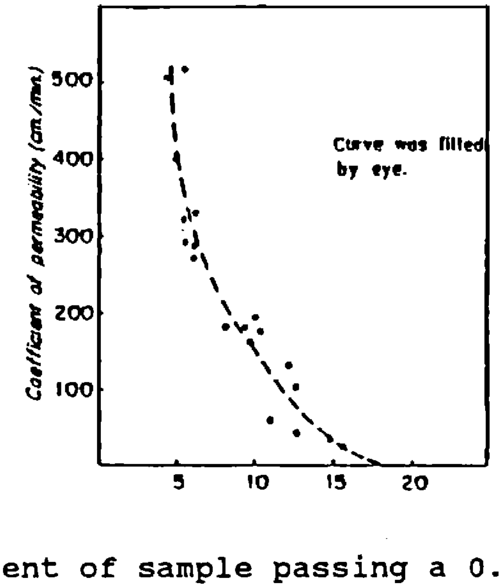


Figure C.4. (From McNeil and Ahnell 1964). Relationship between permeability and percentage of fines smaller than 0.833 mm.

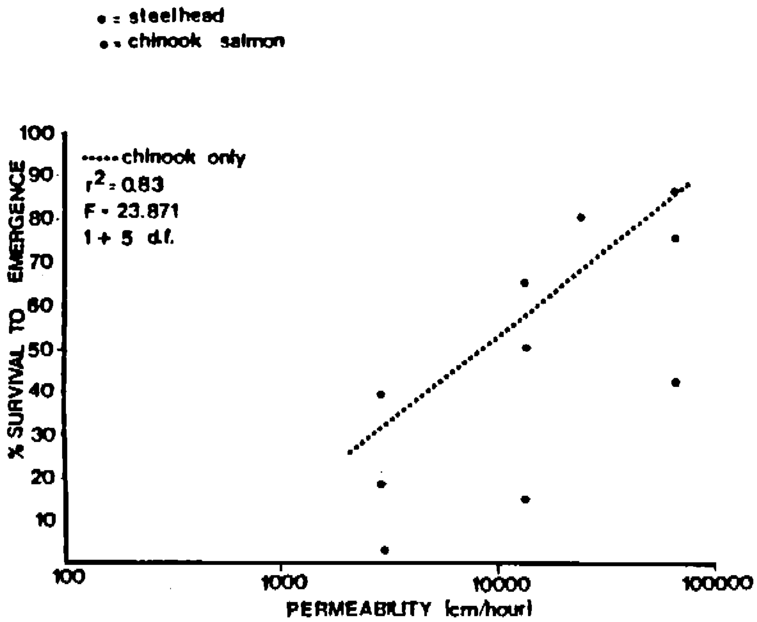


Figure C.5. (Adapted from McCuddin 1977). Survival as a function of permeability of gravel mixes in cells in laboratory studies of survival of chinook salmon and steelhead embryos from green egg to emergence.

C.3. Dissolved oxygen

Alderdice et al. (1958) tested survival of chum salmon eggs exposed to various constant levels of dissolved oxygen for 7 days at various development levels. They showed that exposure to low dissolved oxygen caused premature hatching (Figure C.6), and that rate of oxygen uptake increased steadily from fertilization to hatching. They also calculated and plotted critical dissolved oxygen levels (the oxygen needed for successful incubation) and median lethal levels of dissolved oxygen (Figure C.6) at 10 C.

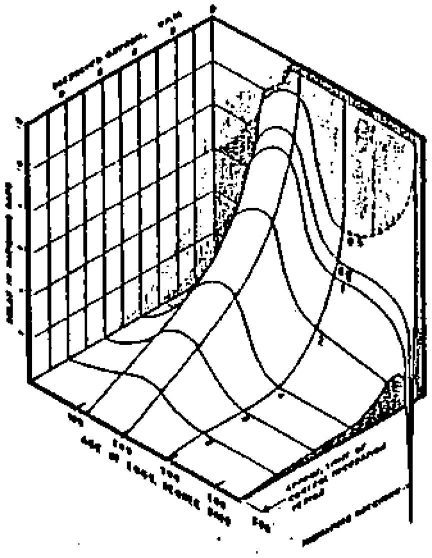


Figure C.5. (From Alderdice et al. 1958). Variation in hatching rate of chum salmon eggs reared at 10C, results of 7-day exposure to prescribed oxygen levels at intervals through incubation.

Critical level depended on stage of embryonic development in degree days.

For the purposes of our review, and in view of the great importance of dissolved oxygen in incubation of salmonid embryos, we provide some detail on the calculation of critical oxygen levels by Alderdice et al. (1958):

> Oxygen respired by the embryo diffuses through a thin enclosing spherical capsule of species-specific diameter and thickness. If a homogenous spherical body uses oxygen at a constant rate, and if the oxygen tension may be assumed to be maintained at zero in the center of the body, then
>
> $C_0 = Ar^2/6D$, where
> C_0 = concentration of oxygen at surface of the sphere in atmospheres,

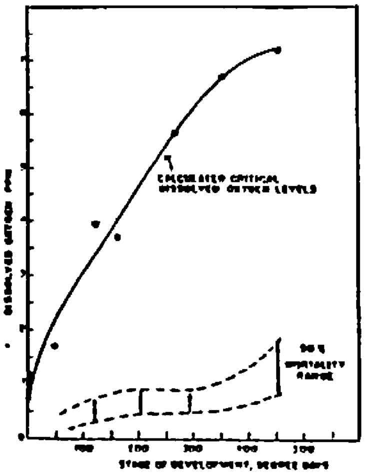


Figure C.6. (From Alderdice et al. 1958). Lethal and calculated critical levels of dissolved oxygen for chum salmon ova incubated at 10 C.

A = oxygen consumption of the sphere in ml/g/min.
r = total radius of sphere in cm.
D = diffusion coefficient of oxygen through the capsule in ml/cm per cm^2 of capsule area/min.

This formula may be applied to the egg before a functional circulatory system develops to estimate ambient oxygen required to maintain respiration at a rate independent of the environmental supply.

When an egg reaches the stage of possessing a functional circulatory system (about 200 degree-days, calculated in centigrade), oxygen is transported to the embryo tissue with greater efficiency. The tension difference needed for diffusion of oxygen in this phase is:

$C_0 = ArT/3D$, where
T = thickness of the capsule in cm
A = oxygen consumption of the sphere, in ml/g tissue/min.

Alderdice et al. (1958) assumed D = 0.0000123 ml/cm/cm^2/min, T = 0.006 cm for chum salmon, weight of the chum egg as 0.29 g, egg radius as 0.37 cm, and calculated critical oxygen level for various stages of development as in Figure C.6. Critical oxygen level is that concentration at which respiratory demand is just satisfied. The key finding is that oxygen need rises with development, and by the stage of development at 250 degree-days has reached 5 ppm at 10C. As noted later, the 5 ppm figure is too low.

Alderdice et al. (1958) recommended that critical levels of dissolved oxygen be regarded as a measure of oxygen requirements for successful incubation, and that studies be undertaken to determine if theoretically-estimated critical levels of oxygen are similar to empirical limiting levels.

Silver et al. (1963) showed that growth of chinook salmon embryos was restricted before the 24th day at all tested oxygen concentrations below 11.7 mg/l. For steelhead, growth is restricted before the 30th day at all tested oxygen concentrations below 11.2 mg/l. Growth of coho salmon at 11 C is restricted before the 7th day after fertilization at concentrations of dissolved oxygen at least as high as 6 mg/l, and before the 28th day at concentrations slightly below 11.9 mg/l. Other data show restricted growth of embryonic steelhead at 12.5 C before the 11th day at oxygen levels slightly below 10.4 mg/l.

Silver et al. (1963) concluded that the theoretical critical oxygen levels calculated for embryos by Alderdice et al (1958) are far below actual limiting oxygen levels for salmonid embryos throughout most of development at temperatures of 10 to 12.5 C. These authors ascribe the difference to the impropriety of the models (summarized above) used by Alderdice et al. The error may be associated with assumption that the limiting respiratory surface before establishment of blood circulation is the entire periphery of the chorion, when in likelihood it is the surface of the embryo itself. Another possible error is associated with the post-hatch period. Alderdice et al. assumed that the perivitelline fluid after establishment of blood circulation has zero oxygen. The embryo could not survive with no oxygen in the fluid. This means that realistic tensions are less than assumed by Alderdice et al. Higher oxygen concentrations in the water would be needed to achieve the same embryo development. Silver et al. (1963) suggested that a realistically determined critical oxygen concentration in the surrounding water cannot be assumed to be very much lower than the critical concentration in the water for newly hatched sac fry.

Davis (1975) extensively reviewed the oxygen requirements of salmonids, including anadromous forms. He shows a mean threshold of incipient oxygen response for hatching eggs and larval salmonids as 8.09 mg/l (SD = 1.65, SE = 0.58, n = 3) and 76% saturation (SD = 22.9, SE = 13.2, n = 3).

Development of embryos often proceeds at temperatures less than 10 C. In the interior plateau and Rocky Mountains, winter water temperatures during incubation by fall spawners often reach 5 C (Columbia River mainstem), or even less than 1 C (tributaries at high elevation). Critical levels for dissolved oxygen at low temperatures are not established, but may be somewhat less than those reported by Silver et al. (1963). Wickett (1954) tabulates data from Atlantic salmon (Lindroth 1942) obtained at about 5 C. These indicate a critical dissolved oxygen level of 5.8 ppm just before hatching.

Wickett's own data for chum salmon suggest a critical level of less than 5 ppm for 85-day eggs (faintly eyed) at 3.6-4.9 C. The limited data indicate that an assumption that critical oxygen levels are lower at low temperature is reasonable. Hobbs (1937) noted that the oxygen requirement per unit of tissue and unit of time at 3 C was about one-third, and at 7 C about one-half what it is at 12 C.

The fairly convincing results, summarized below, of Silver et al. (1963) and Shumway et al. (1964), who showed that any reduction of dissolved oxygen could be shown to reduce length of fry at hatching, suggest that reduction of dissolved oxygen in natural environments below natural levels should be assiduously avoided. Silver et al. (1963) demonstrated that water velocities must be high enough within the redd to transport enough oxygen to support all embryos in the redd, but also to deliver sufficient oxygen to the surface of the chorion around each embryo. Steelhead and chinook salmon embryos held at 9.5 and 11 C, respectively, all died at an oxygen concentration of 1.6 mg/l. Alderdice et al. (1958) found that the incipient median lethal level for dissolved oxygen rose with development from about 0.4 ppm early in embryo development to 1.0-1.4 ppm before hatching.

Silver et al. (1963), in an important study, showed that sac fry from embryos reared at low and intermediate oxygen concentrations were smaller and weaker than sac fry from embryos reared at high concentrations. Figure C.7 clearly shows that length of steelhead fry is a function of water velocity at given oxygen concentrations, and that at higher oxygen concentrations, water velocity increase has less effect on size of fry than at low oxygen levels.

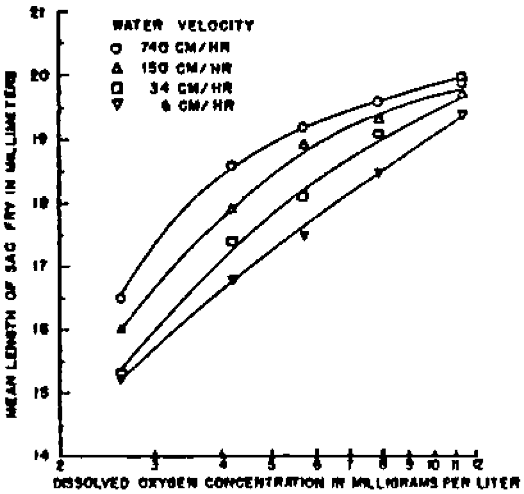


Figure C.7. (From Silver et al 1963). Mean lengths of steelhead sac fry when hatched in relation to dissolved oxygen during incubation, at different water velocities and 9.5 C.

Figure C.8, compared with Figure C.7, allows one to see that dissolved oxygen is relatively more important as an influence on steelhead fry size than water velocity. The velocities measured by Silver et al. approach true pore velocity (the actual velocity past the surface of the embryo). Apparent velocities as measured in field studies are lower than actual velocities in the substrate, and cannot be compared absolutely with these laboratory studies. However, the results of Silver et al. (1963) demonstrate clearly the combined effects of dissolved oxygen and velocities, regardless of absolute values for velocity.

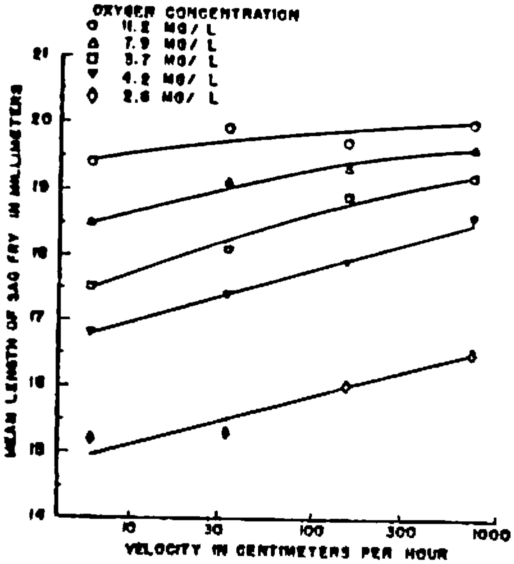


Figure C.8. (From Silver et al. 1963). Relationship between length of steelhead sac fry when hatched and water velocities, at different dissolved oxygen concentrations and 9.5 C.

Shumway et al. (1964) demonstrated that when embryos were incubated in a laboratory environment among glass beads, rather than on a porous plate such as that used by Silver et al. (1963), a given water volume per unit of time in experimental cells led to larger embryos at a given oxygen concentration, an effect especially pronounced when a mix of large and small beads was used. The clear inference is that true pore velocities were higher in the substrate mix, and that it is correct to conclude that velocities in pores in redds are higher than is reflected by apparent velocity determinations. Figures C.9 and C.10 for chinook salmon fry (Silver et al. 1963) duplicate the pattern of fry size and dissolved oxygen and water velocity found for steelhead.

As Mason (1969) later showed, any reduction in size at emergence has important effects on subsequent social success, hence survival, of post-emergent fry.

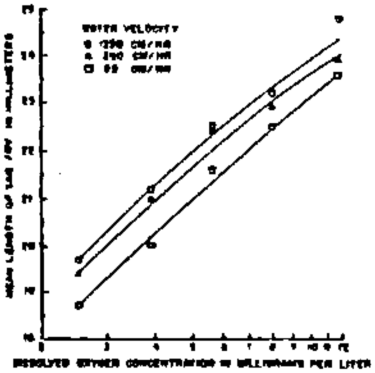


Figure C.9. (From Silver et al. 1963). Mean length of chinook salmon sac fry at hatching as a function of oxygen level at 11 C.

Effects on emergence itself will be discussed later in this review.

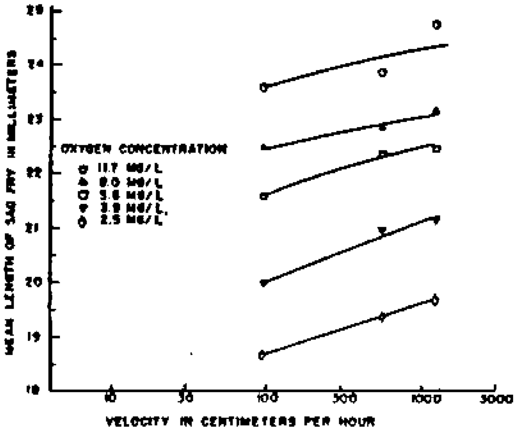


Figure C.10. (From Silver et al. 1963). Mean length of chinook salmon sac fry as a function of water velocity at 11 C.

Shumway et al. (1964) provided a three-dimensional model of the effects of dissolved oxygen and water velocity on size of fish at hatching (Figure C.11). They also modeled the effect of the two variables on hatching delay.

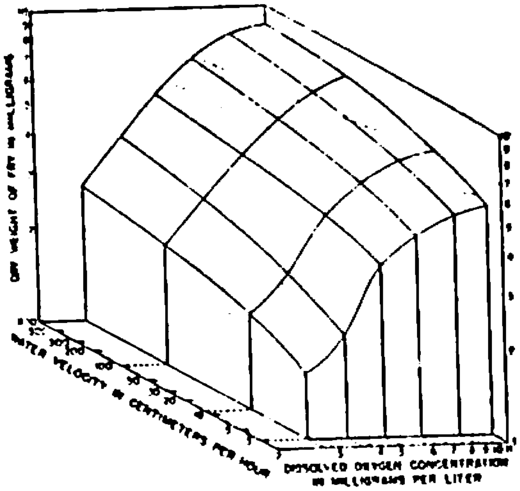


Figure C.11. (From Shumway et al. 1964). Model of influence of both dissolved oxygen and water velocity on size of fry at hatching.

McNeil (1969) discussed compensatory growth in alevins by noting that Brannon's (1965) studies of newly-hatched embryos incubated at 3, 6, and 12 mg O_2/l reported average wet weight of newly hatched alevins as 22, 30, and 42 mg for the respective dissolved oxygen levels. At absorption of yolk, fry from eggs exposed to 3 mg O_2/l were over 5 times their weight at hatch, fry from the 6 mg O_2/l history were 4 times weight at hatch, and fry from eggs provided with 12 mg O_2/l were 3 times their weight at hatching.

Coble (1961) demonstrated that embryo survival in steelhead was related to dissolved oxygen concentration in artificial redds constructed in a field environment, but found that apparent velocity and dissolved oxygen effects could not be separated.

Phillips and Campbell (1962) buried newly-fertilized steelhead and coho salmon ova in stainless steel perforated boxes in a glass bead medium; the boxes surrounded short standpipes that were buried in shovel-dug redds in tributaries of Drift Creek, an Alsea River drainage. Percent survival of steelhead to a time about 3 weeks after hatching was negligible where mean dissolved oxygen levels were below 7 mg/l (Figure C.12).

For coho, high survivals occurred above 8 mg/l (Figure C.13) and alevin size correlated with amount of dissolved oxygen. For steelhead, no relationship between alevin size and oxygen level was apparent. These authors concluded that oxygen requirements of incubating embryos were higher than had previously been suspected.

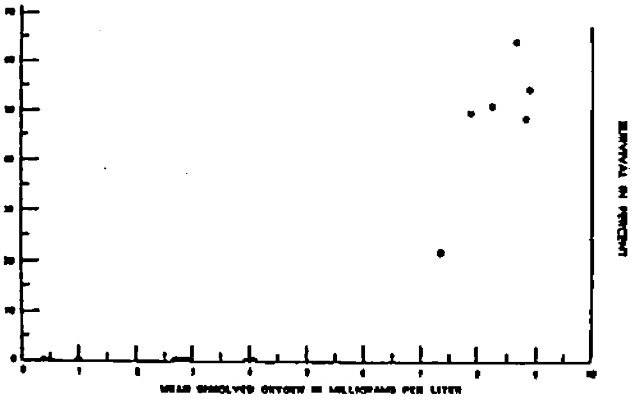


Figure C.12. (From Phillips and Campbell 1962). Survival of steelhead embryos in relation to dissolved oxygen levels.

Wells and McNeil (1970) noted that the largest and fastest developing embryos and alevins of pink salmon were found in Sashin Creek, Alaska, in spawning gravels with high levels of dissolved oxygen in intragravel water.

Koski (1975) showed that survivals of chum salmon to emergence were about one-third as high when embryos had been subjected to dissolved oxygen levels of less than 3 mg/l as compared

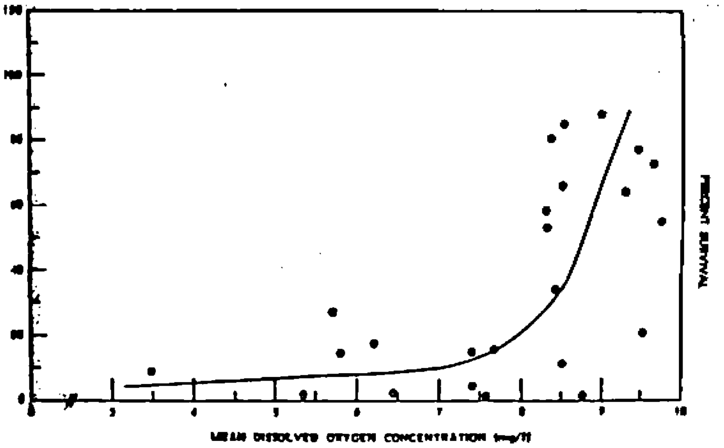


Figure C.13. (From Phillips and Campbell 1962). Survival of coho salmon embryos in relation to dissolved oxygen level.

to levels over 3 mg/l. Emergence was delayed in groups exposed to oxygen levels lower than 3 mg/l.

McNeil (1966) stated that oxygen requirements of embryos rises to a maximum just before hatching, and that larvae are more tolerant of low dissolved oxygen levels than are embryos. Hays et al. (1951) reported that the oxygen concentration that would limit metabolism of Atlantic salmon decreased after hatching. McNeil attributed this change to availability of vastly increased respiratory areas (gills) after hatching.

Sowden and Power (1985) found that survival of rainbow trout embryos in a groundwater-fed streambed depended upon mean dissolved oxygen content and velocity of groundwater in redds. Figures C.14 and C.15 demonstrate these relationships. Survival increased directly as oxygen content rose above 6 mg/l.

Mason (1969) exposed coho salmon embryos and alevins to dissolved oxygen levels of 11, 5, and 3 mg/l. Mortalities to time of yolk absorption amounted to 17, 23, and about 41% for these respective dissolved oxygen levels. Embryos subjected to

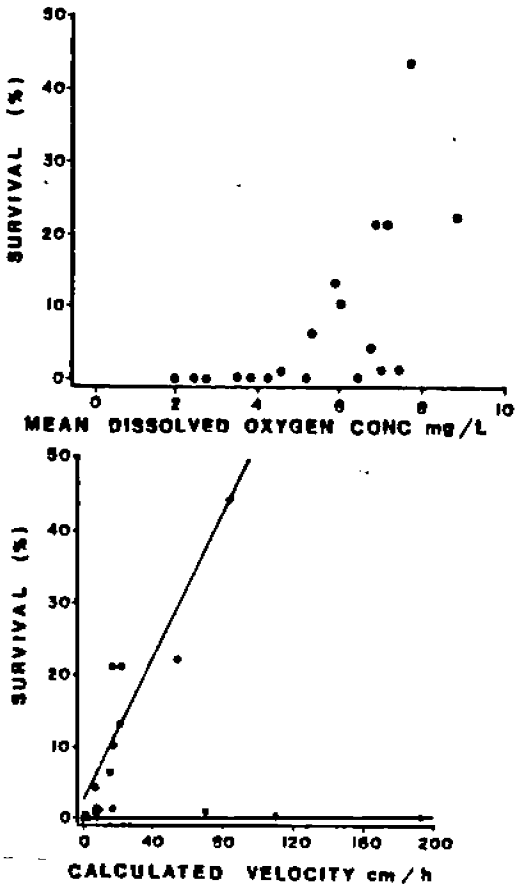


Figure C.14. (From Sowden and Power 1985). Relationship between percent survival of preemergent rainbow trout embryos and mean dissolved oxygen content (top graph) and apparent velocity (bottom graph) of groundwater in redds.

the lower oxygen levels were significantly smaller ($p < 0.01$) at hatching (22.9, 25.4, and 28.1 mm for the 3, 5, and 11 mg/l respective oxygen concentrations). Alevins that were subjected to 3 mg/l were about 33 mm long at yolk absorption, while alevins subjected to the higher oxygen levels were over 37 mm long.

Fry that had been exposed to the most severe hypoxial conditions were most prone to emigrate after emergence because of competition in the post-emergence period. Mason compensated for low dissolved oxygen levels by increasing temperatures so that fish would emerge from all 3 groups at the same time. Had he maintained all groups at the same temperature, the social disadvantage faced by fry with hypoxial histories would have been exacerbated because they would emerge later <u>and</u> smaller.

The key point in regard to Mason's study and the work of Silver et al. (1963) and Shumway et al. (1964) is that deprivation of dissolved oxygen leads to subtle problems not detectable in tests of survival in various oxygen levels. It appears incorrect to set critical oxygen levels at any arbitrary point, or to assume that survival to time of emergence is sufficient evidence of ecological success. In fact, any reduction in dissolved oxygen levels from saturation appears to reduce likelihood of survival to emergence or post-emergent survival for embryos.

Davis (1975) suggested three levels of protection against effects of low dissolved oxygen concentrations:

<u>Level A</u>: This level is 1 SD above the mean average incipient oxygen response level (incipient response is defined as a dissolved oxygen level at which sublethal response to hypoxia first becomes apparent) for the group. The rationale is that few members of a fish population, or fish community, will likely exhibit effects of low oxygen at or above this level. Level A represents more or less ideal conditions and permits little depression of oxygen from full saturation. It represents a level that assures a high degree of safety for very important fish stocks in prime areas.

<u>Level B</u>: This level represents the oxygen value where the average member of a species of a fish community starts to exhibit symptoms of oxygen distress. These values are derived from the class mean averages of incipient response. Some degree of risk to a portion of fish populations exists at this level if the oxygen minimum period is prolonged beyond a few hours.

<u>Level C</u>: At this level a large portion of a given fish population or fish community may be affected by low oxygen. This deleterious effect may be severe, especially if the oxygen minimum is prolonged beyond a very few hours. The values are 1 SD below the B Level, or class average, for the group. This level should be applied only if the fish populations in an area are judged hardy or of marginal significance, or of marginal economic importance and, as such, are dispensable (i.e. in the socioeconomic sense).

Davis notes that the use of standard deviations is based on the statistical concept that in normally-distributed data, about 68% of the values lie within plus or minus 1 SD of the mean. Thus, the recommended levels span the range of responses that include both sensitive and insensitive individuals, both within and between species. Davis prepared a table of oxygen criteria for various fish communities, using the foregoing protection levels at various temperatures (Table C.1).

C.4. Fines

One difficulty in relating percentages of fines to survival of embryos and alevins is absence of a common sieve standard for definition of "fines". Various workers have used sieve criteria of 0.83, 0.85, 1.0, 2.0, 3.0, 6.0 and 9.5 mm as limits of "fines" categories. Section A contains a lengthy description of efforts to unify gravel characterizations. In general, the information suggests that the greater is the proportion of fine sediments in redds, the lower will be survival.

Table C.1. (From Davis 1975).

Oxygen criteria based on percentage saturation values derived with three levels of protection as outlined in the text. PO_2's and values of mg O_2/liter were extracted from Table 9 and rounded off for use here. The values shown for milliliters O_2/liter were calculated from the values of milligrams O_2/liter in this table.

The criteria essential for protection of aquatic fish populations are expressed as percentage saturation values at various temperatures. They were derived from both PO_2 and mg O_2/liter values, as both oxygen tension and oxygen content are critical factors. At the lower temperatures, the percentage saturation value was determined using the PO_2 values essential for maintaining the necessary oxygen tension gradient between water and blood for proper gas exchange. Higher percentage saturation values are necessary at the higher temperatures to provide sufficient oxygen content to meet the requirements of respiration as defined by the mg O_2/liter values.

Percentage saturation values are defined as "oxygen minima" at each level of protection. Graphical presentation of the results is found in Fig. 19. The temperatures corresponding to the percentage saturation criteria are defined as "seasonal temperature maxima."

Group	Protection level	PO_2	ml O_2/liter	mg O_2/liter	% Satn. at C for criteria					
					0	5	10	15	20	25
Freshwater mixed fish population including salmonids	A	110	5.08	7.25	69	70	70	71	79	87
	B	85	3.68	5.25	54	54	54	57	54	63
	C	60	2.28	3.25	38	38	38	38	39	39
Freshwater mixed fish population with no salmonids	A	95	3.85	5.50	60	60	60	60	60	66
	B	75	2.80	4.00	47	47	47	47	47	48
	C	55	1.75	2.50	35	35	35	35	35	36
Freshwater salmonid population (including steelhead)	A	120	5.43	7.75	76	76	76	76	85	93
	B	90	4.20	6.00	57	57	57	59	65	72
	C	60	2.98	4.25	38	38	38	42	46	51
Salmonid larvae and mature eggs of salmonids	A	135	6.83	9.75	98	98	98	98	100	100
	B	120	5.60	8.00	76	76	76	79	87	95
	C	85	4.55	6.50	54	54	57	64	71	78
Marine, nonanadromous species*	A	140	6.13	8.75	88	88	95	100	100	100
	B	110	4.73	6.75	69	69	74	82	90	98
	C	80	3.15	4.50	50	51	51	55	60	65
Anadromous marine species, including salmonids*	A	160	6.30	9.00	100	100	100	100	100	100
	B	125	4.55	6.50	79	79	79	79	87	94
	C	90	2.80	4.00	57	57	57	57	57	58

*Percentage saturation calculations based on salinity of 28‰.

Tagart (1984) measured survival from egg deposition to fry emergence in 19 redds of naturally-spawning coho salmon in the Clearwater River in northwestern Washington. The range in survivals extended from 0.9 to 77.3%. Survival was directly related to intragravel permeability, and percentage of "good gravel" (defined as the fractional volume between 3.35 and 26.9 mm) (Figure C.15). Survival was inversely related to the percentage of "poor gravel" (particle volume under 0.85 mm). For 9 redds for which minimum and mean dissolved oxygens were available, Tagart (1984) showed that dissolved oxygen was inversely related to the percentage of fines under 0.85 mm in size. The reason for the relationship is not clear, but biochemical oxygen demand in the substrate may have reduced oxygen levels where permeability was low (high percentage of fines), or low permeability prevented interchange of oxygenated surface waters with intragravel water. It is important to remember in considering this point that fines were assessed by Tagart in redds rather than in egg pockets.

Tagart's relationship between survival and permeability in Figure C.15 is not a strong one because it depends so strongly on an extreme point for regression development. In a later section on predictors of survival, we provide a more robust development of the relationship between permeability and survival.

Tagart's data show survivals to emergence from redds with less than 20% fines as 31.9%, while that for groups with greater than 20% fines was 17.7%, a difference significant at $p = 0.05$. Trapping results have particular value because no management of gravel mix or stratification is involved when natural redds are sampled. However, as we note elsewhere, Tagart did not obtain his independent variables with reference to the egg pocket.

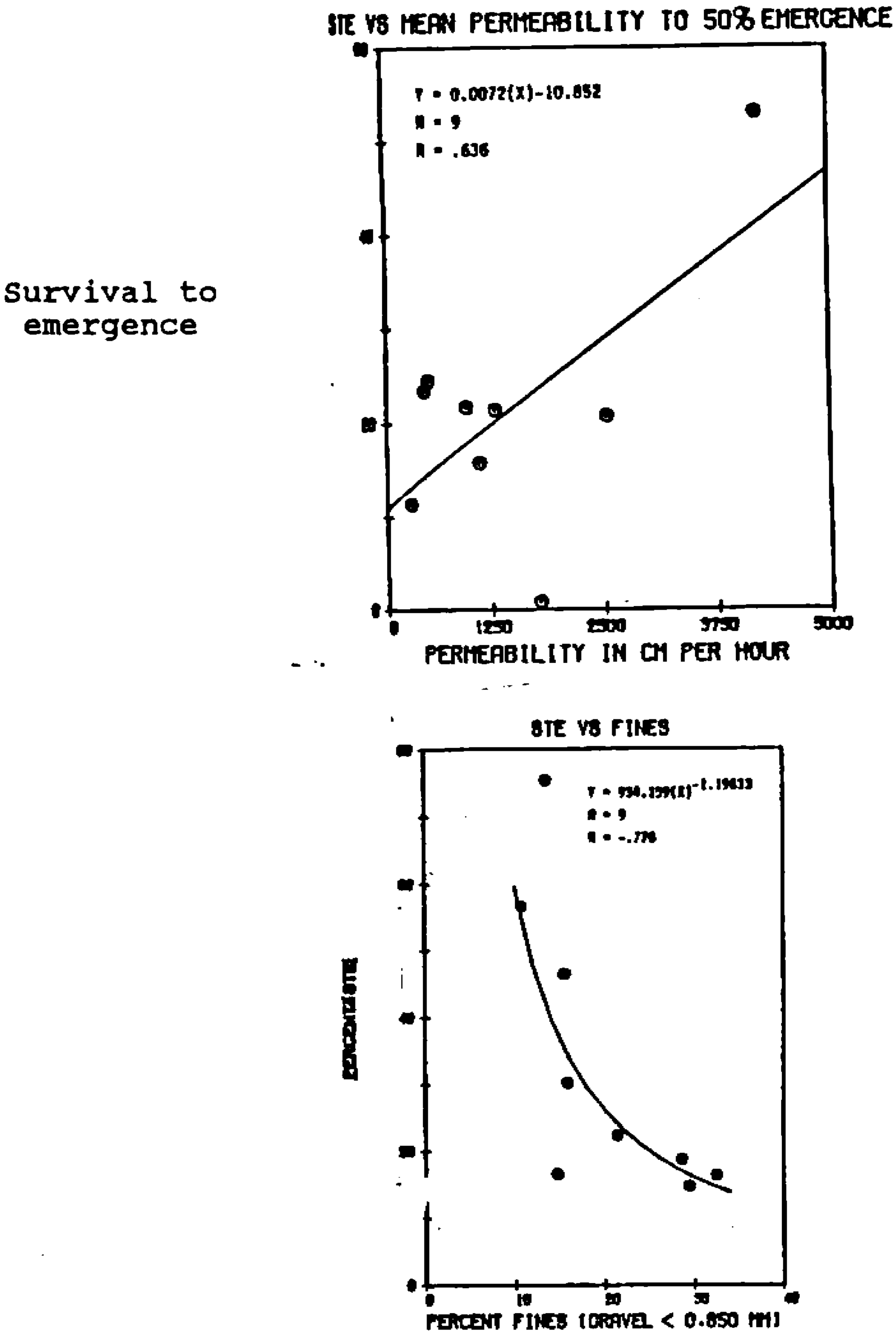


Figure C.15. (From Tagart 1984). Survival of coho salmon embryos to emergence in natural redds as a function of gravel permeability (top graph) and percent fines <0.85 mm (bottom graph).

Koski (1966) trapped fry emerging from 21 natural redds of coho salmon in three Oregon streams. Survival was generally related to a permeability index and loosely to minimum dissolved oxygen concentration. It was also inversely related to percentage of fines, the percentage of fines smaller than 3.3 mm having the highest correlation (Figure C.16.).

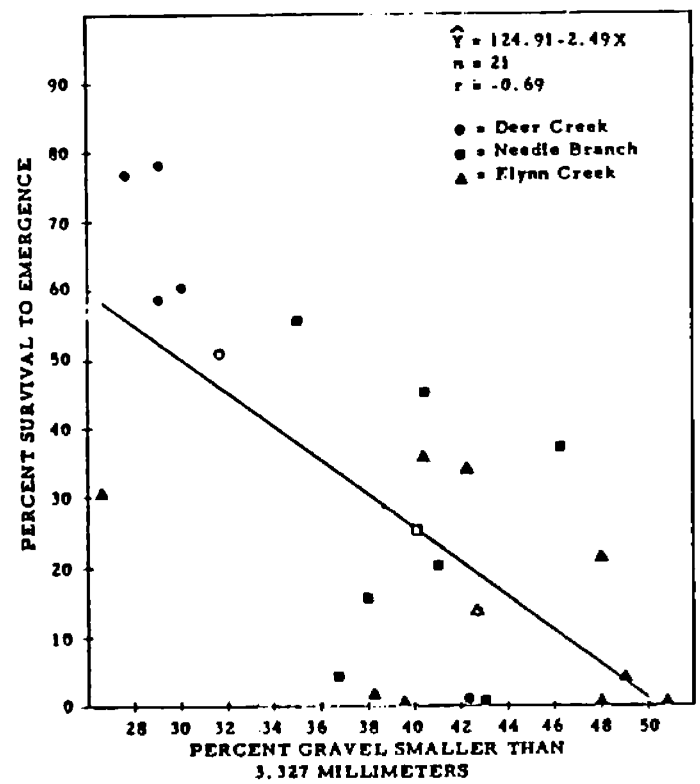


Figure C.16. (From Koski 1966). Survival to emergence in natural coho redds in relation to percentage of fines < 3.3 mm.

He found a similar relationship for chum salmon survival to emergence in gravels placed in a spawning channel in Washington (Figure C.17). However, Koski's data on chum salmon were taken from the channel cell in which fish spawned, not in the egg pocket. They should not be used for quantitative prediction of effect of fines on survival in the wild.

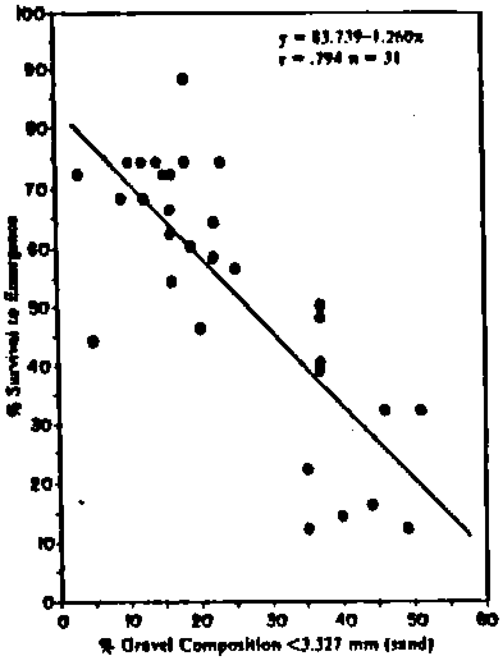


Figure C.17. (From Koski 1981). Percent survival of chum salmon embryos to emergence in relation to fines smaller than 3.3 mm.

Coho salmon survival from green egg to emergence was tested in artificial stream troughs by Cederholm and Salo (1979). The inverse relationship between percentage of fines smaller than 0.85 mm and survival (Figure C.18) is fairly strong. The mix and stratification of gravels in these experiments was chosen to provide an analog of actual conditions in various streams of the Clearwater basin, but "actual conditions" refers to spawning gravels; areas used by fish, and not to the egg pocket. Thus, the data can provide no quantitative predictor of survival except for the specific laboratory conditions that were studied.

Some readers may consider the foregoing concerns irrelevant, for they may not readily see how a gravel mixture in a trough, if based on data on gravel composition from spawning areas, would differ from a gravel mixture in a natural redd. The general maxim that "nothing is as simple as it seems" comes into play,

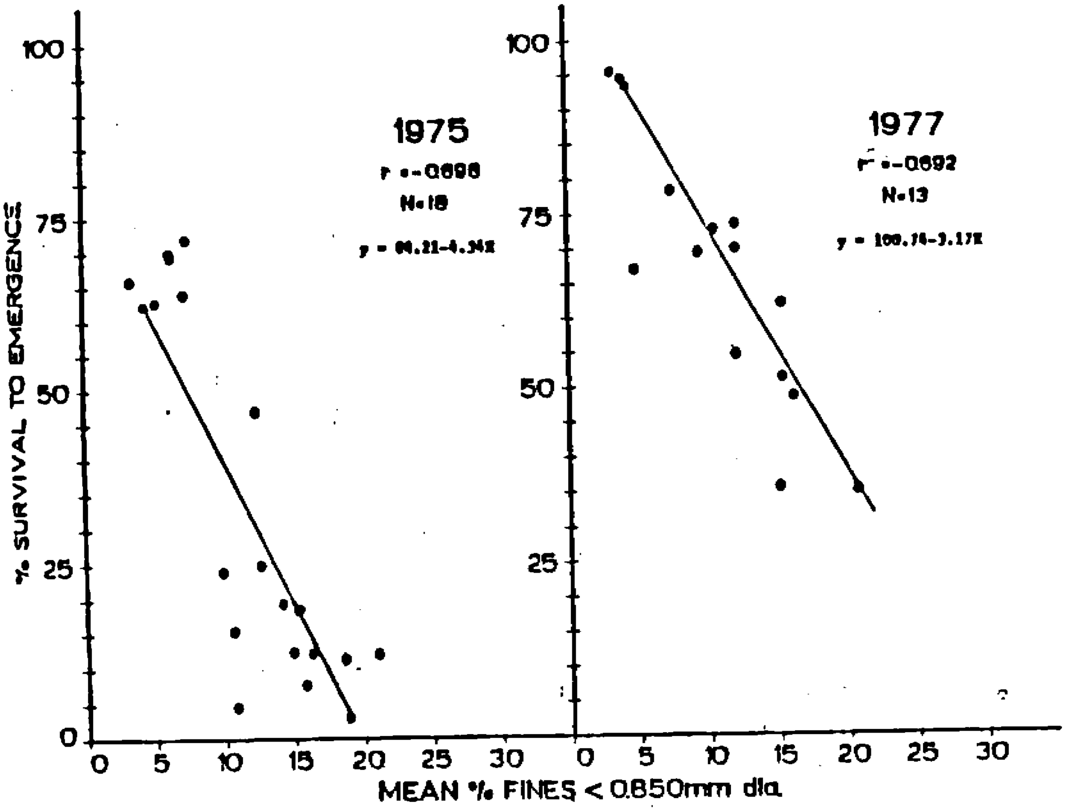


Figure C.18. (From Cederholm and Salo 1979). Coho salmon survival from green egg to emergence in gravel troughs in relation to percent fines smaller than 0.85 mm.

for the way in which the gravel matrix lies in the redd affects emergence success. This problem is addressed earlier in the review with regard to the work of Tappel and Bjornn (1983), and later in reference to Irving and Bjornn (1984), and in numerous references to failure of tools to accurately sample the makeup of the egg pocket.

Peterson and Metcalfe (1981) measured emergence of Atlantic salmon eggs that had incubated in various gravel and sand mixtures and two directions of water current. Fine sand (0.06-0.5 mm) was more effective than coarse sand (0.5-2.2 mm) in reducing emergence success. Strong upwelling water current in the gravel bed mitigated effects of sand (reduced porosity, hence permeability) to some degree, and induced earlier fry emergence. These workers showed that where the percentage of fine sand rose above about 12%, survival declined sharply. Where the percent of coarse sand rose above about 22%, emergence dropped sharply. The gravel mix used by Peterson and Metcalfe had a high ratio of small:medium gravels (particles 22-62 mm had a ratio to medium and fine gravels of 2.3-22 mm of about 5:3), a mix similar to that found in natural spawning areas for Atlantic salmon, but not normal for western streams used by Pacific salmon and steelhead.

MacCrimmon and Gots (1986) investigated the effects of fines <4 mm on survival of rainbow trout from eyed egg to emergence. Survivals were 51-74% in gravels with 40-100% fines, although fines led to earlier emergence of smaller alevins. It appears that alevins responded to a high percentage of fines by exiting the substrate early, independent of dissolved oxygen levels. Survivals equaled 87-92% in 0-20% fines. This work was completed in incubation cells that had vertical water movement adjusted to 130 ml/min regardless of substrate composition. This means that actual pore velocities were increased in fines.

McCuddin (1977) tested ability of chinook salmon and steelhead to survive and emerge in troughs of various gravel-sand mixtures that were designed to simulate natural spawning areas. Survival decreased as the proportion of sand in the substrate increased (Figure C.19) above 10-20%. For tests with newly-fertilized eggs placed in the substrate, any percentage of 6-12 mm particles above about 10-15% appeared to reduce survival. Any percentage of fines (< 6 mm) above about 20-25% reduced survivals.

Fines appeared in McCuddin's work to interfere more with emergence than with incubation, as dissolved oxygen levels in the channel remained above 9 ppm and no relationship was found between fines and length, weight, or time of emergence of fry. Typicality of the gravel beds in artificial channels is always an issue, and in McCuddin's work the egg pocket structure did not appear typical of a natural redd. The effect of this on his results is uncertain.

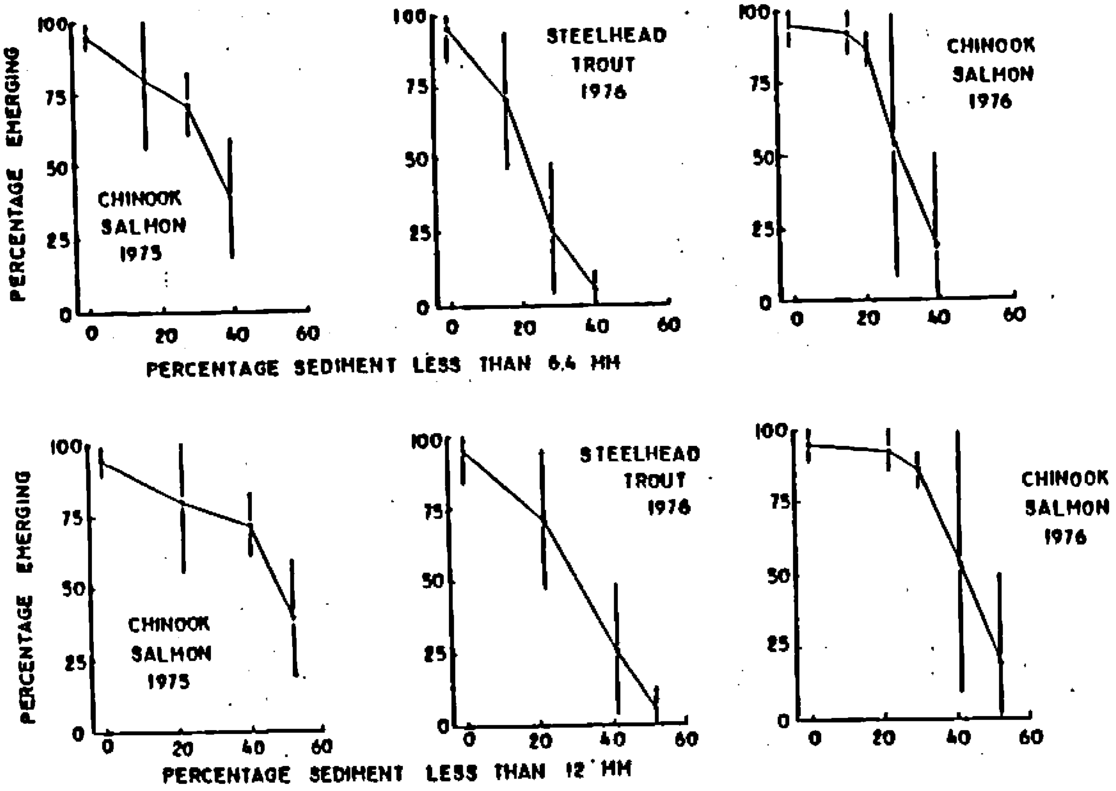


Figure C.19. (From McCuddin 1977). Percent emergence of chinook salmon and steelhead in relation to percentage of fines < 6.4 mm (top 3 graphs) and < 12 mm (bottom 3 graphs).

The percentage of survival of bull trout from fertilized eggs to emergence was measured in fiberglass screen bags in artificial redds (Shepard et al. 1984). Open bags were used in part of the work and emergence traps placed over the redds. Survival to emergence was negatively correlated with percent fines (< 6.4 mm) (Figure C.20).

NCASI (1984b) studied the survival of rainbow trout embryos to emergence (Figure C.21). This work showed that survival was inversely related to percentage of fines smaller than 0.8 mm. For each percent increase in fines over the range of 10-30%,

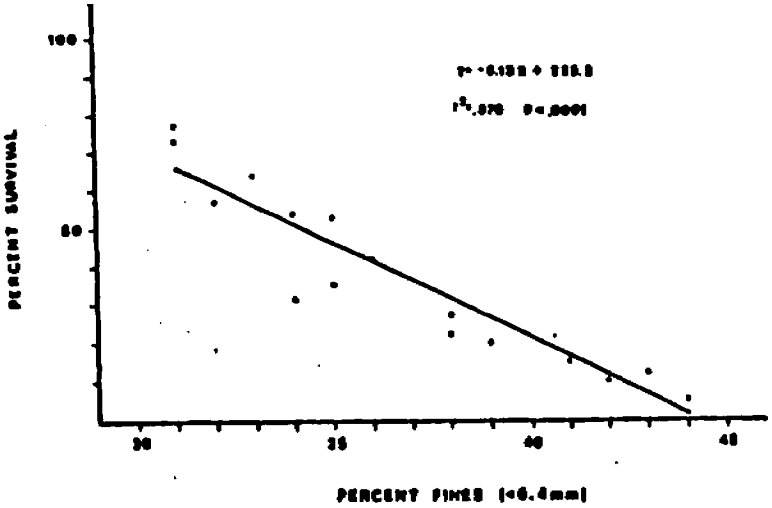


Figure C.20. (From Shepard et al. 1984). Survival of bull trout to emergence in relation to percent fines < 6.4 mm.

survival declined 1.3%. In a second study, each percent increase over the range 10-40% decreased survival 1.1%. The work also found a significant negative relationship between survival and percentage of fines smaller than 6.4 mm. The authors stated that failure to emerge was probably associated with physical entrapment, as the dissolved oxygen content of the intragravel water at any gravel mix was similar. No information on apparent velocities was obtained.

The high survival (near 90%) at 20% fines (< 6.4 mm) is of interest. The authors felt that these particles prevented smaller fines and organic debris from entering the incubation environments. This bridging effect would also occur in the egg pocket. We infer, from this and other information, that some fines aid survival, and that the particular mix and stratification in the egg pocket governs emergence success.

Where the substrate is supplied with groundwater instead of surface waters, the relationship between fines and survival would be an unsatisfactory predictor of survival. Sowden and Power (1985) reported that survival of rainbow trout was not significantly related to the percentage of sediments smaller than 2.0 mm, to d_g, or to the fredle index of substrate quality. Rather, it was strongly related to dissolved oxygen level and water

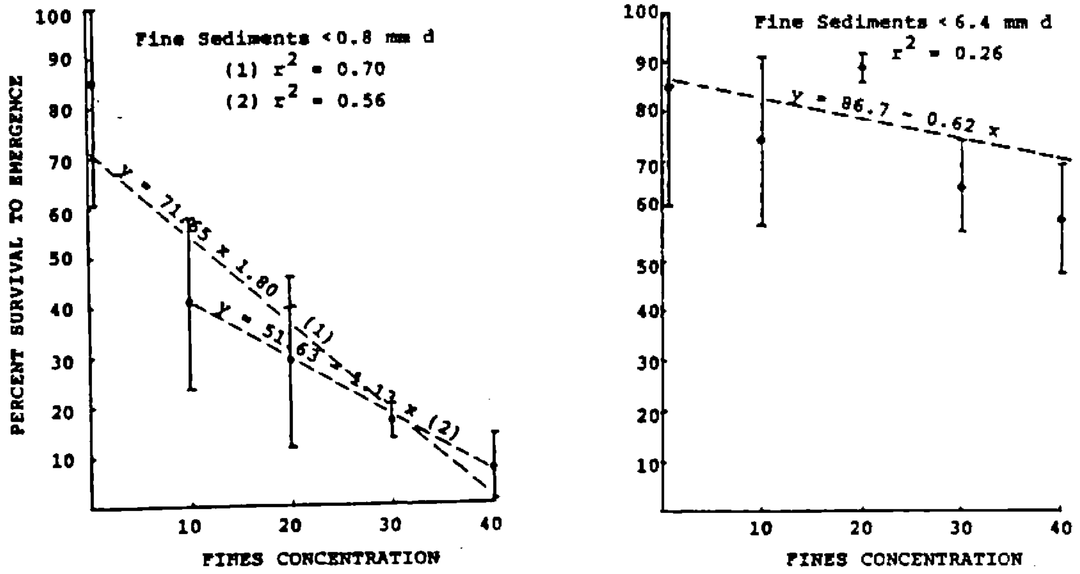


Figure C.21. (From NCASI 1984b). Survival of rainbow trout embryos and alevins to emergence in various mixes of gravel in relation to fines of < 0.8 mm (left graph) and < 6.4 mm (right graph.

velocity, with oxygen content determined by groundwater conditions rather than by factors causing biological oxygen demand within the redd. Sowden and Power measured survival to the sac-fry stage, not to emergence. They note that further studies that take survival to emergence would be desirable, but urge cautious application of survival models based on substrate particle sizes. Their omission of the period from sac-fry to emergence makes it impossible to draw conclusions about effects of fines on survival.

The extensive studies by Tappel and Bjornn (1983) as described earlier are pertinent in review of effects of fines, but will not be re-summarized here. Irving and Bjornn (1984) extended the laboratory techniques that Tappel and Bjornn used for study of chinook salmon and steelhead survival in various gravel mixes to investigation of survival of kokanee salmon and cutthroat and rainbow trout. Figure C.22 depicts their data on survival in relation to the percentage of fines smaller than 6.35 mm, together with those of Tappel and Bjornn (1983). These workers also prepared isoline graphs for 0-80% survival in

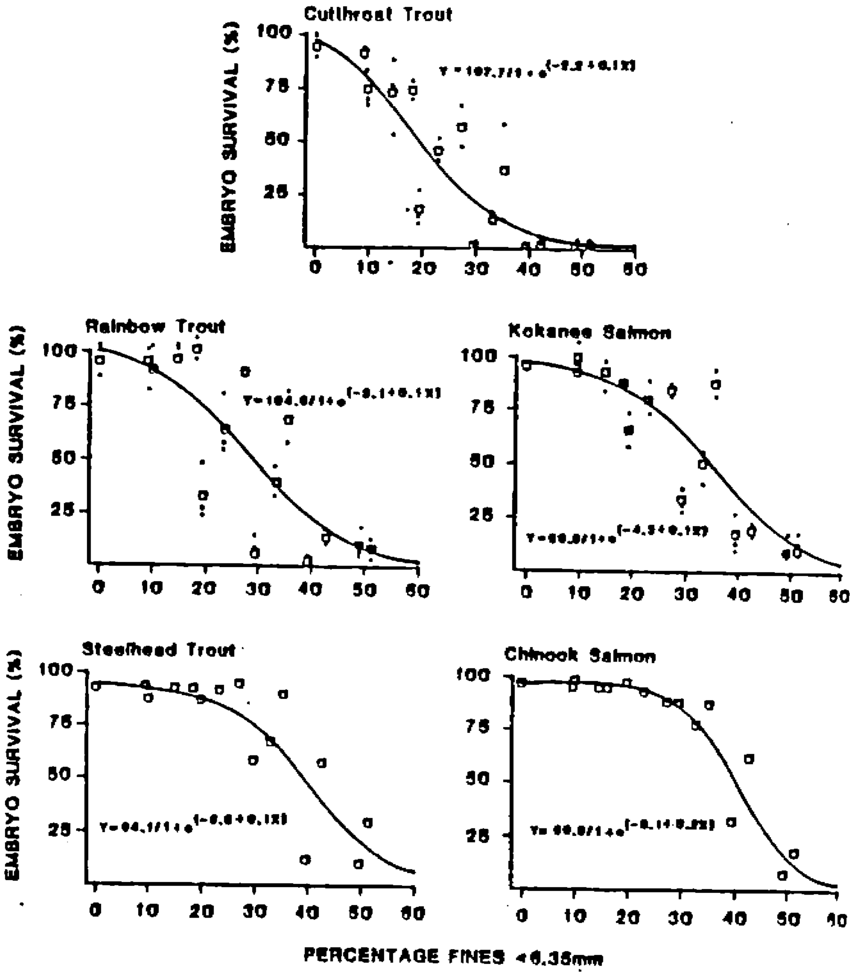


Figure C.22. (From Irving and Bjornn 1984). Embryo survival as a function of percentage of fines smaller than 6.35 mm in laboratory troughs and gravel mixes.

relation to percentage of fines smaller than 9.5 and 0.85 mm (Figure C.23).

The data of Irving and Bjornn, taken at face value, tend to demonstrate that tolerance of higher percentages of fines (< 0.85 and < 6.35 mm) as depicted in figures C.22 and C.23 is lower for cutthroat and rainbow trout and kokanee salmon than for chinook salmon. Irving and Bjornn state that "rainbow and cutthroat trout and kokanee salmon tolerated gravels with more fine particles than chinook salmon studied by Tappel and Bjornn (1983)." In making this statement, they refer to a table of coefficients of determination (r^2) of survival as a function of

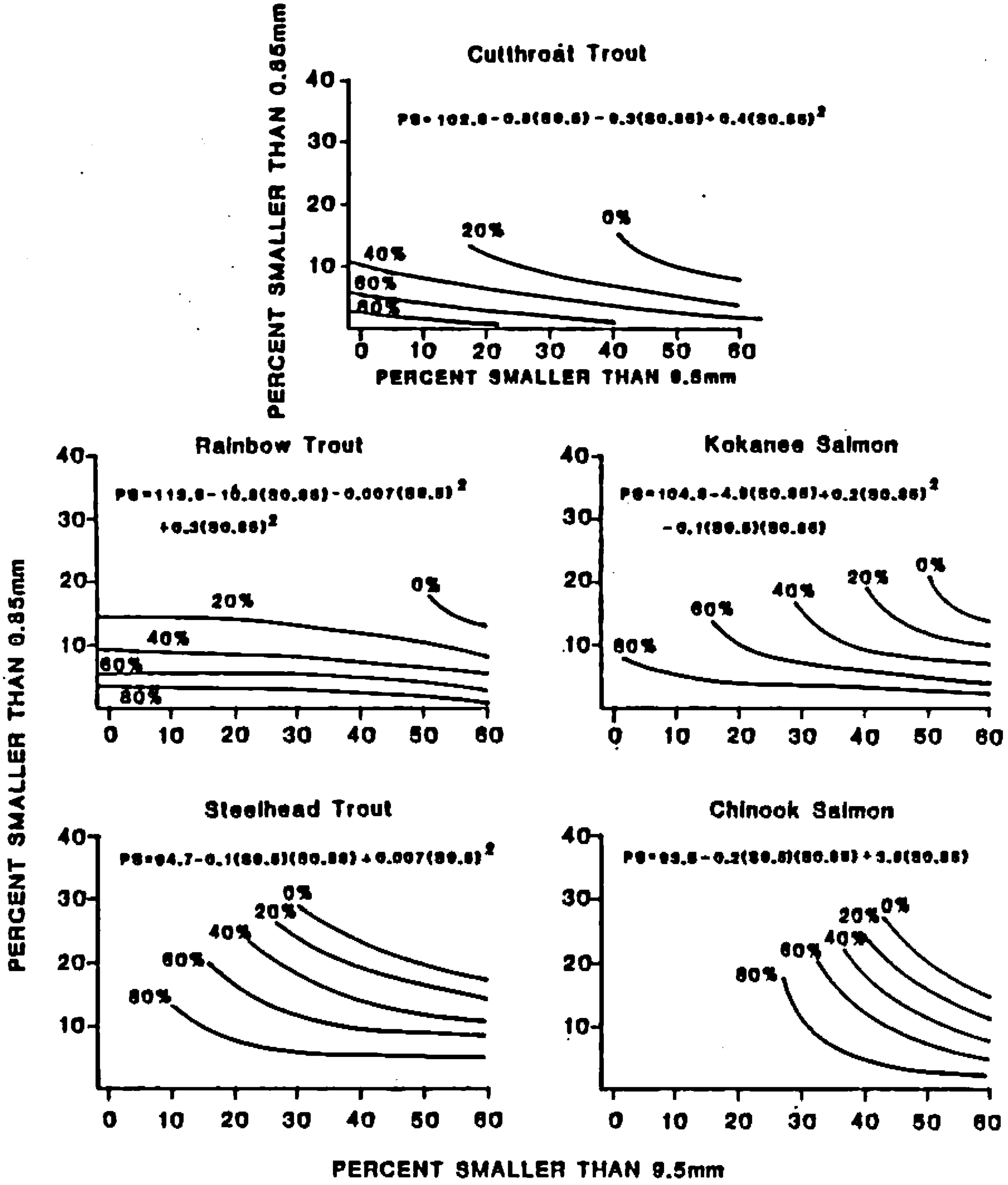


Figure C.23. (From Irving and Bjornn 1984). Isolines of predicted survival of embryos to emergence in relation to percentage of particles smaller than 9.5 and 0.85% in laboratory troughs and gravel mixes.

various particle sizes for support of their statement. In fact, r^2 values describe the fit of data to regressions, not the slope, and thus cannot be used in support.

More importantly, why should chinook salmon have a higher tolerance to fines than cutthroat trout, kokanee salmon, rainbow trout, or steelhead (figures C.22 and C.23) in laboratory mixes of gravels? The answer probably lies partly with embryo size and alevin strength. Laboratory mixes of gravels are not packed tightly by substrate shifts or intrusion of additional sediments during the incubation process. The relatively large chinook salmon alevins may butt their way to the surface more successfully in these mixes.

The answer more clearly lies with depth of burial of embryos in the laboratory channels. The channel diagram provided by Irving and Bjornn indicates a burial depth of about 20 cm (8 in) for embryos, rather deeper than burial depths in natural redds for small trout and kokanee salmon, but less than the depth of chinook salmon egg pockets. In fact, the data used by Irving and Bjornn (1984) for chinook salmon were obtained from Tappel and Bjornn (1983), who stated that chinook salmon in Vibert boxes were actually placed at a depth of about 15-20 cm. But Tappel and Bjornn provided a diagram of the experimental apparatus that they used, which showed that the total depth of gravels in the trough ranged from 15 to 20 cm and the center of the Vibert boxes lay at about 12-15 cm below the gravel surface. The depth at which alevins first encountered the experimental gravel mixes lay approximately at the top of the Vibert boxes. Whether embryos were actually at 15-20 cm or 12-15 cm, these depths are considerably less than the depths from which chinook salmon and steelhead alevins must emerge in natural egg pockets. The relationships shown in figures C.22 and C.23 are consistent with this explanation.

The point of the foregoing comments is that the conditions imposed in laboratory research will determine results. It is inappropriate to extrapolate such information to field conditions. One cannot quantitatively estimate survival of chinook salmon and steelhead in the field based on gravel composition through use of laboratory data, for example, as did Stowell et al. (1983) and Talbert (1985).

The graphs provided by Tappel and Bjornn (1983) and Irving and Bjornn (1984) may tempt the reader to extrapolate laboratory data to the field, yet these authors noted "---predictions of embryo survival generated by the equations may be inaccurate when applied to field conditions" (Tappel and Bjornn 1983), and "Embryo survival in natural stream (sic) may nor may not match the rates presented in these papers" (Irving and Bjornn 1984).

Tappel and Bjornn (1983) and Irving and Bjornn (1984) suggest that the greatest applicability of their model functions is in predicting the relative change in embryo survival rates that may occur if changes occur in the spawning and incubation substrate. We submit that the greatest applicability of their laboratory data, however elegant the laboratory approach and resultant data, is to conditions in the laboratory. It is incorrect to assume, for example, that a 10% incremental increase in particles smaller than 0.85 mm will result in a predictable decline in embryo survival of a given salmonid in a field environment, as is implied by these authors and by others who assume that laboratory data can be quantitatatively applied to the field. We explain why in several places in our report, but draw the attention of the reader particularly to the section on predictive tools for assessing the effects of fine sediments in the field.

Everest et al. (1981) also criticized laboratory studies of effects of intragravel conditions on survival to emergence because they are not useful in predicting survival to emergence in the field. Gravel mixes used in the laboratory bear little resemblance to particle size composition within the vertical zones of egg pockets found in nature, and planting of eyed eggs at uniform depth is not representative of nature, according to these workers. They concluded that only vertical subsampling of gravel cores from natural environments will show the actual conditions that fry must face during emergence.

We point out, however, that embryos are usually found at the lower portion of the egg pocket in nature in a very limited vertical zone, making the criticism of <u>uniform</u> burial depth moot. More critical is the fact that laboratory studies fail to duplicate egg pocket structure, and merely place a thoroughly-mixed substrate matrix in a study "cell". This point is discussed further in the next section.

It is appropriate to treat laboratory studies of embryo survival as models useful in assessing mechanistic responses rather than as exact analogs of nature that permit accurate assessment of quantitative biological response.

D. EMERGENCE FROM GRAVELS

D.1. Entrapment by fines

White (1942) reported that where Atlantic salmon incubated in areas with high quantities of sand, 80% of the eggs were dead and 20% of the complement could not emerge through the compact sand layer. White found entombed fry even in redds where emergence had occurred.

Koski (1966) excavated in known redds of coho salmon that had been surrounded with netting to assess emergence success. He found one redd in which 260 emaciated dead fry were present several inches below the surface of the gravel. No data on gravel composition are available for that redd.

Phillips et al. (1975) followed Koski's observation of entombed fry by examining effects of fines on emergence success. They prepared 8 mixtures of sand and gravel, then inserted coho and steelhead fry into the substrate through a vertical standpipe arrangement. Emergence success declined (from near 100%) above about 10% fines (1-3 mm) for steelhead and coho. Presence of 20% fines reduced emergence success about 60-70% (Figure D.1).

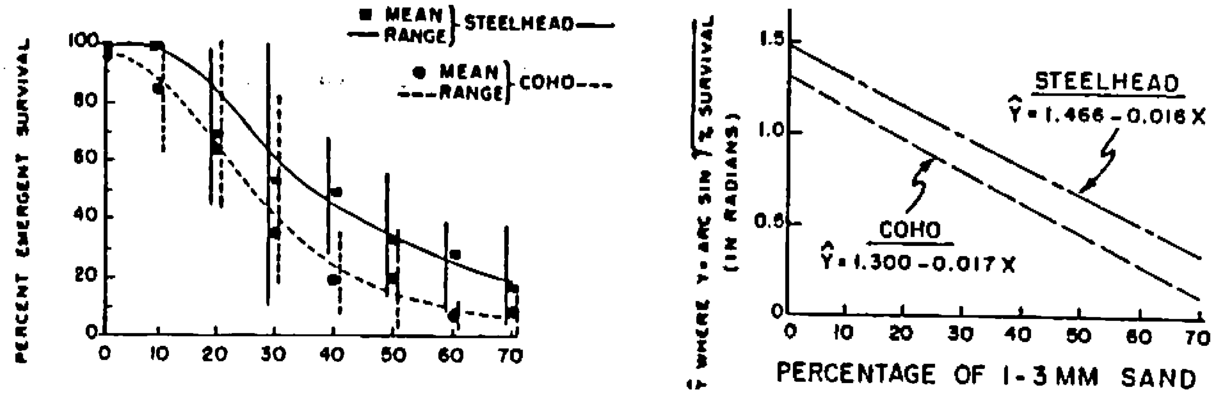


Figure D.1. (From Phillips et al. 1975). Survival to emergence of steelhead and coho salmon from gravels with various percentages of sand 1-3 mm.

The amount of fines (< 3.3 mm) in spawning gravels used by coho salmon in unlogged Oregon watersheds varied from 27 to 55% (Koski 1966 and Moring and Lantz 1974). The implication that one might draw, using laboratory studies of survival to emergence in various gravel mixes (Phillips et al. 1975), could be that survivals of coho salmon and steelhead from pre-emergent state to emergence would be 25-50% in undisturbed environments. The incremental effects of incubation from deposition to pre-emergent state would be subtracted from these percentages. However, the data of Phillips et al. (1975) only illustrate that emergence success declined in the laboratory mixes of gravel that contained high percentages of fines. They do not permit quantitative predictions in field situations, partly because no information is available for the egg-to-alevin stage and partly because fines in "spawning gravels" cannot safely be used as an indicator of conditions in egg pockets, or even in "redds".

Data from natural redds as reported by Koski (1966) and Tagart (1984) support a mean survival from deposition to emergence of about 27 and 30%, respectively, in undisturbed (Alsea watershed) and partially-logged (Clearwater River, Washington) drainages. We use these data extensively as examples in the report section on predictive tools.

Bjornn (1969) studied survival and emergence of steelhead trout and chinook salmon in gravels with various amounts of granitic sands in troughs. Steelhead emerged with undiminished success (about 50%, calculated from green egg placement) in gravels with percentages of sand (< 6 mm) as high as 20% (Figure D.2). Chinook emergence success was undiminished (about 70-75%, from green eggs to emergence) until sands exceeded about 10-15%.(Figure D.2). "Control" survivals were adjusted upward by Bjornn to about 90% for both species because of variables unrelated to fines, but without effect on the trends in survival

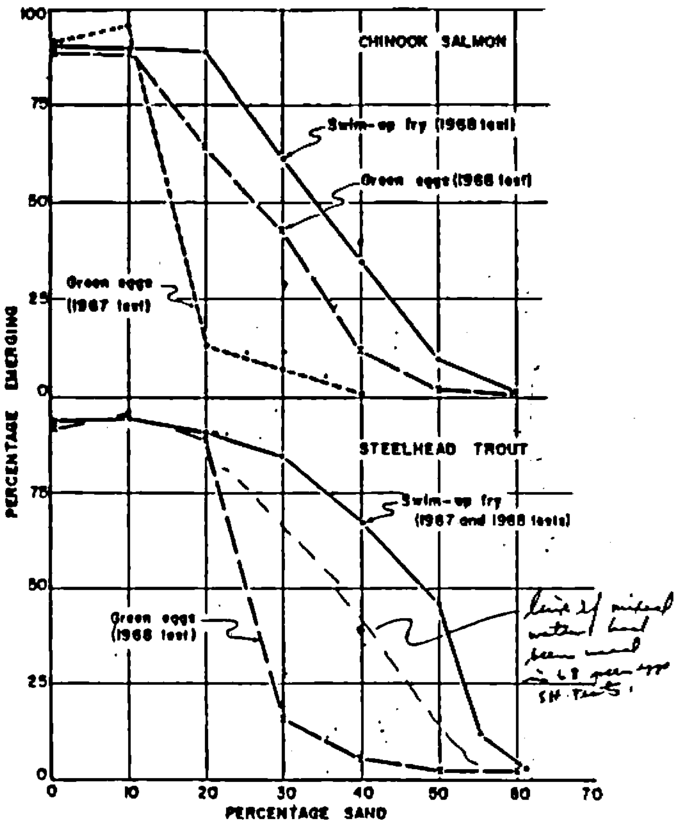


Figure D.2. (From Bjornn 1969). Percent survival of steelhead and chinook salmon to emergence from various mixes of sand.

after given percentages of sand were reached in tests.

NCASI (1984b) reported significant negative relationships between survival and percentages of fines smaller than 0.8 mm in test mixes of gravels, probably because of interference of sands with emergence, inasmuch as dissolved oxygen content did not differ in various mixes of sand.

The remarks in the previous section concerning application of laboratory data to field situations pertain in reference to the laboratory data of Bjornn (1969) and NCASI (1984b). The data demonstrate that emergence success declines in gravels with a high percentage of fines. They do not permit prediction of emergence in natural redds from knowledge of percentage of fines in "spawning gravels" or "redds" and survivals in laboratory situations.

As a further commentary on the criticisms of Everest et al. (1981) of laboratory studies, it should be noted that use of an "emergence box" such as a Vibert perforated container that permits fish to leave through holes, may slightly vitiate criticism of unrealistic gravel mixes by providing a simulated egg pocket. The word "may" is required because even a Vibert box cannot provide a correct analog of the egg pocket structure and attendant bridging of fines in the pocket centrum and higher in the pocket.

The reason the egg pocket is important in simulation exercises is that it tends to be structured toward large particles while upper redd portions tend to have more fines. This means that emerging alevins begin moving vertically from an area that in theory should have more pore space. Dr. W. Platts reported that a chinook salmon redd component, removed intact with multiple freeze probes, had what appeared to be "tunnels" through the egg pocket (W. Platts, personal communication).

Movement upward by alevins, as reported by Bams (1969), promotes dropping of fines into the deeper pores. It is very likely that this gradation is an important component of intragravel ecology. Clearly, exceptions to the gradation will occur, especially where very fine particles are added to a cleansed substrate (Adams and Beschta 1982). In geographic areas where sands make up the bulk of the fines, gradation and bridging are very likely to be important.

D.2. Effects of fines on size of emergent fry

The effect of fine sediments on size of emergent fry has been reported by several workers. Tappel and Bjornn (1983) found that size of steelhead fry that emerged from gravels with low percentages of fines slightly exceeded that of fry from gravels with high percentages of fines, but size of chinook salmon fry varied little through the range of experimental gravel mixtures. The effect of different incubation histories (steelhead were placed in gravels as newly-fertilized ova while chinook salmon were placed in gravels as eyed embryos) is unknown. The observations of Tappel and Bjornn on effect of fines on emergent fry size should be considered in light of the shallow depth of burial of chinook salmon embryos in the laboratory mixes of gravel. Had the chinook salmon been forced to emerge through 25-30 cm, the results might have been quite different.

Inasmuch as gravels with high percentages of fines and low permeability tend to have low dissolved oxygen levels, embryo development is slower. Hence size of emergent fry would be reduced, with the potential subsequent ecological disadvantages noted by Mason (1969).

Phillips et al. (1975) reported that coho salmon fry that emerged from high percentages of sand were smaller than those from gravels with low percentages, but that steelhead fry were similar in size after emergence. Koski (1966) found that coho salmon size at emergence directly related to permeability of the substrate (Figure D.3). In a study of intragravel ecology of chum salmon, Koski (1981) showed that fish emerging from gravels with high proportions of sand were smaller. He attributed this to restriction by sand of size of fish that could physically emerge.

Hausle and Coble (1976) were unable to find a relationship between percentages of sand and size of emerging brook trout, but the sand mixes ranged from 0 to 25% and overall survivals from hatching to emergence averaged 70% Absence of high percentages of sand probably prevented definition of a size-related effect. NCASI (1984b) also found no effect of fines on size of emerging rainbow trout. We cannot ascertain the reason for this in their report.

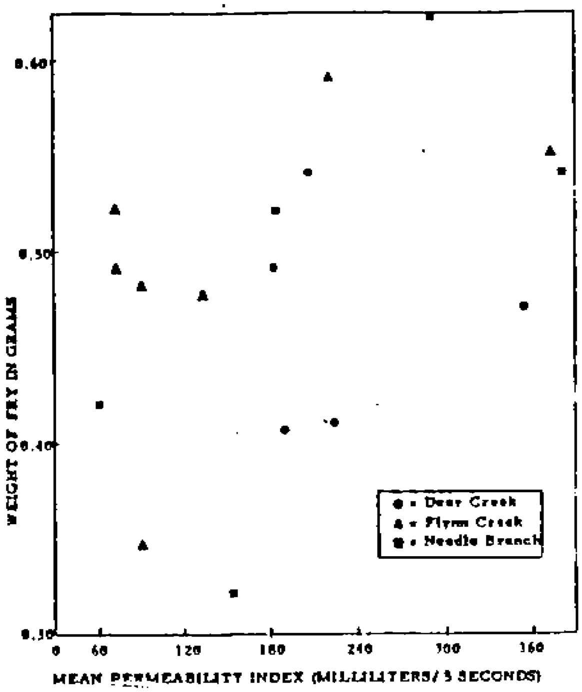


Figure D.3. (From Koski 1966). Mean weight of emergent coho fry from natural redds in relation to the mean gravel permeability index in the redd.

McCuddin (1977) stated that he found no relationship between fines and size of emerging chinook salmon or steelhead, although survival was related to percentage of fines. McCuddin's laboratory procedures involved placement of fry in a horizontal pipe section 25 cm long and 10 cm in diameter. Numerous 1 cm holes were drilled in the pipe section. His diagrams indicate that the horizontal pipe lay on the bottom of his experimental troughs, and he states that his troughs contained 25 cm of gravel. A vertical standpipe, connected to the horizontal pipe, permitted gentle introduction of alevins to the horizontal emergence chamber, to which the fish were then confined by a foam rubber stopper. Introduced fry could emerge by passing through the 1 cm holes or out the open ends of the horizontal pipe. The top of the horizontal pipe cylinder lay only 15 cm below the gravel surface. McCuddin placed newly-fertilized eggs 21 cm beneath the gravel surface (in gravel without the horizontal pipe), and later introduced swim-up alevins to horizontal pipe chambers. He then compared survival to emergence of swim-up fry and newly fertilized eggs, and drew several conclusions regarding effects of fines on emergence. One of these was that emergence success of swim-up fry was greater than had been reported by other workers. He compared emergence success of fish that passed upward through 21 cm of gravel matrix with that of fish that emerged through as little as 15 cm of matrix in his systems. The latter group initiated upward movement from an open cylinder with a volume of 1.96 liters (probably reduced somewhat by spill-in of gravels into the ends of the pipes).

Tagart (1984) reported a strong inverse correlation between percentage of fines and mean length of fry emerging from natural redds. He also found a positive correlation between dissolved oxygen concentration in redds and fry length at emergence, and a negative relationship between percentage of fines and dissolved oxygen. The relative effects of these variables are unknown. In the sense of empirical effect, it is unimportant whether low dissolved oxygen or impeded emergence reduced size and survival. In terms of improved understanding of intragravel ecology, however, such distinctions are of obvious importance.

Smaller fry, bearing a substantial yolk sac, may move through small substrate particles more easily than larger fry. The egg sac is malleable, and may almost "ooze" through pore constrictions. Dill and Northcote (1970) investigated intragravel movements of coho salmon, showing both vertical and lateral movement, but the gravel sizes used in their study were too large (1.9-6.3 cm) to permit inference about normal substrata with fines. Bams (1969) suggested that presence of large quantities of fines may stress embryos and lead to premature emergence.

Inasmuch as embryo and alevin size tends to be related to adult female size and to species, some of the conflicting results on effects of fines on emergence size is probably a function of female size. In other words, given the same mix of fines, one would expect that rainbow trout fry would better be able to exit the gravel than would chinook salmon fry. Corrections for species differences in embryo size were incorporated by Shirazi et al. (1981) (Figure II.A.3).

MacCrimmon and Gots (1986) investigated effects of various sediment mixes on emergence success and size of rainbow trout alevins. They found a strong positive relationship between alevin size (weight and length) at emergence and the geometric mean particle size. The mixes with high proportions of fines led to much earlier emergence of fry that did not have fully absorbed egg sacs. We are unable to determine why NCASI (1984b) and MacCrimmon and Gots (1986) obtained contradictory results, but the reason may involve gravel types and percentages of various particle sizes, which interacted with percentages of fines.

D.3. Effects of fines on emergence timing

Bams (1969) described the emergence-oriented behavior of sockeye salmon fry as swimming motions upward, presumably oriented to gravitational force. Normal emergence movements are slow and appear restrained, with long periods of rest between movements. However, in favorable substrata, movements of 5 cm per minute were frequently recorded. Bams described the field of movement of fish released from a given point as an inverted cone with a vertical axis. Fry can drop backward or pull themselves backward by flexion and a pulling action provided by tail purchase.

Bams reported that when fish confronted a sand barrier near the surface of an experimental gravel bed, they "butted" upward with repeated short thrusts. This action loosened the sand grains, which fell down and past the butting fish, forming an open passage as the fish worked upward. This behavior can be related to descriptions in Section B.1 of redd structure and bridging of fines. Bridging within the egg pocket may be breached by butting behavior.

Koski (1966) reported mean length of the emergence period in coho redds was 30-39 days, and that 90% of fry emerged from redds in 15-20 days. The number of days to first emergence was inversely but loosely related to the amount of fines smaller than 3.3 mm in redds of coho salmon (Figure D.4). The total period of emergence was greatest for redds with highest percentages of fines.

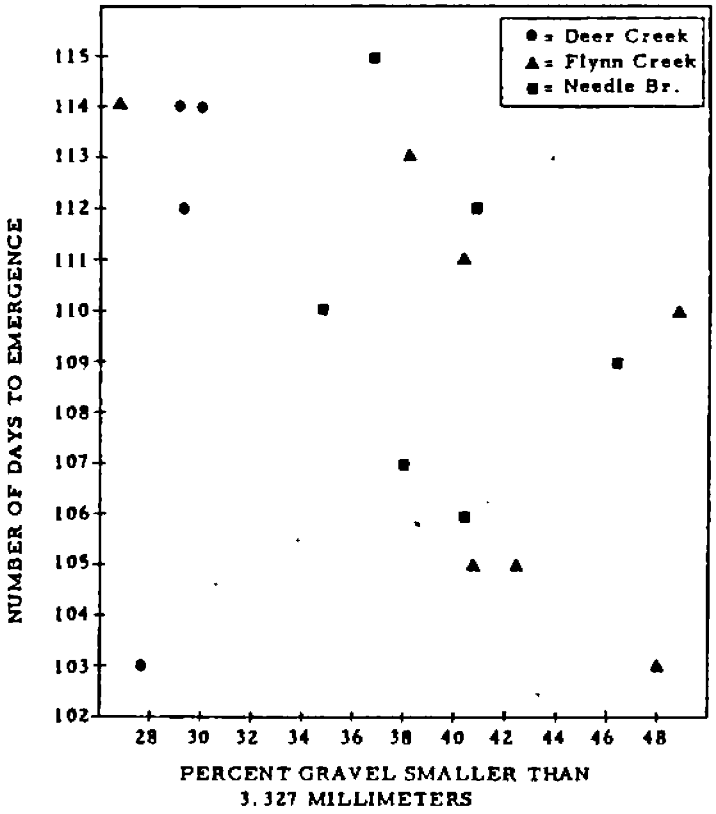


Figure D.4. (From Koski 1966). First emergence of coho fry from natural redds in relation to gravel composition.

For chum salmon, Koski (1975) noted that the number of temperature units required for the first 5% of emerging fry to reach the surface decreased with increasing percentages of fines (Figure D.5). This may show that high sand compositions cause some stress in alevins in the substrate, leading to rapid emergence.

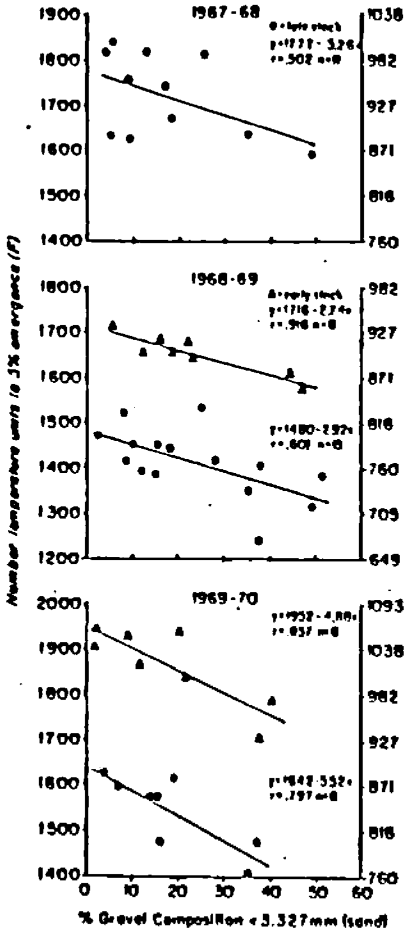


Figure D.5. (From Koski 1975). Relation between the percent of fines <3.3 mm in the gravel and temperature units needed for first 5% of chum salmon fry to emerge.

Hausle and Coble (1976) recorded increases, rather than the decreases reported by most workers, in the time required for emergence of brook trout in gravels that contained higher percentages of fines (< 2.0 mm).

McCuddin (1977) stated that he found no relationship between timing of fry emergence in chinook salmon and steelhead and percentages of sand in the substrate. However, his analysis may have been incomplete. Figure D.6, although not sufficiently labeled for the reader to identify the species and year, shows considerable differences. In the top graph, emergence through 0-22% sand peaked earlier than at 41-52% sand. On the contrary, emergence peaked earlier at 52% sand in the bottom graph. Based on other information in his thesis, we believe the top graph is for steelhead; the bottom for chinook salmon. Although McCuddin's data do not shed light on the cause for the difference, it may relate to stress level in the two species. The behavior of chinook salmon seemed to parallel that recorded for chum salmon by Koski (1975), a study in which higher percentages of fines correlated inversely with number of temperature units required for emergence. Steelhead observed by McCuddin seemed to behave in a manner opposite to Koski's chum salmon. The degree to which laboratory circumstances affected the results is unknown.

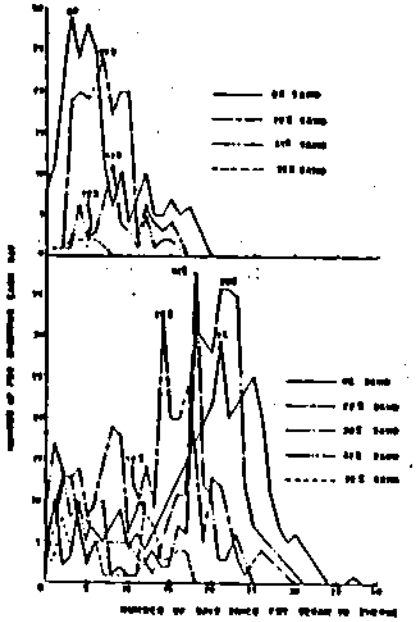


Figure D.6. (From McCuddin 1977). Number of fry emerging daily from trough mixes of sand of various percentages.

MacCrimmon and Gots (1986) found that most rainbow trout alevins incubated in 60-100% fines loadings began moving toward the surface of the substrate immediately after hatching, while those in 0-20% mixes tended to move deeper in the incubator columns. MacCrimmon and Gots (1986) also found in uniform substrata that alevins emerged earlier in finer homogeneous gravels than in coarser gravels.

The weight of evidence shows that alevins emerge earlier from gravels with high percentages of fines. We interpret this as an adaptive mechanism that increases survival. Head and body size increase as the yolk sac is absorbed, which should make passage through fines more difficult. Early emergence would trade mortality in the substrate against mortality caused by early emergence into surface waters.

Bams (1969) reported that pre-emergent sockeye salmon could be induced to move out of the gravel by a reduction in flow in the redd environment, while for alevins at an earlier stage of development a flow reduction led to burrowing. Bams explained these adaptations by noting that escape into the stream might be appropriate for survival of fish nearly ready to emerge, but that burrowing would be appropriate for alevins with much yolk unabsorbed.

III. SUBSTRATE CHARACTER AND ECOLOGY OF REARING SALMONIDS

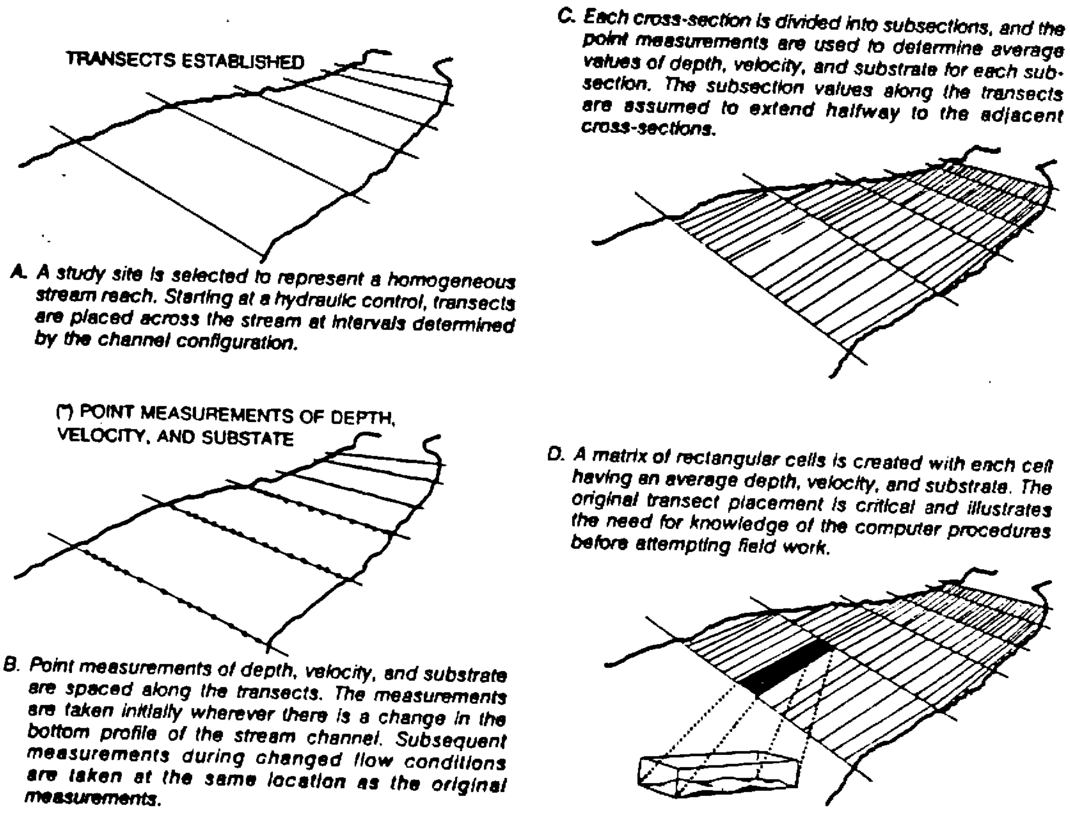
A. SUBSTRATE CHARACTERIZATION

Substrate characterization in rearing and wintering habitat for salmonids and for macroinvertebrates requires techniques suited for quantification of large particles that are usually not found in areas selected by salmonids for spawning, as well as assessment of fines. Visual assessment, coring, embeddedness, and free matrix particles each may have a role for particular purposes.

A.1. Visual assessment

An example of visual assessment utility is provided by substrate surface evaluations used by the Instream Flow Incremental Methodology (IFIM). IFIM practitioners place several transects across study sites, and obtain various measurements along a tape, or tag line, stretched over the stream on each transect. Conditions in each segment are defined by measurements or assessments at the ends of the segment, called "verticals". Thus, substrate condition in each segment usually consists of the average of two measurements. This average condition is assumed to obtain in the "cell" bounded by the tape, the segment ends, and a cross-stream line usually halfway upstream toward the next transect and another cross-stream line usually halfway downstream to the next transect (Figure A.1).

Quantification of substrate at each measurement point is visual, with a coding system of complexity that depends on investigator decision. The first digit, for example, could reflect the dominant particle size, the second digit the second most dominant size, the third a percentage of fines smaller than 6 mm. Coding could include embeddedness level if required.



A. A study site is selected to represent a homogeneous stream reach. Starting at a hydraulic control, transects are placed across the stream at intervals determined by the channel configuration.

B. Point measurements of depth, velocity, and substrate are spaced along the transects. The measurements are taken initially wherever there is a change in the bottom profile of the stream channel. Subsequent measurements during changed flow conditions are taken at the same location as the original measurements.

C. Each cross-section is divided into subsections, and the point measurements are used to determine average values of depth, velocity, and substrate for each subsection. The subsection values along the transects are assumed to extend halfway to the adjacent cross-sections.

D. A matrix of rectangular cells is created with each cell having an average depth, velocity, and substrate. The original transect placement is critical and illustrates the need for knowledge of the computer procedures before attempting field work.

Figure A.1. (From Hilgert 1982). Subdivision of IFIM study site into cells.

Table A.1 offers an example of codings.

Substrate scoring has been used by workers to describe habitat suitability for aquatic insects (Sandine 1974, Bjornn et al. 1977, Brusven and Prather (1974), and for fish (Crouse et al. 1981). Scoring categories differ somewhat among workers, primarily because of sieve size differences. An example of such substrate scoring is offered in Table A.2 (Crouse et al. 1981). The predominant particle size is assigned a rank number, as is the second most dominant substrate. The third rank is the size of material surrounding the predominant substrate particles, and

Table A.1. Examples of substrate codings used in IFIM studies. (From WDF 1983).

Code	Description	Diameter	
		mm	in
0	Organic detritus		
1	Silt, clay	<2	<0.1
2	Sand	<2	<0.1
3	Small gravel	2-12	0.1-0.5
4	Medium gravel	12-38	0.5-1.5
5	Large gravel	38-76	1.5-3.0
6	Small cobble	76-152	3.0-6.0
7	Large cobble	152-305	6.0-12.0
8	Boulder	>305	>12.0
9	Bedrock		

Table A.2. (From Crouse et al. 1981). Substrate characteristics and associated ranks for calculation of Substrate Scores, as modified from Sandine (1974).

Rank	Characteristic
	Particle size or type
1	Organic cover over 50% of bottom surface
2	< 1-2 mm
3	2-5 mm
4	5-25 mm
5	25-50 mm
6	50-100 mm
7	100-250 mm
8	> 250 mm
	Embeddedness[a]
1	Completely embedded, or nearly so
2	3/4 embedded
3	1/2 embedded
4	1/4 embedded
5	Unembedded

---

[a] - Extent to which predominant-sized particles are covered by finer sediments.

the fourth rank is the level of embeddedness of predominant substrate by material ranked in the third evaluation. The sum of the ranks constitutes a single Substrate Score.

Substrate score was related by Crouse et al. (1981) to d_g, as shown in Figure A.2. The visual scoring system appears to correlate reasonably well with d_g.

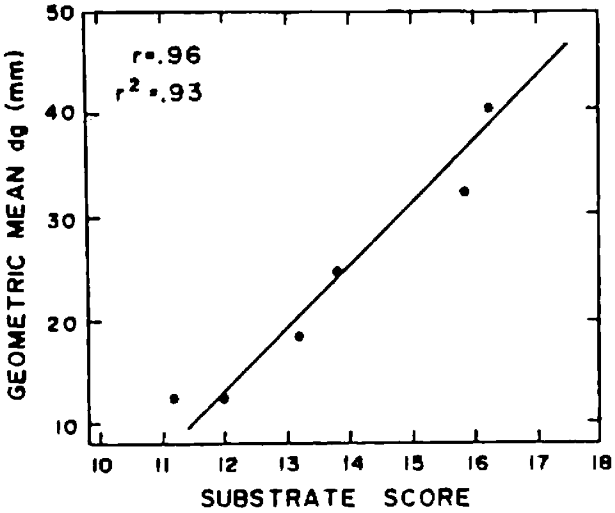


Figure A.2. (From Crouse et al. 1981). Geometric mean particle size of laboratory sediments and substrate score obtained by evaluating four sample areas in each channel. Points are means of two replications.

Shirazi and Seim (1981) assessed the efficacy and accuracy of visual assessment of substrate in connection with evaluation of spawning gravels. Section II.A of the current review discusses this assessment. Criticism of the visual assessment method (Everest et al. 1981) as failing to determine conditions in the egg pocket would not pertain as appropriately to descriptions of the substrate relevant to juvenile rearing. However, examination of surface conditions will not adequately measure crevice availability for macroinvertebrate hiding or for salmonid refugia in winter, especially in armored substrate surface zones. At best, visual assessments would be indicators of microhabitat conditions in the surface zone in areas not armored.

Konopacky (1984) compared substrate scoring with mean particle size and percentage of fines assessed in substrate coring in several streams in central Idaho. He believed he could determine any two of these statistics from the third. Figures A.3 and A.4 show his data in two forms.

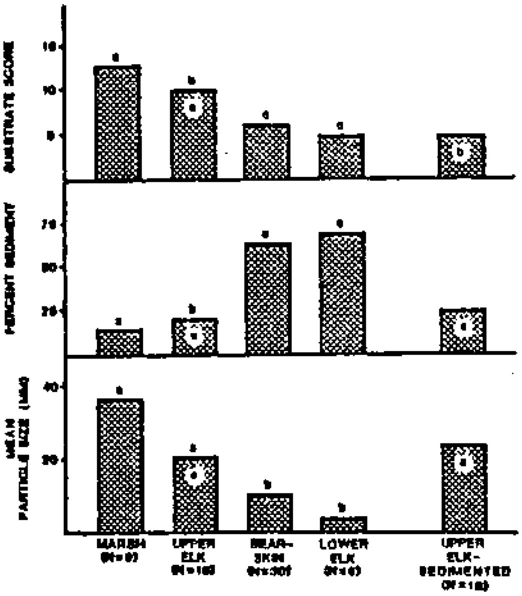


Figure A.3. (From Konopacky 1984). Substrate score, percent fines, and mean particle size of riffles in several streams of central Idaho.

Ocular assessment of surface fines as an indicator of gravel composition has been abandoned on the Payette National Forest because of failure of the surface system to accurately (in comparison with core samples) detect the percentage of fines smaller than 6.3 mm (D. Burns, Payette National Forest, personal communication). It cannot discriminate between heavily-sedimented and pristine habitats in the range of values found on the Forest.

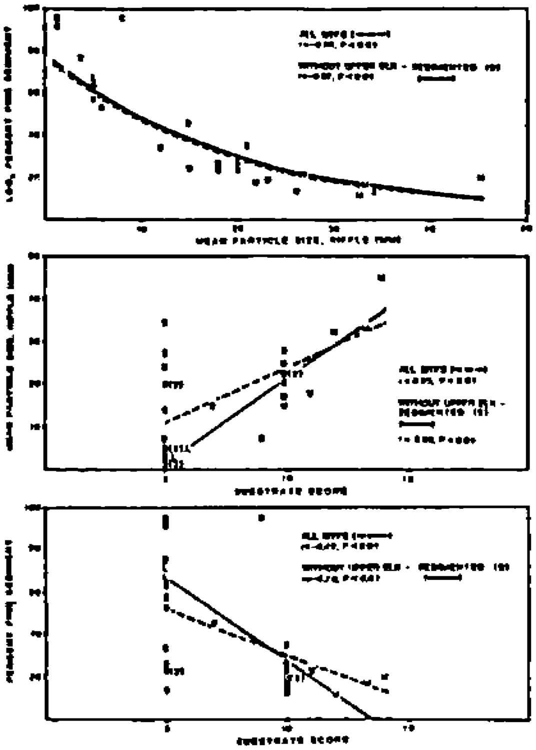
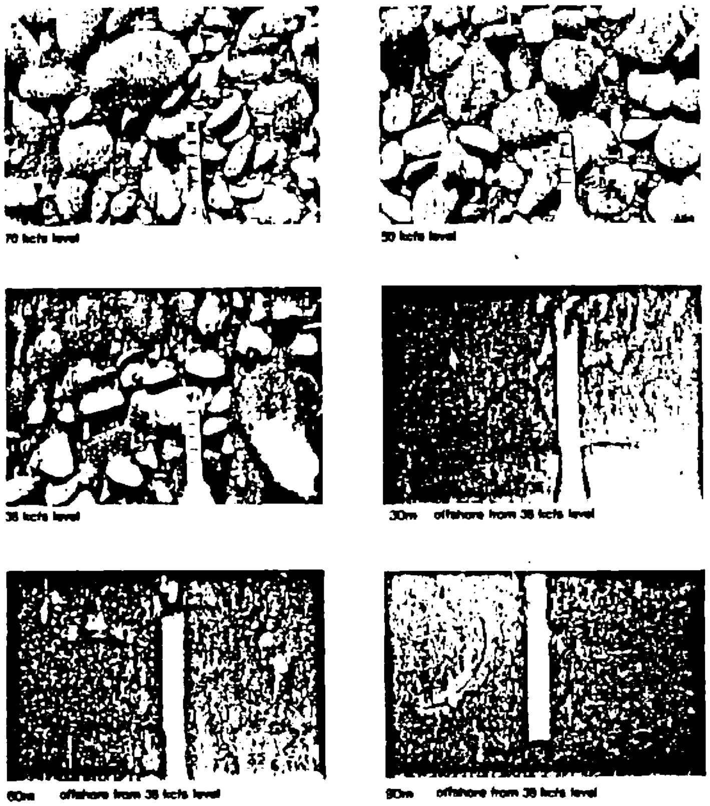


Figure A.4. (From Konopacky 1984). Relationships between percent sediment and mean riffle particle size, percent sediment, and substrate score for several streams in central Idaho.

A.2. Photographic measurement

Chapman et al. (1986) determined percentages of 3 groups of particle diameters on photos of the substrate surface in exposed gravels and underwater in the Columbia River to depths of 10 feet in high water velocities. Figures A.5 and A.6 offer examples of the photos and data that can be developed from them. The percentage of materials smaller than 7.6 cm was a suitable indicator of surface gravels at various points across the river channel, but detection of fines in the <6 mm category was not attempted. Surface armoring made the attempt pointless.

Burns (1978) used photographs to measure surface substrate composition (section II.A). The Payette National Forest has since abandoned use of photos for substrate characterization. Photographic assessment could not distinguish between areas where embeddedness was 19% and those where it equalled 30%. Comparison



70 kcfs level

50 kcfs level

38 kcfs level

30m offshore from 38 kcfs level

60m offshore from 38 kcfs level

90m offshore from 38 kcfs level

Figure A.5. (From Chapman et al. 1985). Photographs of substrate in the Columbia River at fixed distance from the camera. Scale marks are 2.54 cm apart.

of core samples with photo evaluations showed that where the percentage of fines smaller than 6.3 mm was equal to or over 30%, photo-assessed surface fines were estimated as only 10%. This seems reasonable, for armoring would probably make the gravel surface unlike gravels at two or more inches below the surface.

A.3. <u>Core samples</u>

Core samples, whether obtained by freeze probes or in McNeil cylinders, offer the most complete assessment of substrate components. Study objectives would determine whether core strata should be analyzed as a lumped sample to the depth normally examined in assessment of spawning gravels to evaluate potential

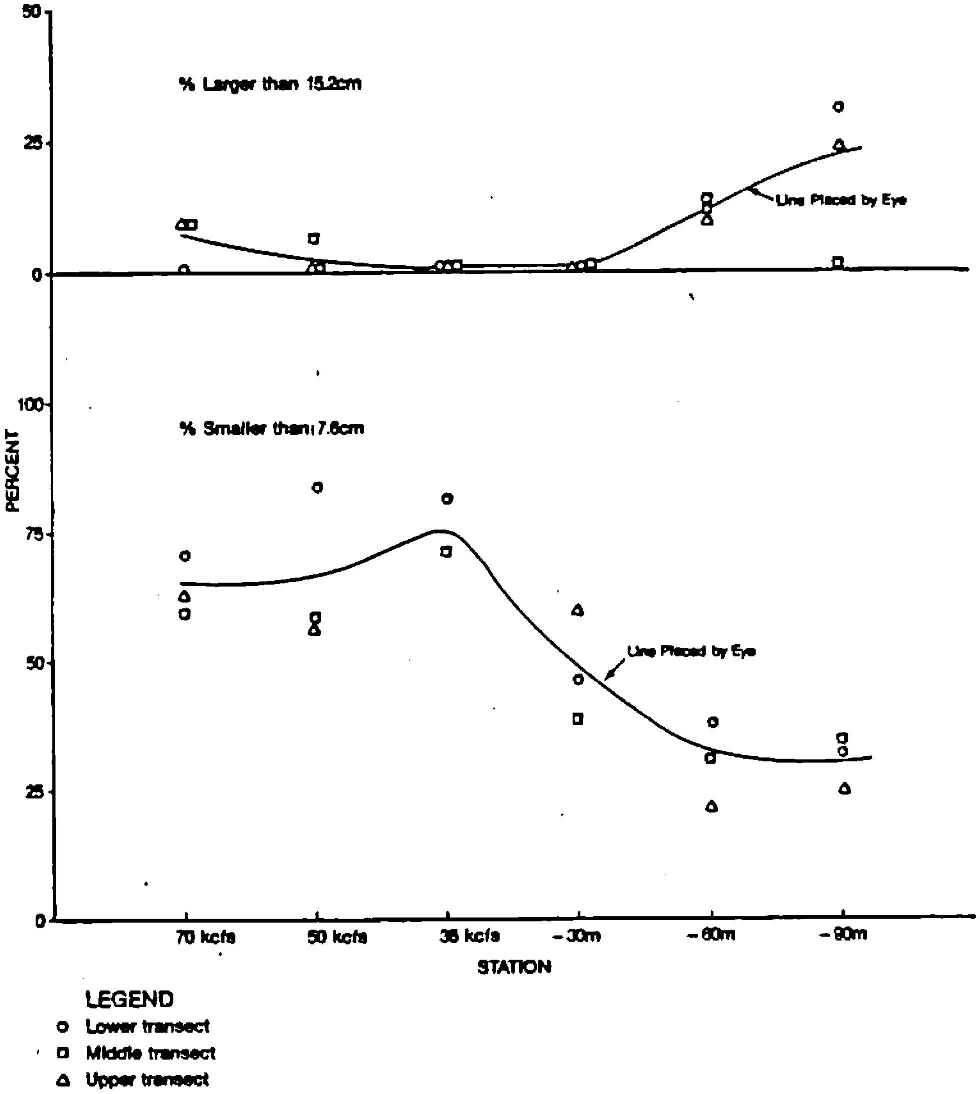


Figure A.6. (From Chapman et al. 1985). Mean percentages of gravels smaller than 7.6 cm and larger than 13.2 cm as measured from photographs along a transect normal to streamflow, both above the stream edge and at depth.

for winter habitat for salmonids or confined to the top few cm of the core, the zone more important to macroinvertebrates and salmonid fry.

Sieve examination of substrate cores appears an awkward way to approach evaluation of suitability of substrate for summer rearing or winter hiding habitat. In fact, visual methods, photographic techniques, or embeddedness measurements seem more direct. However, measures of coarseness may have utility. Much attention has been devoted to fines because of their effects upon reproductive success, but the other end of the particle scale has been virtually ignored.

Part of the problem with core samples as a descriptor of winter habitat is that they are difficult to obtain in the stream zones where they are most needed, that is, in areas with the higher proportions of rubble and boulders. In theory, a descriptor such as "% finer than 100 mm" should offer utility for analysis of winter refugia. However, if this descriptor were adopted and coring used to define winter habitat, variance would be high (Adams and Beschta 1980) and bias would increase. Large particles are not sampled satisfactorily by McNeil cylinders (the sampler is stymied when two large particles lie partly in and partly out of the cylinder and the cylinder cannot be forced deep enough into the substrate) or by freeze probes (large particles are frequently frozen to the core only at one end and are extracted without a surrounding matrix of small particles).

In stream zones dominated by medium gravels and smaller particles, freeze-cores or samples from McNeil cylinders have less bias associated with them. Thus for some streams, coring may be useful as a substrate descriptor. (Carried to extreme, this would mean that these tools would work best as descriptors of rearing conditions in streams badly damaged by sedimentation.)

Geometric mean particle size and geometric variance or a fredle index offer descriptors of the substrate, but suffer from bias associated with the sampling tools. Thus, failure of the McNeil or freeze-core systems to accurately sample large particles would bias d_g as well as percentage of particles in large size categories. Bias would be reduced in these situations by increased core sampler diameters, but with an obvious cost in practicality.

Cores can serve to evaluate such engineering features as road crossings. Figure A.7 illustrates temporal changes in fines as a result of road construction measures over 3 years in one stream.

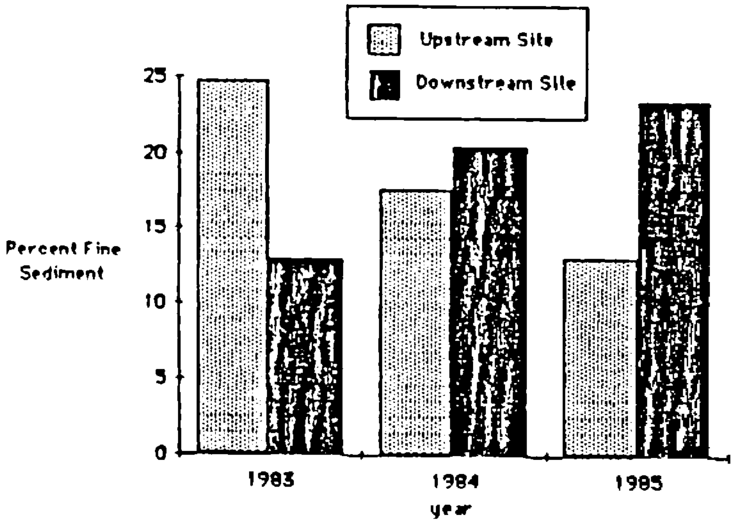


Figure A.7. (From Munther and Frank 1986b). Percent fine sediment <6.35 mm and > 0.21 mm from core samples in Randolph Creek (Lolo National Forest).

A.4. Embeddedness

Embeddedness is generically defined as the amount of fine sediment that is deposited in the interstices between larger stream substrate particles (Burns 1984, Burns and Edwards 1985). Embeddedness ratings have been developed and applied in rearing and overwintering habitat rather than in spawning gravels.

Kelley and Dettman (1980) measured embeddedness of particles larger than 4.5 cm in a California stream, and Klamt (1976) estimated the degree to which key rocks or dominant rocks in streams were embedded (using 25, 50, and 75% as embeddedness levels).

Specifically, Burns used embeddedness level to refer to the proportion of an individual matrix particle (4.5 to 30.0 cm in greatest diameter) surrounded by fine sediment (< 6.3 mm in diameter). The proportion is calculated by Burns and Edwards (1985) as:

$E = d_2\ (100)/d_1$, where

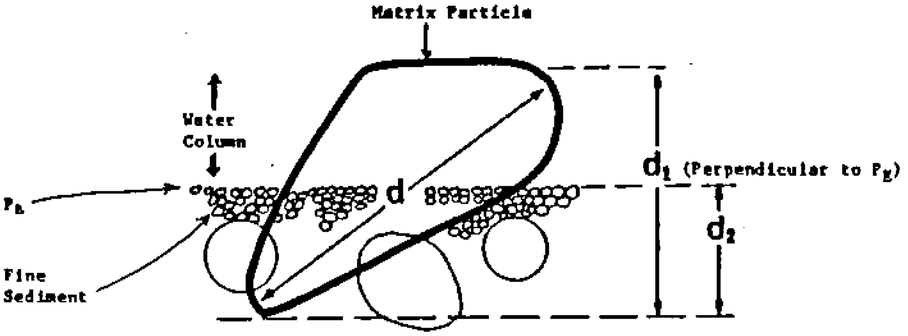
E = % embeddedness,

d_1 = longest diameter of a matrix particle of 4.5-30 cm greatest diameter at right angles to the plane of deposition of fine particles (< 6.3 mm diameter), and

d_2 = distance along d_1 covered by fine sediment (< 6.3 mm diameter) or "embedded" in the stream bottom.

Figure A.8 demonstrates the relationships among variables used to calculate embeddedness.

The population of single matrix particles must be sampled to characterize substrate conditions (Burns 1984). Burns treated an embeddedness measurement made for one rock as one observation. Burns used a 60 cm steel hoop to define particles in the substrate to be measured, a 30 cm transparent ruler to measure lineal dimensions and water depth, and a float and stopwatch to measure water velocity. These simple tools offer practical means



$$E = \frac{d_2}{d_1}(100)$$

Figure A.8. (From Burns and Edwards 1985). Embeddedness criteria. See text above.

of assessing embeddedness, provided the measure itself is deemed useful.

Burns examined embeddedness in a specific stratum within various streams, making no effort to obtain a simple random sample or even a stratified random sample of conditions reflecting average stream character. His approach should substantially reduce variance. He chose a sample stratum in each stream that had laminar surface flow over a cobble bottom suited for winter cover selection by overwintering juvenile salmonids. Kelley and Dettman (1980) used a random-toss method to quantify embeddedness for assessment of general stream condition.

Burns sampled embeddedness in 19 tributaries to the South Fork of the Salmon River, chosen to represent the full range of past development ("undeveloped", "partially developed" with low road mileage constructed, and "developed" with heavily roaded mileage). Burns found that streams with more development had more-embedded substrate than undeveloped or partially developed streams. The embeddedness in developed, partially developed, and undeveloped streams averaged a respective 44, 24, and 24%. The three categories had significantly different mean embeddedness ($p = 0.00009$). Developed streams had a significantly higher mean embeddedness than the other two categories ($p = 0.05$). Burns was unable to distinguish partially-developed and undeveloped streams by embeddedness information.

Burns (1984) regressed percentages of fine sediment from core samples (Lund 1982 and Corley and Newberry 1982) against mean embeddedness for 11 sites for which both measures were available. His regression, significant at $p = 0.01$, had an $r^2 = 0.64$ (Figure A.9).

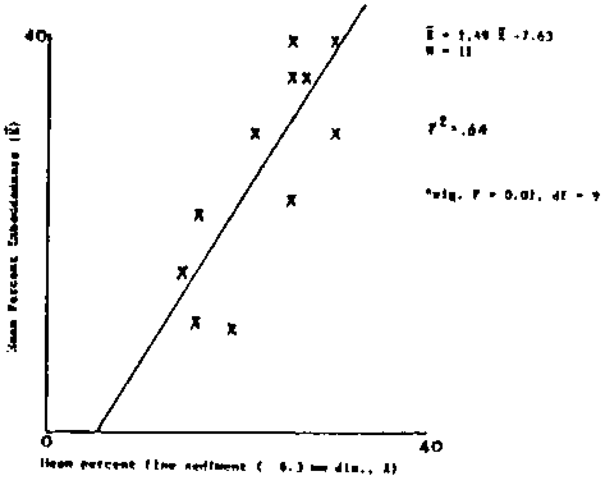


Figure A.9. (From Burns 1984). A regression between mean % fines from core samples (Lund 1982, Corley and Newberry 1982) collected in 1981 and mean % embeddedness assessed in 1983 from 11 locations in the South Fork Salmon River.

Each data point in Figure A.9 represented a mean derived from 40 core samples and at least 100 individual matrix component (individual rock) embeddedness measurements. There appears to be a real relationship between embeddedness and percentage of fines. Burns did not address temporal changes or variation of embeddedness measures within a sample site. He also regressed relative frequency of free matrix particles (loose rocks) against mean embeddedness. This regression ($r^2 = 0.82$), significant at $p = 0.01$ (Figure A.10), suggested that at the regression intercept of 45% embeddedness, no rocks were free, and that at 0% embeddedness, only about 85% of rocks would be free. A "free" particle should probably be defined as one not wedged by either fines <6 mm in diameter or very fine gravel. The latter should explain why 85% of rocks are free at 0% embeddedness. Burns suggested that free matrix particles may offer a measure more sensitive than embeddedness percentages in conditions between 0 and 50%.

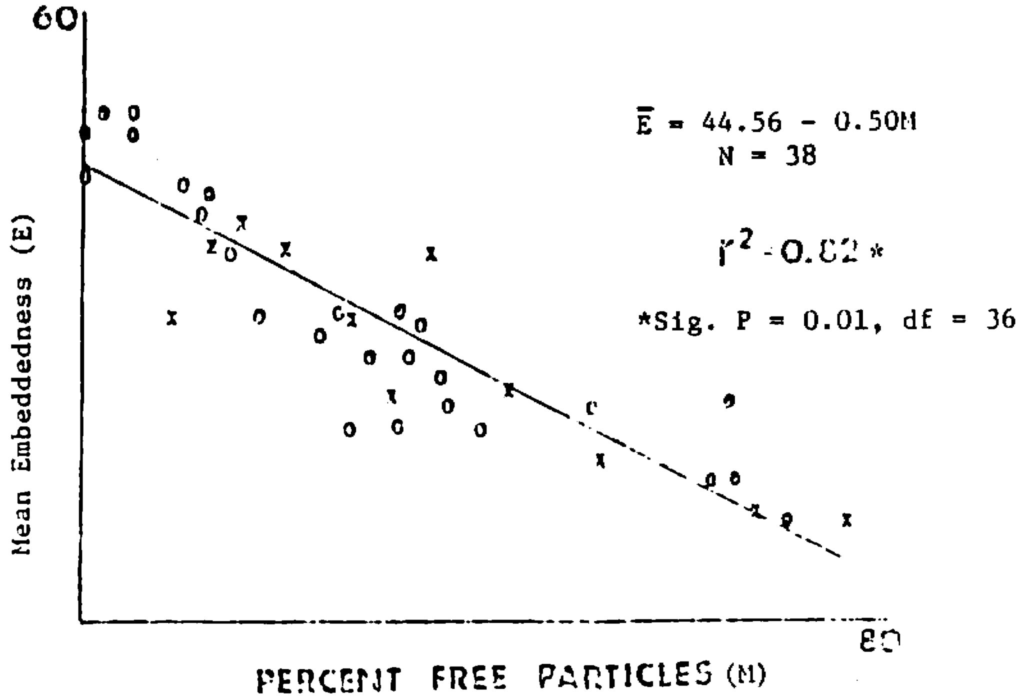


Figure A.10. (From Burns 1984). Mean embeddedness in relation to percent free particles from 38 locations in the South Fork Salmon River.

Munther and Frank (1986 a,b) regressed embeddedness against core-sampled fines larger than 0.21 mm and smaller than 0.84 mm, and found significant positive correlations (r^2 = 0.55 to 0.73). Regressions of free matrix ("matrix" here means the mosaic of substrate particles) particles against fines revealed negative correlations (r^2 = 0.73 to 0.90).

It is important to note that although embeddedness offers promise as a measure of substrate characteristics in the Idaho Batholith, it apparently has not worked well in basalt parent materials such as those on the western side of the Payette National Forest (Burns, personal communication and Burns and Edwards 1985). A quick way of stating this is that it works where sand is an important component of the substrate. Fines in basalt areas tend to consist of clays and silts easily moved by streams, hence armoring is more pronounced. That is, surface appearance cannot be used to assess substrate quality a short distance below the surface where armoring has occurred.

Kelley and Dettman (1980) found embeddedness a useful measure of substrate character in Lagunitas Creek, California. They did not indicate that they stratified habitats to eliminate zones outside the criteria of Burns and Edwards (1985), and apparently estimated embeddedness percentage on particles larger than 45 mm in diameter visually rather than with the system of Burns and Edwards.

Munther and Frank (1986 a,b,c) used embeddedness measurements to quantify conditions in Montana streams. They noted that excavation below the surface layer of substrate is commonly needed to reach the substrate level where all further particles are completely embedded. They removed all free matrix particles from the area of the sample hoop, then proceeded to remove and measure all embedded matrix particles. The resulting statistics apparently are the same as those obtained by the embeddedness techniques described by Burns (1984).

Munther and Frank (1986 a,b,c) regressed free matrix particles on embeddedness (eg. Figure A.11). They reported coefficients of determination of 0.73 to 0.92.

Embeddedness offers a useful "before and after" or "above and below" measure of changes over time or space. Burns (1983 and 1984) and Burns and Edwards (1985) demonstrated that Mule Creek, a Monumental Creek tributary, contributed to downstream degradation of Monumental Creek, by using upstream-downstream embeddedness measures. They also reported that Boulder Creek, a tributary of the Little Salmon River, had high embeddedness (42%) immediately downstream from logging and road construction relative to an upstream control area (20% embeddedness).

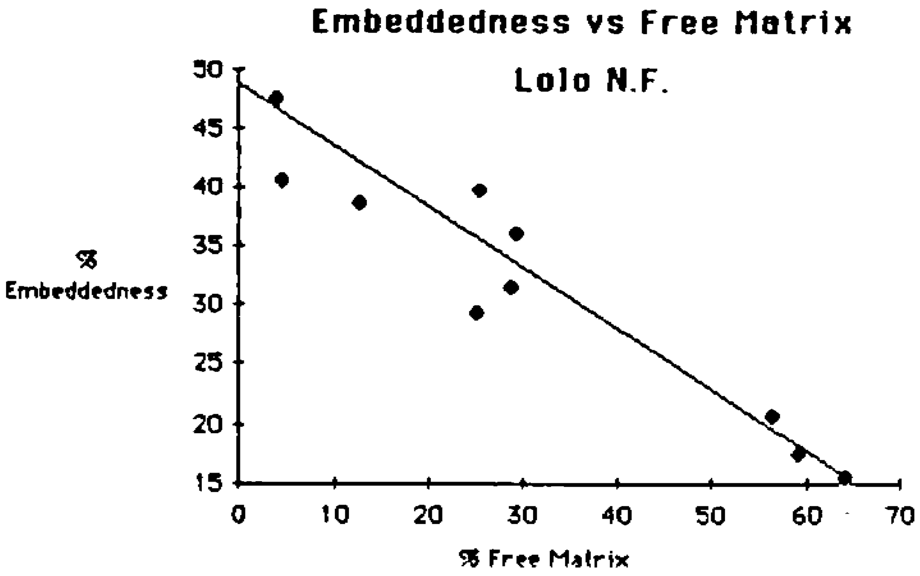


Figure A.11. (From Munther and Frank 1986a). Relation between embeddedness and free matrix particles on the Lolo National Forest. $r^2 = 0.90$.

The final sentence in Burns and Edwards (1985) states that data acquisition needs to be extensive before the extent and degree of impact to fish habitat from man-caused sedimentation can be properly evaluated. D. Burns (personal communication) estimated that for samples of 100 particles in a carefully-selected stratum, inter-mean differences of about 12-18% could be detected, but that about 400 samples would be needed to assess an inter-mean difference of about 5%.

Munther and Frank (1986c) compared similar morphologic sites on developed and undeveloped streams. In 4 of 8 pairings of riffles, tailouts, and runs, they found significant differences in embeddedness between developed and undeveloped streams (Table A.3).

Table A.3. (From Munther and Frank 1986c). Results of t-tests for comparison of embeddedness means of paired streams and stations. Martin and Meadow creeks are developed drainages (Meadow Creek roading 3.63 mi/section, 18.9 mi^2, Martin Creek roading 4.24 mi/section, 6.8 mi^2) and Tolan and Moose creeks are undeveloped (Tolan Creek roading 1.15 mi/section, 18.5 mi^2, Moose Creek roading 0.28 mi/section, 15.5 mi^2).

Compared Stations	Results	Two tailed probability
Meadow riffle (Site 1, Sta A) Tolan riffle (Site 1, Sta A)	Significant Difference at .01 level	.000
Meadow riffle (Site 2, Sta A) Tolan riffle (Site 1, Sta A)	No Significant Difference at .05 level	.974
Meadow pool tailout(Site 2, Sta B) Tolan pool tailout (Site 2, Sta A)	Significant Difference at .01 level	.003
Moose pool tailout (Site 1, Sta A) Martin pool tailout(Site 1, Sta C)	No Significant Difference at .05 level	.064
Moose pool tailout (Site 1, Sta C) Martin pool tailout(Site 1, Sta C)	No Significant Difference at .05 level	.542
Moose riffle (Site 1, Sta B) Martin riffle (Site 1, Sta A)	No Significant Difference at .05 level	.145
Moose riffle (Site 1, Sta E) Martin riffle(Site 1, Sta A)	Significant Difference at .01 level	.000
Moose run (Site 1, Sta D) Martin run (Site 1, Sta B)	Significant Difference at .05 level	.030

It is important to sample embeddedness in a carefully-defined stratum. Clearly, one should expect embeddedness to differ among various stream gradients and in various positions within a stream section, even within a pool. Burns and Edwards (1985) described a series of criteria for sampling, which we summarize below:

1. Float speed across a randomly-thrown steel hoop should indicate a surface velocity of 24 cm/s to 66.7 cm/s.

2. Water depth should not be less than 15 cm or the hoop or part of the hoop lie in an eddy caused by a pool or large boulder.

3. Particles in the hoop should not all be less than 4.5 cm or greater than 30 cm. (This restriction obviously implies that some particles can be larger or smaller than these limits.)

When Burns (1984) measured embeddedness in spawning areas, samples were not taken where water depth was less than 30 cm, core sampling had disturbed the site, spawning had occurred, or where particles in the hoop were all less than 4.5 cm or greater than 30 cm. Samples were avoided where the hoop partly or completely lay in an eddy caused by a pool or large boulder.

Klamt (1976), Kelley and Dettman (1980) and Burns (1984) intended embeddedness measures to pertain to habitat suited for rearing or winter hiding rather than for spawning gravels. In severely armored surfaces, percentages of free particles may offer useful ancillary measures of substrate condition for winter hiding. In boulders, it may be impossible to obtain suitable measures of embeddedness or percentage of free particles.

A.5. <u>Sediment traps</u>

A variant of analysis of gravel composition that may serve in "above and below" and "before and after" comparisons is the placement of buckets of washed gravels in pool tailouts above and below such features as road crossings. An example of the results of such comparisons, where the crossing caused sedimentation, is found in Figure A.12.

Bucket samples still require sieving for determination of percentages of fines. Theoretically, it should be possible to withdraw the bucket from the substrate after covering it with a plastic cap, then to evaporate all moisture from the bucket. Weight of contents before placement and after evaporation should measure increment of particles. This would shed no light on particle sizes of incoming material. Munther and Frank covered the buckets with "chicken wire" to minimize scouring of particles on the surface of the bucket.

Buckets of cleaned gravels embedded in the substrate are subject to effects of gravel shifting and vandalism. Nevertheless, they may serve in particular circumstances. An example might be to evaluate increment of fine particles below a road crossing during the period between late June (after spring freshets) and October.

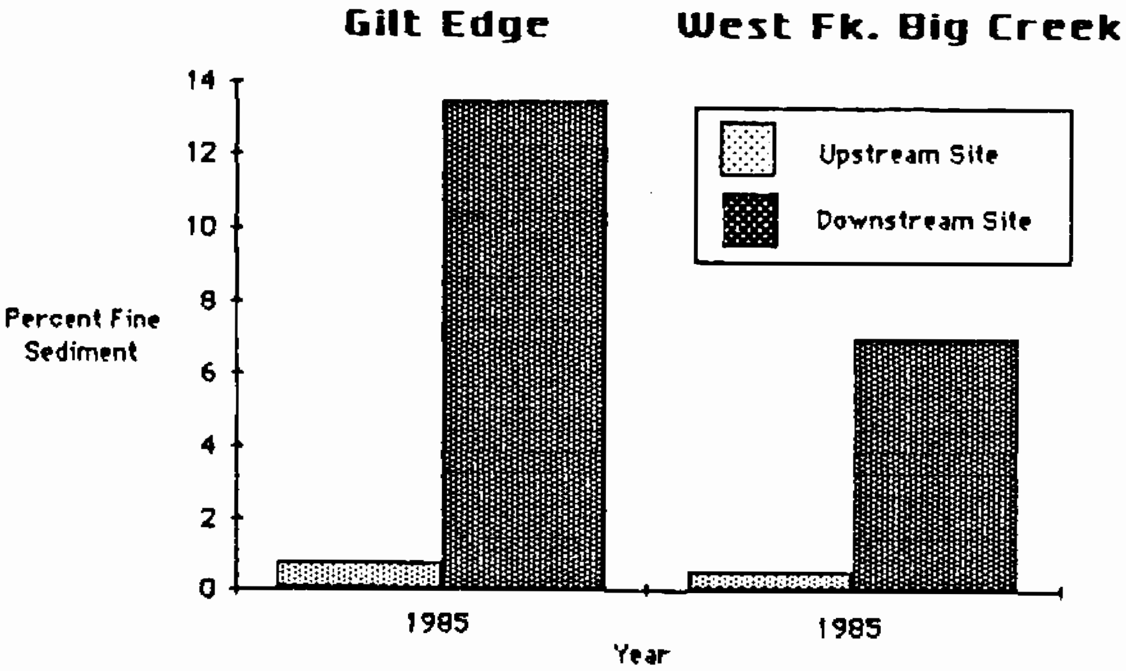


Figure A.12. (From Munther and Frank 1986a). Percent fine sediment <6.35 mm and >0.212 mm in buckets in Gilt Edge Creek and in West Fork of Big Creek above and below road crossings. Three buckets of washed gravel were placed above and below each crossing.

B. SUBSTRATE UTILIZATION BY REARING SALMONIDS

B.1. Newly-emerged fry

All salmonid fry utilize shallow water areas with low velocity after they emerge from the redd. In many streams these areas also have a substrate composed of fine sediments and organic debris, although fry also utilize quiet shallows in rubble. Recent work by T. Hillman in the Wenatchee River (T. Hillman, personal communication) indicates that substrate type is not important for age 0 chinook salmon and steelhead, but rather that these fish key on other habitat features, such as velocity.

Everest and Chapman (1972) and Lister and Genoe (1970) reported that fish use faster, deeper water as they become larger, but that newly-emerged fry remain close to the stream margin in quiet water. Availability of these marginal areas in spring and summer is important, but would be considered unlikely to control overall output of anadromous smolts or recruitment of resident adult salmonids to the fishable phase (see discussion later in this report on limiting factors).

B.2. Parr and fingerlings

Effects of fines on juveniles in the size groupings classed as age 0, I, and II are of particular concern because abundance of these fish is generally conceded to affect recruitment of fish to the fishable phase or to adulthood.

After the first few weeks of stream life, juvenile salmonids can be called fingerlings or parr. They begin using deeper, faster water for feeding (Everest and Chapman 1972, Lister and Genoe 1970, Campbell and Neuner 1985). They associate with velocity shear lines and occupy habitat much like that used by adults.

These sites would usually have less sedimented substrata than inshore areas, simply because of stream competency. Saunders and Smith (1965) observed in a silted stream that brook trout tended to associate with small patches of clean bottom, and suggested that turbulence kept those areas clear, or that clear areas provided better feeding places. Another explanation is that clean patches may lie close to favorable velocity strata that fish prefer.

Crouse et al. (1981) demonstrated in laboratory stream channels that coho salmon production (g/m^2/112 days) related directly to substrate score in both spring and summer (Figure B.1). Crouse et al. considered substrate scoring (see Table A.2) as a reasonable and meaningful way to evaluate quality of rearing habitat for salmonids.

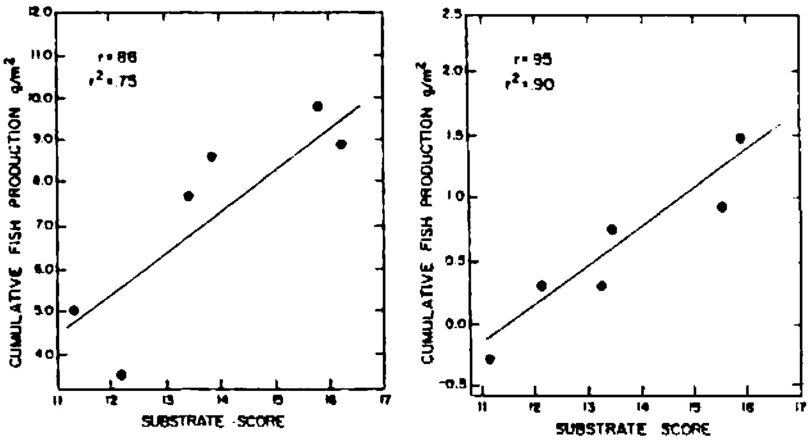


Figure B.1. (From Crouse et al. 1981). Cumulative production of coho salmon (g/m^2/112 days) in spring (left graph) and summer (right graph) as a function of substrate score.

Figure B.1 contains elements of trophic relationships confounded with fish behavior because production equals growth in biomass, whether the tissue survives or dies, hence is an amalgam of instantaneous growth rate and fish density.

Alexander and Hansen (1983) experimentally reduced sandy bedload sediments in a Michigan stream by means of a sediment settling basin, and observed the control (upstream from sediment basin) and treatment (downstream from sediment basin) reaches for 6 years. They used ratios of treatment to control populations, growth, and production by size-grouped fish to evaluate effects of reductions in bedload fines. The basin reduced sand bedload by 86%.

Small brown and rainbow trout increased by 40% in the treated area. Trout production increased 28%, but growth rate changed little, hence most of the increase was associated with increased numbers of fish (survival), and, apparently, with improved habitat and production of macroinvertebrates. The useful experimental approach of Alexander and Hansen (1983) provides excellent and conclusive data on the negative effects of sediment on population density and growth in the test stream. We suggest that a similar experimental technique could profitably be applied to one or more streams in Idaho.

Bjornn et al. (1977) studied effects of granitic sediments on juvenile chinook salmon, steelhead and cutthroat in central Idaho streams. In laboratory stream studies they evaluated three levels of sediment embeddedness, one-third, two-thirds and full in 1974 and two levels, one-half and full in 1975. Juvenile anadromous salmonids were placed in the channels in excess of estimated carrying capacity and traps captured fish that departed. The experiments used both wild and hatchery trout and chinook salmon.

Figure B.2 depicts the density of fish 5 days after summer experiments were begun. Test areas (with sediment embedded) tended to hold less fish than did control environments that did not have embedded sediments. Tests continued for 35 days with age 0 steelhead of hatchery origin also showed that embedded environments held less fish than control channels (Figure B.3).

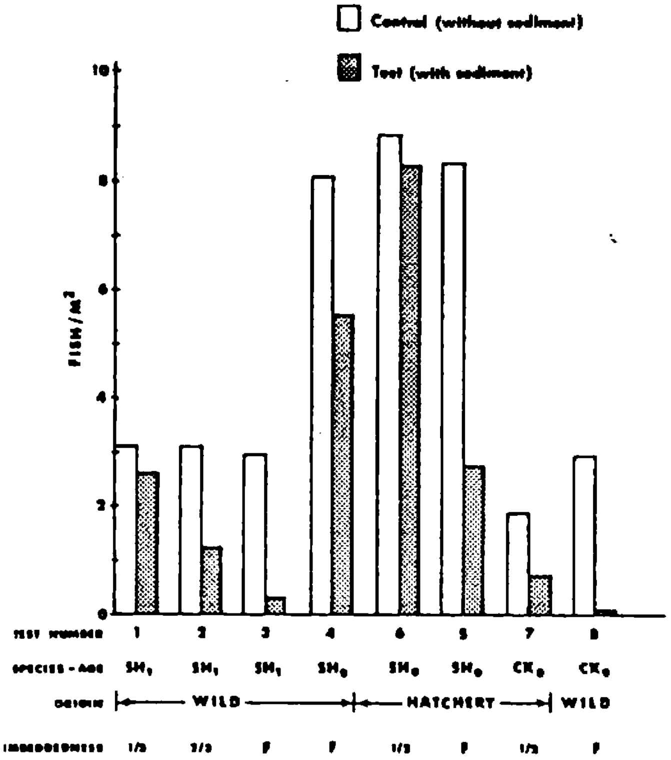


Figure B.2. (From Bjornn et al. 1977). Densities of fish in artificial stream channels after 5 days during summers of 1974 and 1975. SH_1 = age I steelhead: CK_0 = age 0 chinook; F = fully embedded.

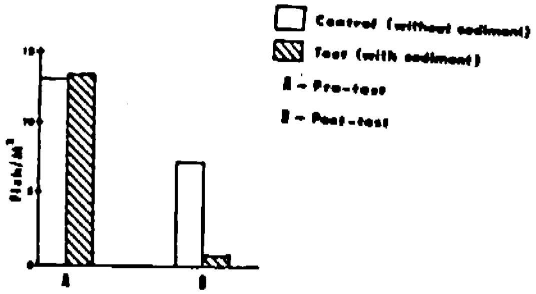


Figure B.3. (From Bjornn et al. 1977). Density of age 0 hatchery steelhead 35 days after introduction to the test channels. Fish could leave at will.

Konopacky (1984) placed steelhead trout and chinook salmon (each in allopatry) in pools with rubble cover in laboratory stream channels that were supplied by in-channel drift food from either sand/pebble or gravel riffles. A downstream trap permitted volitional residence. Densities of fish at the end of the studies equalled 9-10 fish/m^2, and fish did not grow in test or control channels with either sand or gravel riffles. The Konopacky (1984) results are difficult to relate to natural streams because beginning densities of fish were extremely high (steelhead densities of 10 fish/m^2 and chinook salmon densities of 12.5/m^2)), the tests were conducted with large hatchery fish (steelhead of 61 mm and chinook salmon 102 mm in length) that were accustomed to hatchery fish loadings and naive to natural drift at the beginning of the study, and all work was conducted after mid-September.

One would expect that fish densities for naturally-produced fish in Konopacky's channels would adjust, as a result of social interaction, to under 1 fish/m^2, but ending densities were usually 9-10/m^2. Given the limited food-producing area of riffles in the artificial channels, it is not surprising that fish could not grow, whether supplied from sand or gravel riffles.

Other work by Konopacky in natural environments suggests that each pool in his artificial channels should have held less than 8 g of chinook salmon biomass, or the equivalent of less than 1 juvenile chinook salmon at 9 g, for the 3.36 m^2 riffle areas for production of drift above the pools. Density problems obscured any effect of substrate type on fish production. However, the study concepts used by Konopacky merit pursuit, and have promise for better defining relationships between riffle condition and downstream fish production.

Alexander and Hansen (1986) experimentally added sand sediment to Hunt Creek, a Michigan stream. The addition increased bedload 4-5 fold and significantly reduced brook trout numbers and habitat. The brook trout population declined to less than half its normal abundance, although fish growth was not affected. Population adjustment occurred <u>via</u> a decrease in brook trout survival rates, particularly in the egg to fry and/or fry to fall fingerling stages of the life cycle. However, the authors ascribed the deterioration in survival largely to loss of cover, pool volume, depth, and channel widening. Figure B.4 indicates test:control ratios of numbers of brook trout before and after bedload addition. Interestingly, although macroinvertebrate density declined sharply after treatment, the decline in food base was apparently offset by reduced fish abundance, hence no effect on growth was noted.

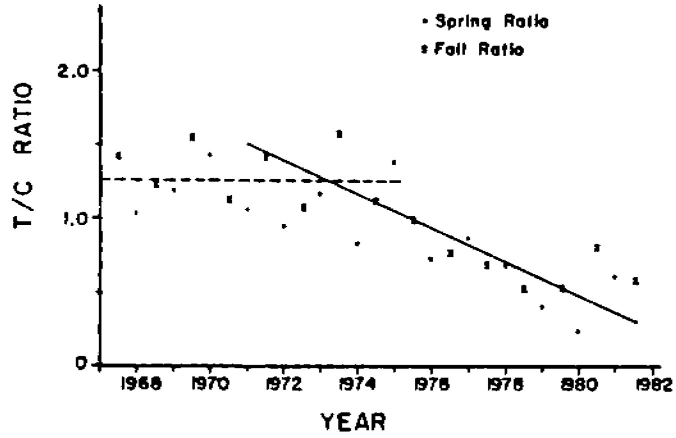


Figure B.4. From Alexander and Hansen (1986). Ratios of the total number of brook trout present in treated (T) and control (C) areas each spring and fall. Dashed line is for pretreatment years and solid line for post-treatment.

Bjornn et al. (1977) added sediment to a section of Knapp Creek, a tributary of the Middle Fork of the Salmon River in Idaho. Careful evaluation of the subsequent changes over a period of several days, two weeks, and a year showed that total fish density and density of chinook salmon in summer decreased as fine sediment decreased the amount of pool area (Figure B.5). Decreases in the area of pool deeper than 0.30 m caused a linear decrease in fish numbers in the pool. The authors cautioned that because fish utilize only a small proportion of large pools, the decrease in fish numbers with lost pool volume may not occur in large pools.

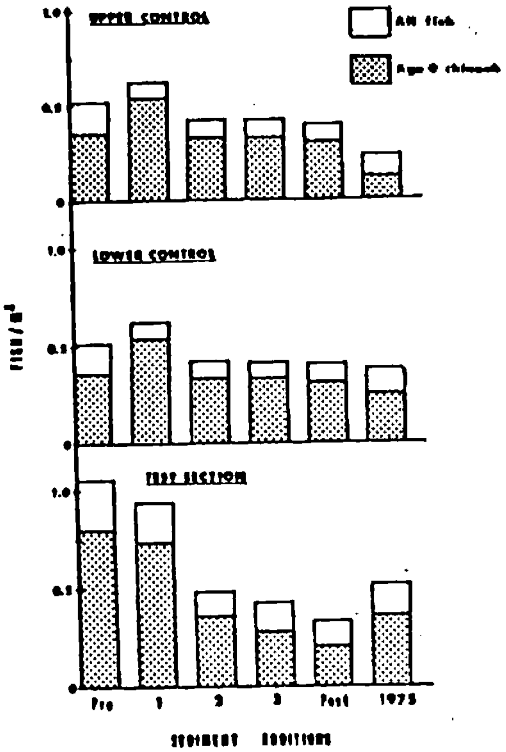


Figure B.5. (From Bjornn et al. 1977). Fish densities in control (unsedimented) and test (sedimented) sections of Knapp Creek prior to sedimentation and at 1 day (1), 4 days (2) after first addition of sediment and 3 days (3) and 13 days (post) after second addition, and one year later (1975).

Correlational work in two additional streams revealed no relationship between fish density and percentage of fine sediments in riffles, as measured by core sampling. The riffles examined were partially or fully embedded. Even in stream areas with 66% fines smaller than 6.35 mm, no significant decrease in fish density could be shown (Figure B.6). Because the relationships shown between fish density and percentage of fines are within-stream, seeding should not be a major concern. The best correlations were with percentage of pool area having cover and with drifting insect abundance. Lack of a clear effect of addition of fines in Bjornn et al. (1977) may have been a result of the small area involved in the experiment (291 m^2 in 165 m of stream).

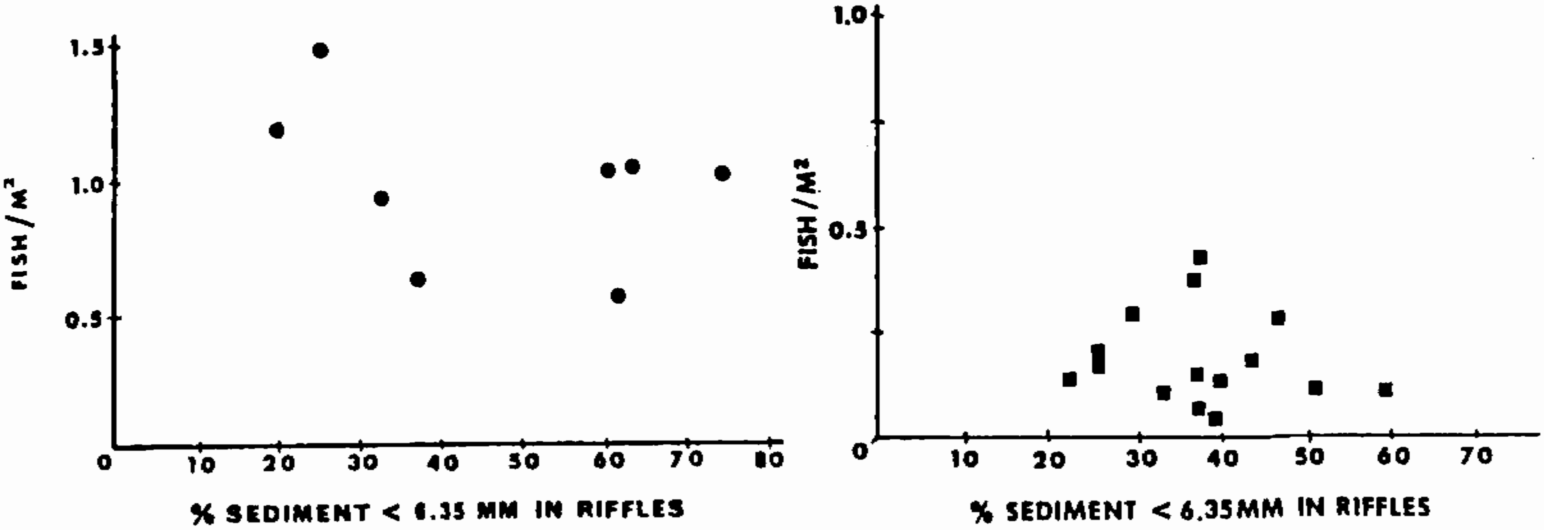


Figure B.6. (From Bjornn et al. 1977). Fish density in pools versus percentage of sediment <6.35 mm in riffles in Bearskin Creek (left graph) and Elk Creek (right graph), August 1975.

Saunders and Smith (1965) reported that low standing crops of brook trout were associated with silting, and that the chief effect on rearing habitat was destruction of hiding places. The streams studied by these workers had higher standing crops of trout after scouring removed the silt from the surface of the substrate.

Shepard et al. (1984) found a significant positive relationship ($p<0.001$) between bull trout abundance and substrate score (the higher the score, the less fines were present and/or the lower the degree of embeddedness). Score consisted of the sum of the number (Table B.1) of the dominant particle size, subdominant particle size, and embeddedness. These authors did not provide information on stratifications that might have influenced their results. Figure B.7 (Shepard et al. 1984) depicts the relationship between substrate score and density of bull trout longer than 75 mm.

Table B.1. (From Shepard et al. 1984). Substrate characteristics and associated ranks for calculating substrate score.

Rank	Characteristic
	Particle size class (range)
1	Silt and/or detritus
2	Sand (<2.0 mm)
3	Small gravel (2.0-6.4 mm)
4	Large gravel (6.5-64.0 mm)
5	Cobble (64.1-256.0 mm)
6	Boulder and bedrock (>256.0 mm)
	Embeddedness[a]
1	Completely embedded (or nearly so)
2	3/4 embedded
3	1/2 embedded
4	1/4 embedded
5	Unembedded

[a] Extent to which dominant sized particles are buried in sand and silt (see Bjornn et al. 1977 for an illustration).

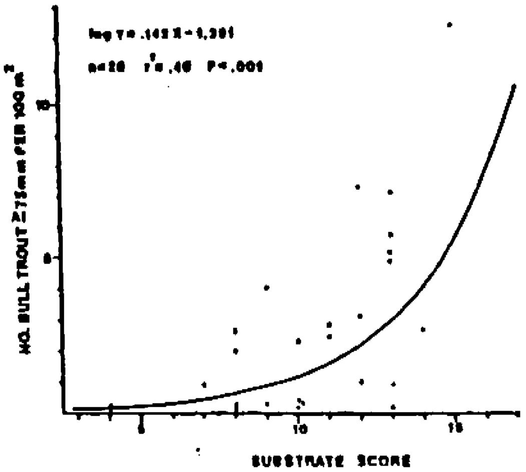


Figure B.7. (From Shepard et al. 1984). Relationship between juvenile bull trout density (fish at least 75 mm in length per 100 m^2 of stream area) and substrate score for 26 stream reaches in the Swan River drainage, Montana.

Shepard et al. provided no information on other habitat variables or on seeding effects.

Konopacky (1984) examined a spectrum of natural pool/riffle environments in central Idaho, obtaining data on riffle and pool areas, pool volume, fish abundance, riffle sediment, discharge, and invertebrate drift. He found that upstream portions of study streams contained resident, relatively large salmonids, while downstream reaches contained primarily age 0 chinook salmon. The salmon were either products of spawning within the study areas or had immigrated from downstream areas. More-upstream areas had less fine sediments, hence substrate particles of greater mean size.

Konopacky noted that fines in riffles did not consistently correlate with density of chinook salmon in the pools below the riffles. Pool area and invertebrate drift at dusk accounted for more variation. Riffle area, mean particle size in riffles, and pool area accounted for more variation in biomass than did other variables. Fine sediments in riffles influenced invertebrate drift, which in turn influenced fish diet. Resident trout in upstream reaches of study sites used cobble, boulders and vegetative cover within those areas during cold periods.

Edie (1975) reported a negative relationship between fines smaller than 0.85 mm and the density of age 0 trout but not older trout in the Clearwater River basin of Washington. His correlations for age 0 trout also were significant and positive for stream gradient, discharge, riffle area, percentage of the basin cut, percentage of steelhead in the population, and abundance of *Cottus rhotheus*. He stated that the negative correlation for percentage of fines was of importance to the land manager, who presumably would want to avoid increases in fines so that juvenile steelhead would be unaffected. However, it appears that small juvenile steelhead tend to prefer somewhat higher gradients where sediments are less likely to accumulate, and the negative correlation with fines, while real, may in fact mislead. Edie was unable to find a correlation of coho abundance with any habitat variable.

Kelley and Dettman (1980) related density of age 0 steelhead in late summer to embeddedness (Figure B.8). We examined the report of Kelley and Dettman, and found that seven data points had not been recorded in Figure B.8. Hence we plotted all 22 points in Figure B.9. Although the model in the latter figure is not as "clean" as that in Figure B.8, we see a strong negative relationship between embeddedness and juvenile steelhead densities.

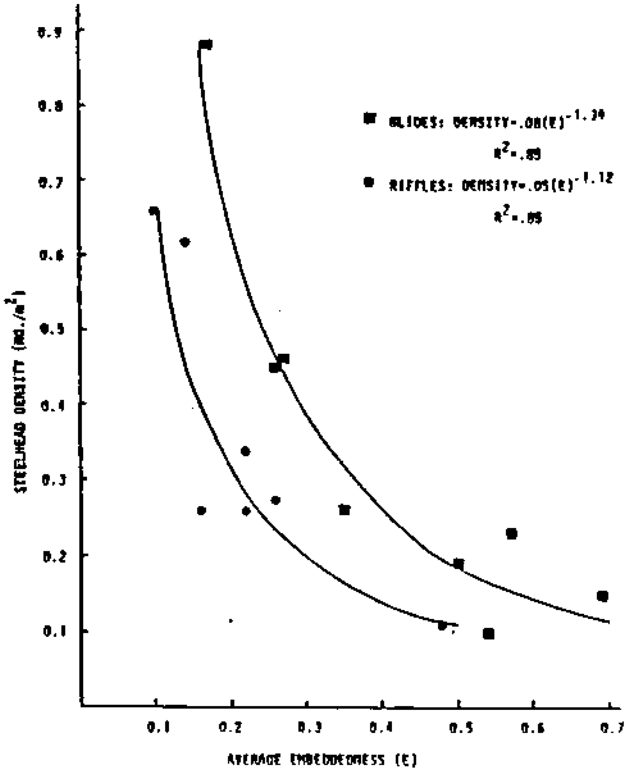


Figure B.7. (From Kelley and Dettman 1980). Age 0 steelhead density in short sections of Lagunitas Creek, California. Dots indicate riffles, squares indicate glides.

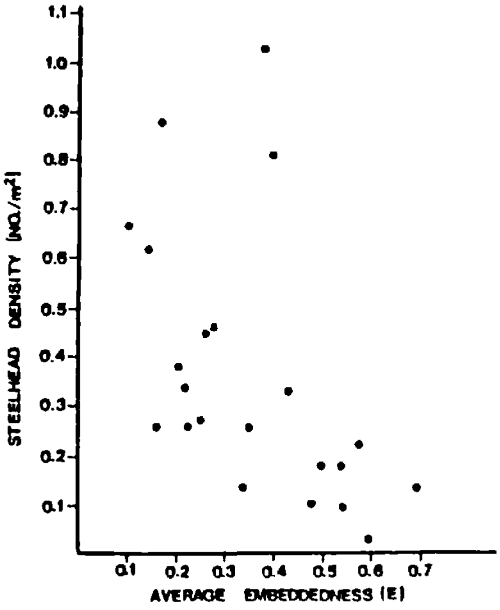


Figure B.8. (Adapted from Kelley and Dettman 1980). Density of steelhead in Lagunitas Creek, California, in relation to embeddedness, all points plotted.

The Kelley and Dettman data are strengthened because they were obtained in one stream that had been fully seeded in late spring with hatchery steelhead to fill any carrying capacity not occupied by naturally-spawned progeny. Kelley and Dettman did not provide other data that might permit evaluation of relative effects of embeddedness and other variables on fish density, but the model in Figure B.8 is qualitatively convincing. However, we do not consider it useful for quantitative prediction of effects of embeddedness on steelhead in Idaho.

D. Burns and R. Thurow (unpublished data, South Fork Salmon River) used sampling data from a range of stream gradients and orders to develop a general relationship between embeddedness and density of age 0 and age 1 chinook salmon, steelhead and cutthroat trout (Figure B.9). Highly variable seeding contributed to data scatter. Other physical and biological habitat variables are confounded within the relationship. High fish densities did not occur where embeddedness exceeded 35-40%, but

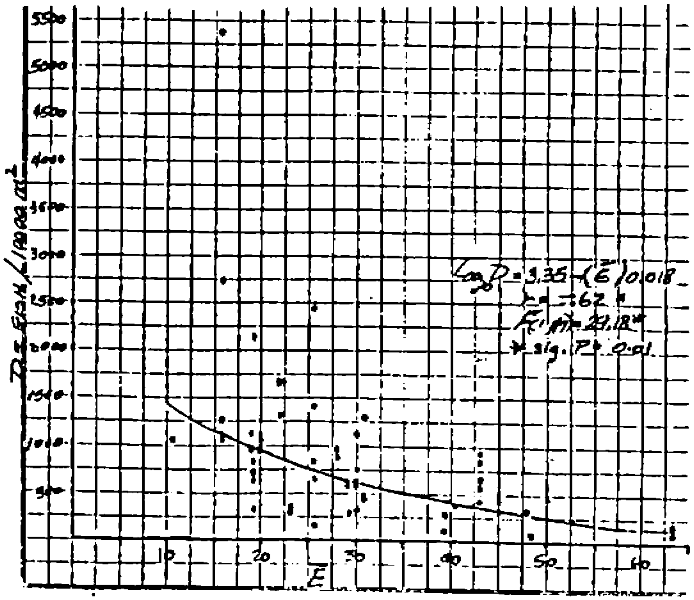


Figure B.9. (From unpublished data of R. Thurow and D. Burns). Density of age 0 and 1 chinook salmon, steelhead, and cutthroat trout in granitic watersheds of the Idaho batholith in relation to percent embeddedness.

did at embeddedness levels under 30-35%. Bull trout appeared to flourish at low embeddedness as well (Figure B.10). Many streams of different order, species suitability, and seeding levels were

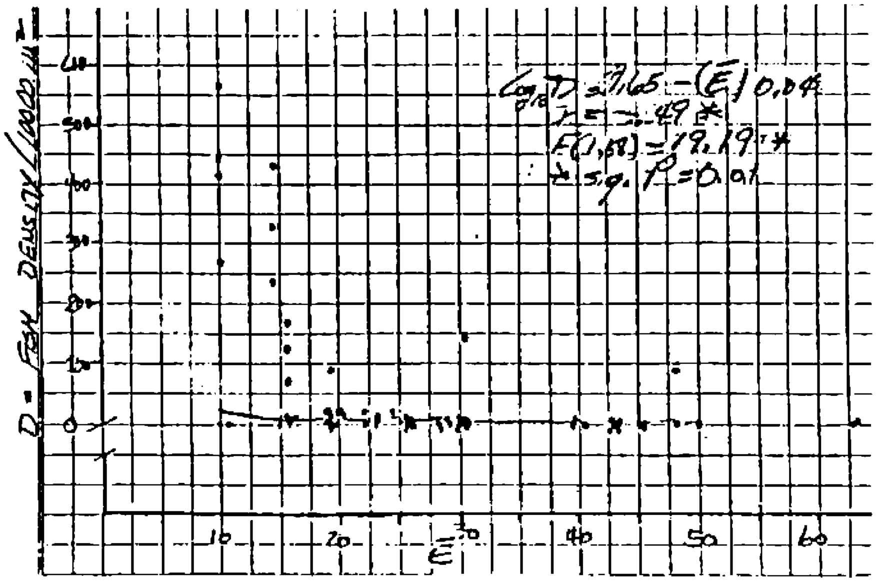


Figure B.10. (from unpublished data of R. Thurow and D. Burns). Density of bull trout in streams in granitic drainages in central Idaho.

included in the relationships in the previous figures. Although higher densities occurred in sites with lower embeddedness, we cannot state with any confidence that embeddedness affected density of fish.

When Thurow and Burns examined maximum combined fish densities (steelhead, cutthroat, all chinook salmon) found in any single site at each embeddedness interval (10-19, 20-29, 30-39, 40-49, 50-59, and 60-69%), they calculated an inverse relationship between embeddedness and fish density (Figure B.11). Their aim in this procedure was to reduce any effects of inadequate seeding and other confounding variables. Lumping by embeddedness strata does not eliminate problems of grouping different habitats and stream orders. High embeddedness may co-vary with other habitat features. Multi-variate regression analysis within strata (selected to reduce variance caused by such factors as gradient, riparian condition, etc.) may profitably be used to extract the correlational effect of embeddedness alone.

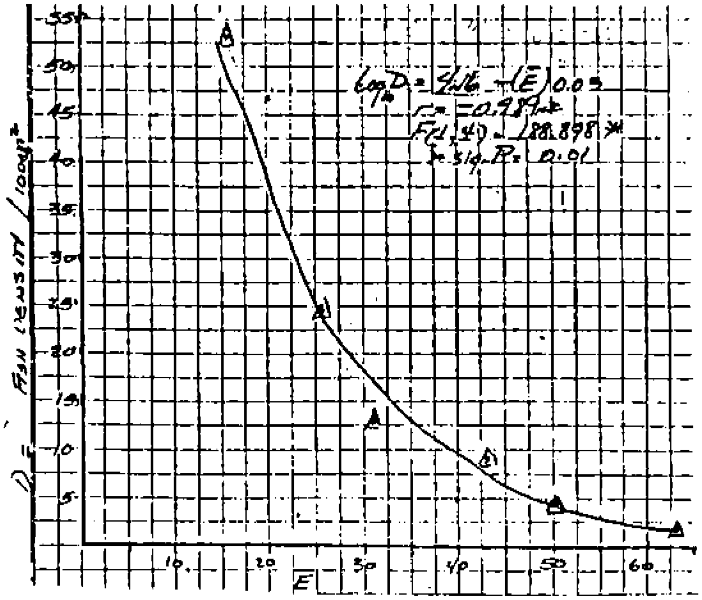


Figure B.11. (From unpublished data of R. Thurow and D. Burns). Relation between maximum fish density at any single site to various embeddedness levels.

In order to avoid reliance on a single snorkel site, we regrouped data of Thurow and Burns in tabular form by embeddedness intervals (Table B.2). The information for steelhead shows little apparent effect of embeddedness level on fish density. Densities of chinook salmon tended to decline at higher embeddedness levels.

Table B.2. (adapted from unpublished data of Thurow and Burns). Mean and range in density of juvenile steelhead and age 0 and 1 chinook salmon within embeddedness intervals. Numbers are in fish/100 m^2.

% Embeddedness	No. sites	No. juv. sthd. mean (range)	No. juv. chin. mean (range)
10-19	25	3.25(0-14.46)	5.57(0-44.2)
20-29	19	4.46(0-24.83)	5.05(0-40.0)
30-39	9	2.89(0- 7.74)	3.39(0-11.4)
40-49	10	4.45(0- 9.41)	0.44(0- 3.3)
50-59	1	4.46(-----)	0 (-----)
60-69	2	0.37(-----)	1.37(-----)

Another difficulty with the "maximum density" approach in Figure B.11 is that it confounds habitat features at different sites (see locations noted beside each point in the figure) with the effect of embeddedness. That is, the single data point for low embeddedness was derived from Chamberlain Creek, and the data points for the higher embeddedness levels were obtained from the South Fork Salmon River.

Edwards and Burns (1986) correlated stream gradient with embeddedness, but obtained an r^2 of only 0.19 (not significant, $p = 0.07$). We believe the stratification procedure used by Burns and Edwards (1985) reduces the possibility of securing a significant negative slope for the regression of embeddedness on gradient by selecting a limited range of velocities, depths, and particle sizes for embeddedness determinations. We believe that the probability of $p = 0.07$ may reflect a real relationship between gradient and "embeddedness" in the wider sense of the term; that is, in a stream at large rather than in the strata used by Edwards and Burns.

Certainly fines accumulation is a function of stream gradient. Figure B.12, from Platts (1974b) illustrates this point. The percentage of fines in Figure B.12 declined sharply until a stream gradient of about 4-5% was reached, then declined more gradually, according to Platts' figure.

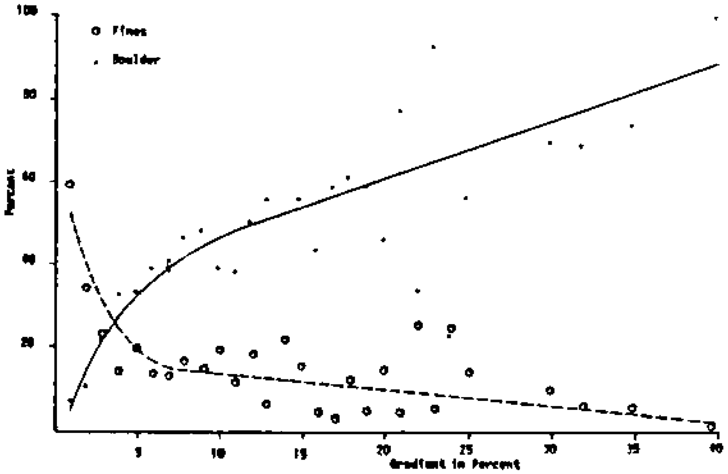


Figure B.12. (From Platts 1974b). Relationship of fines and boulders to stream gradient.

Munther and Frank (1986 a,b,c) reported r^2 values for linear relationships between embeddedness and fish populations in several streams in Montana (Deerlodge, Lolo, and Bitterroot national forests). In 53 such regressions, coefficients of determination were usually termed "extremely low" by the authors. One r^2 exceeded 0.70, but only 3 observations were included and that test was considered by the authors to be invalid.

Konopacky et al. (1985) provided data on snorkel counts of abundance of age 0 chinook salmon and pool embeddedness. The methods section of the report does not indicate methods used to measure embeddedness. Personal communication with Konopacky and Shoshone-Bannock tribal biologists indicates embeddedness was estimated visually in pools rather than with the accurate and detailed measurement techniques of Burns and Edwards (1985). Their data do not support a relationship between embeddedness and chinook salmon density in Yankee Fork and Bear Valley creeks, both Salmon River tributaries, but must be evaluated in light of the visual estimation procedure that they used.

C. Johnson (Cottonwood District, Bureau of Land Management) provided unpublished data on fish densities in his district in relation to embeddedness. His embeddedness values were obtained with the methods of Burns and Edwards (1985). Density of age 0 and 1 rainbow and cutthroat trout was negatively related to embeddedness level (Figure B.13), but with r^2 of only 0.07. Summer standing crop, in kg/ha, correlated negatively with embeddedness level at $r^2 = 0.27$ (Figure B.14). Another data set,

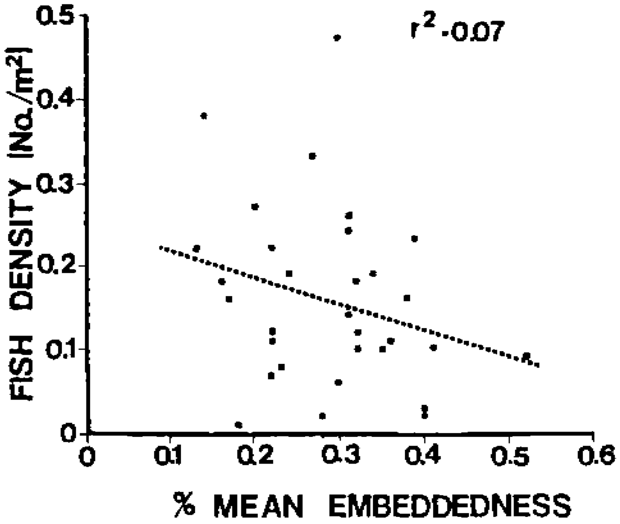


Figure B.13. (From data of C. Johnson, BLM). Density of age 1+ rainbow and cutthroat trout in stream sections in the Cottonwood District, BLM.

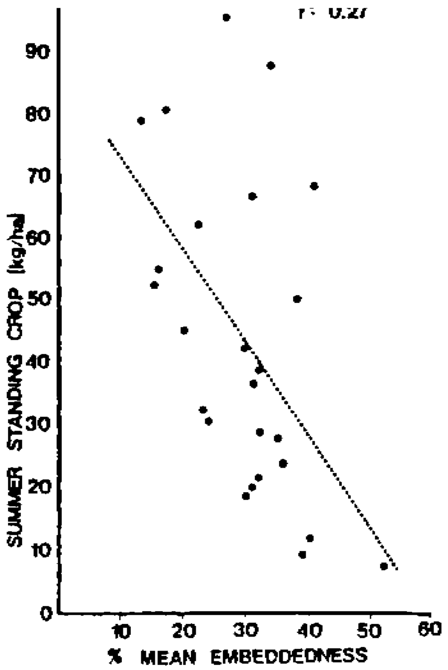


Figure B.14. (From data of C. Johnson, Cottonwood District, BLM). Summer standing crop in kg/ha of rainbow and cutthroat trout of age 0 and 1+.

presumably for different study sites, showed a weak positive correlation (r^2 = 0.06) between age 0 rainbow and cutthroat trout and embeddedness level (Figure B.15). Another data set, for streams with an overall embeddedness > 35% and/or substrate with more than 30% fines < 6.3 mm, had a negative correlation of fish density with mean embeddedness level (r^2 = 0.20)(Figure B.16).

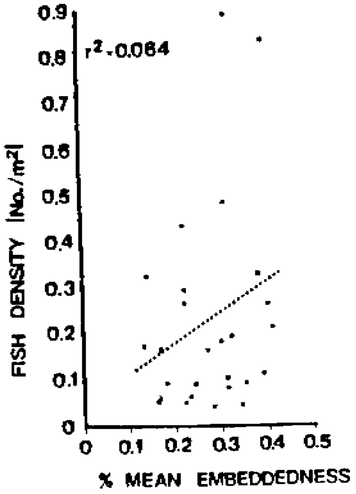


Figure B.15. (From data of C. Johnson, Cottonwood District, BLM). Density of age 0 rainbow and cutthroat in relation to embeddedness in stream sites in the Cottonwood District.

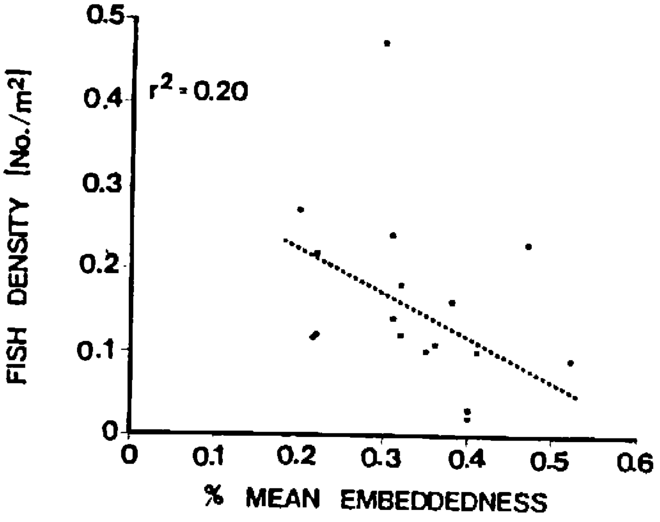


Figure B.16. (From data of C. Johnson, Cottonwood District, BLM). Density of age 1+ rainbow and cutthroat trout in relation to embeddedness in streams with mean embeddedness in excess of 35% and/or substrate with > 30% fines in the < 6.3 mm category.

Gamblin (1986) provided information on cutthroat trout density in 21 streams in the Coeur d'Alene River and Hayden Creek drainages in relation to embeddedness. He used the embeddedness measurement system of Burns and Edwards (1985). He found no significant relationship ($p=0.05$) between embeddedness and trout densities. The plot of the data ($r^2 = 0.12$) indicated a positive relationship to about 40% embeddedness (Figure B.17).

Although the data on fish density and embeddedness provide only weak coefficients of determination in all cases, the weight of the evidence tends to indicate that areas with high embeddedness (50% embeddedness may define "high") tend to have lower

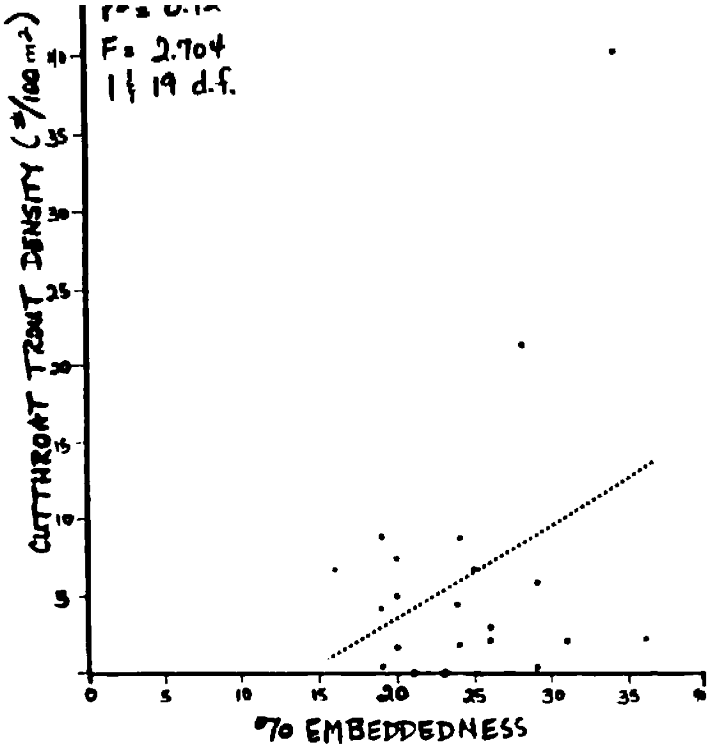


Figure B.17. (From Gamblin 1986). Relationship between age 1+ cutthroat trout density and embeddedness level in streams in the Coeur d'Alene River and Hayden Creek drainages.

densities of salmonids. However, the low r^2 values suggest to us that other factors may be more important than embeddedness. Embeddedness should co-vary with morphology of the stream channel, and the latter may have greater influence on fish rearing densities than embeddedness level.

Konopacky et al. (1985) assessed fish density and substrate fines as part of a feasibility study for habitat improvement. Figure B.18 shows the relationship between percentage of fines smaller than 4 mm and age 0 chinook salmon per 100 m^2 for two streams in August, 1984. Fines were evaluated in riffles at 25 equidistant points in each of three riffle cross-sections by eye. Fish counts were by snorkel observations. The data, for Bear Valley Creek and Yankee Fork, tributaries within the Salmon River drainage, do not support a negative relationship between riffle fines and fish density in pools. Again, seeding, cover, and stream order are confounded in the data, although interstream variability was reduced because the authors obtained their data in several strata within the same stream. Figure B.19 shows the

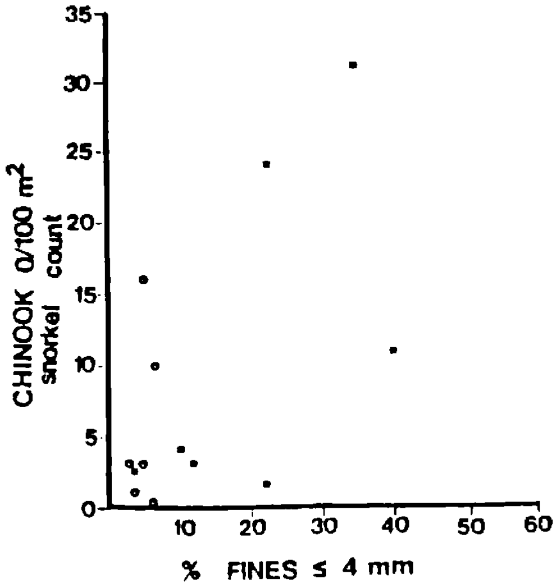


Figure B.18. (Extracted from Konopacky et al. 1985). Relationship between visually-assessed percentage of fines smaller than 4 mm and density of 0-age chinook salmon.

relationship between percent riffle fines and total density in pools of all chinook salmon, steelhead, and cutthroat trout. This figure also does not support a negative relationship between fines and fish density, up to 40% fines.

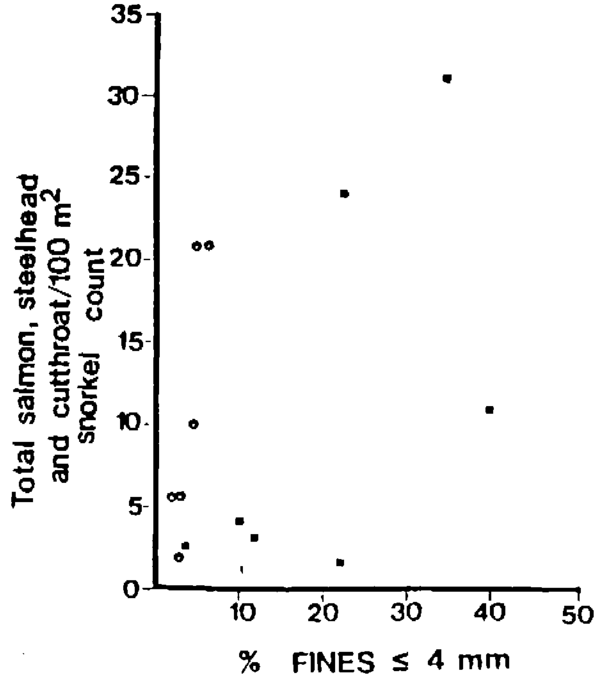


Figure B.19. (Adapted from Konopacky et al. 1985). Relationship between fines smaller than 4 mm and total density of chinook salmon, steelhead, and cutthroat trout.

Hillman et al. (1986) investigated microhabitat selected by juvenile chinook salmon and steelhead in Red River, a Clearwater River tributary. They found most chinook salmon of age 0 over sand-gravel substrate in summer. In this fines-embedded stream, they found chinook salmon densities greater than 60 fish per 100 m^2 in habitat with water velocities less than 20 cm/s, depths from 20-80 cm, and with associated cover in the form of undercut banks.

Petrosky and Holubetz (unpublished report, 1986) plotted snorkel-observed densities of age 0 chinook salmon in many Idaho streams in relation to visually-assessed percentage of fines. Their figures (figures B.20 and B.21) seem to support a negative relationship between fines and chinook salmon density. [In examining the figures, the reader should ignore the medians.] However, the data in figures B.20-B.21 include data points from a wide spectrum of habitat conditions. Because we would expect fines to vary inversely with increasing gradient, we stratified

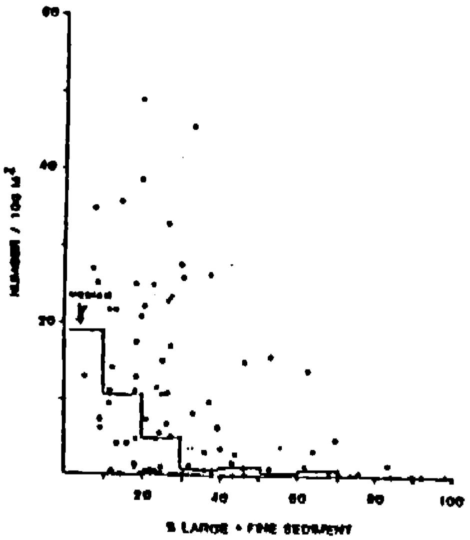


Figure B.20. (From Petrosky and Holubetz 1986). Density of age 0 chinook salmon in relation to visually-assessed percentage of fines <5.0 mm in Marsh Creek, Bear Valley/Elk creeks, upper Salmon River, and Valley Creek, all central Idaho streams.

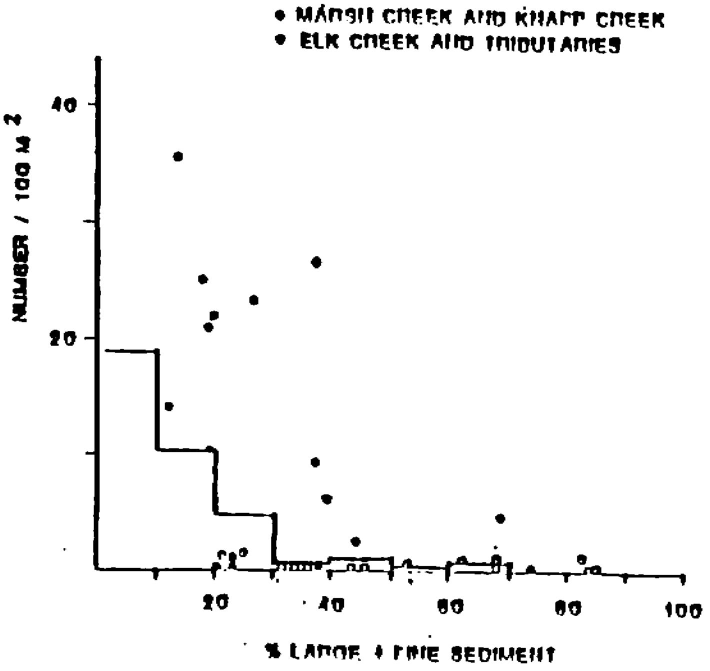


Figure B.21. (From Petrosky and Holubetz 1986). Density of age 0 chinook salmon in relation to visually-assessed percentage of fines <5.0 mm in Marsh, Knapp, and Elk creeks in central Idaho.

source tabulations (obtained from C. Petrosky, personal communication) by gradients of 0-1%, 1-2%, and over 2%, plotted densities against fines in these strata, then calculated regressions and correlations. The resulting relationships in Figures B.22-B.24 provide little support for a generalization about effects of fines on rearing densities of chinook salmon. Coefficients of determination (r^2) were only 0.21, 0.084, and 0.002 for the respective gradient strata, although they decreased with gradient as one might expect. Only the regression for gradients of 1-2% was statistically significant ($F = 8.45$, $p = 0.05$). The fact that r^2 values were extremely low leads us to the tentative conclusion that other habitat features were much more important than fines. The combined r^2 value for the data for all gradients combined is only 0.058. Another important source of data scatter in the foregoing three figures may be seeding, but if we take the data

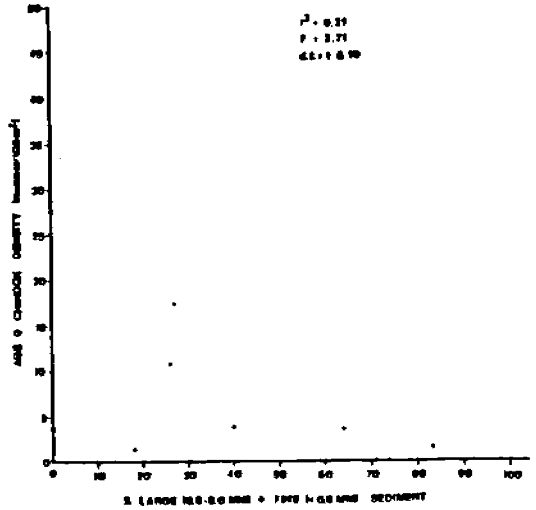


Figure B.22. (plotted from data of Petrosky and Holubetz 1986). Relationship between snorkel-assessed densities of age 0 chinook salmon and visually-determined percentage of fines in stream gradients of 0-1%.

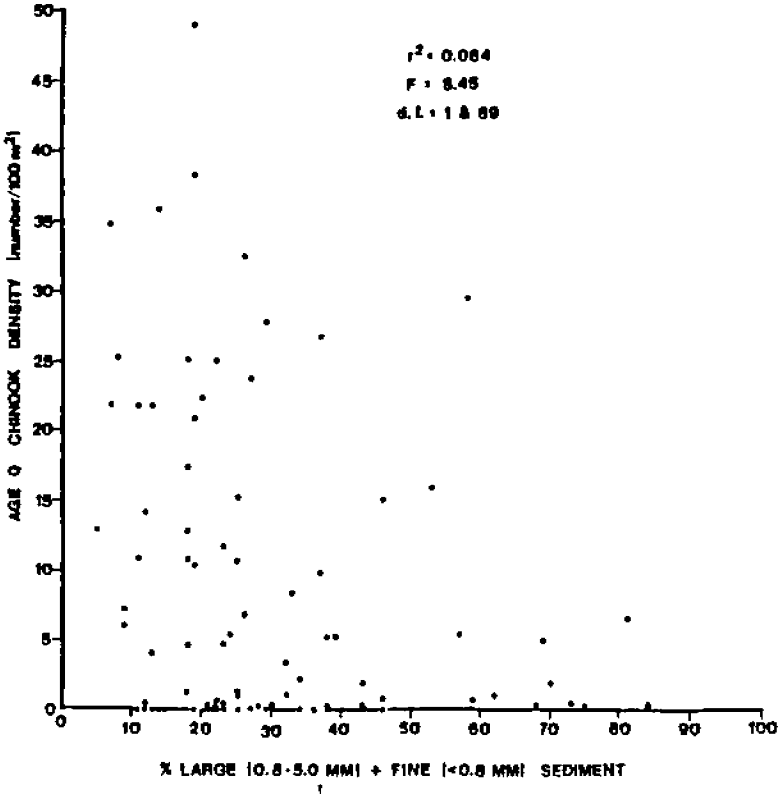


Figure B.23. (plotted from data of Petrosky and Holubetz 1986). Relationship between snorkel-assessed densities of age 0 chinook salmon and visually-determined percentage of fines in stream gradients of 1-2%.

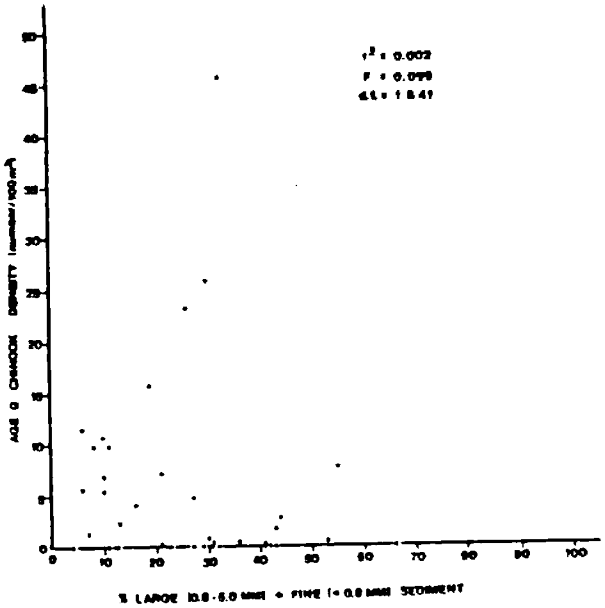


Figure B.24. (plotted from data of Petrosky and Holubetz 1986). Relationship between snorkel-assessed densities of age 0 chinook salmon and visually-determined percentage of fines in stream gradents of over 2%.

at face value, fines "explained" less than 6% of the variability in fish density.

For Valley Creek and tributaries, Petrosky and Holubetz (1986) collected information on brook trout density as well as chinook salmon abundance, together with data on percentage of fines. We prepared a correlation of brook trout density in 32 study sites in Valley Creek with fines smaller than 5 mm (Figure B.25). The regression, significant at $p = 0.01$ ($F = 8.57$, $r^2 = 0.22$) indicates that brook trout density in Valley Creek was higher in the presence of more fines. A similar treatment for the upper Salmon River (Figure B.26) shows the same significant relationship ($F = 41.62$, $r^2 = 0.64$).

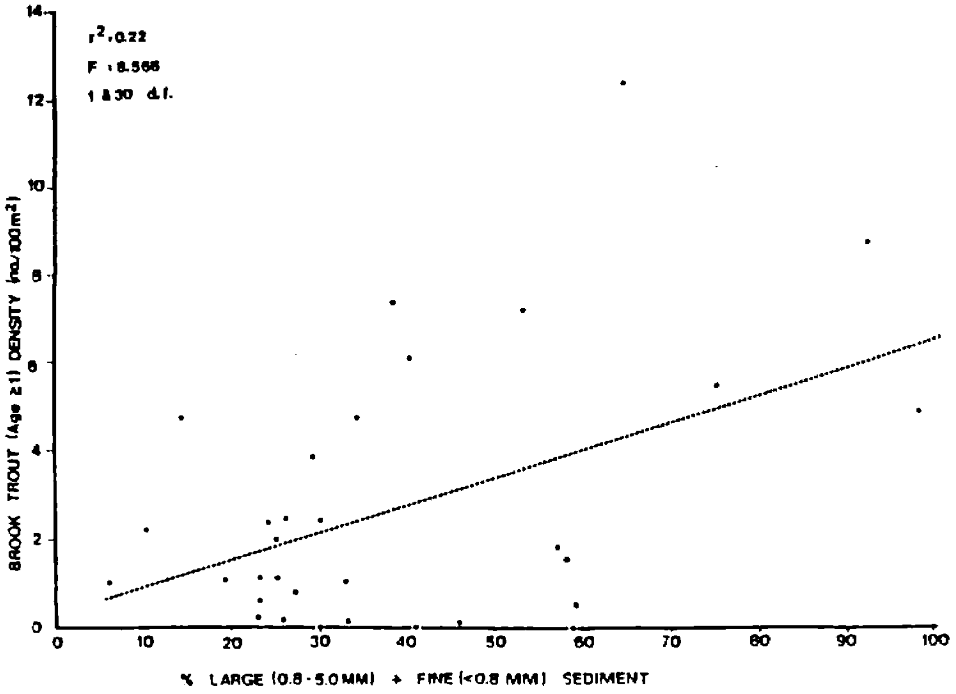


Figure B.25. (From Petrosky and Holubetz 1986). Density of age 1+ brook trout in relation to fines < 5.0 mm in Valley Creek and tributaries.

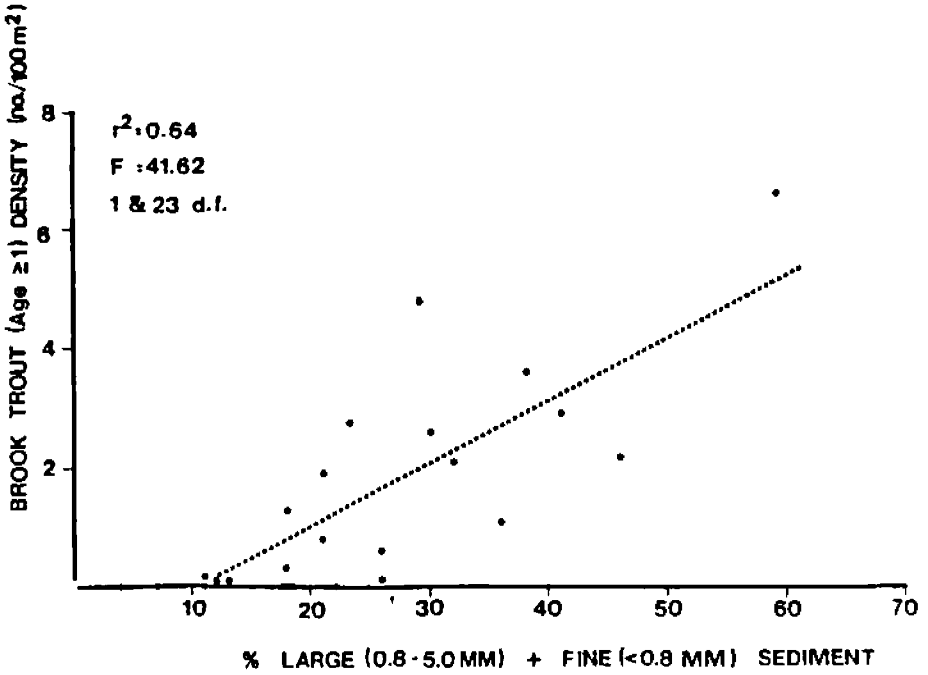


Figure B.26. (From Petrosky and Holubetz 1986). Density of age 1+ brook trout in relation to fines < 5.0 mm in the upper Salmon River and tributaries.

The available field data for the northern Rockies have provided information that indicates that sediment contributes to the variability in densities of chinook salmon juveniles. The data do not permit quantitative assessment of effects. Field correlations have sometimes shown a relationship between abundance of other salmonid species and embeddedness and fines.

In the case of brook trout, fish densities appear higher where more fines are present. This finding is at apparent odds with the information of Alexander and Hansen (1986), but may be explainable partly on the basis of stream morphology. Sand in Hunt Creek in Michigan increased bedload by 4-5 times and dramatically altered stream morphology for the entire one-mile test section. Sand measurements reported by Petrosky and Holubetz (1986) pertain to short stream habitat units.

Laboratory experiments and confounded field data offer some indication that embeddedness and fines affect fish rearing densities in the northern Rockies. Experiments in field sites in which full seeding is assured and a number of habitat variables are examined would be needed before more can be said about the relative and quantitative role of sediments in affecting rearing densities of juvenile chinook salmon and other species. As noted earlier, stream morphology may outweigh embeddedness and levels of fines as legislators of fish rearing density.

Any generalizations about utility of sedimented substrata for fish rearing habitat require bounds. Depositional streams such as Idaho's Silver Creek often lack gravel or rubble in many productive rearing areas, and would rank low in substrate scoring. It is important to note that stream stability and nutrient availability in spring-fed streams lead to abundant growth of macrophytes, with associated populations of amphipods and other macroinvertebrates. The thrust of this review of rearing conditions is not directed at these relatively scarce (in the northern Rockies) environments, although winter hiding areas may remain important in spring-fed streams when macrophytes die off and hence do not offer cover. Hunt (1969) and White (1972) showed clearly that provision of winter cover could substantially increase carryover of juveniles and adults and increase average density of salmonids in spring-fed streams.

It is important to state that habitat utilization by parr and fingerlings differs on a diel basis. Daytime habitat preference places fish near the path taken by drift food and often places fish over less-sedimented substrata. At night these fish tend to move inshore and settle in the shallows on the bottom (Hartman 1963, Edmundson et al. 1968, Campbell and Neuner 1985, Hillman et al. 1986). Species differ in their ability to utilize low light intensities for feeding, but in general, although feeding may become intense at dusk, quiescence inshore appears to be the norm for salmonids of the northern Rockies at night in streams.

B.3. Adults

Adult resident salmonids utilize microhabitat features that tend to have less-sedimented substrata because they use focal points in areas subject to more stream energy. They utilize deeper, faster areas for feeding stations, although attempting to obtain food with maximum gain in relation to energy expended (Puckett and Dill 1985, Bachman 1984) by using focal points in low velocities adjacent to faster water (Campbell and Neuner 1985). Areas close to incoming food streams would tend to have less sediment than more-inshore zones.

Adult salmonids have been noted at night in relatively shallow and quiescent water, resting on the substrate (Campbell and Neuner 1985). These locations are different from daytime focal points. In high-gradient streams they tend to lie in pockets of low velocity that are sand-silt depositional areas. Fish that remain in cover such as rubble during the day may leave it even at low temperatures at night and move to the stream edges (Campbell and Neuner 1985 and unpublished data of J. Griffith, Idaho State University). The proportion of the population that so behaves is unknown. Movement out of the rubble and to the stream edges at night during very low temperatures in winter is mystifying as to adaptive significance. Micro-differences in water temperature may be involved, as the fish seek warmer water at a time when predation should not occur.

Adults require deeper water of suitable velocity with adequate cover than do juveniles. Hence loss of pool volume to sediment deposition (eg. Bjornn et al. 1977) (or to cross-sectional breakdown because of livestock grazing or lost large woody debris, although this topic is beyond the current review) should logically reduce suitability of a stream for adult salmonids. Examination of Hunt (1969) may be instructive. His work showed that increases in average depth and pool volumes, with concomitant reduction in stream surface area and quantity of fines in the substrate, substantially benefited adult salmonids in Lawrence Creek, Wisconsin.

The excellent research of Alexander and Hansen (1983, 1986) demonstrates that fine sediments can limit fish populations. But their results cannot serve as quantitative models for the northern Rockies. The generally low coefficients of determination found in field correlations of fish densities and fines or embeddedness levels in the northern Rockies suggest to us that other factors have strong influences on fish densities. These factors will not be ascertained by single-factor evaluations of sediment effects, nor will the quantitative influence of sediments be determined without holistic ecological evaluations.

C. INSECT ABUNDANCE

C.1. Insect density

McClelland (1972) added sediment to O'Hara Creek, a Selway River tributary in the Idaho Batholith, to examine effects of the addition on aquatic macroinvertebrates. Insect abundance and diversity generally declined as a result of sediment injection. Pteronarcys californica and Arctopsyche grandis were highly sensitive to bottom sediment. Isogenus sp., Rhithrogena robusta, Arcynopteryx sp., Acroneuria pacifica, Ephemerella grandis, and Rhyacophila acropedes were moderately sensitive to small and medium amounts of sediment, and highly sensitive to large amounts. McClelland found that the microhabitat area beneath cobble was very important for most of the species studied. Under-cobble areas sealed by fines could not be used by insects.

Brusven and Prather (1974) investigated laboratory and field preferences of aquatic insects for various substrate types. Substrates with cobble were generally preferred over those without cobble by 5 species of stream insects that represented Ephemeroptera (Ephemerella grandis), Plecoptera (Pteronarcys californica), Trichoptera (Brachycentrus sp. and Arctopsyche grandis), and Diptera (Atherix variegata). Substrata with unembedded cobble were slightly preferred over half-embedded cobble, and completely embedded cobble in fine sand proved unacceptable to most of the species. Embeddedness affected Brachycentrus sp. and Atherix variegata less than was the case for other species, because of autecological requirements.

Reiser and Bjornn (1979) summarized literature that reported the highest production of aquatic macroinvertebrates in streams with gravel and rubble-size substrate. Pennak and Van Gerpen (1947) found, as have other workers, that numbers of benthic invertebrates decreased in the progression rubble to gravel to sand. Nuttall (1972) found that sand deposition tended to lead to increased abundance of only a few forms, to the detriment of many species. Tubificids increased in sands, as did two types of mayflies. Table C.1 lists reactions of various species to sand, according to Nuttall.

Table C.1. (From Nuttall 1972). The reaction of various species of invertebrates to sand deposition in the River Camel in Great Britain.

1. Species immediately eliminated by sand deposition.
   - *Leuctra niger*
   - *L. hippopus*
   - *L. geniculata*
   - *Amphinemura sulcicollis*
   - *Ephemera danica*
   - *Baetis pumilus*
   - *Polycentropus kingi*
   - *Gammarus pulex*
   - *Polycelis felina*
   - *Sericostoma personatum*
2. Species showing an increase in numbers with sand deposition.
   - Tubificidae
   - *Baetis rhodani*
   - *Rhithrogena semicolorata*
3. Species not immediately affected by sand deposition.
   - *Leuctra fusca*
   - *Caenis rivulorum*
   - *Protonemoura meyeri*
   - *Hydropsyche instabilis*
   - *Gyrinus sp.*
   - Naididae
   - *Ancylastrum fluviatile*

Nuttall attributed most of the decline in those species negatively affected by sand to the shifting substrate rather than to abrasion. He also noted that rubble supports more animals than sand does, a phenomenon correlated with the amount of available living space and with the greater lodgement of organic materials among stones, which provides food for macroinvertebrates.

Cummins and Lauff (1969) found that substrate particle size was the main factor involved in microhabitat selection for four species of macroinvertebrates but of lesser importance for 6 others, among 10 species studied.

Alexander and Hansen (1986) reported reductions in benthic macroinvertebrates as a result of increases in sandy bedload in treatment areas of Hunt Creek in Michigan. They compared treatment populations with those in control areas to which no sand had been added.

While sand is not good insect habitat, clay is better and muddy sand still better (Behning 1924), the latter holding 20 to 40 times more animals per m^2 than clean sand. It seems likely that muddy sand would not persist in a substrate that shifts in response to currents, and that Nuttall's comments about instability being responsible for reduced insect abundance are reasonable. Hynes (1970) recalculated data for stream samples collected by another worker, and showed that shifting sand yielded the lowest number of organisms of any substrate sampled (Table C.2).

Table C.2 demonstrates extremely high densities of invertebrates in macrophytes. The plants colonize sediment-laden areas, trap more sediment, and often support higher densities than nearby gravels. These "islands" of macrophytes and entrapped sediments cause a form of channel "braiding" that can increase local velocities and cleanse gravels.

Table C.2. (From Hynes 1970). Mean number of animals per m^2 on various substrata at 3 stations in Doe Run, Kentucky, based on 12 months of sampling.

Station number	I	II	III
Miles from source	0.1	1.9	3.1
Fissidens beds	87,600	102,000	------
Nasturtium beds	9,000	------	------
Myriophyllum beds	------	34,700	------
Myosotis beds	------	------	9.960
Bare riffles	2,700	7,550	------
Travertine riffles	------	------	1,530
Rubble riffles	------	------	1,540
Silty to sandy pools	------	4,640	5,830
Shifting sand	1,860	------	------

Hynes showed that rubble riffles had a fauna composed mostly of Ephemeroptera (70%), while mayflies were absent from shifting sand. Mayflies are known to drift more than any other macroinvertebrate order, with the occasional exception of chironomids. Thus, the effect of fines on mayflies may be expected to have a consequent effect on abundance of drift. The shifting sand substrate had a preponderance of isopods, amphipods, caddis, and snails.

Number of organisms is only one component of the ecological story, of course. "Turnover" of animals is important in contributing to the drift food source used by most salmonids in streams. Turnover time (permanence of station along the upstream-downstream axis) and contribution to drift could provide a different pattern than standing crop information. One suspects that turnover is more rapid in some forms of mayflies and dipterans than in isopods, amphipods, and gastropods. Dipterans in sand tend to consist of burrowing forms not available to fish.

Where fines reduce suitability of the benthic zone beneath the surface (insect habitat in interstices and beneath rocks), indirect effects on fish production may occur. High embeddedness levels, for example, may potentially limit insect production to the upper surfaces of gravel or rubble particles.

The point of these comments is that the low standing crop of organisms on rubble riffles as reported by Hynes (1970) is probably not indicative of the relative importance of such riffles in relation to a shifting sand substrate as sources of drift food for fish.

Tebo (1955) found that logging-related siltation sharply reduced the abundance of macroinvertebrates in a North Carolina stream. The incremental silt consisted of a layer of "sterile sand" and micaceous material that accumulated in some areas to a depth of 25 cm. When the silted substrate was cleansed by flood flows, it again supported insects at the same rate as control sites not affected by siltation from logging.

Martin (1976) noted that silt in the Clearwater River basin in Washington had a short residence time, and was moved by freshets, which can occur even in summer. He suggested that when sediment was present, "poor substrate habitat" reduced bottom fauna populations, but his data did not reveal a consistent significant effect of sedimentation.

Crevice shelter in the substrate is a first requirement for invertebrates in flowing water (Hynes 1961)(note: the simuliids, net-spinners, and some mayflies that rely on camouflage for protection are exceptions). Hynes noted that as an insect grows it needs a larger crevice, hence moves through a progression of successively larger crevices as it grows (this is a pattern similar to the movement into faster, deeper water by fish as they grow, although related more obviously to cover in the case of insects). Cederholm and Lestelle (1974) suggested that loss of intragravel living space causes the inverse relationship between percentage of fines (< 0.84 mm) and insect density in substrate samples.

Diversity also decreases in fines (Williams and Mundie 1978, Chutter 1969). Ephemeropterans and plecopterans do not prosper where fines predominate. Erman and Mahoney (1983) studied streams 6-10 years after logging in northern California with and without narrow buffers. Unbuffered streams showed considerable but incomplete recovery of diversity of macroinvertebrates. The mean diversity of unbuffered logged streams was about 9% lower in 1980-81, compared to 25% lower after an initial post-logging study in 1975. On the other hand, narrow-buffered streams changed little between post-logging and about 6 years later, relative to controls. Mean diversity was about 12% lower than in controls in 1980 as compared to 12% in 1975. The logged streams had significantly more fine seiment in the top substrate layers than did comparable control streams.

Erman and Erman (1984) tested effects of median particle size an heterogeneity on rates at which Ephemeroptera and, specifically, <u>Paraleptophlebia</u> <u>memorialis</u>, colonized cleaned and sorted gravels in trays. More mayflies colonized median particle sizes of 32 mm and 8 mm than 2 mm (Figure C.1).

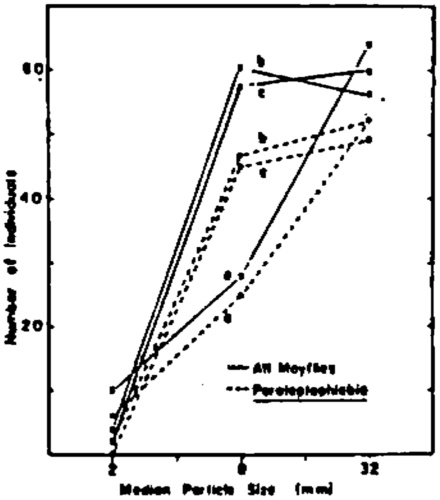


Figure C.1. (From Erman and Erman 1984). Colonization of cleaned, graded substrate trays in a stream by mayflies in relation to particl size. Letters in graph refer to heterogeneity tests not relative to the particle size:colonization point made in the present text.

NCASI (1984c) studied insect density and biomass in artificial channels to which fines were added. Biomasses declined as fines were added. The study suggested that up to 20% fines would not negatively influence biomass in communities already heavily colonized by chironomids, amphipods, and gastropods. Where these sediment-tolerant groups are not well-represented, NCASI indicated that biomass should be expected to decline with higher proportions of fines.

Konopacky (1984) sampled benthic macroinvertebrates over three months in stream troughs supplied with sand-pebble or coarse gravel substrata. The number of organisms was greater in the sand-pebble mix, but biomasses in the two substrata were similar (Figure C.2). Mean weight of individual insects was greater in the coarse gravel mix.

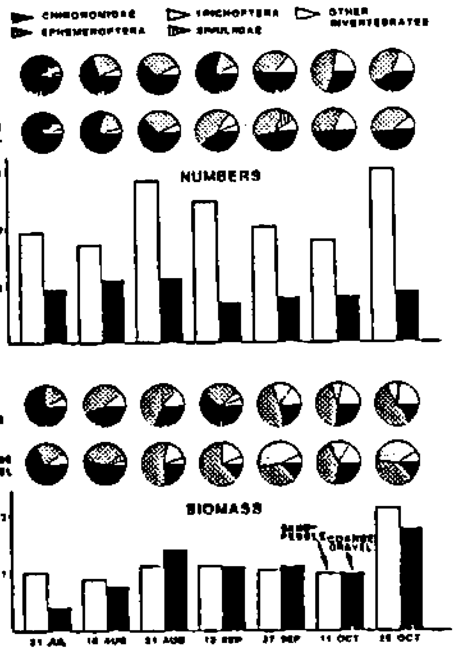


Figure C.2. (From Konopacky 1984). Numbers (top graph) and biomass (bottom graph) of macroinvertebrates over 3 months in sand-pebble (white boxes) and coarse gravel (black boxes) substrata in stream channels supplied with water from a nearby stream.

Bjornn et al. (1977) permitted insects to colonize experimental channels at Hayden Creek for 15 days, then examined standing crops of insects in locations with 4 levels of embeddedness with and without adding sediment to the channels in addition to that represented in the embeddedness indices). Table C.3 (from Bjornn et al. 1977) summarizes the results.

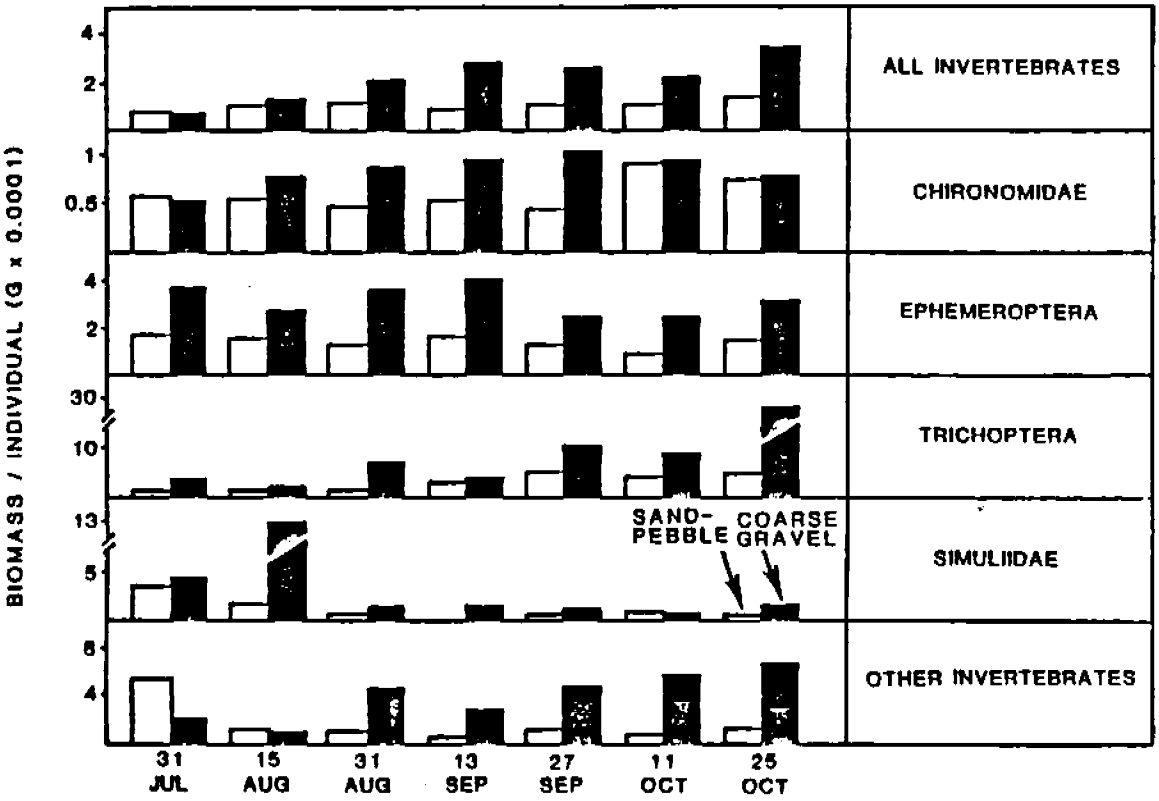


Figure C.3. (From Konopacky 1984). Biomass/individual in two substrate mixes over a 3- month period in stream channels supplied with water from a nearby stream.

Table C.3. (From Bjornn et al. 1977). Number of benthic insects per 0.093 m^2 sample in riffles without and with sediment, at 4 embeddedness conditions.

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

Only at full embeddedness did insect density decline from the highest density (which occurred at 2/3 embeddedness). The authors monitored several species for specific reactions to embeddedness (Epeorus albertae, Cinygmula sp., Ephemerella tibialis, Baetis bicaudatus, Simulium sp.). Only insects of the family Chironomidae did not decline significantly ($p = 0.05$) at high embeddedness. Riffles with sediment added supported slightly larger insect populations than did the control riffles, a finding attributed by the authors to the slight to moderate layer of sediment around cobbles, a condition they considered more natural and often more favorable than the unnaturally clean cobbles in riffles without sediment. E. albertae was particularly intolerant to increased sedimentation, especially at full embeddedness, as were B. bicaudatus and Simulium sp. Table C.4 (Bjornn et al. (1977) summarized reactions of taxonomic groups to embeddedness and sediment addition.

Table C.4. (From Bjornn et al. 1977). Mean insect densities (number/0.093 m^2) in test (sediment added) and control (no added sediment) riffles at experimental channels 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	35.8	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	6.2	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.

Bjornn et al. (1977)' extended insect density sampling to natural stream areas in tributaries of the Middle Fork of the Salmon River. In Elk Creek, which contained large amounts of fines in riffles, the authors used adjacent manually cleaned and uncleaned plots in riffles to check laboratory results. The total number of insects per 0.093 m^2 on cleaned plots was 1.5 times the number collected from uncleaned plots after 45 days of recolonization. There were about 4 times more mayflies and 8 times more _Alloperla_ sp. (the dominant stonefly) on cleaned plots than on uncleaned plots. The effects of sediment cleaning can be seen in Figures C.4 and C.5, from Bjornn et al. (1977).

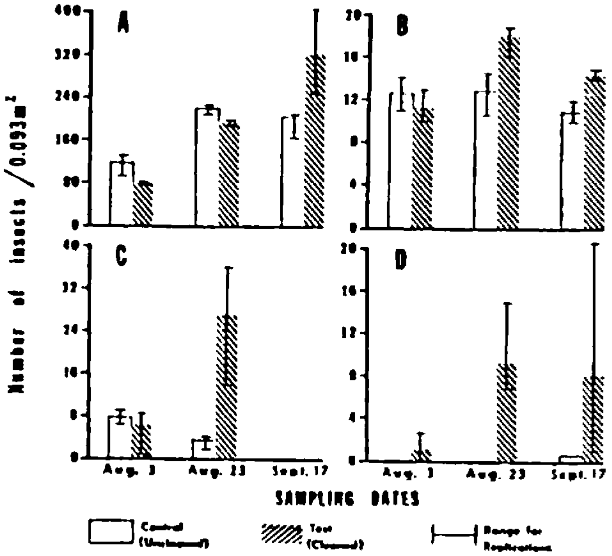


Figure C.4. (From Bjornn et al. 1977). Density of benthic insects in cleaned (test) and uncleaned (control) sections in Elk Creek riffles. A = total insects; B = number of species; C = _Ameletus sparsatus_; D = _Paraleptophlebia heteronea_.

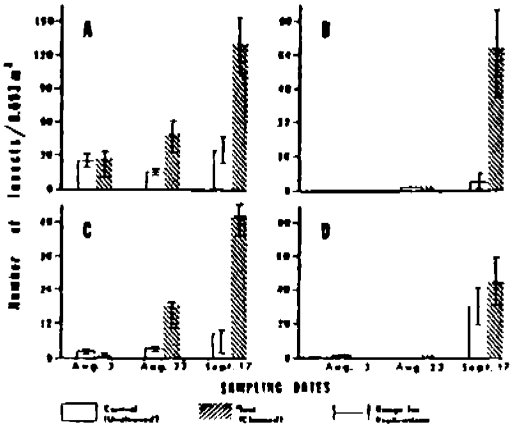


Figure C.5. (From Bjornn et al. 1977). Density of benthic insects in cleaned (test) and uncleaned (control) sections in Elk Creek riffles. A = Ephemeroptera; B = _Rhithrogena robusta_; C = _Alloperla_ sp.; D = _Ephemerella inermis-infrequens_ complex.

Bjornn et al. (1977) summarized their results by stating that several substrate parameters, namely (1) predominant substrate, (2) level of cobble embeddedness, and (3) size of sediment surrounding cobble can be compared with criteria for benthic insect habitat in Idaho batholith streams. Less insects lived where cobble embeddedness by fine sand (< 6.35 mm) exceeded 2/3, and where large amounts of sand were present. On the other hand, embeddedness caused by a heterogeneous mix of sediment around pebbles and small cobbles provided good habitat for insects. Completely clean cobbles apparently do not provide as suitable an environment for benthic insects as partially embedded cobbles.

Bachman (1958) reported a significant reduction in standing crop of aquatic insects in a northern Idaho stream after sedimentation had increased as a result of logging, and Tebo (1955) reported similar results for a small stream in North Carolina. Cederholm and Lestelle (1974) found highly significant negative correlations between the mean percentage of fines smaller than 0.84 mm and the mean number of benthic insects per 0.10 m^2 sample (Figure C.6.)

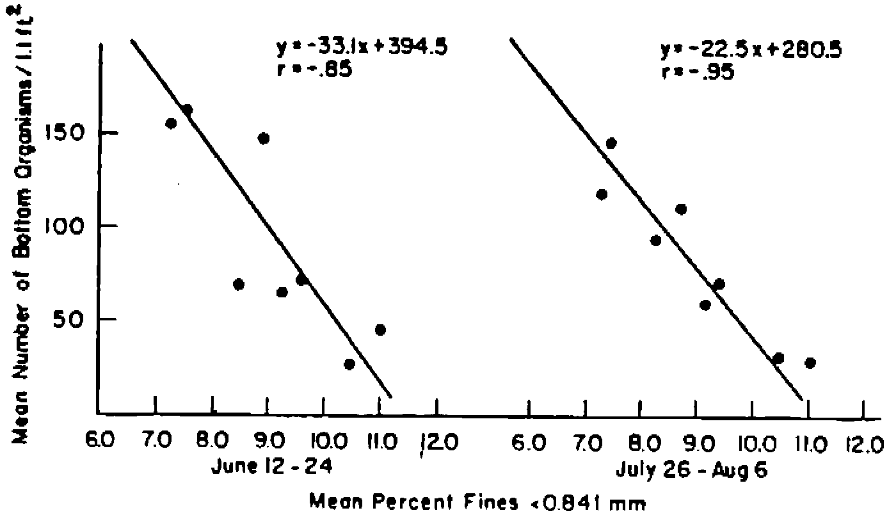


Figure C.6. (From Cederholm and Lestelle 1974). Mean numbers of bottom organisms correlated with mean percentages of fines smaller than 0.841 mm in diameter.

Munther and Frank (1986 a,b,c) reported extremely poor correlations between embeddedness or free-matrix particles and various macroinvertebrate habitat utilization indices. Table C.5 lists invertebrate niche characteristics and r^2 values, none of which exceeded 0.32, and all of which were non-significant.

Table C.5. (From Munther and Frank (1986 a,b,c). Linear relationships between embeddedness, free matrix particles and invertebrate habitat utilization indices for 20 sample locations in the Deerlodge, Lolo, and Bitterroot national forests.

Particle Measurement	Invertebrate Measurement	r2 value
Embeddedness %	% Taxa are Sediment Tolerant	.05
Embeddedness %	% Community Numbers are Sed. Tolerant	.21
Embeddedness %	% Biomass is Sediment Tolerant	.04
Embeddedness %	% Taxa require Intersticial Spaces	.00
Embeddedness %	% Comm. Numbers require Interstic. Space	.07
Embeddedness %	% Biomass require Intersticial Spaces	.08
Embeddedness %	% Taxa use Top of Substrate	.05
Embeddedness %	% Community Numbers use Top of Substrate	.14
Embeddedness %	% Biomass use Top of Substrate	.32
Free Matrix %	% Taxa are Sediment Tolerant	.06
Free Matrix %	% Community Numbers are Sed. Tolerant	.22
Free Matrix %	% Biomass is Sediment Tolerant	.04
Free Matrix %	% Taxa Requiring Interstical Spaces	.00
Free Matrix %	% Comm. Numbers Req. Interstic. Space	.02
Free Matrix %	% Biomass Requiring Intersticial Space	.07
Free Matrix %	% Taxa Using Top of Substrate	.17
Free Matrix %	% Community Numbers use Top of Substrate	.24
Free Matrix %	% Biomass Using Top of Substrate	.22

Munther and Frank (1986 a,b,c) attempted to relate embeddedness and free matrix particles to macroinvertebrate habitat groupings (forms that use the substrate surface, interstitial users, and burrowers, sediment-tolerant groups). Munther and Frank felt that one possible explanation for failure of abundance of species groupings to correlate with embeddedness could have been that some forms are neither discrete nor obligate residents of the habitat zones to which they were assigned. The approach of these authors has a logical basis in that one would expect more sediment-tolerant forms to utilize embedded habitat differently from less tolerant animals, and that residents that depend on the areas beneath the gravel surface should suffer declines in embedded zones.

In light of the results of Spaulding (1986), in which a strongly significant negative effect was shown for embeddedness on insect density and yet r^2 equaled only 0.13, some of the coefficients of determination found by Munther and Frank may require more attention. Three dependent variables had r^2 values greater than 0.13; percent of community numbers that are sediment tolerant ($r^2 = 0.21$), percent of community numbers that use the top of the substrate ($r^2 = 0.14$), and percent of the biomass that uses the top of the substrate ($r^2 = 0.32$).

Munther and Frank had four dependent variables that had r^2 values greater than 0.13 when related to free matrix particles; percent of community numbers that are sediment tolerant ($r^2 = 0.22$), percent of taxa using top of the substrate ($r^2 = 0.17$, percent of community numbers and biomass using top of the substrate ($r^2 = 0.24$ and $r^2 = 0.22$, respectively). Of course, values for r^2 do not demonstrate regression slope. Munther would have to reanalyze data so that the regressions could be evaluated.

Spaulding (1986) extensively evaluated two sections of Big Creek, Utah. One section in a rest-rotation grazing allotment was compared with another that had been rested from grazing for four years. He extracted 32 Surber samples on transects in the treatment (grazed) and control (rested) sections. Mean abundance of macroinvertebrates was 99.6 on the ungrazed and 73.7 on the grazed sections (significant at $p = 0.05$). The greatest differences occurred among the collector and shredder groups, with the former more abundant in the grazed site and shredders more plentiful in the ungrazed section.

Spaulding (1986) regressed insect abundance against percent surface embeddedness (measured with U.S. Forest Service methods) and found a significant negative effect of embeddedness on density ($F = 11.6$, 1 and 62 d.f., $p = 0.05$, $r^2 = 0.13$). Although the degree of variability explained by the data was not high, insect abundance was reduced by an absolute 21% where embeddedness was 3/4 to full in comparison to where embeddedness was 1/2 to 3/4.

C.2. Insect drift

Bjornn et al. (1977) examined effects of sediment on quantity of drifting insects in artificial stream channels. Drift at sunset was not related to embeddedness in the channels (Figure C.7), or to sediment addition in given levels of embeddedness, according to the authors. However, they did not try to quantify the immediate effect of sediment introduction on insect drift.

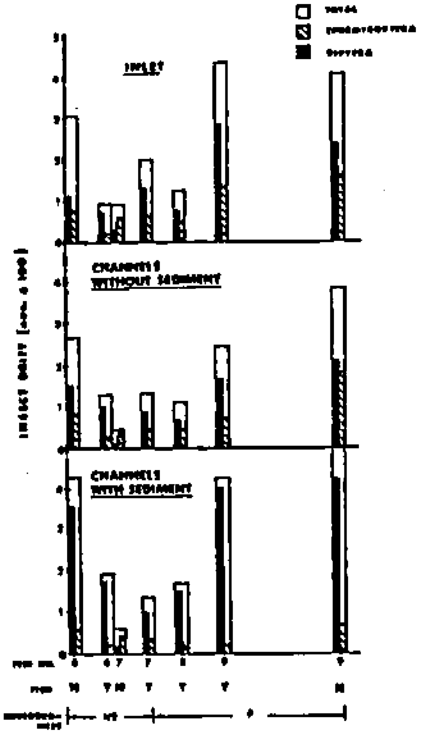


Figure C.7. (From Bjornn et al. 1977). Insect drift at sunset in two experimental channels. 1/2 = half cobble embeddedness; F = full embeddedness; Y = fish in channels; N = no fish. Horizontal scale is temporal.

In correlational sampling in Bearskin Creek, Bjornn et al. (1977) found that drift density in pools was significantly (p = 0.05) related to riffle area, but not to sedimentation in riffles (Figure C.8).

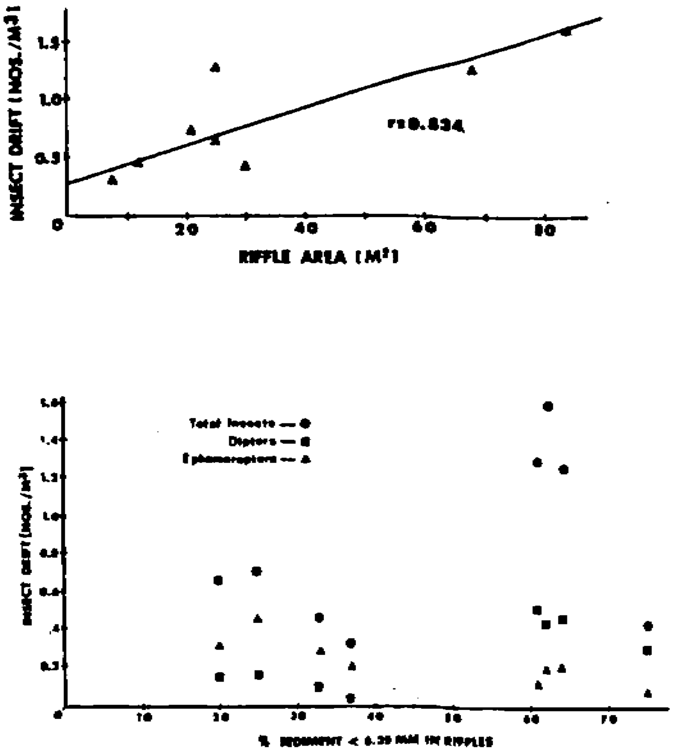


Figure C.8. (From Bjornn et al. 1977). Relationship between riffle area and insect drift (upper graph) and between riffle fines and insect drift (lower graph).

Drift density did not correlate with drift density in Bearskin and Elk creeks, both tributaries of the Middle Fork Salmon River (Figure C.9).

The results of Bjornn et al.(1977) are somewhat surprising. Sedimented substrata should offer fewer hiding places and livable substrate (Hynes 1970 and Cederholm and Lestelle 1974) for aquatic insects than would clean substrate. The literature on predation suggests that prey vulnerability decreases as environmental complexity increases (Huffaker 1958, Stein and Magnuson 1976, Saiki and Tash 1979).

Wilzbach et al. (1986) investigated effects of reducing habitat complexity in trout-macroinvertebrate predation by covering the bottoms of test pools with fiberglass screening to deny insects access to crevices. They showed that cutthroat trout captured a higher percentage of drifting prey in crevice-

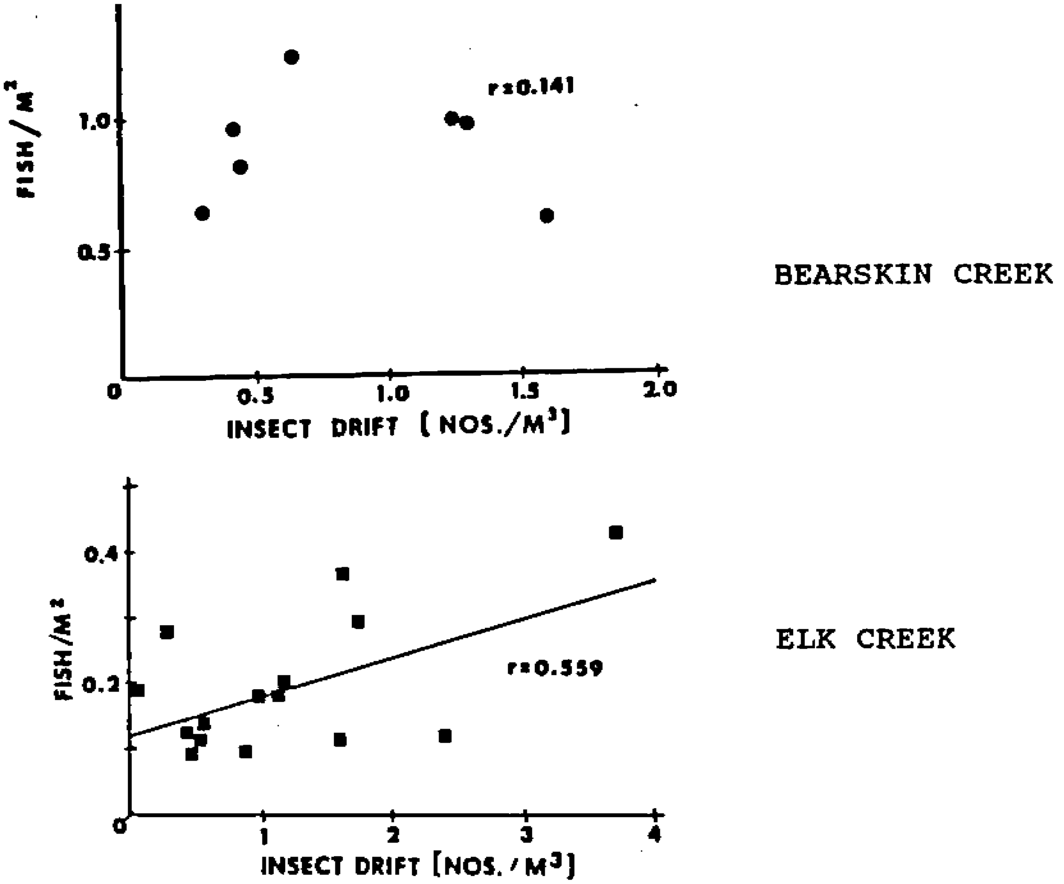


Figure C.9. (From Bjornn et al. 1977). Relationship between fish density and insect drift in Bearskin and Elk creeks, Middle Fork Salmon River, Idaho.

covered pools. The authors felt that the increased efficiency was associated with increased visibility of drifting prey, rather than with inability of prey to escape to crevices.

Embedded substrata should be somewhat similar to a substrate covered with fiberglass screening. That is, visibility of drifting prey should increase and the work required to find prey should decrease as the substrate becomes smoother. Net energetic efficiency of salmonids should increase in this circumstance. Bjornn et al. (1977) (Figure C.10) showed that density of fish in the fully sedimented channel was much lower than density in the unsedimented channel, that fish in both environments grew in length and weight, but that fish in the unsedimented channel were longer and weighed more than in the unsedimented one. Perhaps improved foraging efficiency, in the sense of net gain for units of work, was responsible. This is of scientific interest, but the negative influence of sedimentation on density and growth rate is the main concern.

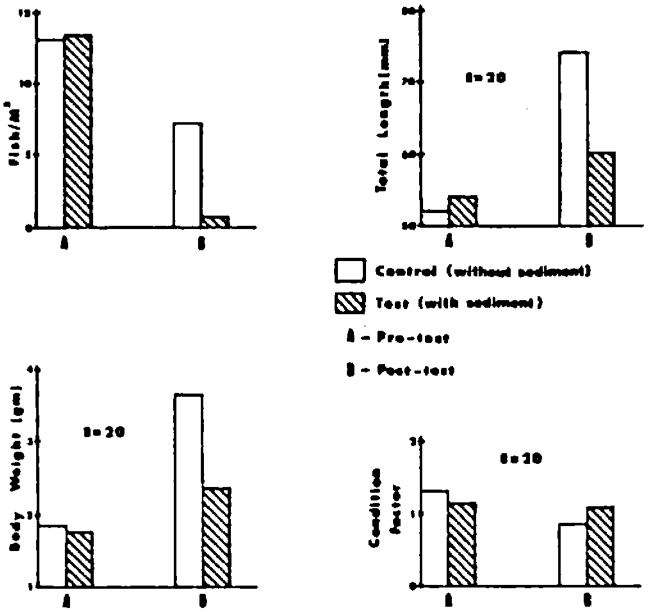


Figure C.10. (From Bjornn et al. 1977). Fish density, length, weight, and condition factor in control and embedded channels, for age 0 hatchery steelhead, 1975. Condition factor = length^3/weight.

Konopacky (1984) felt that work reported by Bjornn et al. (1977) and other University of Idaho researchers probably did not take adequate account of in-channel vs. inflow drift, and area of substrate that produced food upstream from the drift-sampling points. Konopacky blocked incoming drift by placement of nets 0.25 mm in mesh opening across the entire inflow. Thus, drift out of the stream channels originated within the channels. He compared drift from a sand-pebble mixture (2.1 mm median particle size) and a gravel (36.9 mm median size) (Figure C.11). Drift from the sand-pebble mix contained more organisms but similar biomass of invertebrates in comparison with the gravel mix (Figure C.11). Individual weight of organisms tended to be larger from the gravel-bottomed channel than from the sand-pebble mix.

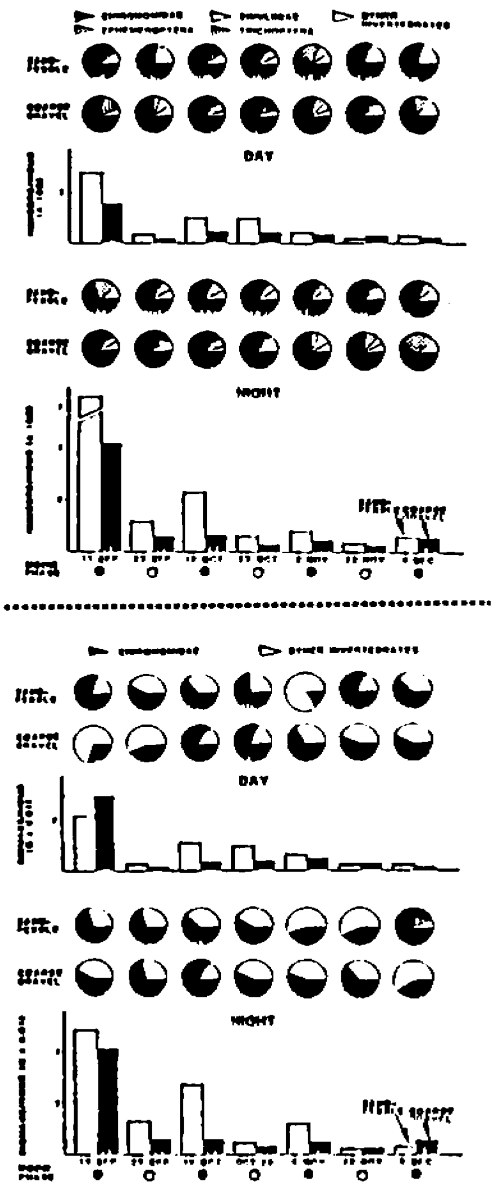


Figure C.11. (From Konopacky 1984). Abundance (top graph) and biomass (bottom graph) of invertebrate drift from channels with a sand-pebble (white boxes) and gravel (black boxes) substrate.

The gravel used by Konopacky had 5.9% less surface area and 17 times more interstitial area than the sand-pebble mix. The gravel did not offer a heterogenous habitat and probably did not trap as much detritus as a mixture of gravel, small gravel, and sand. Bjornn et al. (1977) showed that a substrate that was 1/3 to 2/3 embedded contained more insects than a substrate free of embeddedness. Kennedy (1967) and Rabeni and Minshall (1977) offered data that showed that a substrate with a mix of particle

sizes offers better habitat for macroinvertebrates.

D. RUBBLE COVER FOR SALMONID WINTER HIDING.

D.1. Effects of temperature on substrate use

Rimmer et al. (1983) observed that juvenile Atlantic salmon moved into the substrate in rearing areas at water temperatures below 10 C (Figure D.1).

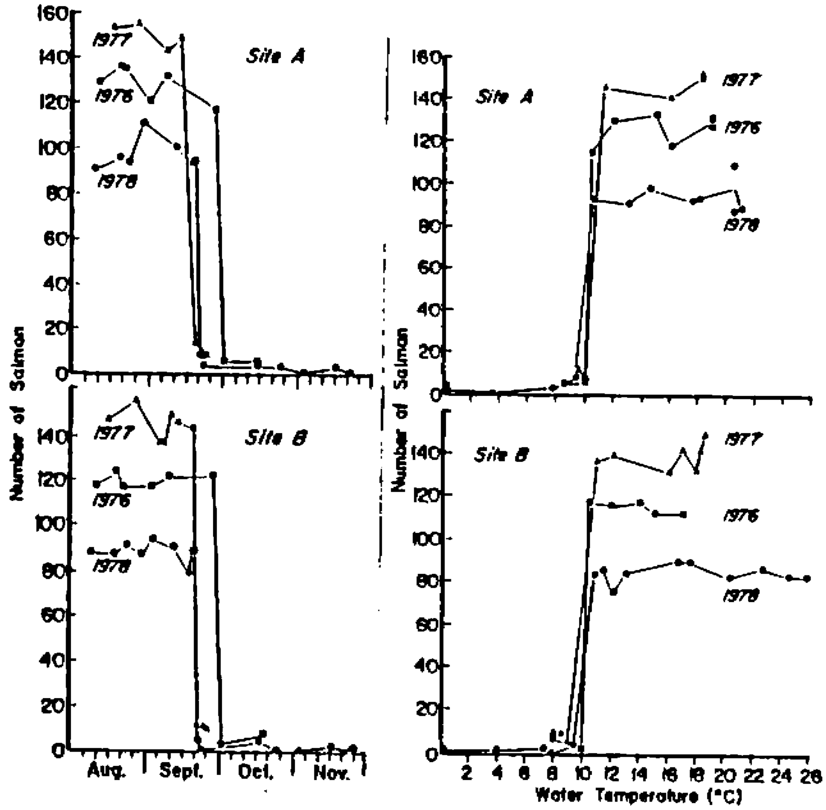


Figure D.1. (From Rimmer et al. 1983). Temporal changes in number of visible Atlantic salmon juveniles in two sites (left graphs), and counts in relation to water temperature in 3 years (right graphs).

Hartman (1963) reported that brown trout tended to associate with the stream bottom in winter at temperatures of 0.5 C, but to be well above the substrate in spring at 12.5 C. Juvenile chinook salmon and steelhead trout move into the substrate at temperatures below about 5 C (Chapman and Bjornn 1969), at least during the day. Figures D.2 and D.3 graphically demonstrate cover-seeking behavior of steelhead and chinook salmon in an experimental environment in laboratory tanks.

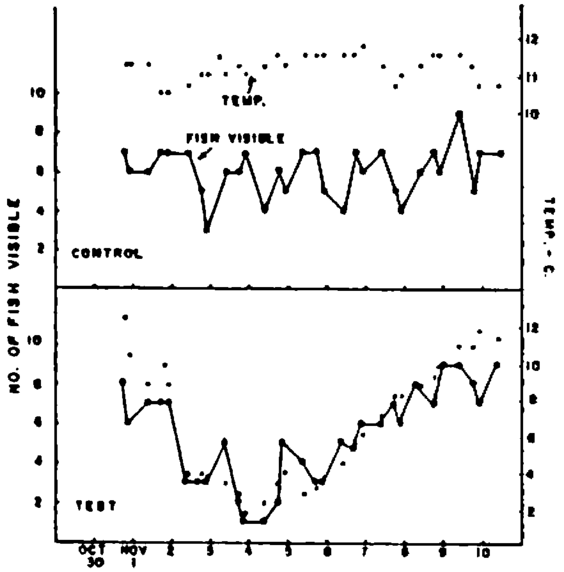


Figure D.2. (From Chapman and Bjornn 1969). Numbers of juvenile steelhead visible above a rubble substrate during the day in laboratory tanks in relation to water temperature.

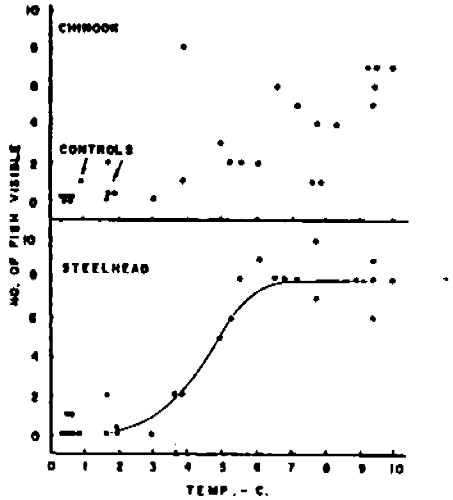


Figure D.3. (From Chapman and Bjornn 1969). Chinook salmon and steelhead juveniles above rubble substrate during the day as a function of temperature.

The experiments first noted above (Figure D.2) were conducted with age 1+ steelhead, and those in Figure D.3 with age 0 steelhead and chinook salmon. Everest et al. (1986) reported that age 0 steelhead remained active above the substrate at lower temperatures than yearling steelhead (Figure D.4). The ecological or physiological significance of this difference is unknown.

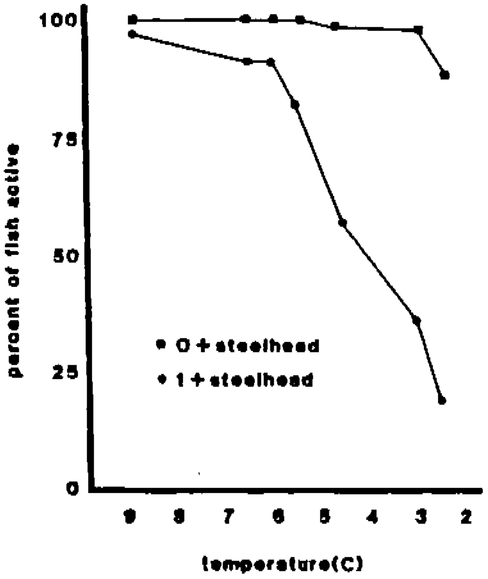


Figure D.4. (From Everest et al. 1986). Percentage of juvenile steelhead observed active in a laboratory stream as temperatures declined.

The laboratory observations stimulated tests in artificial streams that more closely simulated natural environments of juveniles. Fish that were actively moving downstream in the Lemhi River in Idaho were placed in stream troughs at 12.2 C and at 0-10 C, with substrate consisting of relatively smooth gravel and clean rubble. A higher percentage of fish remained in the lower-temperature environments with rubble. Downstream movement was reduced in the tests in water of higher temperature (Chapman and Bjornn 1969)(Figure D.5).

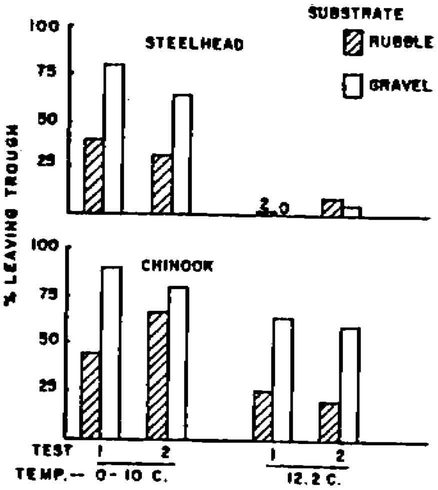


Figure D.5. (From Chapman and Bjornn 1969). Percentage of active downstream migrants that left experimental troughs in 10 days. Data include 2 replicates, 2 water temperatures, and 2 substrate types.

Morrill (1972) assessed downstream migration of age 0 chinook salmon from two stock sources (Lemhi River and Stanley area of upper Salmon River) in stream channels with rock and rubble (termed good substrate) and from gravel or shale (poor substrate) and constant or declining water temperatures (fall months, 1970 and 1971). As temperature declined below 10 C., fish began emigrating. No residual fish were seen above the substrate in daytime at temperatures below 5-7 C. No difference in behavior was noted for the two different stocks of chinook salmon.

Morrill also found that more of the larger chinook salmon moved out of channels with unsatisfactory substrate than did smaller salmon, and that as chinook salmon approached 80 mm in size, they showed increasing preference for suitable substrate in which to hide. Morrill contended that suitable substrate for winter hiding was an important part of winter habitat requirements.

Stuehrenberg (1975) found that age 0 steelhead trout and chinook salmon did not remain in riffle sections of artificial streams in winter when sediment had filled the interstitial spaces of the gravel substrate. Age 1 steelhead used the depth of pools for winter cover, hence tended to remain in the artificial streams.

Observations of densities of juvenile chinook salmon that remain in artificial channels at reduced temperatures as a function of substrate type should be viewed with some caution. Miller (1971) found that retention of fish in channels was a function of water temperature, but that population density, race of fish, and moonlight all influenced movement out of experimental channels. In 4 of 5 experimental densities of juvenile chinook salmon, more fish held in troughs with 13-15 cm gravels than in 5-8 cm gravels. However, at the most-replicated density (75 fish per trough, or 8.6 fish/m^2), more fish remained in the channels with smaller gravels.

Several times in this section we have referred to daytime observations of winter behavior. J. Griffith (unpublished) has observed that some juvenile rainbow trout move out of daytime winter cover and into shallower water during the night, even at low temperatures. T. Hillman (unpublished) observed that pre-smolt chinook salmon in winter remain in the substrate during the day, but often appear on the bottom at night near the crevices or interstices that they used during the day. The percentage of fish that so move has not been determined, and the adaptive significance of such movement is obscure.

D.2. Winter carrying capacity

The next step in experimentation on effects of rubble on downstream movements of juveniles, reported by Bjornn (1971), involved placement of rubble piles in late summer on otherwise relatively smooth substrate in Big Springs Creek, a Lemhi River tributary. Subsequent electrofishing in winter demonstrated that more fish inhabited the areas with rubble piles than control areas without rubble (Figure D.6). Fish continued to use the rubble areas for summer habitat and were found in greater numbers in rubble late in the succeeding winter.

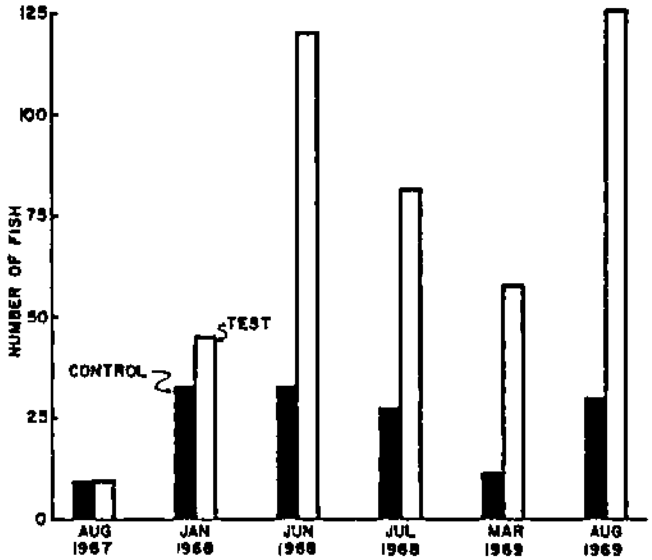


Figure D.6. (From Bjornn 1971). Number of juvenile rainbow-steelhead yearlings electro-sampled from control and test (rubble added) sections of Big Springs Creek.

Hillman et al. (1986) demonstrated in Red River, a Clearwater River tributary with high percentages of fines in the substrate, that density of juvenile chinook salmon at declining temperatures could be increased several-fold if rubble piles were provided for hiding cover (Table D.1), especially when rubble was provided under sheltering streambanks. By March of the succeeding year, cobble piles in the open stream were partially displaced 0.5-1.0 m downstream and severely embedded with fines. Cobble placed under the banks was not as severely embedded. No sampling occurred after early November until March, hence it is unclear exactly when embeddedness increased in rubble piles, or how long juvenile chinook salmon remained in them.

Bjornn et al. (1977) found that embedded channels that contained boulders held fewer chinook salmon, steelhead, and cutthroat trout than channels with boulders and no embeddedness. Everest et al. (1986) reported that large rubble associated with large boulders offered better steelhead overwintering habitat than did rubble or boulders surrounded by small rubble, or boulders alone (Figure D.7).

Table D.1. (From Hillman et al. 1986). Numbers and densities per m^2 (in parentheses) of age 0 chinook salmon in control (no rubble piles added) and test (rubble piles added) areas of Red River, South Fork Clearwater River, Idaho in early winter 1985 and in March, 1986.

Habitat	Date	Exposed substrate		Underbank substrate	
		Altered	Control	Altered	Control
Glide	10/10/85	12(2.4)	0(0)	33(10.3)	8(1.3)
	11/08/85	16(3.1)	0(0)	20(6.3)	4(0.6)
	3/17/86	0(0)	0(0)	5(1.6)	1(1.6)
Riffle	10/10/85	10(2.4)	0(0)	18(8.2)	0(0)
	11/08/85	8(1.9)	0(0)	16(7.3)	1(0.2)
	3/17/86	0(0)	0(0)	1(0.5)	0(0)

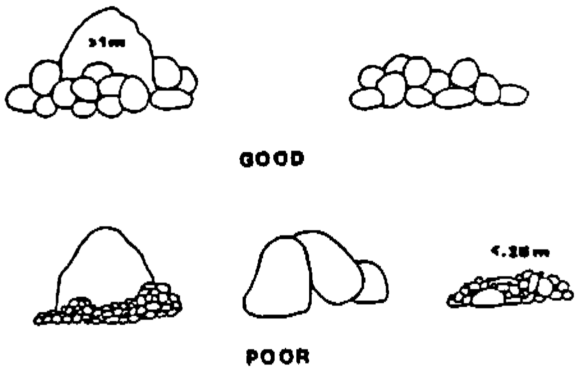


Figure D.7. (From Everest et al. 1986) Examples of winter habitat in which 1+ steelhead were observed in Fish Creek, a Clackamas River tributary.

It is logical to extend the observations of Everest et al. (1986) with the data of Bjornn et al. (1977), which showed that juvenile steelhead, chinook salmon, and cutthroat trout tended to remain in unsedimented channels with boulders and to leave embedded channels (Figure D.8). We conclude that embedded habitat reduces winter carrying capacity.

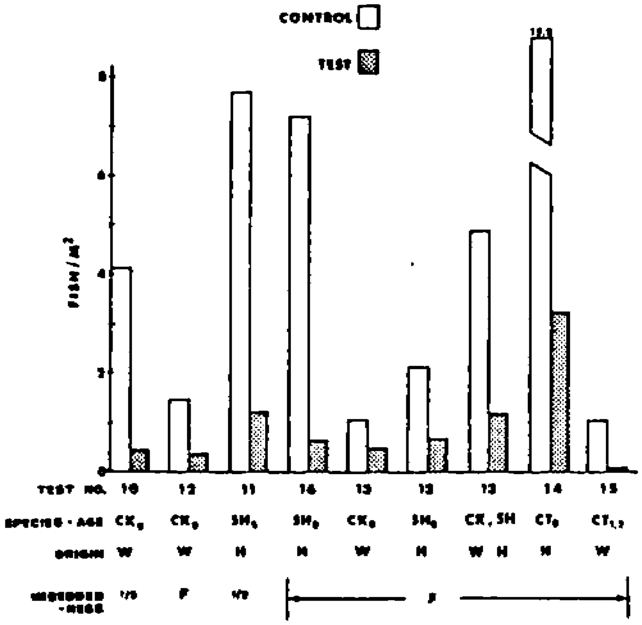


Figure D.8. (From Bjornn et al. 1977). Densities of fish remaining in artificial stream channels after 5 days in winter tests, 1975. W = wild; H = hatchery; CK_0 = age-0 chinook salmon, SH_0 = age 0 steelhead; CT_0 = age 0 cutthroat trout; $CT_{1,2}$ = age I, II cutthroat trout.

D.3. <u>Habitat and species differences</u>

As Chapman and Bjornn (1969) pointed out, not all salmonids behave similarly in winter, nor do fish of the same species behave in the same way in winter in all habitats. Species or races of salmonids that have been found under rubble or stones in winter include Atlantic salmon (White 1939 and Rimmer et al. 1983), brook trout in northern Quebec and Newfoundland (Cunjak and Power, unpublished data cited in Cunjak and Power 1986, and Cunjak, M.S. thesis cited in Cunjak and Power 1986), brown trout (Hartman 1963), steelhead (Bjornn 1971, Chapman and Bjornn 1969, Bustard and Narver 1975a, Everest et al. 1986), cutthroat trout (Bustard and Narver 1975b), chinook salmon (Chapman and Bjornn

1969, Hillman et al. 1986). Coho salmon tend to aggregate on the bottom of pools in winter (Hartman 1965, Mason 1976, Bustard and Narver 1975a). Cunjak and Power (1986) reported that brook and brown trout in the Credit River did not enter the substrate in winter, instead they aggregated beneath cover in pools and close to point sources of groundwater discharge.

Hartman (1963) reported that brown trout hid within the substrate in cold water, and Stuart (1957) recorded a downstream movement of brown trout in October as water temperatures dropped or in advance of declines to winter temperatures less than 4 C. Allen (1951) reported for the Horokiwi Stream in New Zealand that brown trout fed all winter, generally had no winter check on scales, and did not move seasonally. The Horokiwi Stream generally had water temperatures in excess of 7 C.

Rimmer et al. (1983) found a dramatic shift by Atlantic salmon from summer feeding stations to winter hiding locations in the rubble substrate as water temperatures decreased below about 10 C (Figure D.9). These workers established that this shift

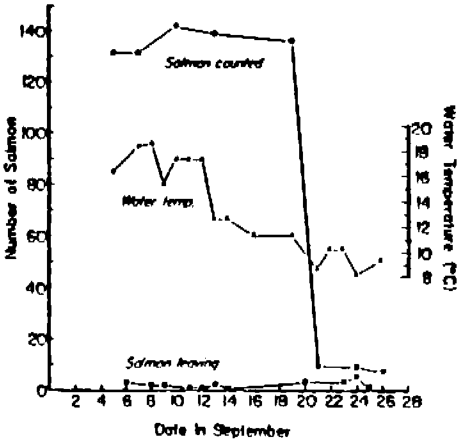


Figure D.9. (From Rimmer et al. 1983). Chronological changes in numbers of visible juvenile salmon counted, and relationship between number counted and water temperature in the same years, and salmon trapped as they left the site.

occurred within the habitat areas used in summer, and that it was not accompanied by downstream movement out of the area.

Cutthroat trout of larger size tend to leave summer habitat in the Middle Fork of the Salmon River (Mallet 1963) and the upper Clearwater River (Ball 1971, Hogander et al. 1974) and to return in spring. Chapman (1962), Salo and Bayliff (1958), and Shapovalov and Taft (1954) found little or no downstream movements of juvenile coho salmon during fall and winter.

Petersen (1980) found that juvenile coho salmon in the Clearwater River on Washington's Olympic Peninsula often moved considerable distances downstream in fall, then entered wall-base channels (small streams that issue forth from the base of incised terrain along main river channels) or spring ponds, where they over-winter. Everest et al. (1986) stated that small ponds provided important overwintering habitat for juvenile coho salmon in Fish Creek in the Clackamas River, and suggested that provision of this type of habitat would be a productive enhancement tool. Steelhead used large boulders and rubble for overwintering in the main channel of the stream.

Murphy et al. (1986) examined effects of various habitat features on winter fish densities in Alaskan coastal streams. Fine sediment, defined as percentage of cross-stream transect length covered by particles smaller than 2 mm, was not significantly related to density of coho salmon fry, parr, Dolly Varden parr, or trout parr (steelhead and cutthroat combined). Coho salmon parr density was significantly related to undercut banks, pool volume, and instream debris (large woody debris). Debris would be a correlate of pool volume. Dolly Varden parr density was significantly related only to woody debris; trout parr density to undercut banks and canopy density. Sediment percentage on transects averaged less than 11.2% in the most sedimented stratum, and no single sediment percentage exceeded

19.2%. Average sediment ranged from 7.8 to 11.2% on old-growth, buffered, and clear-cut strata. These surface sediment proportions are not particularly high when compared with, say, the South Fork Salmon River in Idaho (Platts and Megahan 1975), although fines in the latter were assessed as smaller than 4.7 mm rather than 2 mm. Particle size distributions in samples from the South Fork Salmon River indicated that the percentage of particles smaller than 5 mm (about 35%) was roughly equivalent to 20% particles smaller than 2 mm.

Apparent differences in winter behavior in various populations may be associated with fish size, severity of winter temperatures to which the population has adapted, availability of refugia from freshets, and time-series behavior. One would expect, for example, that streams with a snow-melt hydrograph would have salmonid populations adapted to in-substrate overwintering of small fish (juvenile chinook salmon, steelhead, and probably one-and two-year-old cutthroat and bull trout).

That populations of salmonids can adapt genetically to local temperature patterns was shown by Miller (1971), who demonstrated that three races of spring chinook salmon, all from the upper Salmon River drainage in Idaho, differed significantly in temperature-related behavior in artificial channels. Cunjak and Power (1986), comparing substrate hiding in brook trout in northern latitudes of Canada with above-substrate aggregations beneath cover in the southern latitudes, hypothesized that these different behaviors reflected differences in severity of winter. Severe freezing in the stream would favor overwintering in the substrate, while alternating freezing and thawing and different types of ice formation would make a more active wintering behavior adaptive.

Where suitable rubble substrate is not available, pre-smolt salmon and steelhead appear to move downstream until they find such habitat. These fish would not have to return in the following spring. Absence of nearby clean rubble should be particularly limiting for juvenile cutthroat and bull trout, or for young resident rainbow trout, which should have difficulty in returning against freshet flows from the same downstream migration as made by larger, older fish of the same species. Juvenile salmonids (eg. age-0 steelhead) that must remain in the stream for two or more years would also suffer from absence of winter hiding habitat in the rearing areas. Ice and ice scour would cause a difficult situation for juveniles unable to find refugia within summer habitat areas.

Larger, older fish capable of reascending streams in spring should have difficulty in burrowing down into interstices in summer habitat, simply on grounds of relative size of fish and crevices. Movement downstream is probably adaptive for these fish.

In coastal watersheds with a rainfall hydrograph and where ice formation in rivers is unusual, as well as in areas with mixed hydrologic pattern, steelhead use rubble refugia in winter (Bustard and Narver 1975a, Everest et al. 1986) while coho salmon aggregate over bottoms of pools, under log jams, or utilize spring ponds and wall-base channels (Peterson 1980, Tschaplinski and Hartman 1983).

Mason (1976) and Ruggles (1966) offered experimental refugia to coho, in the form of flat rocks on pool bottoms, but were unable to increase habitat capacity during winter. Bustard and Narver (1975b) reported that coho do not enter rubble substrate during winter. It appears that quiet, relatively deep pool bottoms, undercut banks, and log jams offer the best winter habitat. Tschaplinski and Hartman (1983) showed that water velocities in the areas used by juvenile coho during winter were always less than 0.3 m/s.

Bustard and Narver (1975a) reported that focal point velocities used by young steelhead in winter were directly related to water temperature (Figure D.10). Both steelhead and coho salmon yearlings tended to use deeper water than age-0 fish (coho salmon take one or two years and steelhead 2-4 years to reach smolt size) (Figure D.11) in the area studied by these authors.

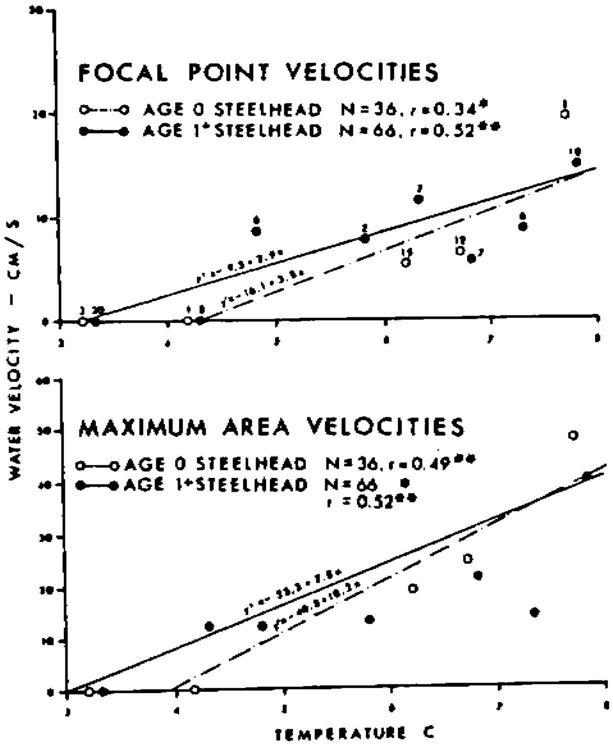


Figure D.10. (From Bustard and Narver 1975a). Mean focal point and maximum area water velocities selected by age-0 and age 1+ steelhead in relation to temperature.

Bustard and Narver found little winter use by age-0 steelhead of substrata with diameters smaller than 10 cm, at least in the main portion of Carnation Creek, but it is unclear whether this was because of scarcity of fines. The report tends to indicate that fine particles were available but not used. Steelhead did not winter in side channels as did coho salmon.

Bustard and Narver (1975b) showed that both coho salmon and cutthroat preferred sidepools that offered overhanging bank cover

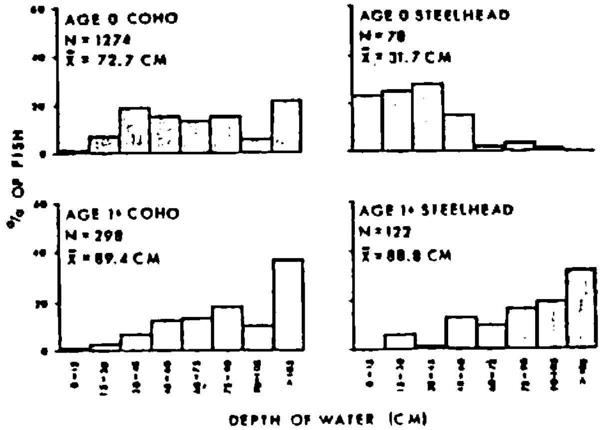


Figure D.11. (From Bustard and Narver 1975a). Depth of water selected by coho salmon and steelhead at water temperatures of 7 C or less.

and clean rubble substrate as opposed to silted rubble. In tests that offered equal amounts of side-bay rubble with and without silt, cutthroat were at least 10 times more abundant in clean rubble areas (Figure D.12).

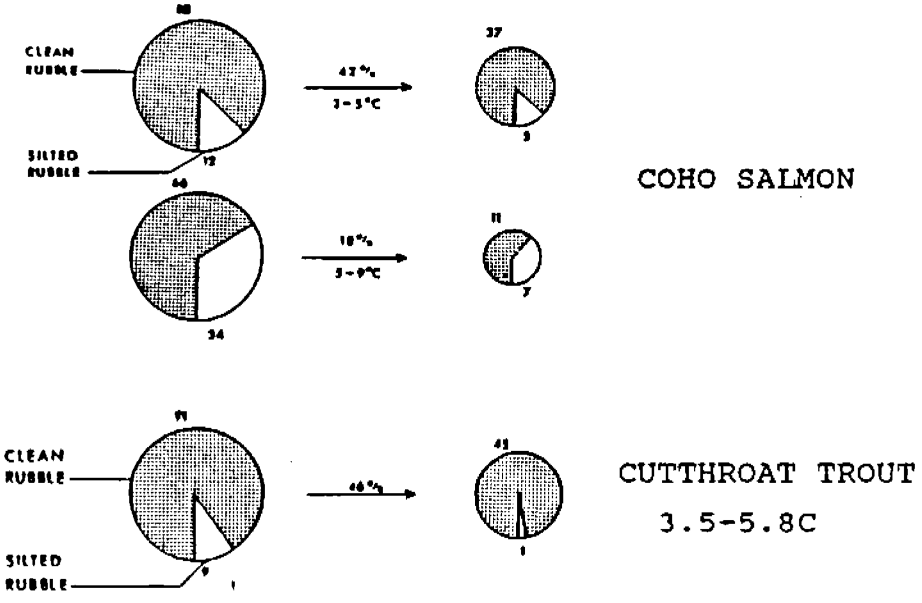


Figure D.12. (From Bustard and Narver 1975b) Percentage of coho salmon and cutthroat trout that chose clean and silted rubble when offered equal amounts of clean and silted rubble in sidepools. Left circles pertain to periods of obligatory residence, right circles to volitional access to main stream.

D.4. Conditions in the Northern Rockies

Throughout the Northern Rockies, snow-melt hydrographs dominate flow patterns except in relatively uncommon spring-fed streams. Addition of sediments to the substrate would tend to block juvenile salmonids from essential winter refugia. Most species of juvenile salmonids in the region either are known to, or thought to, seek refuge in the substrate in winter, although they may leave these sites during the night. Inasmuch as such night shifts, to whatever extent they occur, are followed by disappearance of fish during the following day, winter refugia are apparently required during the day.

Embedded substrata would potentially limit carryover of resident juveniles to the next growing season, and force downstream movement of anadromous fish. Whether the latter movement would reduce survival over that occurring, on average, in rearing areas has not been determined. The fact that juveniles stay in rearing areas if offered suitable overwintering conditions suggests that fall migrants seek the most-upstream available substrate near rearing areas.

We do not know if winter habitat is in short supply. The work of Mason (1976) showed that winter cover controlled overwintering abundance of coho salmon. Chapman (1966) hypothesized that population regulation in winter was solely space related, without a food component. Cunjak and Power (1986) suggested that space limitations in winter mean that many fish simultaneously seek a common goal (suitable winter space). This results in a clumping or squeezing effect where fish are restricted in their occupation of a limited spatial commodity (Cunjak and Power 1986).

We suggest that at the higher densities of salmonids observed by Thurow and Burns (unpublished) and by Petrosky and Holubetz (1986), about 50-60 fish/100 m^2, winter densities in stream reaches where fish winter where they reared would also equal about one fish per two square meters. Given that interstices do not occur everywhere in any stream reach of several hundred meters, in fact lie in "clumped" or contagious distributions, densities of fish per unit area must be much higher in those limited areas during the winter if all fish in the rearing areas were to find refuge in the substrate. The possibility of competition for winter spaces certainly exists.

Why should lower, larger stream areas in the northern Rockies region not provide better habitat than smaller tributaries? The answer may lie with ice scour, which occurs in winters with extended extreme cold when rapid warming follows the cold period. Small streams at high elevation tend to freeze over quickly, and are insulated from cold air by bridging of deep snow in most of the northern Rockies. They may have less tendency to lose ice cover during temporary warm spells, and to offer more moderate water temperatures beneath the snow. Larger streams do not freeze over as readily, but may often reach colder temperatures than snow-insulated tributaries and have more extensive substrate disturbance during ice scour. Ice block buildup can develop massive proportions, and breakup may bring catastrophic scouring.

The solid cover of ice and snow at high elevation has an additional benefit for salmonids that overwinter there. Warm-blooded predators do not have access beneath the snow in most such areas. In the larger streams at lower elevation, birds and mammals may have easier access to prey.

Another advantage accrues to fish that overwinter in the same areas in which they reared. They do not have to move downstream in the low, clear flows of fall to reach wintering habitat. They continue to have access to familiar cover or move relatively short distances to winter habitat. The longer the journey to winter habitat in low, clear water, the higher will be the likelihood that the transient is taken by a predator, either warm- or cold-blooded. It might be argued that anadromous smolts must traverse the same distance (equivalent to the distance from rearing area to downstream wintering area) sooner or later. We contend that later is better, at least for fish of smolt size, largely because spring flows are higher and water more turbid, factors that should reduce predation.

In light of the foregoing discussion, we suggest a scenario for the worst of all worlds for salmonids of the northern Rockies. This would be a winter of light snow and cold air temperatures (no snow bridging for protection), followed by a late winter "chinook" or thaw with accompanying ice scour, in turn followed by low flows in the following summer because of low snow pack. Anadromous fish that move toward the sea in the spring could avoid the summer low flows but face truly difficult passage problems in reservoirs because of low discharge in spring.

Hillman et al. (1986) found that rubble piles that they placed in Red River became embedded with fines between November and March. Although no data exist to establish the fate of fish that were using the piles for wintering in November, the role of fines in filling interstices of winter habitat may be important. If the displaced fish were less likely to survive the displacement and subsequent search for replacement winter habitat than other members of the cohort that departed in early fall, addition of rubble piles conceivably increased mortality for fish induced to winter in them.

Whether the foregoing, or other hypotheses, represent reality, it seems prudent to follow the lead offered by existing information. That is, to assume that fish seek winter habitat in upstream locations, and addition of sediment that reduces availability of this environmental requisite probably increases mortality.

IV. FINE SEDIMENTS AND CHANNEL MORPHOLOGY

Although we have not specifically discussed channel morphology as a function of sediment recruitment, we believe we cannot ignore this topic. Our work assignment dealt with sediment-related criteria for evaluation of best management practices. We concentrated on the intragravel environment and fine sediments as if the larger sediment components were fixed. Although an appropriate approach for the assignment, it ignores the role of unusual storm events and landslides in controlling channel shape. This report section, while certainly not exhaustive, may serve to caution readers about the importance of channel structure in legislating conditions for salmonid spawning and rearing.

A. AGGRADATION AND DEGRADATION

Lisle (1982) recorded changes in channel structure after a major storm event in northwestern California. Gaging station cross-sections widened by up to 100% and aggraded as much as 4 m, then degraded to stable levels over 5 years or more. Pools and bar relief diminished. Figure A.1 plots width, mean depth and mean velocity against discharge for preaggradation, peak aggradation, and post-aggradation periods. Aggradation reduced friction, increased width, decreased depth, and increased average velocity for given discharges. Increased aggradation tended to increase the effectiveness of moderate discharges in bed load transport, hence in shaping the streambed. Slight increases in sediments from the watershed would more easily be transported under these aggraded circumstances.

The net effect of aggradation would be to reduce channel diversity. More fine sediments would move at low and moderate discharges, and channel roughness would decrease, suggesting probable increases in embeddedness levels.

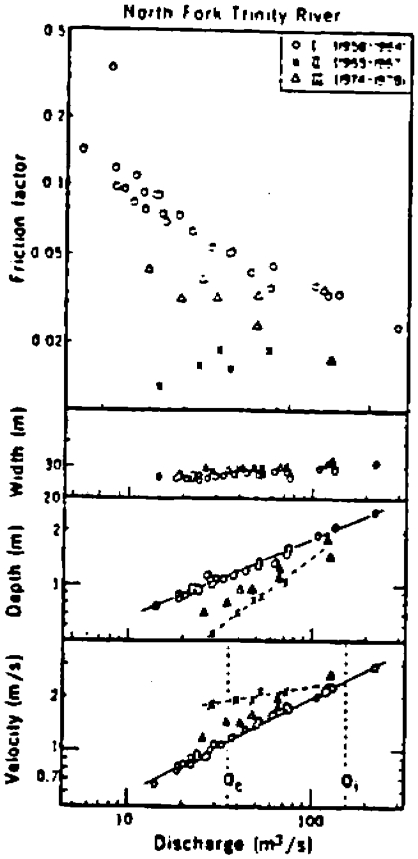


Figure A.1. (From Lisle 1982). Relationships of stream width, mean depth, and mean velocity to discharge in three periods; preaggradation (I), peak aggradation (II), and postaggradation (III). Q_c = discharge at initiation of gravel transport, Q_i = discharge at intersection of hydraulic geometries for pre- and peak aggradation periods.

Nolan and Marron (1985) recorded major changes in bed profiles as a result of floods in Redwood Creek and in the San Lorenzo River in California. Figures A.2 and A.3 indicate that the changes were quite dramatic. The authors noted that changes in channel geometry in northwestern California tend to be long-lasting, and that human activity may have reduced the storm magnitude required to cause channel changes from landslides.

Pearce and Watson (1983) recorded channel morphology after

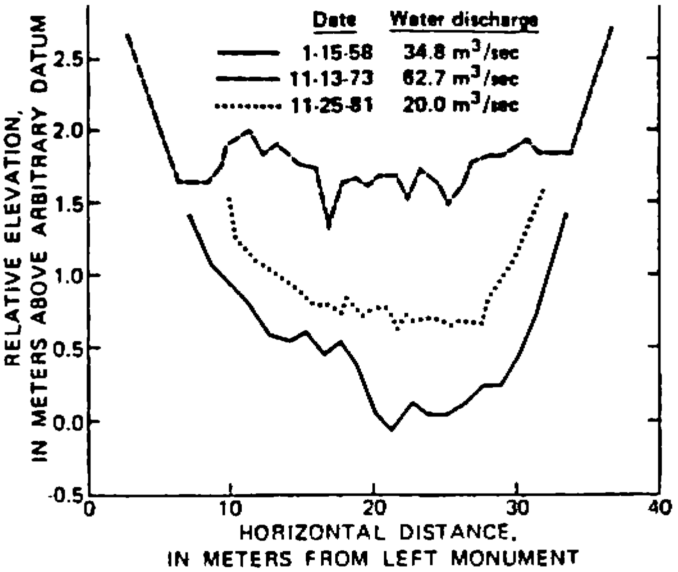


Figure A.2. (From Nolan and Marron 1985). Pre-and post-flood cross profiles of Redwood Creek at a gaging station. Profile of 1958 shows pre-aggradation state, that of 1973 shows the post-flood profile. Profile of 1981 was still elevated.

two landslide episodes in six deeply incised streams in New Zealand. Debris torrents carried about 4,700 m^3 of logs and led to formation of major log jams in five streams. This material led to multi-stepped stream profiles, aggradation of channel reaches up to 150 m long to mean depths of 1.2-4.1 m of deposits, reductions in average gradient, and a reduction in average particle size in the substrate. The authors estimated that sediment stored behind log jams equaled normal supply of sediment for 50-220 years from hillslopes to stream channels. Log jam failure would lead to major morphological changes in higher-order streams.

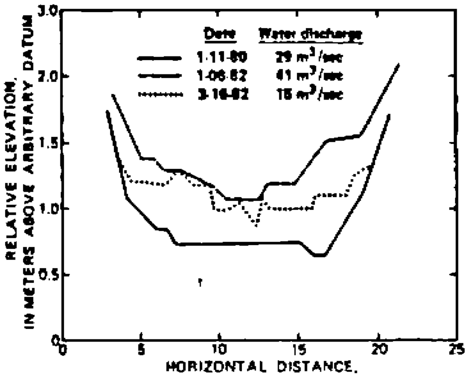


Figure A.3. (From Nolan and Marron 1985). Cross profile of the San Lorenzo River before and after January 1982 flood. Significant quantities of sediment had been removed by March 1982.

Beschta (1983a) studied aggradation in the upper Kowai basin in New Zealand. A 150-year storm there in 1951 stored sediments in the stream channel that remain to date. As distance downstream from sediment input points increased, widths and lengths of the deposits increased and depths of deposition decreased. He noted that the major storm caused hillside stability thresholds to be exceeded, and that thresholds can vary with rock type, faulting, weathering rates, and land use. In another paper, Beschta (1983b) reported that the channel of the Kowai River widened in the vicinity of landslides, and that the widening from aggradation proceeded downstream at a rate of less than 1 km/yr.

B. ROLE OF BED MATERIAL IN GOVERNING MORPHOLOGY OF STREAMS

Beschta and Platts (1986) discussed the important role of bed material in influencing channel characteristics. They noted that a change in the median particle size can influence the frequency and magnitude of bedload transport and may affect channel dimensions.

Increased deposition of fines between gravel particles may affect subsequent bedload transport. Fines in interstices of the bed may delay the onset of bed movement during large flows Beschta and Platts (1986); a movement critical to removal of accumulated fines in spawning gravels. These authors also recognized that salmonids have evolved and adapted to the natural sediments of the stream channel, and that a complex mix of sediments, in combination with certain hydraulic conditions, is needed. They note, for example, that the optimum spawning substrate appears to consist of gravel with small amounts of fines and small rubble to support egg pockets and stabilize the bed in high flows. This recognition of the importance of rubble to the spawning environment constitutes one of the few in the literature. One can infer from Bjornn et al. (1977) that a mix of various particle sizes also is needed by macroinvertebrates.

Whether fines enter a stream from logging, road-building, natural erosion processes, or exposure of streambanks by livestock overgrazing and trampling would seem at first glance to be irrelevant. The micro-effect of a given increment of particles of a given size should be the same. However, different sediment accelerators and the resulting income to the stream may have profoundly different effects on substrate particle compositions (Sullivan et al. 1986). A landslide as a debris torrent, whether natural or man-caused, brings large and small sediments and woody debris with it, forming a source of materials for major or localized aggradation and altered morphology. Recruitment of sand from roads or livestock use may well provide a source of materials that more insidiously alter not only micro-environments for fish and insects but stream width, depth, and friction factors. Table B.1, from Sullivan et al. (1986) notes the differing effects on channel morphology of debris torrents, landslides, and volcanic fines in several example streams.

Table B.1. (From Sullivan et al. (1986). Case histories of channel response and recovery from disturbances.

Area	Type of Disturbance	Channel Response	Recovery Period (Yrs.)	
			Channel	Riparian
Northern California	Logging-induced landslides, surface erosion; large floods	Widening, aggradation, loss of riparian vegetation	5 - 60	100 - 200
Middle Fork Willamette, Oregon	Logging-induced landslides, debris flows, large flood	Widening, aggradation, loss of riparian vegetation	10 - 20	100 - 200
South Fork Salmon River, Idaho	Logging-induced landslides, surface erosion; large floods	Aggradation, deposition of fines, infilling of pools	10	Little impact
Mt. St. Helens Blast Area	Large increases in fine sediment; LOD added, then salvaged	Aggradation, fining of the bed, filling of pools	8 - 25?	100 - 200

C. WOODY DEBRIS AND CHANNEL MORPHOLOGY

Woody debris, in conjunction with sediments, has profound effects on salmonid habitat in streams. An extensive literature has developed around this topic and will not be reviewed here, except in summary. We suggest that the reader obtain Bisson et al. (1987), Sedell and Swanson (1984), Sedell et al. (1985), and Everest et al. (1986) for entry into the literature on woody debris. We will only use this topic to further note the importance of stream structure.

Unpublished data of Dr. P. Bisson, as included in Sullivan et al. (1986) show that removal of woody debris reduces the stream area in pools, increasing that in riffles (Figure C.1).

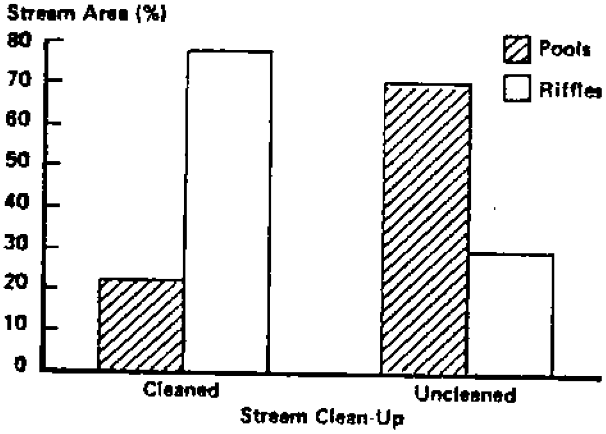


Figure C.1. (From Sullivan et al. 1986). Stream surface area in pools and riffles in zones from which woody debris was cleaned out and in uncleaned zones.

Bisson et al. (1986) reported that hydraulic characteristics of streams influenced habitat utilization patterns of coho salmon, steelhead, and cutthroat trout. Riffles favored steelhead, pools favored coho, and cutthroat used both habitats, although less effectively than the favored species. The authors related body and fin shape of the three species to habitat utilization. Coho salmon have a deep, laterally compressed body with large median and paired fins, a morphology that promotes rapid turns and quick but transient burst swimming. Steelhead have a cylindrical shape with short median fins and large paired fins; attributes well adapted to holding position in swift water. Cutthroat trout are not morphologically specialized, a finding that may explain why coho and steelhead dominate them in sympatry.

Dolloff (1986) removed debris smaller than 60 mm and large debris that was not embedded in the stream channel from sections of two streams. Subsequent population densities and production by coho salmon and dolly varden were higher in the uncleaned sections (Table C.1).

Table C.1. (From Dolloff 1986). Average production and difference in production of coho salmon and dolly varden in cleaned and uncleaned sections of Tye and Toad creeks during three summers, 1979-1981.

Species and age class	Cleaned (g/m²)	Uncleaned (g/m²)	Difference (%)
	Tye Creek		
Coho salmon			
Age 0+	0.80	0.76	+5
Age 1+	0.25	0.39	−36
Dolly Varden			
Age 1+	0.13	0.16	−19
Age 2+	0.12	0.24	−50
	Toad Creek		
Coho salmon			
Age 0+	0.43	0.48	−10
Age 1+	0.25	0.35	−29
Dolly Varden			
Age 1+	0.13	0.24	−46
Age 2+	0.24	0.46	−48

Dolloff attributed the decline in density and production in the cleaned areas to reduced visual isolation in summer and to loss of winter cover. Reductions in production appeared somewhat more severe for dolly varden than for coho salmon.

The foregoing studies illustrate how stream structure may favor or detrimentally affect particular salmonids.

D. RELATIVE ROLE OF STREAM MORPHOLOGY AND FINES

In the northern Rockies, stream morphology, as controlled by sediment and geologic structure and, in some cases, by woody debris, together with bank integrity and riparian vegetation, may be more important as density legislators than is the quantity of fines in and on the substrate. Woody debris may be especially important in headwater streams and in smaller, low gradient stream reaches in Idaho. We do not mean to imply that excessive fines have no negative impact on reproductive success, or that our opinion should be taken to mean that we believe control of recruitment of fines is unnecessary.

It is crucial to our understanding of stream systems in the northern Rockies that more holistic approaches be developed for studies of factors influencing salmonid survival and densities. Much more attention must be paid to effects of stream morphology. We need investigations of the role of woody debris in affecting use of habitat specifically by steelhead, chinook salmon, cutthroat trout, bull trout, and rainbow trout. We would benefit from investigations of riparian vegetation as cover and source of terrestrial insects. Winter habitat as a population legislator in relation to summer habitat requires study.

Without these types of research, without recognition of multivariate response-surface functions, questions about quantitative effects of fines or embeddedness on fish are fated to elicit vague and equivocal responses.

Studies of effects of various habitat features on fish abundance require imaginative approaches to assure full seeding so that the effect of recruitment is minimized. Transfer of fish from one site to another to assure full recruitment may solve this problem. Stocking of hatchery fry or fingerlings may serve.

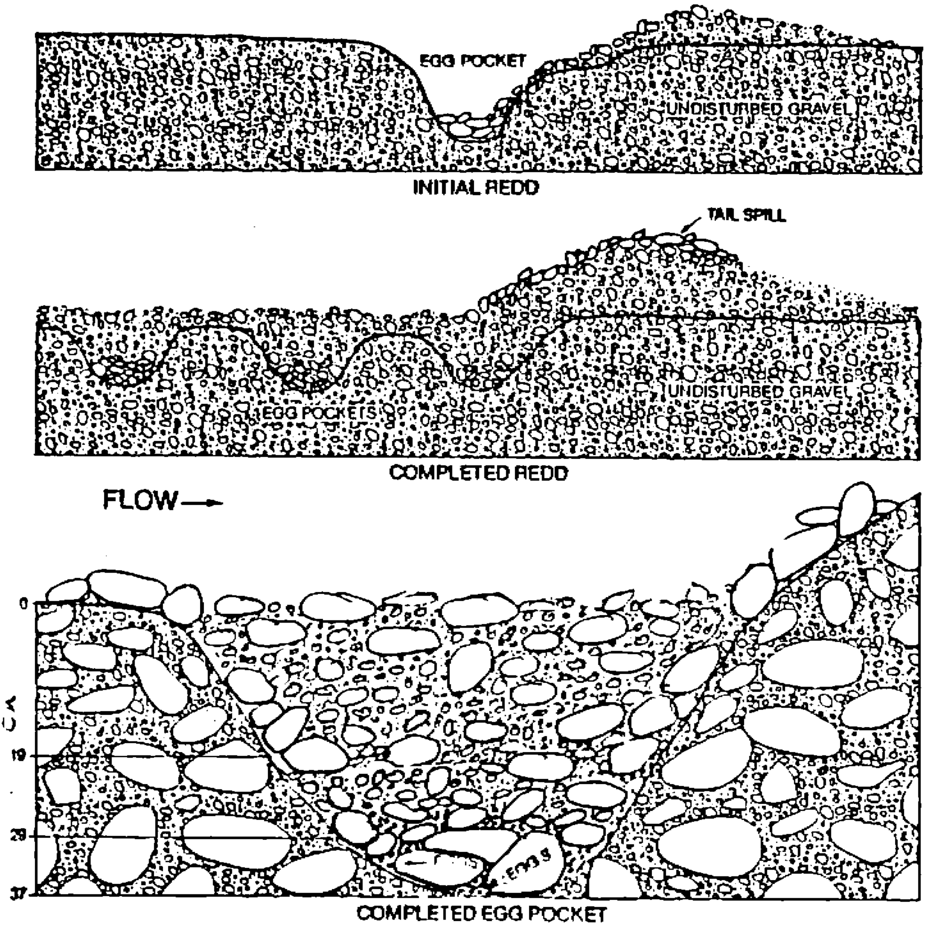
V. TOOLS FOR PREDICTING EFFECTS OF FINE SEDIMENTS ON FISH AND AQUATIC MACROINVERTEBRATES

We use the term "tools" in this report segment in the sense of "models". Specific techniques for securing data on fines in and on the substrate can be found in the summaries by Levinski (1986), and in the papers of Brusven and Prather (1974), Crouse et al. (1981), Burns and Edwards (1985), Lotspeich and Everest (1981), Shirazi et al. (1981), Walkotten (1976), and Platts et al. (1979). Terhune (1958) provides details on the Mark VI standpipe, used to assess permeability and apparent velocity in gravels.

A. INTRAGRAVEL SURVIVAL OF EMBRYOS TO EMERGENCE OF ALEVINS

In light of section II, we now discuss several tools that have been proposed for prediction of effects of fine sediments in field conditions. The models include the fredle index, geometric mean particle size, percentage of fines, and gravel permeability. Platts et al. (1983), Burns and Edwards (1985), Shirazi and Seim (1979), Terhune (1958), and Levinski (1986) provide procedural details for various types of physical sampling tools. We confine our comments primarily to questions of sampling validity, bias, and precision.

Any and all of these independent variables, to offer utility, reality, and permit quantitative prediction of survivals, must be shown to reflect conditions <u>in the egg pocket of the salmonid redd</u>. It is not sufficiently accurate to assume that data from the salmonid redd applies to the redd pocket, for the redd consists of substantial areas outside egg pockets (Figure A.1). Much misleading information and unnecessarily high variances may have been reported in the literature because workers accepted "redd" and "egg pocket" as synonymous.



INITIAL REDD

COMPLETED REDD

COMPLETED EGG POCKET

Figure A.1. Schematic conception of egg pockets within a salmonid redd, in this case a chinook salmon. This diagram is based on numerous nightly measurements of developing redds and excavation of redds (Chapman et al. 1986). Note cobbles that form the centrum in the bottom of the egg pocket, multiple egg pockets spaced sequentially upstream, and depths of egg placement in pockets.

We concede that it is possible that conditions "in the redd" may serve as indicators of conditions in the egg pocket. Inasmuch as data from only one egg pocket have been examined (Platts et al. 1979), substantial testing of the relationship between average conditions within the redd periphery and those in the egg pocket is required before possibility progresses to fact.

Currently-available data that relate survival to gravel composition and permeability in "redds" may be viewed as broadly instructive but specifically speculative as quantitatively predictive analogs. Some of the field sampling information may be accurate, in that coring or permeability samples actually included information from an egg pocket or pockets, but <u>we have no means of determining if that was the case</u>.

In order to demonstrate the generic problem of sampling in egg pockets, we have prepared a diagram to scale that shows three McNeil cores inserted into a chinook salmon redd in longitudinal section (Figure A.2). The diagram of the redd section was developed with the experience of sequential nightly measurements by T. E. Welsh of redd construction in 274 chinook salmon redds in the Columbia River, and excavations in 369 redds (Chapman et al. 1983 and 1986).

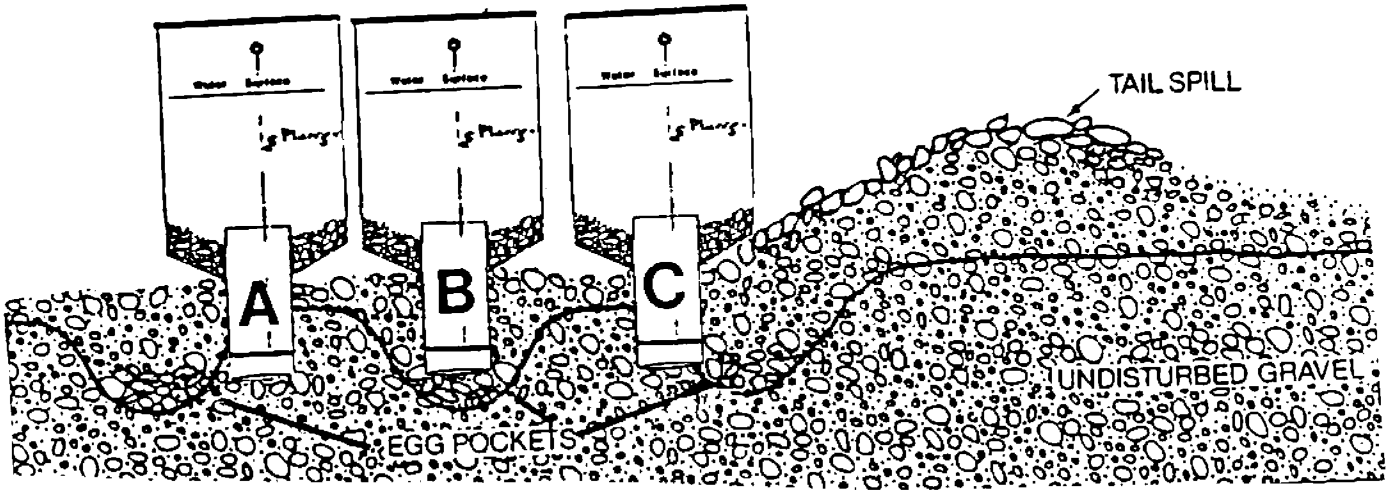


Figure A.2. Scale schematic diagram of egg pockets in a chinook salmon redd in the Columbia River, with three hypothetically-placed McNeil core samplers to scale. This information is based on observations of Chapman et al. (1983, 1986). Note failure of B to reach centrum of egg pocket and that A and C lie outside pockets.

The ridges between egg pockets in Figure A.2 may be slightly wider in upstream-downstream direction than those one might find in smaller streams or redds of smaller adults, but this difference is immaterial in the following discussion. We have slightly exaggerated the number of cobbles in the egg pocket centrum in order to illustrate the sampling problem.

Cores A and C would sample materials entirely out of the egg pocket and partly in consolidated materials not cleansed by the female. Core B would sample above the egg pocket portion holding most of the eggs (see Figure A.1), thus missing the large particles in the centrum.

The tools shown as A, B, and C in Figure A.2 have a core diameter of 15 cm. Doubling the diameter would reduce bias associated with whether one treats large particles at the edge of the cylinder as in or out of the sample. The larger cylinder would enclose a larger sample, but would not solve the problem of sampling outside of the egg pocket components that harbor the bulk of the incubating embryos.

While a core of depth similar to that in Figure A.2 would more probably reach the bottom of the egg pocket in core B in, say, the shallower egg pockets of a coho salmon or steelhead redd, problems represented by cores A and C would remain. In the case of redds of smaller fish, such as resident rainbow, risk would increase of extending the core <u>through</u> the egg pocket into the consolidated material below it. Shortening the core for smaller fish would reduce this likelihood while leaving problems of missed egg pockets unsolved. Reducing core diameter for small fish and predominantly small substrate particles, while advisable, would not solve problems represented by A and C in Figure A.2.

The section in Figure A.2 does not address the problem of laterally missing the egg pocket. Figure II.B.2, from Hawke (1978) shows longitudinal placement of egg pocket in plan view, and demonstrates that the unwary redd sampler is much more likely to miss than hit the egg pocket.

While a freeze-core, say a triple-probe sampler, would not eliminate problems represented by A and C in Figure A.2, or errors in plan-view context, extraction of an intact core permits the field worker to visually examine the core as a vertical representation of the substrate. Consolidated materials below the egg pocket can be identified and eliminated, and absence of large particles at the bottom of the core would be grounds for sample discard.

Shirazi et al. (1981) compared McNeil and freeze-core systems, and found (see section II.A.1) that triple-probe freeze cores and McNeil samples yielded similar results <u>in spawning habitat</u>. The reader should not interpret these results as pertaining to the egg pocket or to the problems elucidated above.

In the following subsections, we suggest that careful field researchers might find it profitable to observe redd development for a number of redds, identify egg pockets during the construction process, then survey the location of the pockets. Triangulation or surveying instruments would permit later location of the exact egg pocket for coring or permeability measurements. If level-rod elevations were taken in the egg pockets, and diameter of cobble or large gravel particles at the bottom of the pocket were estimated, it would be possible to take core samples, even with a McNeil sampler, exactly within the egg pocket and to assure that the core extends to the bottom of the pocket and no further. The McNeil cores could not be used for information on vertical stratification, for only freeze cores provide these data. For large fish, such as chinook salmon, longer tubes might be required for the McNeil sampler to extend to the bottom of the pocket.

We believe that data scatter in, for example, the relationship between fines and survival or between d_g and survival would decrease for information obtained solely within the egg pocket.

With data from egg pockets and redd capping, quantitative models and predictive tools could then be developed for field data. Even if redd capping were never successful, knowledge of structure and composition of the egg pocket could be applied to laboratory experimental conditions, making them better analogs of egg pockets in the field.

In the material to follow, we suggest some predictive tools that might be developed, using available information on gravels and survivals as examples. The models shown are not intended for use directly as quantitative predictors of survivals in the northern Rockies or elsewhere.

A.1. Fredle index

In this section, we re-analyze survival data from natural redds, as reported by Tagart (1976, 1984) and Koski (1966). We calculated the fredle index for gravel samples as if the latter were obtained in egg pockets, although they were obtained "in the redd". Figures A.1 and A.2 show why samples taken with McNeil cores probably included materials not pertinent for the egg pocket.

We have not used the fredle index with laboratory data. Laboratory data of Phillips et al. (1975), as tabulated with the fredle index by Lotspeich and Everest (1981), demonstrate that emergence (data for period from button-up fry to emergence only) positively relates to the fredle index. However, these data do not include the full intragravel period and should not serve for quantitative prediction in field conditions. They merely demonstrate that a relationship exists between fredle index and emergence success.

The fredle index incorporates the advantages of d_g, as elucidated by Platts et al. (1979) and by Shirazi et al. (1981), with a mixing index. We deem the mixing index desirable because gravels with quite different percentages of fines and of cobble can have the same d_g (Lotspeich and Everest 1981). The mixing index must incorporate assessment of large as well as small particles because of the important role of large gravel and cobble in egg pockets in natural redds. We do not agree with elimination of large particles (Adams and Beschta 1981, Tappel and Bjornn 1983) from model functions.

For all works in which natural redds were capped with netting and survival to emergence was measured in concert with sieving of redd particles, we plotted particle size compositions by weight for gravel samples from each redd, determined d_g and appropriate percentile particle sizes (d_{25}, d_{75}), then calculated the fredle index. We next plotted survivals from these redds against the fredle index. (Figure A.3). Figure A.3 represents an

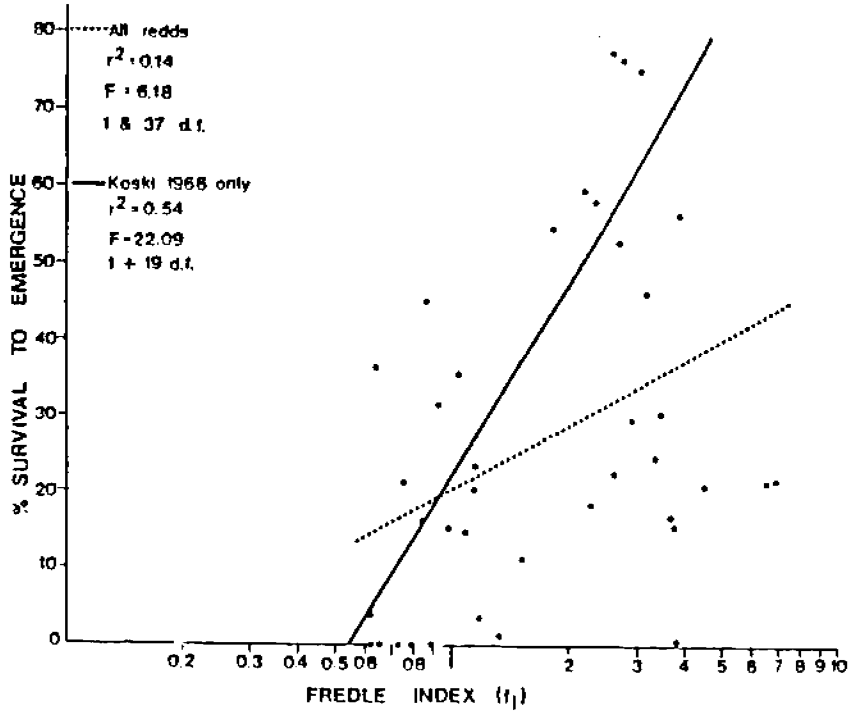


Figure A.3. (From Tagart, 1984 and file data at Oregon State University, from work of Koski 1966). Survival to emergence of coho salmon from natural redds in relation to the fredle index. Note low r^2. Regression is significant at $p = 0.05$.

example of an analysis that should be done with survivals and gravels from egg pockets. The figure does not purport to offer a quantitative prediction tool. The fredle index should not drop below 1.0, but does in a few cases from Koski's work because we had to extrapolate to estimate some small size components in the data retrieved from files at Oregon State University. We requested these because Koski's thesis did not contain data for individual redds.

The fredle index for a given survival as plotted in Figure A.3 may be lower or higher than was the case in actual egg pockets. The fredle index from corings of Tagart (1984) and Koski (1966) may include more coarse fines and less small fines than would be present in an egg pocket, because of such problems as corings on the "ridges" between egg pockets, failure of cores to penetrate to the bottom of unconsolidated redd materials, and intrusion of fines in egg pockets in a manner different from that outside the pocket.

The plots in Figure A.3 would lead one to infer that as the fredle index drops below about 1.5, one should expect survival to decline below 25%. Again, these data should not be used for quantitative predictions in the field. They are from coho redds and have a high scatter about the semi-log regression; a scatter possibly caused in part by gravel sampling outside of the egg pocket.

We suggest that to develop useful and accurate quantitative predictions of survival in relation to the fredle index, it would be necessary to freeze-core repeatedly in the redd being sampled until an egg pocket is identified by presence of several embryos or alevins frozen in the core. Any undisturbed substrate that "floors" the egg pocket should be eliminated from the sample, and the remaining core components should be sieved. Ideally, several egg pockets would be so-sampled, thus providing data that would permit assessment of variance and, incidentally, better simulation in the laboratory of egg pocket structure and composition.

Unfortunately, the work suggested in the preceding paragraph, however useful in defining egg pocket structure and composition, would disturb the natural redd and kill embryos, preventing unbiased assessment of survival to emergence by redd capping. Survival to the time of freeze-coring is not sufficient, as it does not include the emergence phase. It may be necessary to accept a lesser objective. That is, one could cap the redd to assess survival to emergence, then freeze-core two or three times, progressing in an upstream centerline of the redd from just forward of the tailspill, and taking care that the subsequent sample is not disturbed by earlier samples. Any sample that does not incorporate one or more large gravel or cobble particles near the bottom of the core (egg pocket components) would be thrown away.

One may ask: "What is the improvement of the suggested system over McNeil coring after emergence is complete?". The answer is that one is assured, with the freeze-core, that any undisturbed egg pocket "floor" is removed from the core, and it is possible to visually determine that the core has a pocket base component (large gravel or cobble) present. Without prior mapping of the pocket, there is still no absolute assurance that only the egg pocket is incorporated in a freeze-core, but this system should be much superior to McNeil coring.

Another, better system involves observation of redd construction progress, triangulation or bearings and distances from a survey stake to the egg pocket, and sampling only in surveyed egg pockets for as many redds as time and money permit. Surveying could be combined with level-rod work so that elevation of the bottom of the egg pocket is assessed in relation to a temporary benchmark. Thus, it would later be possible to determine whether a freeze-core extracts the full vertical spectrum of the egg pocket.

Freeze-cores obtained after emergence is complete would provide representation of gravel condition at emergence time, not average conditions faced by incubating embryos. We expect that the percentage of fines in a redd would tend to increase as intrusion of suspended bedload continues through the period from redd construction (cleanest condition) to emergence (highest percentage of small fines). Ringler (1970) provided data that permit us to estimate in the tributaries that he sampled, redds (not necessarily egg pockets) constructed in one year will acquire fines smaller than 0.833 mm at a rate of a little over 1% per month for the following year. The rate of accretion should be much greater in the incubation period than in summer in the Alsea River tributaries studied by Ringler, so a linear calculation does not reflect reality. We have no data on the rate of fines intrusion in redds in the northern Rockies.

It is also likely that the microdistribution of fines will deepen during emergence, as alevins butt toward the surface and fines drop down into the egg pocket. The combined effects of upward butting and gravity as several hundred embryos leave an egg pocket may well move fines lower, but analysis probably would not be able to detect this change in stratified samples.

The procedure suggested above for assessment of conditions in the egg pocket in relation to emergence is labor-intensive, hence expensive. We suggest that the alternative is to continue to use flawed data of low accuracy and precision and to extrapolate inappropriate laboratory data to field environments.

A.2. Geometric mean particle size

At the cost of information on gravel grading provided by the fredle index, the d_g offers another model of survival against particle size. Again, we do not agree with inclusion of laboratory data in the model. Even where laboratory data may fit reasonably well with the function for data from natural redds, we would not include them, for they would merely contribute to the "fallacy of misplaced concreteness". In the present context, this would simply mean that sample error would decrease as degrees of freedom increase, without logical physical and biological support.

In Figure A.4, we have plotted survival to emergence for natural redds (Koski 1966, 1981, Tagart 1984) against d_g. This relationship was developed for all 39 redds and for data from Koski only. The latter provided a significant regression and r^2 of 0.47. Data of Koski (1966) indicate that when d_g drops below about 5.0, survival declines below 25%.

A procedure for sampling that is the same as that suggested for the fredle index is needed for assessing d_g, involving freeze-coring after redd capping.

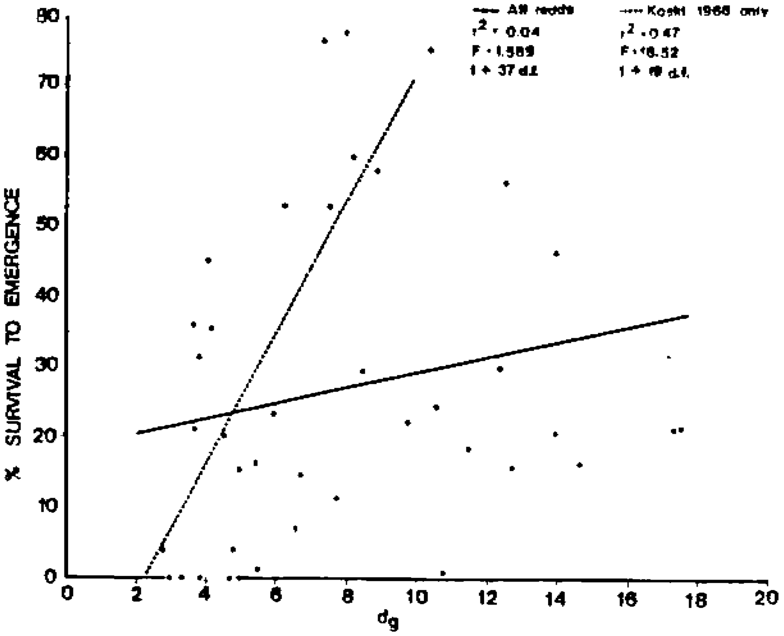


Figure A.4. (Adapted from Tagart 1984 and data obtained from Oregon State University as acquired by Koski 1966). Survival to emergence in individual coho salmon redds as a function of d_g.

We also plotted the survival data for 39 individual redds of Koski (1966) and Tagart (1984) as a function of d_g in the mode of Shirazi et al. (1981). Then we placed the curve of the latter authors through the data (Figure A.5). The scatter and placement of individual redd data is so great that the curve of Shirazi et al. (1981) would not be an appropriate descriptor.

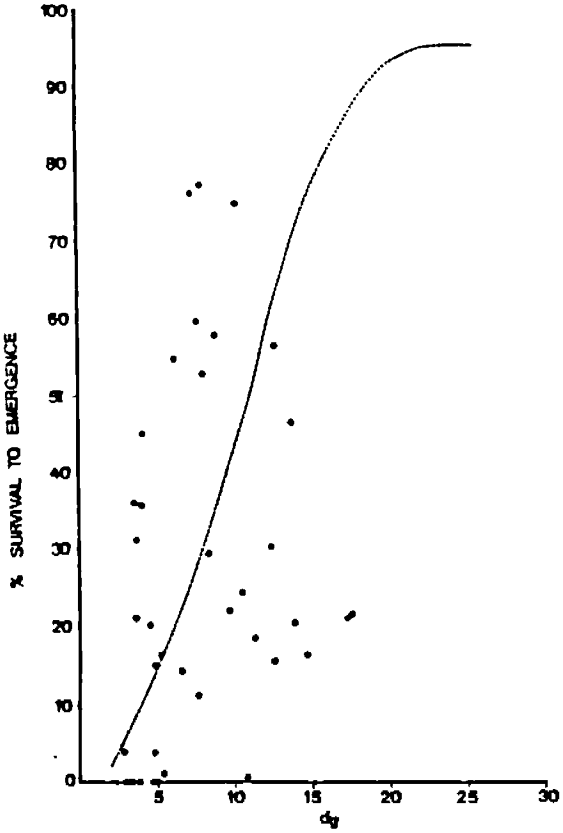


Figure A.5. (From Figure 4 and Shirazi et al. 1981). Curve of survival to emergence as a function of d_g from Shirazi et al. (1981) placed through data on survival and d_g for 39 individual redds.

A.3. Percentage of fines

Use of only percentages of fines in models of survival to emergence explicitly neglects large particles in the redd. However, if we use data exclusively from natural redds, we might assume that fish behavior implicitly incorporate large particles in the analysis because redds constructed by adults normally lie in areas that have suitable egg pocket materials. In any event, fines should be assessed with freeze-coring procedures described above, making concerns about large particles moot, as large gravel and cobble of the egg pocket would be a part of acceptable cores. McNeil cores would also serve for assessment of percentages of fines if they originated in egg pockets.

We plotted percentage of fines smaller than 0.85, 2.0, and 6.0 mm in figures A.6, A.7, and A.8, respectively. These plots,

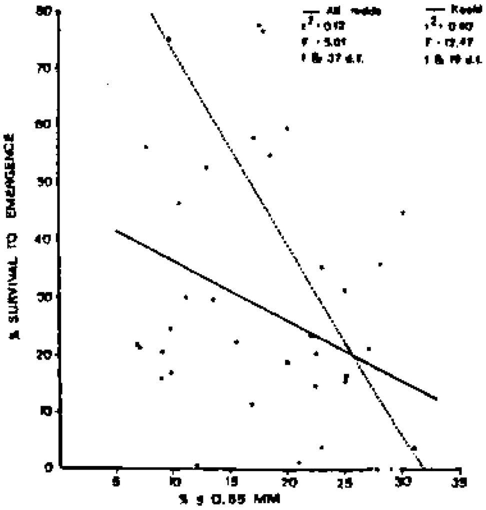


Figure A.6. (Adapted from Tagart 1984 and Koski 1966). Survival of coho salmon to emergence in natural redds in relation to fines smaller than 0.85 mm in redd corings.

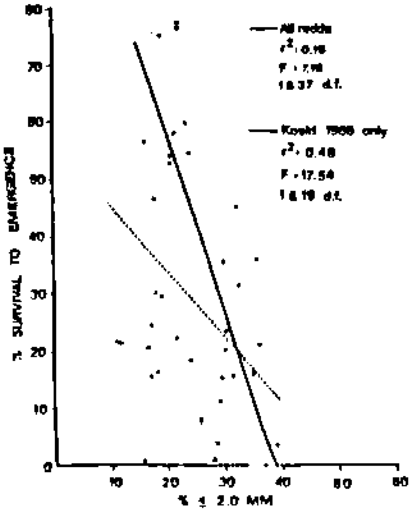


Figure A.7. (Adapted from Tagart 1984 and Koski 1966). Survival to emergence of coho salmon in natural redds as a function of fines < 2.0 mm.

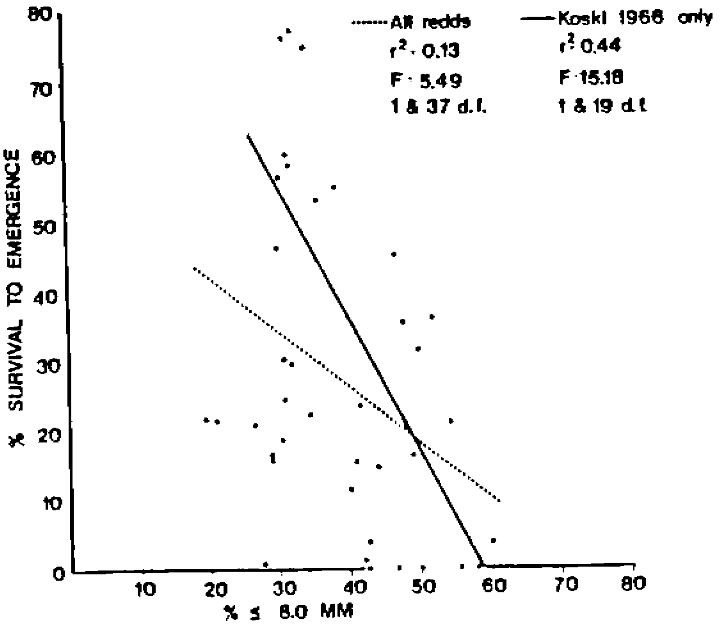


Figure A.8. (Adapted from Tagart 1984 and Koski 1966). Survival of coho salmon to emergence in natural redds as a function of fines < 6.0 mm.

various forms of which have been used by many investigators, would lead one to infer that survival of embryos to emergence declines as the percentage of fines smaller than 0.85 mm increases. The relationship was significant (p = 0.05) for all redds combined and for redds trapped by Koski.

Survival was significantly related to percentage of particles smaller than 2.0 mm and smaller than 6.0 mm for all redds combined, although the "F" value was somewhat lower for the larger category of fines.

We also attempted to plot survivals at percentages of particles smaller than 0.85 and 9.5 mm (Tappel and Bjornn 1983), again using only data from natural redds. Isolines of survival could not rationally be placed through the data.

NCASI (1984b) prepared regressions of survival to emergence for all available works, and we plotted NCASI data on the same figure (Figure A.9). The regressions have major differences in placement and slope, only partly because of different categorization of fines.

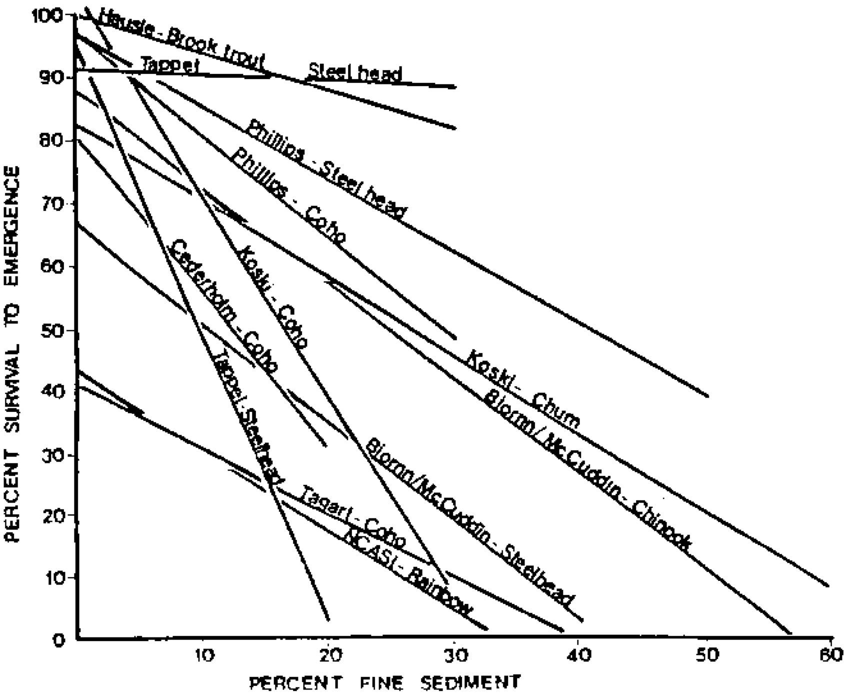


Figure A.9. (Adapted from NCASI 1984b). Regressions of survival against percentages of fines for all available works.

We can conclude that fines decrease survival, but cannot predict the amount of the decrease in field conditions from a given increase in fines from available information. The relationships between fry emergence and percentage of fines that Stowell et al. (1983) developed (Figures A.10 and A.11) include much data that should not, with present knowledge, be used for field environments. Even the data for field environments are flawed, as we have abundantly discussed elsewhere. A procedure like that suggested for assessing survival in relation to the fredle index in egg pockets would be needed to evaluate effects of fines, and to better focus laboratory studies so that the resulting data can serve for field predictions with some confidence.

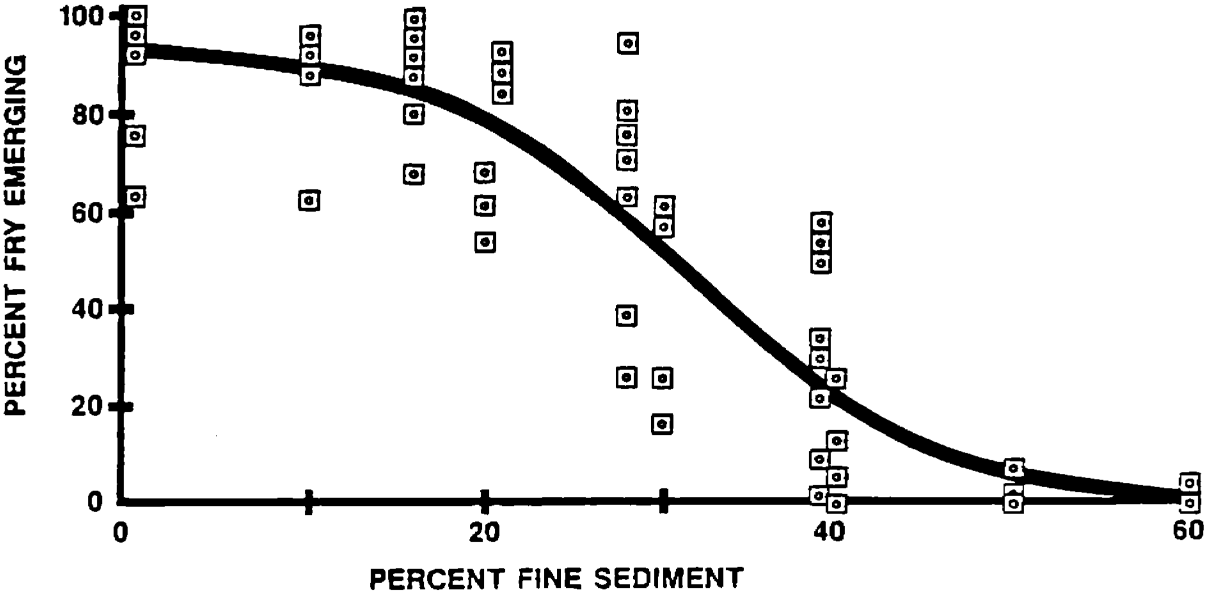


Figure A.10. (From Stowell et al. 1983). Fine sediment by depth versus alevin emergence for chinook salmon.

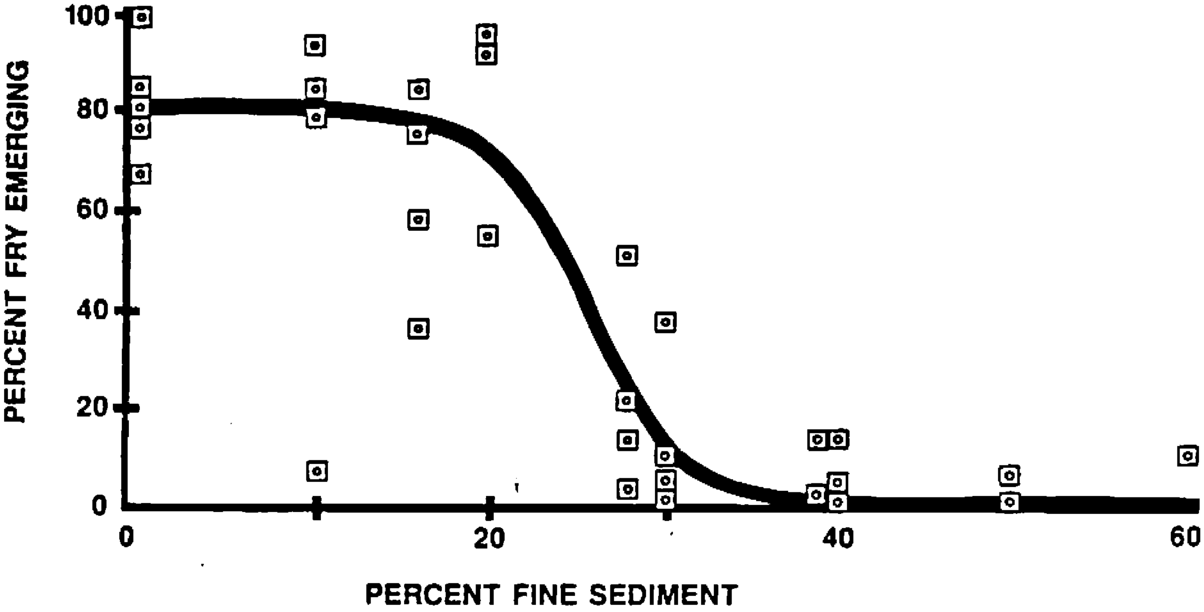


Figure A.11. (From Stowell et al. 1983). Fine sediment by depth versus alevin emergence for steelhead.

A.4. Permeability

Platts et al. (1979) showed that permeability is a function of d_g, which itself is related to porosity. Permeability, the ability of gravels to pass fluid under given hydraulic head, is related to survival in natural redds. In our opinion, permeability as measured in standpipes quite often has not been obtained in egg pockets, but rather elsewhere in the redd, which increased variability in the data. Only the condition within the natural egg pocket has direct import for embryos incubating there. This does not mean that conditions in the redd outside the egg pocket have no influence on conditions in the pocket. One need only examine Figure II.B.1 and figures II.B.10-11 to support the latter statement.

In Figure A.12, we plot the available data on survival and permeability from natural coho salmon redds. The regression is significant (F = 11.69, 1 and 28 d.f., $p = 0.005$, $r^2 = 0.30$). The model does not permit quantitative prediction in egg pockets, but

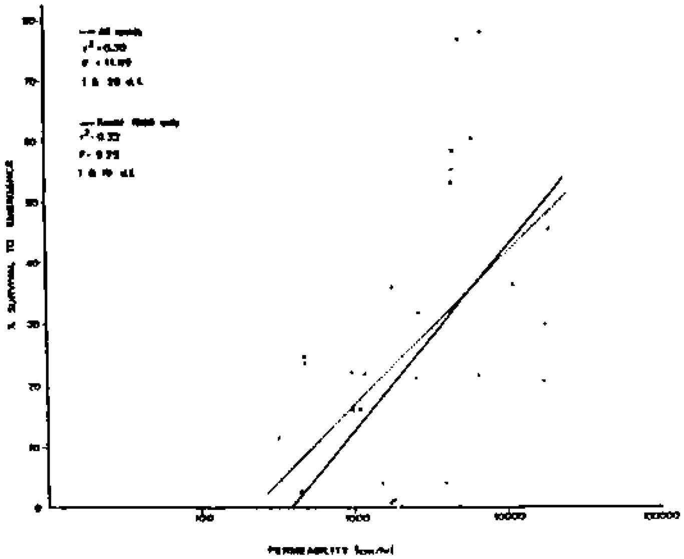


Figure A.12. (Plotted from data of Tagart 1984 and Koski 1966). Survival to emergence in natural coho redds as a function of permeability.

shows that where permeability, as measured by Tagart (1984) and Koski (1966), declined below about 2,000 cm/h, survival declined below 25%.

Moring (1982) stated, after showing that permeability decreased in a stream draining a clearcut drainage in comparison to unlogged control streams, that this variate may be a more important indicator of intragravel conditions than are changes in fine sediments. We believe that if permeability in the egg pocket could be ascertained, it would provide a measure of gravel quality useful in predicting survival. Permeability assessment is easier by far than gravel coring, work on permeability is needed in natural redds in the northern Rockies, and too little attention has been directed to assuring that permeability data came from egg pockets.

Examination of Figure A.2, above, and Figure II.B.2, from Hawke (1978), illustrates how permeabilities would often derive from locations outside the egg pocket. In fact, the probability of driving a standpipe well-point into the egg pocket centrum on any single sample without knowledge of precise pocket location is likely to lie much below 50% because of longitudinal, lateral, and even vertical error.

We suggest, as one sampling alternative, that multiple measurements, perhaps 10 to 20, should be obtained from each sampled redd, and that the highest measurement, or perhaps the top tenth of measurements, might be accepted as egg-pocket permeability. One would not be absolutely certain that the well point of the standpipe does not penetrate the egg pocket "floor", or that the well-point has reached the most important zone in the egg pocket, but use of the top 10% of measurements should reduce such errors. Unlike the situation for gravel coring, multiple permeabilities could be obtained before the redd is capped, but we see unacceptable risk that driven pipes would loosen gravels and alter the emergence environment.

Another possibility for the careful field worker would be to observe redd construction for as many adults as possible, with tools for triangulating or obtaining bearings and distances to egg pockets for many redds. Subsequent permeability information could be obtained from re-located egg pockets only. Egg pockets can be identified during redd development where water over the redd is clear enough for the observer to see to the substrate. Either a semi-permanent truncated standpipe could be driven and left in the egg pocket, or a standpipe could be driven into the pocket near the end of the incubation period. Other sampling possibilities could be developed.

Another advantage of the surveying system for locating egg pockets is that a level rod could be placed in the completed egg pocket before the female deposits eggs there, and elevation recorded in relation to a temporary benchmark. This procedure would later permit the researcher to use a leveling instrument to determine when the standpipe well-point lies exactly at the desired elevation in the egg pocket.

A.5. Electronic probe measurement of pore velocity

A similar set of comments could be made about instantaneous measurement of pore velocity with electronic probes that measure water movement independent of vector. Such a measure should correlate with permeability and survival, but must come from within the egg pocket to reduce data variability and increase relevance. Multiple measurements within a redd might be easier than coring, and perhaps one should take the top decile or the top measurement as indicative of conditions in the egg pocket. Unfortunately, we can find no survivals to emergence for correlation with probe data. It is our understanding that the electronic probe has not worked satisfactorily in Idaho because of difficulty in inserting the probe in substrata, in part due to relatively large particles. The tool should be more satisfactory in gravels used by small adult trout or kokanee, or in spawning areas of pink salmon.

A.6. Dissolved oxygen assessment

Dissolved oxygen could be used to assess conditions in the substrate, but measurements should be taken in the egg pocket centrum, just as for other independent variables used to relate survival to physical conditions. We base this caveat on Cooper's (1965) work on water currents within the redd as opposed to currents in the surrounding undisturbed gravels.

Davis (1975) has suggested that valuable salmonid stocks should enjoy minimum dissolved oxygen levels of 9.75 mg/l. Stocks of moderate value would have a minimum of 8.00 mg/l, and other stocks could have a minimum of 6.50 mg/l. The level for valued stocks would be 98% of saturation at 0-15 C; stocks of intermediate and lower value would enjoy 76-79% and 54-64% saturation, respectively, at 0-15 C (see Table II.C.1).

We suggest that an example of application of the criteria of Davis to a valued chinook salmon stock would be to determine if dissolved oxygen in egg pockets exceeds 98% saturation. If not, no addition of fines should occur, whether a result of best management practices or not. As long as oxygen level exceeds 98% saturation, land management practices could be considered compatible with production of fish. We do not suggest this example as the only possible application of criteria; merely as one alternative. Fines lying over the egg pocket centrum could affect emergence success even where dissolved oxygen remained at 98% saturation. Dissolved oxygen might provide one of several criteria.

A.7. Best available information

As noted in earlier report sections, we do not favor extrapolation of the available laboratory data on survival to field situations, for in this we quite agree with Everest et al. (1986). We have abundantly explained our reservations about the laboratory data that we reviewed.

Tappel and Bjornn (1983) stated:

> "Although embryo survival instreams may not exactly parallel "equation" predictions (from laboratory data), the equations should provide a good index of relative changes in survival. As an example, suppose the steelhead equation predicted that embryo survival in a stream would decrease from 80 to 60% as a result of increases in fine sediment in the spawning substrate. Even if survival in the stream was not 80% for a given substrate before increases in fine sediment occurred, the 20% reduction in embryo survival predicted by the equation should be close to the decrease in embryo survival in the stream. If embryo survival was actually 50% in the stream instead of 80%, survival of steelhead embryos should still decrease by 20% as a result of a given increase in fine sediment."

They further wrote:

> "Predicting the consequences of an increased deposition of fine sediment in spawning areas is an important application of our research." -----"Such predictions could be used in the equations presented here to forecast the effects of human activities on steelhead and chinook salmon embryo survival."

Readers who have patiently followed the logic trail through the thickets of the literature analyses in Section II of our report will not be surprised that we disagree with the foregoing assertions. We do not consider it appropriate to predict the percentage change in embryo survival in field situations from laboratory tests that did not duplicate egg pocket structure and gravel size distributions. The only natural egg pocket for which d_g has been reported for chinook salmon (Platts et al. 1979) had a d_g of 32 mm, 49% higher than the highest d_g (21.5 mm) used by Tappel and Bjornn (1983), about three times larger than the average d_g (11.1 mm), and eight times the lowest d_g (4.0 mm). The data of Tappel and Bjornn (1983) reflect good laboratory research. They can be used to infer that the mix of fines, as indicated by weight percentages of fines of two diameters, has an effect on survivals of steelhead and chinook salmon embryos in natural egg pockets.

In spite of the foregoing arguments, we realize that a substantial body of information in laboratory and field conditions shows that increases in percentages of fines in gravels negatively affects survival. We consider it appropriate to summarize it here.

From Tappel and Bjornn (1983) and other sources, we provide Tables A.1-A.3, which summarize what we consider to be the best available information on intragravel survival to emergence in salmonids of the northern Rockies in relation to various potentially useful tools. We consider the tables as a "state of the art" information summary.

Table A.1. Best available information on survival to emergence of salmonids in certain intragravel conditions. Sources include Tappel and Bjornn (1983), Davis (1976), Irving and Bjornn (1984), Lotspeich and Everest (1981), and Shirazi et al. (1981), McCuddin (1977), and materials that we developed in our report.

			Fines indices[a]			
	D.O.	K	<6.3mm	<0.85 and <9.5mm	d_g	Fredle
80% survival						
Chinook salmon	98	10,000	20	Use Fig. II.C.23 at 80% survival	15	6
Steelhead	98	10,000	20	" "	15	6
Rainbow trout	98	10,000	20	" "	15	6
Kokanee	98	10,000	10	" "	15	6
Cutthroat trout	98	10,000	10	" "	15	6
Bull trout	98	10,000	25	Use cutthroat data in Fig. II.C.23 at 80% survival	15	6

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a - D.O. in % saturation, K in cm/h, fines in % by weight, d_g in mm, Fredle with no dimension.

Table E.2. Estimated dose:response relationships from best available information on intragravel survivals to emergence between 80% and 25%. Each indicated increment or decrement in an independent variable would correspond with a 10% decrease in survival to emergence. Sources include Tappel and Bjornn (1983), Davis (1976), Irving and Bjornn (1984), Lotspeich and Everest (1981), and Shirazi et al. (1981), McCuddin (1977), and materials that we developed in our report.

	Increment (+) or decrement (-) causing 10% reduction in survival between 80% and 25% survival[a]					
Species	D.O.	K	<6.3mm	<0.85 and <9.5mm	d_g	Fredle
Chinook	-5%	-1,600	+4%	See Fig. II.C.23	-1.6	-1.0
Steelhead	-5%	-1,600	+4%	" "	-1.6	-1.0
Rainbow trout	-5%	-1,600	+5%	" "	-1.6	-1.0
Cutthroat trout	-5%	-1,600	+3%	" "	-1.6	-1.0
Kokanee	-5%	-1,600	+4%	" "	-1.6	-1.0
Bull trout	-5%	-1,600	+3%	" "	-1.6	-1.0

---

a - D.O. % saturation, K in cm/h, d_g in mm, Fredle w/o dimension.

Table E.3. Best available information on intragravel conditions below which survivals to emergence would be equal to or lower than 25%. Sources include Tappel and Bjornn (1983), Davis (1976), Silver et al. (1963), Phillips and Campbell (1962), Sowden and Power (1985), Shumway et al. (1964), Irving and Bjornn (1984), Lotspeich and Everest (1981), and Shirazi et al. (1981), McCuddin (1977), and materials that we developed in our report.

	Fines indices[a]					
Species	D.O.	K	<6.3mm	<0.85 and <9.6mm	d_g	Fredle
Chinook	65%	2,000	45%	See Fig II.C.23	7.0	1.2
Steelhead	65%	2,000	45%	" "	7.0	1.2
Rainbow trout	65%	2,000	35%	" "	7.0	1.2
Cutthroat trout	65%	2,000	30%	" "	7.0	1.2
Kokanee	65%	2,000	45%	" "	7.0	1.2
Bull trout	65%	2,000	30%	" "	7.0	1.2

---

a - dimensions as in Table E.1.

It would be inappropriate to place confidence limits about the estimates in the foregoing tables, even if it were possible. The data come from a mix of sources, each of which has an unknown statistical distribution, and from situations with different experimental and sampling biases.

B. SUBSTRATE FINES AND EFFECT ON REARING DENSITIES

We found little information that indicates the quantitative effects of sediments on actual rearing densities in the field for most species of the northern Rockies. We will discuss predictors in no preference order in the material that follows.

B.1. Embeddedness

Evidence that embeddedness affects densities of juvenile or adult salmonids in field environments in summer is only moderately convincing. Munther and Frank (1986 a,b,c) reported very low r^2 values for 53 relationships between embeddedness and fish densities. Konopacky et al. (1985) provided data on embeddedness and fish densities in various reaches of the same stream (thus reducing, although probably not eliminating, data scatter caused by highly variable seeding, different limnological features, etc.). It appears that his data were obtained by a visual estimate rather than with the careful techniques of Burns and Edwards (1985), hence should be considered less useful. His results lend no support for a negative relationship between embeddedness and chinook salmon density.

Thurow and Burns (unpublished), provided fish densities and embeddedness data that can be used to develop a negative relationship between embeddedness and fish densities, and particularly maximum densities of age 0 chinook salmon, but we cannot accept their models as quantitative predictors of fish density because streams of different order, gradient, size, and seeding levels were included without stratification. Their model for maximum density of age 0 chinook salmon included only stream habitats in Chamberlain Creek and the South Fork Salmon River, hence may reduce some of the effects of extraneous environmental variables.

Data obtained from C. Johnson (BLM) and from Gamblin (1986) are only moderately convincing and of mixed message in regard to effects of embeddedness on salmonid densities.

Stowell et al. (1983) used experimental data of Bjornn et al. (1977) to prepare models of effects of embeddedness on densities of age 0 steelhead, age 0 chinook salmon, and age 1 steelhead (Figure B.1). The relationships for age 0 chinook and age 0 steelhead in Figure B.1 might better be represented by linear regression or ocular placement, but this minor criticism is overshadowed by another, much more serious problem.

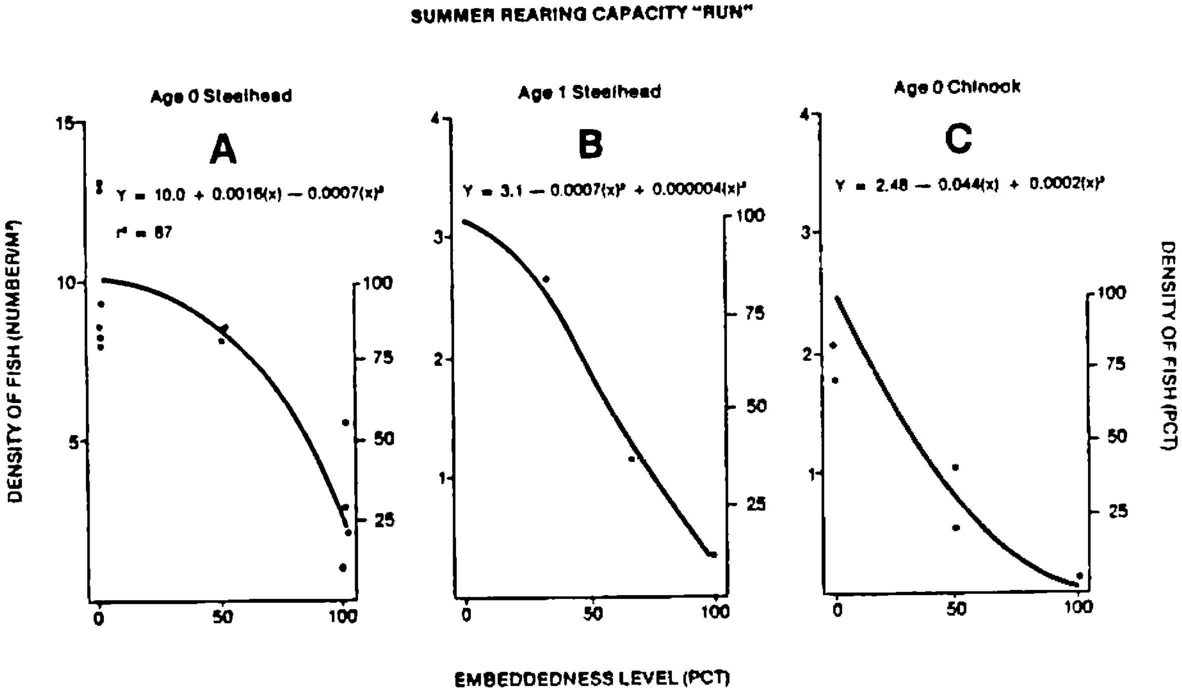

Figure B.1. (From Stowell et al. 1983). Summer rearing capacity and substrate embeddedness in runs for age 0 and 1 steelhead and age 0 chinook salmon (Bjornn et al. 1977).

We see information contradictory to Stowell et al. in the correlational studies of Thurow and Burns (unpublished). Thurow and Burns offer a model with a predicted maximum density of about 4 fish per 100 m^2 at 50% embeddedness, while Bjornn et al. (1977), hence Stowell et al. (1983), predict a 22-fold higher density of 90 fish per 100 m^2 at the same embeddedness.

In fact, Bjornn et al. should not be used for prediction of field densities of chinook salmon at any embeddedness level. At 0% embeddedness, the densities of chinook reported by Bjornn et al. (1977) and used by Stowell et al. are about 250 fish/100 m^2, four times higher than the maximum density found anywhere by Thurow and Burns (unpublished) or by Petrosky and Holubetz (1986). The effect of these excessive densities on the responses of juveniles to embeddedness is unknown. Stowell et al. (1983) attempted to normalize for the high densities of fish in the laboratory environments of the artificial streams by treating maximum density (250 fish/100 m^2) as a fish density of 100% (Figure B.1), and predicting fish densities in percentages of maximum density.

Stowell et al. (1983), based on experimental data of Bjornn et al. (1977), would predict age 0 steelhead densities of 800 fish per 100 m^2 at 50% embeddedness and 1000 fish/100 m^2 at 0% embeddedness, many times higher than densities found in natural environments. Densities of age 1 steelhead are predicted as 150 fish/100 m^2 at 50% embeddedness and over 300 fish/100 m^2 at 0% embeddedness. In fact, the only density for steelhead that appears close to that to be expected in the wild was at 100% embeddedness (about 30 age 1 fish/100m^2). Stowell et al. (1983) attempted to normalize fish densities as percentages, with maximum densities at an embeddedness of 0%. However, we have no way of knowing the effect of the inordinately high densities reported by Bjornn et al. (1977) on reaction of fish to embeddedness in the wild.

In summary, we reject the predictions of fish density from embeddedness in the artificial environments of Bjornn et al. (1977), even where densities were normalized as percentages. Had densities been more in concert with those in field environments, and had other variables been handled differently, (for example if juveniles emerged into the channels, or had the investigators seined wild fish of smaller size and placed them in the channels at appropriate densities earlier in the summer) the effects of embeddedness could have differed markedly. Had other aspects of the trough environments offered compensatory features probably available in the wild, such as more normal pool/riffle structure and more natural cover, other results, hence different models in Figure B.1, might have been developed.

While we emphasize that we see much scientific merit in mechanistic work in artificial channels, we point out, as for laboratory study of embryo survival to emergence, that experimental circumstances govern outcome, certainly in quantitative, and perhaps in qualitative senses. We feel it is not appropriate to apply the available information in quantitative ways to natural stream systems.

We suggest that field evaluations of embeddedness effects on fish density should be undertaken in carefully-documented stream strata and fully-seeded fish populations. This should entail collection of data on habitat variables and addition of appropriate numbers of juveniles to test areas early in the summer to assure full seeding. Juveniles from nearby areas may be seined or electro-sampled for addition to test strata. Stepwise multiple regressions should help to assess the significance and incremental effect of embeddedness on r^2, but the main point is that field experiments at full seeding in several environmental strata are needed to assess effects of embeddedness on density of fish.

Bjornn et al. (1977) recognized the importance of field investigations, examining habitat variables and fish densities in conjunction with experimental additions of fines in natural streams of the Middle Fork Salmon River. The authors were unable to show an adverse effect of sediment on abundance of fish except where sediment so reduced pool volume that living space decreased. Their work should be extended to a much longer stream segment.

B.2. Effect of fines on rearing densities of fish

Konopacky et al. (1985) visually estimated percentages of fines smaller than 4 mm in diameter and total density of chinook salmon, steelhead, and cutthroat trout. At least to percentages of fines in excess of 40%, we could find no negative relationship between fines and densities (to the contrary, the relationship appeared positive, although we did not calculate regressions).

We used the data of Petrosky and Holubetz (1986) to calculate a weakly negative relationship between percentages of fines smaller than 5 mm and densities of age 0 chinook salmon. The overall r^2 was only 0.058. When we stratified the data by stream gradient, only the 1-2% gradient stratum had a significantly negative relationship between fines and fish density (r^2 = 0.084).

Bjornn et al. (1977) added granitic fines to field environments in two tributaries of the Middle Fork Salmon River, but could not show an effect of fines until pool volume was greatly reduced. No relationship could be shown between percentage of fines (<6.35 mm) in riffles and density of fish in pools just downstream. Konopacky (1984) found no correlation of chinook salmon density in pools and fines in the riffle upstream.

We draw the very obvious inference that a superabundance of fines will reduce density of rearing fish. "Superabundance" means enough fines to reduce living space and overcome ability of the stream to process sediment recruitment so that food production on riffles is smothered and sharply declines.

Regretfully, the model for a relationship of lesser amounts of sediment and fish density has not been developed, nor does embeddedness sampling to date offer a satisfactory surrogate. The model would require data on pertinent habitat variables as well as substrate condition, and assurance of full seeding. Stratification by stream gradient and geology would be desirable.

B.3. Substrate score and fish density

Crouse et al. (1981) related coho salmon production to substrate score in both spring ($r^2 = 0.75$) and summer ($r^2 = 0.90$) in artificial stream channels. The scoring function contains unknown elements of cover and energetics. Shepard et al. (1984) related numbers of bull trout per 100 m^2 to substrate score ($r^2 = 0.40$) in 26 stream reaches in the Swan River system in Montana. No data on other habitat features or seeding were offered.

Substrate score, an amalgam of substrate particle size and embeddedness, should offer more information than embeddedness alone or fines alone, and is worth pursuing in future studies of fish density in relation to habitat variables. This variate currently has insufficient documentation for application to the species of the northern Rockies.

B.4. Best available information

Available information on effects of fines on salmonid rearing densities does not permit a broad statement on effects of embeddedness level or various percentages of surface fines. A very conservative view of the data would be to state that rearing densities are often lower at embeddedness levels greater than 50%. A conservative view in habitat protection, on the other hand, might state that any embeddedness level greater than 25% in rearing areas risks loss of winter habitat in interstices and should be avoided until better information becomes available.

C. MACROINVERTEBRATE RESPONSES TO FINES

Response of aquatic macroinvertebrates to fine sediments has received considerable research attention. We will discuss embeddedness and percentage of fines as predictors.

C.1. Insect density as a function of embeddedness and fines

Mean insect density was shown by Bjornn et al. (1977) to maximize at an embeddedness level of two-thirds in artificial stream channels. In natural stream areas, these authors cleaned plots and compared insect abundance there to uncleaned controls. Final abundance of insects (45 days later) was greater on undisturbed sites than on cleansed plots. The work by Bjornn et al. appears to show that a substrate without any fines offers less habitat niches and diversity than one with some fines around the bases of larger particles.

Munther and Frank (1985 a,b,c) were unable to show that embeddedness explained aquatic insect biomasses in 20 sample locations in Montana. Even when various stratifications by insect species assemblages were attempted, statistical analysis could "explain" little variation caused by embeddedness.

Although Bjornn et al. (1977) offered data on insect density in artificial stream channels, their data should have more applicability to field situations than is the case for fish. Colonization of artificial stream substrata occurred naturally, reducing or eliminating the problem of inappropriate densities, and the animals involved were very small relative to the channels, thus reducing problems with cover, and suitability of sympatric animals. However, the mix of gravels in the channels may not apply to natural streams. The substrate in riffle sections consisted of a layer of cobbles 6.35 to 12.60 cm in diameter over a 0.4 m layer of gravel (size not noted), and that in pools consisted of 0.3 m boulders placed on the bottom. Thus we cannot conclude that an optimum substrate in the wild should have an embeddedness level of two-thirds.

Bjornn et al. (1977) correlated benthic insect densities with the level of cobble embeddedness at Knapp Creek in 1974-75. Embeddedness categories included unembedded, one-fourth, one-half, three-fourths, or fully embedded. The authors found a low correlation between insect densities and embeddedness for mayflies and for the caddis, Brachycentrus sp., but not consistently positive or negative. For example, Brachycentrus abundance correlated positively with embeddedness in riffles to which sediments were added in 1974, but significantly and negatively in both test and control riffle areas in 1975. For all species combined, embeddedness correlated significantly and positively with abundance of insects in 1974 on test riffles, but negatively and non-significantly on test riffles in 1975.

Cleansing of test plots in Elk Creek, another natural system, led to increased insect abundance after several weeks (when embeddedness had reached about one-fourth), in comparison to control areas that were about three-fourths embedded. No means are available to compare effects of two-thirds embeddedness with these data.

Fines have been shown to correlate negatively with abundance of aquatic insects (Cederholm and Lestelle 1974). An increase from 7% up to about 9% percent fines < 0.84 mm appeared to cause a 50% reduction in abundance of benthic insects, although hidden correlates, such as larger fines, may have been involved. The fines were evaluated in core sampling, hence surface fines may have increased relatively much more than subsurface fines.

Bjornn et al. (1977) state that a two-thirds embeddedness level would correspond with a core sample containing 30% or more sediment, a situation in which all of the interstitial spaces in the gravel are filled with fines. The data sets of Cederholm and Lestelle and of Bjornn et al. appear to conflict, probably because the two works used different classifications of fines. Saunders (1986) reported that insect standing crops declined where embeddedness was high, and that insects were less abundant where embeddedness exceeded 3/4 than where it was between 1/2 and 3/4.

C.2. Insect drift as a function of embeddedness and fines

Embeddedness did not affect drift of insects in artificial channels studied by Bjornn et al. (1977). Konopacky (1984) provided data that indicated that a substrate of gravel produced more drift of sizes appropriate for use by fish than did a sand-pebble substrate, although more absolute numbers of insects drifted from the latter.

No useful relationship between substrate type and invertebrate drift is available for predicting effects of fines on the insect drift resource in streams of the northern Rockies.

C.3. Best available information

The thrust of the available information is reasonably consistent in showing that at high embeddedness, insect abundance declines. It appears that the embeddedness level at which insects decline in abundance is about 2/3 to 3/4. Although no relationship between drift and fines is clear, logic leads us to infer that where embeddedness increases sufficiently to reduce insect densities on and in the substrate, drift density/m^3 of water should also decrease.

D. EFFECTS OF FINES ON WINTER HABITAT OF SALMONIDS

D.1. <u>Embeddedness and winter habitat</u>

Stowell et al. (1983) used data from Bjornn et al. (1977) to develop models of the relationship between embeddedness level and winter carrying capacity (Figure D.1). Intuitively, we conclude

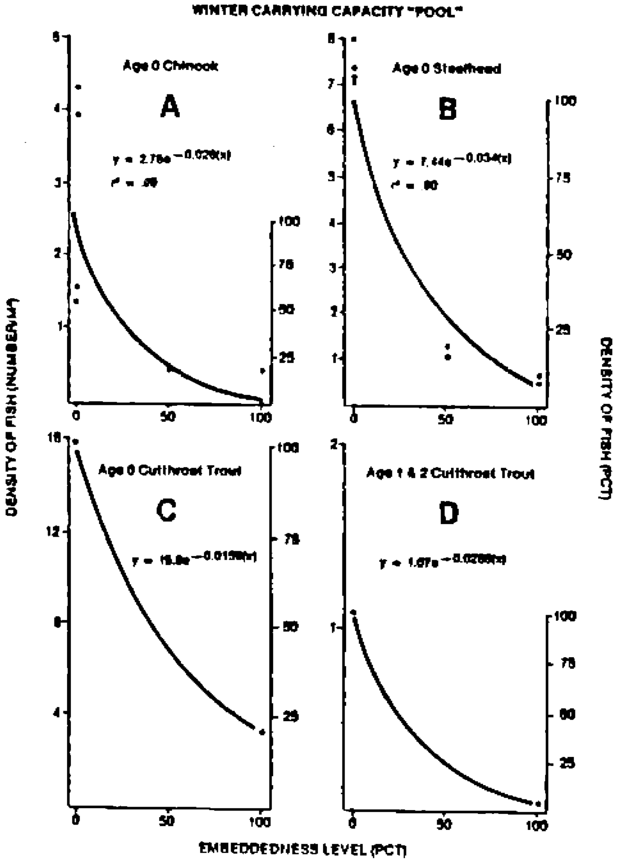

Figure D.1. (From Stowell et al. 1983). Winter carrying capacity of pools and substrate embeddedness, for age 0 chinook salmon, steelhead, cutthroat trout, and age 1 and 2 cutthroat trout.

that more winter habitat in the substrate exists at 0% embeddedness level than at 50% or, certainly, at 100%

embeddedness levels. However, we do not believe that data from artificial streams at Hayden Creek (Bjornn et al. 1977) can be applied to natural stream areas.

The first obstacle to acceptance of Figure D.1, from Stowell et al. (1983), is that the density of fish in artificial stream channels at Hayden Creek was excessive at test initiation. Figure D.1 would predict densities at 0% embeddedness of 250 chinook/100 m^2, over 700 age 0 steelhead/100 m^2, 1,600 age 0 cutthroat trout, and over 100 age 1 and 2 cutthroat trout. All fish were added to the channels when temperatures led to immediate entry into the substrate. Had initial densities been moderate, densities after 5 days might have been different, even at full embeddedness.

The second problem is that 5 days may or may not bring fish numbers into equilibrium with the available habitat, and an interaction between time and embeddedness level would destroy the models in Figure D.1. The third major difficulty is that a different substrate mix or presence of other habitat features different from those in the artificial streams, might well affect the functions in Figure D.1.

The foregoing three problems lead us to reject Figure D.1 as a predictor of the height of the 100% point on the right axis of each model in the figure, and as an indication of the shape of the functions.

We have no doubt that functional relationships exist between embeddedness and winter holding capacity of the substrate for salmonids, and that those relationships differ by fish size and perhaps by species. However, quantitative prediction is currently not possible. We assume that winter capacity for fish in the substrate is greatest at 0% embeddedness level, and that it must decline at some embeddedness betweeen 0% and 100%.

Research effort should be devoted to examination of the effects of various substrate types, starting and ending fish densities, and fish size and species on the shape of the relationship between winter holding capacity and embeddedness. It may be desirable to undertake this work in natural stream channels in which seeding upstream and in the study area is known to be adequate (perhaps based on late summer snorkel index monitoring), then to modify substrate condition and rely on extraction of fish with electrofishing gear within a few weeks after temperatures decline to levels that cause entry of fish into the substrate. Artificial stream channels may play a role, but multiple treatments and semi-natural conditions and surety of appropriate fish behavior will mandate few replicates and treatments because of costs. On the other hand, one season of field work could define fish density and embeddedness functions sufficiently to permit preliminary field use.

Concomitant research should establish the relative survival of fish that remain in the substrate in rearing areas and that of fall "migrants" that move out of rearing areas into larger streams. Recent development of technologically-advanced tags that can be detected in induction coils without handling of fish by humans offer promise for use on anadromous fish in the Snake River basin, where all juveniles pass Lower Granite and Little Goose dams. Work of this type has been proposed and will be implemented on 1987 (R. Thurow, personal communication).

D.2. <u>Best available information</u>

Bjornn et al. (1977) reported that at an embeddedness level of about 2/3, corresponding to about 30% fines in the substrate, all of the interstices in the substrate were filled with fines. This would completely remove rearing areas with such high embeddedness from use by overwintering fish. Reduction in winter habitat must occur at embeddedness levels somewhere between 0%

and 66%.

Best available information indicates that substrate interstices are needed by overwintering salmonids in the northern Rockies, and that fines decrease availability of interstices. Risk, uncertainty, and prudence suggest that any incremental fines above current conditions would be likely to reduce overwinter survival of salmonids.

E. MONITORING

Where the environment already contains large amounts of intragravel and surficial fines, and where redds and spawning gravels cannot be monitored, management agencies may have to adopt other approaches. To evaluate long-term changes in substrate conditions, the manager may have to employ a combination of McNeil coring, embeddedness, substrate scoring, and ocular estimates of surface fines.

Earlier in this section and elsewhere in our report we extensively criticized existing data on intragravel composition as they apply to embryo survival. These and other criticisms do not imply that McNeil corings, embeddedness, ocular estimates of fines, or substrate scoring will not serve to monitor long- or short-term changes in substrate composition in actual or potential spawning and rearing areas. On the contrary, these techniques may work very well as indices of habitat quality. Our argument is with quantification of biological effects of fine sediments, not with habitat monitoring.

Shortage of funds and trained manpower for habitat research and evaluation makes it imperative that data collection in monitoring programs have a clearly-defined purpose and that it receive regular scrutiny of both biologists and statisticians so that waste may be avoided. In very heavily sedimented streams, where spawning gravels are buried, or seeding levels so low that redds do not occur, the advice of a hydro-geomorphologist may be required before a monitoring program is developed.

VI. GENETIC RISK, BIOLOGICAL COMPENSATION AND LIMITING FACTORS

A. GENETIC STRESS ON POPULATIONS

Use of tools for evaluation of sedimentation need not require a presumption of fish population limitation in a numerical sense by fines. Although erosion and sedimentation are natural processes, and all streams in the northern Rockies a product of millenia of process operation, acceleration of erosion processes and concomitant stream processing of fines should be viewed as a genetic risk for fish stocks.

The genetic material represented by indigenous fish species and stocks of the northern Rockies has adapted to evolving and instantaneous climatic, edaphic, and biological constraints and potentials. Risk accompanies acceleration of change and addition of stress in this system, particularly in the case of resident and anadromous stocks already subjected to heavy fishing pressure (usually a discriminant stress), engineered obstacles (often causing indiscriminant stress), and manipulation by resource managers (discriminant and indiscriminant stresses).

In the case of anadromous fish stocks of the Columbia River system, the Northwest Power Act has brought into being a new bureaucracy, the Northwest Power Planning Council, with a mandate to protect and enhance salmon and steelhead stocks of the basin, and to bring fish into parity with power generation. The Council has stated that anadromous fish losses associated with hydropower dams amount to 5.6 - 10.1 million adults, and set tentative near-term goals of doubling mid-1970s runs of 2.5 million fish to 5 million.

It has been reasonably estimated that the natural environments of the Columbia River system can produce a total of one million adult salmon and steelhead. Thus, hatcheries will have to produce the complement of the Council-ordered increase, or about 4 million fish. Genetic change is a concomitant of intense management by hatchery supplementation with accompanying fisheries. Thus, natural stocks of the upper basin, often those in the steeper areas most subjected to accelerated erosion from road building and logging, will face increasing selective pressures downstream. No one knows if selective pressures from stresses caused by sedimentation would be additive, multiplicative, or covary with other selective forces in the life cycle.

B. ROLE OF BIOLOGICAL COMPENSATION

Biological compensation is the adjustment of birth, death, and growth in reaction to fluctuations in recruitment and mortality (Nicholson 1954). Ricker (1954), Ricker (1958), and many others have shown by means of such models as curves of stock and recruitment that fish stocks have high survival when population numbers are reduced by fishing or by density-independent factors, and to have low survival when numbers become excessive when agents of mortality are reduced in intensity, or when recruitment is excessive (Fraser 1969). A similar phenomenon can be demonstrated for growth; that is, fish in populations at low density tend to grow faster than those at high density (Fraser 1969).

It is useful to offer an example of the role of compensation in the present context. If fine sediments increase in the substrate as a result of accelerated erosion in the watershed, in turn resulting in reduced intragravel survival of salmonid embryos, we should expect to see emerging survivors of the incubation period grow more rapidly and survive at higher rates, thus "compensating" for higher embryonic mortality. (Although compensation operates at the individual fish level, biologists often think of compensation as a population phenomenon, as if the population were a super-organism.) If intragravel mortality is high enough, even compensatory mechanisms will not serve to adjust for it and the population will be depressed (limited).

On the other hand, if fine sediments not only reduce intragravel survival and emergence, but also reduce abundance of macroinvertebrates and fill interstices used by salmonids for instream cover in the rearing period and for overwinter hiding places, compensation must be less effective, and carrying capacity would be reduced.

C. LIMITING FACTORS

Limiting factor theory has roots in the classic ecological literature (Pearl 1926, Solomon 1949, Volterra 1931, Lack 1954, Nicholson 1954). These works, as well as basic ecology texts, describe relationships among birth rates, death rates, population distribution, innate capacity for increase, empirical rate of increase, and discuss population legislation by limiting factors.

Figure A.1 illustrates birth and death rates in a regulated population, population growth in relation to density, and approach of population size to equilibrium (often designated as "K") with time. At population densities that exceed K, death rate will, in the long run, exceed birth rate. In the short run, loss of animals to mortality will bring the population toward K. In populations smaller than K, birth rates will exceed death rates in the long run. In the short run, survival rate will increase until the population reaches K.

Populations may oscillate about K as a result of various time lags (lag between ovulation and emergence, lag in predator reaction to prey abundance, etc.), and K itself may vary from year to year in response to climatic or biologic factors. Hence K may be considered a long-term average rather than an instantaneous absolute. The limiting factors that determine K may vary

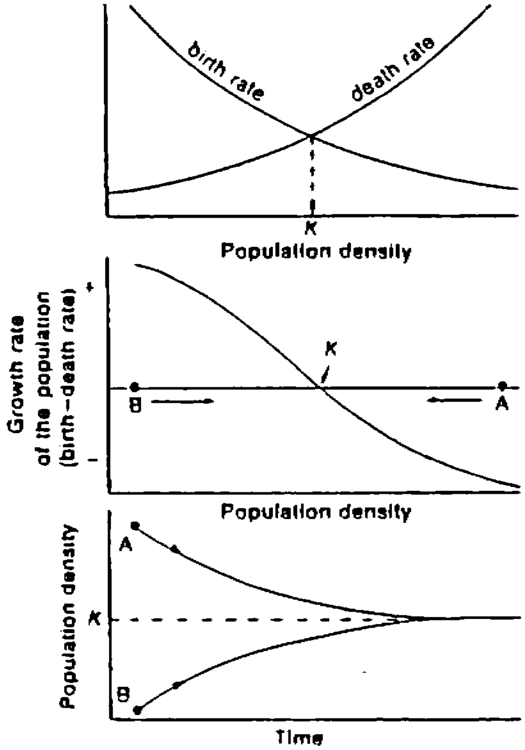

Figure A.1. (From Ricklefs 1973). Birth and death rates in a regulated population (top), population growth in relation to density (middle), and approach of population size to equilibrium (K) with time.

with the seasons.

Nicholson (1954) offered elegant examples of limiting factors in operation. He studied sheep blowflies (Lucilia cuprina) in laboratory cultures. He provided everything in excess except one requisite; water, sugar, space in excess for example, and larval food in limited quantity, or all factors in excess except food for adults. Under these circumstances, provision of double the limiting requisite allowed the population to double.

In natural ecosystems, all factors but one are rarely in perfect excess, and doubling supply of a limiting factor would not normally double the population size. Another factor generally would limit in this circumstance before the population doubled.

Mason (1976) provided an excellent example of "lifting the lid" of food limitation by feeding marine invertebrates to coho salmon in a stream on Vancouver Island. In comparison to unfed stream sections, fed sections produced larger coho salmon with high lipid reserves, and test populations 6- to 7-fold more numerous in terms of fish per 100 m^2 by late September. By February, test (fed) populations of coho salmon had declined to about 25 fish per 100 m^2, a density close to that of nearby natural populations not subjected to testing. Mason concluded that winter hiding spaces limited carryover populations of pre-smolt coho. This study illustrated that the limit on smolt output may be set by a suitable space mechanism in winter.

Although it is generally conceded that coho salmon abundance is determined by suitable space in the summer-fall rearing period (Chapman 1962, 1965), the possibility remains that behavioral mechanisms that regulate density in the rearing period may also have an underlying constraint of over-winter space availability. Hunt (1969) showed that resident trout density in a Wisconsin stream could be increased by provision of winter cover.

Large woody debris (LWD) has been shown to exert a strong effect on abundance of coho salmon (House and Boehne 1986), and Heifetz et al. (1986) showed that LWD also increased winter habitat for coho salmon, Dolly Varden char, and steelhead. Lid-lifting sometimes has unforeseen effects. Sih et al. (1985) examined studies of lid-lifting through predator control, noting two unanticipated effects: (1) removal of keystone predators may increase density of a dominant prey, decreasing diversity, hence stability, and (2) removal of top predators may release a middle level predator and thus reduce numbers of primary consumers; a 3-trophic-level effect. Forty percent of all predator control studies resulted in unforeseen effects in the system; some negative, some positive.

McFadden (1969) defined population <u>regulation</u> as operation of density-dependent factors, as distinct from population <u>limitation</u>, which refers to operation of density-independent factors. In other words, density-independent factors <u>legislate</u> K, and regulatory factors <u>govern</u> populations within the K constraint. A population so-governed would be termed "K-selected" in the evolutionary sense (Pianka 1970). The salmonid populations in streams of the northern Rockies fit this terminology. McFadden (1969) hoped to de-emphasize the quest for single limiting processes or factors and to increase interest in a flexible scheme that would synthesize information about a variety of population processes and environmental factors.

As an example of a flexible viewpoint, McFadden (1969) noted that where a fish stock is very abundant (potential overseeding), behavioral interference leads to retention of part of the egg complement or to destruction of previously-completed redds by late spawners, and to an increased proportion of adults spawning in less-suitable areas where redds may be exposed to subsequent freezing, dessication, scouring, or siltation. Where great numbers of eggs are deposited, oxygen depletion may occur in redds.

Where suitable spawning gravel is available in limited quantity (or where large numbers of fish use the gravels), mortality in the spawning and incubation phases will thus be density dependent (and will act as a population regulator). Where extensive areas of gravel of poor quality are present relative to fish abundance, mortality during the spawning and incubation stages will be density independent (Allen 1962). Hence in the one case, spawning gravel may limit population recruitment (as often appears to be the case for sockeye salmon and pink and chum salmon in Canada and Alaska). In the second case another life history phase may limit (as often appears to be the case for species with extended stream rearing phases, such as spring and summer chinook salmon, steelhead, resident rainbow trout, bull trout and cutthroat trout).

Most areas of the northern Rockies do not appear to suffer from excessive spawner densities at this time, hence are unlikely to support populations of fish that are regulated by density dependent factors in the reproductive phase. Kokanee may be an exception, where limited spawning gravels support large lake populations. More usually, one should expect density-independent survivals in the reproductive phase, as a result of flooding, ice scour, or widespread siltation.

P. Bisson (unpublished draft report 1986) warned of the many pitfalls in the process of identifying limiting factors. He specifically listed (1) excessive reliance on professional judgement, (2) extrapolation in space and time, (3) over-simplification of complex ecological situations, (4) exclusive focus on one aspect of life history, (5) failure to consider critically important factors. Examples of these problems were offered by Bisson. In the context of the present review and synthesis, item (2) is exemplified by erroneous extrapolation of laboratory studies to field environments by workers seeking tools for management and regulation. Item (3) is typified by evaluations of short stream segments without knowing whether the carrying capacity of a segment is limited by some factor in the study section or by factors removed in time and space. Fishery workers have generally confined field studies to daytime in favorable weather periods, thus risking pitfall (5). Instances of pitfall (1) are so numerous as to require no example. Laboratory studies of emergence success embody elements of pitfall (3). Bisson's paper should be widely read.

Assessment of limiting factors for salmonid stocks in the northern Rockies remains an art form rather than a scientific system. Peters (1986) forthrightly discussed work in Montana on effects of forest practices on stream ecology by stating:

> "The sampling of fish populations in this study has raised more questions than the effort has answered so far. Recent literature searches and on-going fisheries work further clouded our results with uncertainty as to what exactly we are measuring in the limited fish population sections. Are we measureing the carrying capacity of that section or the result of some limiting factor either spatially or temporally removed from this site? The ramifications of this difficulty is that our sampling design may only show impacts if the summer habitat contains the limiting factor(s) on the particular population. Studies of cutthroat trout in the Flathead River system indicate that some fish enter the interstitial areas in the substrate while some adult fish move to pools in the larger river system (personal communication with Pat Graham)."

Professional judgement, empirical experience, and the knowledge base for salmonid ecology must be applied with tailoring to each situation, whether the biologist wishes to manipulate nature for improved fisheries or merely wishes to understand and maintain the status quo.

In the face of uncertainty and a limited and fragmentary knowledge base, we contend that resource managers should attempt to maintain maximum ecological diversity as a hedge. In the context of the present report, this concept means that the manager would seek to increase natural diversity in habitats damaged by sediments. This concept means, in the case of the intragravel environment, minimal (or no) introduction of fines to the existing gravel matrix. It means making every reasonable effort to reduce sediment recruitment from basin development.

The rearing phase of salmonid life history appears to be somewhat plastic in regard to effects of surficial fines on fish abundance and growth, but it seems prudent not to increase fine sediments. This prudence would conform to the concept of maintaining diversity in stream systems.

The overwintering phase of salmonid life history requires interstices for hiding. Any increment of fines that decreases abundance and volume of interstices constitutes a risk. It would be imprudent of land managers to decrease habitat diversity by permitting more fines to enter winter cover. The information base is simply too scant to justify any risk, especially where fisheries of high value are involved.

VII. PREDICTIVE TOOLS, MANAGEMENT, AND REGULATORY UTILITY

In the following material we define predictors as independent variables that can serve to quantify effects of fines on fish and macroinvertebrates. We define threshold values as levels of independent variables beyond which serious damage to fish or macroinvertebrate populations would occur.

A. PREDICTORS FOR FISH

We found no functional predictors that would serve environmental regulators in evaluating quantitative effects of sediment on the natural incubation, rearing, or wintering phases of salmonid life history in the northern Rockies. Some predictors have promise that can be met by additional research.

A considerable body of laboratory and field research has been devoted to effects of fines on the intragravel environment in the northern Rockies, particularly in the Idaho batholith, and in the Pacific Northwest. It is clear from the available information that increased amounts of fines that reduce geometric mean particle size, fredle index, permeability, or dissolved oxygen in intragravel water also tend to reduce survival of embryos to emergence. Inasmuch as we cannot support quantitative predictors for use in field environments, either in the northern Rockies or elsewhere, we offer no threshold values. Uncertainty and risk factors lead us to suggest that any incremental increase in intragravel fines in egg pockets should be avoided until functional relationships can be developed.

The only threshold values that have been developed for intragravel parameters in relation to fishery values are those of Davis (1975) for dissolved oxygen. These relate to conditions in the egg pocket because they were developed directly from investigations of embryo survival in various oxygen concentrations, rather than indirectly (through indexing fines in the redd or permeability, for example). We see no reason why these cannot be adopted. We suggest that threshold levels of minimum dissolved oxygen content in intragravel water in the egg pocket could be set at 98% of saturation at temperatures of 0-10 C for high value fisheries, 76% of saturation at 0-10 C for fisheries of moderate value, and 54-57% of saturation for fisheries of lower value. Judgement and negotiation would have to set fishery value categories. Chinook salmon, steelhead, and westslope cutthroat trout would nearly always fall in the high-value group.

Abundance of salmonids, with the exception of brook trout, appears loosely and negatively correlated with embeddedness level and percentage of surficial fines. Embeddedness appears promising as a tool for evaluation of effects of sedimentation on rearing phases of salmonids. No threshold value can be set. We can make no recommendation regarding surficial fines as they may affect salmonid rearing densities.

The relationship of surface fines and embeddedness to overwintering success in salmonid populations of the northern Rockies has not been quantified. The body of available laboratory and field information leads us to infer that maximum crevice availability (minimum embeddedness) should provide the greatest overwintering capacity. No threshold value can be set for embeddedness as it affects overwintering. In view of uncertainty and risk factors, we believe it prudent and conservative on the side of salmonid gene pools to permit no man-caused incremental embeddedness until functional relationships can be established, at least in areas that support fisheries of moderate to high value. How these fishery values may be established lies beyond the scope of our report, but we suggest that judgement of biologists and negotiation with resource managers must determine them.

B. PREDICTORS FOR MACROINVERTEBRATES

The relationship between aquatic insect density and embeddedness appears to us to be sufficiently strong that we feel reasonably secure in stating that at embeddedness levels above about 2/3 or 3/4, aquatic insect density declines. We see no evidence that embeddedness levels below 2/3 reduce density; in fact, density tends to be higher at embeddedness of 2/3 than at very low embeddedness levels. This is probably a phenomenon caused by environmental complexity and space availability in mixed particle sizes. In view of uncertainty regarding other aspects of effect of fines on stream ecology in the northern Rockies, it would be prudent to consider an embeddedness level of 2/3 as a tentative threshold level. Embeddedness this high would probably violate needs of sediment-free interstices for overwintering space for fish.

We see no relationship between embeddedness and insect drift, although drift should logically decline at very high embeddedness levels.

C. MEASURES OF LAND USE

Real and detectable relationships appear to exist between disturbances such as stream crossings and fines (Munther and Frank 1986 a,b,c). Where above/below and before/after studies can be conducted with adequate sample sizes, it should be possible to determine whether given land management activies cause fines to increase in corings or in cleaned gravels in buckets inserted in the stream bottom. Cleansed gravels of moderate to high geometric mean particle size offer the most sensitive "trap" for sediments in these evaluations.

Edwards and Burns (1986) prepared correlations of embeddedness and various drainage characteristics in 19 tributaries of the Payette National Forest. Their results, for 23 independent variables, provide several significant ($p < 0.05$) relationships. (Table C.1).

Table C.1. (From Edwards and Burns 1986). Correlations of embeddedness with 23 independent variables, with r^2 and probability that correlations equaled zero.

Variable	r	r^2	p of r = 0
1. Drainage size	-0.19	0.04	0.46
2. Stream mileage	-0.30	0.09	0.23
3. Stream gradient	-0.44	0.19	0.07
4. Water yield	-0.31	0.09	0.22
5. Percent glaciation	-0.51	0.26	0.03
6. Drainage density	-0.09	0.01	0.71
7. Road density	0.74	0.55	0.00
8. Road acres/decade	0.79	0.62	0.00
9. Acres sediment slope group 6+	-0.27	0.07	0.28
10. Ac. sed. slope group 11-12	-0.19	0.04	0.46
11. Acres road	0.72	0.52	0.00
12. Acres road on sed. slope grps. w/mass waste hazard during original 2 decades post-construction	0.45	0.20	0.06
13. Acres road on sed. slope grps. w/mass waste hazard current	0.65	0.42	0.00
14. Acres riparian road	0.25	0.06	0.32

Table C.1, continued.

Variable	r	r^2	p of $r = 0$
15. Number stream crossings	0.61	0.37	0.01
16. Natural sediment yield	-0.22	0.05	0.38
17. Accelerated sediment 1955-65	0.44	0.20	0.07
18. % accel. sed. over natural 1955-65	0.60	0.36	0.01
19. Total sediment 1955-65	0.11	0.01	0.67
20. Accelerated sed. 1975-85	0.29	0.08	0.25
21. % accel. sed over natural 1975-85	0.52	0.27	0.03
22. Total sediment 1975-85	-0.16	0.02	0.54
23. Natural sediment/acre	-0.15	0.02	0.54

The authors eliminated variables 9, 10, 16, 22 and 23 because the correlations were low and did not make physical sense. After transformation with logarithms for non-linear relationships and tests of interactions, the authors used stepwise regressions to examine a best combination of independent variables. A significant relationship was:

$$\text{Embeddedness} = 34.59 + 12.90 \log_{10}(\text{acres road with current mass waste hazard} + 1) - 0.16(\%\ \text{glaciation}).$$

This regression accounted for 83% of observed variability in embeddedness and was highly significant ($p = 0.0009$, $F = 37.01$, 2 and 15 d.f.).

The next best regression was for embeddedness against road density and percent glaciation. After examining interactions, Edwards and Burns calculated a stepwise regression of the following form:

$$\text{Embeddedness} = 32.17 + 10.95 \log_{10}(\text{road density} + 1)(\text{acres road with current mass waste hazard} + 1) - 0.13(\%\ \text{glaciation}).$$

This relationship was highly significant ($r^2 = 0.85$, $p = 0.0009$, $F = 42.8$, 2 and 15 d.f.).

Equations of the foregoing types, based on careful field work, offer utility for assessing arbitrarily-selected threshold levels in embeddedness in fish habitat. However, a prerequisite is that functional quantitative relationships between fish densities and embeddedness, or winter habitat capacity and embeddedness, must be developed.

Moring (1982) showed that stream gravel permeability decreased in a clear-cut watershed in the Oregon Coast Range after logging. Permeabilities dropped from a prelogging average of about 4,900 cm/h to an average of 1,100 cm/h in the first year after logging, then remained at an average of about 2,400 cm/h for the next 6 years. Both the first-year and later changes were significant ($p < 0.01$). No similar decline occurred in a drainage in which 25% of the watershed was clear-cut, and permeabilities in a control watershed did not differ significantly before and after logging in the test drainages (Figure C.1).

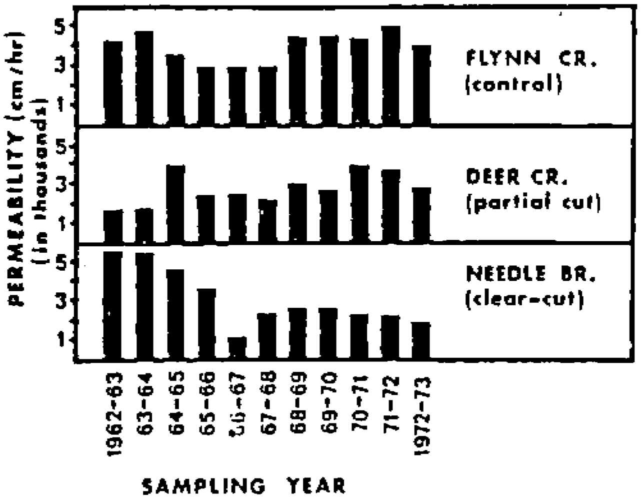

Figure C.1. (From Moring 1982). Annual average permeability in three tributaries of the Alsea River, Oregon, 1962-1973. In Deer Creek and Needle Branch watersheds, road construction was completed after the 1964-65 season, and logging after the 1965-66 season.

Clear-cut logging by Georgia-Pacific Corporation in the Needle Branch watershed was in accord with what would have been termed best management practices at the time. Permeabilities in the streams were recorded at two-week intervals in three permanent Mark VI standpipes installed in each stream. Had they been obtained in egg pockets, the results would probably have differed in absolute means and extent of change. We would expect egg pockets to have higher mean permeabilities and to show greater change over the incubation period than the temporal changes in permanent pipes.

D. ROLE OF JUDGEMENT IN CRITERIA FOR MANAGEMENT PRACTICES

In the absence of quantitative models of fish density in relation to embeddedness, fishery managers and water quality regulators may have to use professional judgement and negotiations with development-oriented interests to establish interim estimated threshold levels for embeddedness. Instances may develop in which best management practices would lead to sediment recruitment above judgement-based and negotiated limitations. In this case, uncertainty and risk factors may be be deemed to mandate that no incremental development occur in the watershed.

Fishery values and estimated stream recovery rates may be important considerations in the negotiated interim settlement of threshold levels. Certain stocks and species may justify more stringent protective limitations than others.

We acknowledge that our inability to find or develop quantitative functional relationships that can be used as regulatory tools will disappoint some readers and please others. Among the latter may be some who have a vested interest in logging and road construction. Our failure may also please those who have contended that best management practices should be sufficient protection for aquatic communities, or that protective criteria must have quantitative tools before they can be justified. We direct the following comments to advocates of best management practices.

The interface between water and air is, to a very real degree, the interface between relatively easy and very difficult ecological assessments. Too often, it is also the interface below which research funding has been insufficient. Even after 35 years of intensive work on the effects of fine sediments on the intragravel environment, we are only now focusing on that which directly influences survival of embryos to emergence. Only now have researchers begun to realize the importance of habitat for overwintering by salmonids in the northern Rockies.

Quantitative tools for evaluation of effects of fines will not supplant scientific judgement. The complexity and variety of stream systems in the northern Rockies will make it impossible to broadcast fixed criteria. We suggest that every system and subsystem must be evaluated as a discrete unit; that conservatism in favor of the fishery resource is prudent, especially in the case of high-value fisheries, and should be quite amply justified simply on the grounds that unforeseen externalities are easy to cause and hard to rectify; and, finally, that informed judgement should drive the system, rather than any arbitrary set of best management practices. We feel that best management practices can too easily be interpreted to mean economical practices. While "economical" in this sense serves the timber or mining interests well, it totally neglects consideration of the state of knowledge in stream ecology and hidden costs passed on to the general public in the form of deteriorated fishery resources and future rehabilitation requirements.

Criteria for evaluation of best management practices, however desirable, will not relieve the resource manager of his responsibility in watershed husbandry. One may easily lose sight of the fact that accelerated stream sedimentation reflects poor land husbandry. But after all, what good land manager would voluntarily sluice away the soil resource? Thus the two most important criteria for critical evaluation of land management practices in areas of valuable fisheries or slow recovery, be those practices best or otherwise, should be: (1) Are we conservative enough to avoid unforeseen externalities, and (2) Will these measures result in zero acceleration in soil wasting? We believe these criteria would meet the prudent and conservative caveats noted above in sections A and B.

The foregoing two criteria place the responsibility for good stream protection through good land management where it belongs; on the land manager. The aquatic resource professional must use best judgement to establish habitat requirements and protective measures in site-specific circumstances, thus providing guidance for the land manager. Negotiation will have to precede final decisions on fishery values, and protection measures.

VIII. SUMMARY OF RESEARCH NEEDS

In this section we summarize our principal suggestions regarding research that we believe will be required for development of quantitative tools for assessment of effects of fines on salmonids in the northern Rockies.

A. INTRAGRAVEL ENVIRONMENT

We recommend that assessment of survival to emergence be pursued for salmonid redds by means of careful mapping of egg pocket locations and depths in relation to temporary benchmarks, followed by redd capping shortly before onset of emergence. Timing of emergence can be determined from knowledge of spawning time and accrued temperature units in the substrate.

Depths and precise locations of egg pockets should be established when redds are mapped during spawning. A program for periodic sampling of permeabilities and dissolved oxygen percent saturation in the egg pocket centrum should be designed. Three-probe freeze cores of egg pockets should be obtained after alevins have emerged from the redd.

Concurrent programs should be conducted in redds outside the egg pocket and in "spawning gravels" around the intensively-studied redds so that relationships between survival (as assessed from redd capping) and various physical statistics in the egg pocket, in the redd area outside the pocket, and in the nearby unused gravels can be compared. This should permit researchers to learn whether conditions outside the egg pocket can serve as surrogates for parameters in the pocket.

In addition to permeability and percent dissolved oxygen saturation, researchers should assess geometric mean particle size in and outside the egg pocket in up to three vertical strata and for the composited vertical strata. Other statistics to be calculated include the fredle index, and percentage of fines by weight in various sieve categories. These data will permit workers to assess conformity, if any, of survival and conditions in the field to information obtained in various laboratory studies.

Even if redd capping proves impossible in field situations in Idaho, the work described above will establish physical conditions in egg pockets, permitting laboratory workers to develop better, more accurate, physical analogs for field conditions. Even live:dead ratios obtained by hydraulically sampling egg pockets before emergence begins (after appropriate physical statistics have been obtained) would bring laboratory work to date into better focus, offering a substitute for survivals to emergence.

As soon as data become available on egg pockets and the egg pocket centrum, we suggest that laboratory studies be designed to duplicate, as closely as possible, conditions in the pocket.
The type of work typified by Tappel and Bjornn (1983) should be pursued, but with better surrogates for natural egg pockets. The independent variates that need to parallel natural conditions this work include:

1. Geometric mean particle size.
2. Fredle index.
3. Gravel mix components.
4. Permeability.
5. Organic matter in the gravel mix.
6. Physical structure of the surrogate pocket.

B. REARING HABITAT

Embeddedness, substrate score, surface percentage of fines, and other habitat variables such as gradient, riparian cover, instream cover, stream orientation (north-south, east-west) need to be evaluated in a program of randomly selected sites in several habitat strata in the northern Rockies. It may be necessary to adjust densities of fish (at least in anadromous fish areas in which seeding by adults may not be sufficient to lead to full recuitment of juveniles) in study sites by means of adding fish seined, minnow-trapped, or electrofished from areas not intensively studied. Fish abundance and biomass would then be examined in relation to independent habitat variables.

Stream areas in which resident species not subjected to heavy fishing pressure are the target animals may not require population adjustments before studies begin. But whether densities are enhanced or not, habitat and species variability may well dictate that large numbers of study sites be evaluated.

C. WINTERING HABITAT

Intensive study should be allocated to the question of overwintering habitat used by anadromous and resident salmonids in the northern Rockies. The first priority is to establish relative survivals of fish that overwinter in areas near the summer rearing zones and those that move downstream in fall to overwinter in larger streams. "PIT" tags can be used for these studies on steelhead and chinook salmon in Idaho streams because detection devices for the tags will provide for reasonably efficient sampling at Lower Granite and Little Goose dams on the Snake River.

The next or concurrent step is to better define where and how densely salmonids are found in winter. Condition of habitat in which fish are found should be defined in terms of gradient, substrate particle sizes, embeddedness, cover, width, flow, and other habitat variables. Areas not used, lightly occupied, and heavily occupied should be described. We need to learn if low wintering use by salmonids is associated with high incidence of fines in the substrate.

Study of overwintering habitat and survivals may be the most important work that we suggest in section VIII.

D. EXPERIMENTAL MANIPULATION OF FINES

We believe that test and control areas should be set up in several drainages to evaluate the effect of trapping and removing fine sediments on salmonid density and growth. This may require careful selection of upstream control zones and downstream test zones separated by large-volume sediment traps. Alexander and Hansen (1983 and 1986) offer useful reading for those interested in such manipulations. The size of the experimental environments should be large enough to lead to detectable changes in habitat quality and fish populations. Alexander and Hansen (1986) separated a two-mile stream reach into a one-mile upstream control and a one-mile downstream test area by removing fines at the midpoint in a sediment trap.

IX. SUMMARY

1. Several measures of streambed character offer indices of habitat quality. These include percentages of fines (most useful categories in the northern Rockies are <6.35 mm, <0.85 mm, <9.5 mm), geometric mean particle size (d_g), fredle index, and permeability.

2. Percentage of fines in the intragravel environment varies spatially and temporally. To reduce this sampling variability where survival is to be related to substrate fines, samples should be taken in redd egg pockets during the period when embryos are incubating within the pockets.

3. Geometric mean particle size (d_g) offers a workable measurement as a companion to percent fines, for a more complete index of habitat quality. High survivals tend to occur in association with high d_g, but failure of researchers to sample in egg pockets and to relate d_g to survival from deposition to emergence reduces utility of the relationship for quantitative predictions of survival.

4. Tappel and Bjornn (1983) tested embryo survival in relation to gravel mixtures on the basis of two substrate variables, fines percentages <9.5 mm and <0.85 mm. They eliminated particles larger than 25.4 mm and used relatively small d_g. This neglects the fact that for many salmonids, the egg pocket centrum in natural redds is formed of particles much larger than 25.4 mm. We did not support use of these laboratory results to quantitatively predict conditions in natural egg pockets.

5. Field research has yet to verify the utility of the fredle index (d_g/s_g) in a variety of field situations. Because it embodies d_g and a mixing index, it offers promise.

6. Visual assessment offers a reasonable measure of major change in surficial fines where used as a time-trend indicator. It does not necessarily reflect conditions deeper in the substrate or differences in depths of intrusions of fines.

7. Permeability offers a useful tool for correlations with survival and for assessment of fines intrusions.

8. Assessment of conditions in the substrate as they control salmonid incubation and emergence requires sampling in natural egg pockets. To determine overall condition of "spawning gravels" without reference to embryo survival, a somewhat less-restrictive stratification could suffice.

9. The structure of salmonid redds is critical to the role of fine sediments in affecting survival of incubating embryos and emergence success. The lack of understanding of redd internal

structure by researchers has hampered quantification of the role of sediment in affecting incubation and emergence.

10. Survival of salmonid embryos is positively related to apparent velocity and permeability. Dissolved oxygen affects both emergence success and timing.

11. Survival to emergence tends to decrease as the proportion of fine sediments increases in the incubation environment.

12. Studies on the effects of fines on emergence size have shown conflicting results for the same species and among species. Female size may have caused some variance.

13. Alevins tend to emerge earlier from gravels with high percentages of fines. This does not appear to have any direct deleterious effects on the alevin, and may be an adaptive mechanism that has the effect of trading-off mortality in surface waters against mortality in the substrate.

14. Various forms of substrate scoring have been used to describe habitat suitability for aquatic insects and fish. Substrate score correlates reasonably well with d_g. Visual assessments at best offer indicators of microhabitat conditions in the surface zone in areas not armored.

15. Photographic assessment of fines has been pursued by a few workers but appears to underestimate fines smaller than 6.3 mm when compared with core samples.

16. Core samples seem to offer the most complete assessment of substrate components, but do not serve well for evaluation of summer rearing or winter hiding habitat. Measures of coarseness may have utility concert with visual methods, photographic techniques or embeddedness measurements.

17. Embeddedness, free matrix particles, and percent of fines are related. Embeddedness works best where sand is an important component of the substrate. These measures offer useful "before and after" or "above and below" measure of changes over time and space. Sediment traps may provide useful tools as well.

18. All newly emerged salmonid fry utilize shallow water areas with low velocities, where fines tend to accumulate. Newly-emerged fry remain close to the stream margin in quiet water, making availability of these areas in spring and summer important, but not likely to be limiting.

19. Effects of fines on juveniles in the size groupings classed as age 0, I and II are of particular concern. As juveniles grow they begin using deeper faster water. The weight of evidence tends to indicate that areas with high embeddedness (50%

embeddedness may define "high") tend to have lower densities of salmonids. The data do not consistently or convincingly support a negative relationship between fines and fish rearing density. In some cases density correlates positively with fines.

20. Loss of pool volume due to sediment deposition reduces suitability of a stream for adult salmonids.

21. Macroinvertebrate biomass and diversity decrease where fines predominate. Also aquatic insect density declines at embeddedness levels above about 2/3 or 3/4. We saw no relationship between embeddedness and insect drift.

22. At water temperatures below 10 C, salmonids often begin to emigrate or seek cover in the substrate. This behavior varies by species/race.

23. From the available data we infer that as embeddedness increases, winter carrying capacity declines. However, fish response to embedded habitat may vary between species and populations. Fish appear to seek winter habitat in upstream locations. Addition of sediment that reduces availability of this environmental requisite probably increases mortality.

24. We believe the role of channel structure in legislating conditions for salmonid spawning and rearing is of great importance and deserves greater research emphasis.

25. Aggradation reduces channel diversity, leading to probable increases in embeddedness levels.

26. Fines in interstices of the bed may delay the onset of bed movement during large storm flows, a movement critical to the removal of accumulated fines in spawning gravels.

27. Woody debris is an important component of stream structure, especially in smaller streams. Stream structure may favor or detrimentally affect particular salmonids.

28. For any of the independent variables that have been previously studied (fredle index, d_g, percent fines, and permeability) to offer utility, reality, and permit quantitative prediction of survivals, they must be shown to reflect conditions in the egg pocket of the salmonid redd. Given the existing information, we do not favor extrapolation of laboratory data on survival to field situations.

29. In order to develop useful and quantitative predictions of survival in relation to the fines, fredle index and geometric mean particle size, we suggest several alternative sampling scenarios, all of which incorporate redd capping to assess survival to emergence and freeze-core sampling of the egg pocket.

30. As with the other procedures, care should be taken when assessing permeability that the measures come from within egg pockets. We suggest that permeability assessment is easier by far than gravel coring and we offer some possibilities for sampling.

31. Dissolved oxygen measurements from within the egg pocket could be used to assess incubation conditions.

32. Field evaluations of embeddedness effects on fish density should be undertaken in carefully documented stream strata and fully-seeded fish populations. This may require the addition of juveniles from other nearby areas to the test strata. Such field experiments at full seeding in several environmental strata are needed to assess effects of embeddedness on density of fish.

33. The relationship between density of fish and percentage of fines in rearing areas is fairly weak until there is a superabundance of fines. "Superabundance" means enough fines to reduce living space and overcome ability of the stream to process sediment recruitment so that food production on riffles is smothered and sharply declines.

34. Substrate score currently has insufficient documentation for application to the species of the northern Rockies but does merit pursuit in future studies for it should offer more information than embeddedness alone or visually-estimated fines alone.

35. The embeddedness level above which aquatic insects decline in abundance is about 2/3 to 3/4.

36. No useful relationship between substrate type and insect drift is available for predicting effects of fines on the insect drift resource in streams of the northern Rockies.

37. We believe that functional relationships exist between embeddedness and winter holding capacity of the substrate for salmonids and that those relationships differ by fish size and perhaps by species. It is currently impossible to form quantitative predictors. Research should examine the effects of various substrate types, starting and ending fish densities and fish size, and species on the shape of the relationship between winter holding capacity and embeddedness.

38. We contend that resource managers should attempt to maintain maximum ecological diversity as a hedge. This concept means, in the case of the intragravel environment, for example, minimal (or no) introduction of fines to the existing gravel matrix and every reasonable effort to reduce sediment recruitment from basin development. In overwintering habitat, the diversity hedge would prevent any increment of fines until predictive tools are

developed.

39. We found no functional predictors that would serve environmental regulators in evaluating quantitative effects of sediment in the natural incubation, rearing, or wintering phases of salmonid life history in the northern Rockies. In the absence of criteria, we suggest that due to uncertainty and risk factors, any incremental increase in intragravel fines in egg pockets should be avoided until functional realtionships can be developed.

40. We suggest that threshold levels of minimum dissolves oxygen content in intragravel water in the egg pocket could be set at 98% of saturation at temperatures of 0-10 C for high value fisheries, 76% of saturation at 0-10 C for fisheries of moderate value, and 54-57% of saturation for fisheries of lower value. Judgement and negotiation would have to set fishery value categories.

41. We make no recommendation regarding surficial fines as they may affect salmonid rearing densities.

42. No threshold value can be set for embeddedness as it affects overwintering. We believe it prudent and conservative on the side of salmomid gene pools to permit no man-caused incremental embeddedness until functional relationships can be established, at least in areas that support fisheries of moderate to high value.

43. As mentioned before, insect density declines at embeddedness levels above about 2/3 or 3/4. It would be prudent to consider an embeddedness level of 2/3 as a tentative threshold level. Embeddedness this high would probably violate needs of sediment-free interstices for overwintering space for fish.

44. Real and detectable relationships exist between land-disturbing activities and increased fines in the aquatic environment.

45. In view of uncertainty and environmental variability, professional judgement must play an important role in evaluating effects of fine sediments in salmonid habitat in the northern Rockies.

46. Regulatory agencies may have to provide interim criteria for non-point source sediment delivery to salmonid habitat. We summarize best available information from the body of laboratory and field information. We offer examples of the variables that might serve for this purpose. We urge that research proceed apace to develop criteria that will permit quantitative predictions of survival or density of fish and to evaluate efficacy of any interim criteria that are adopted.

47. Assessment of survival to emergence on salmonid redds should be conducted by mapping of egg pocket locations and depths, redd capping shortly before emergence, sampling of permeability and DO in the egg pocket, and three-probe freeze-coring in the egg pocket after emergence. Similar sampling should be conducted in substrate areas outside the egg pocket to compare physical statistics that may serve as surrogates for parameters in the pocket. Even where redd capping fails to provide good information on survival, data on egg pocket structure will permit laboratory studies to better model field conditions.

48. Assessment of rearing habitat requires an evaluation of random sites in several habitat strata in the northern Rockies. Embeddedness, substrate score, surface percentage of fines, and other habitat conditions such as gradient, riparian cover, instream cover, and stream orientation should be defined. Densities of fish may need to be adjusted by addition of fish from nearby areas.

49. Much work is needed to define overwintering habitat. Survival of fish overwintering in summer rearing areas versus downstream areas and where and at what density salmonids spend the winter are the major evaluations of concern.

50. Experimental manipulation of fines should help evaluate the effect of fine sediment on salmonid density and growth.

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Researchers in the program supervised by T. C. Bjornn, at the University of Idaho, deserve a special thanks. Their efforts through the years have provided high-quality research in profusion, and numerous working hypotheses pertinent to effects of fines on salmonids of the northern Rockies. The criticisms that we have offered of that work do not detract in the slightest from our admiration of the intelligence and diligence represented in in the many graduate theses and publications that have evolved from the program.

We have come to better appreciate the human ingenuity represented in the many research works that we reviewed and criticized. If no risks had been taken, criticism and progress would wither. We dedicate our report to those who took the risks.

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