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A Stream Systems Evaluation— An Emphasis on Spawning Habitat for Salmonids

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As a result of silvicultural activities in the Pacific Northwest, various levels of sediments and debris enter the streams, often degrading spawning substrate of salmonid fishes. Simple but reliable procedures are needed to monitor spawning gravels to assess the level of these impacts. This paper presents a preliminary rationale for conducting a monitoring program with the objective of assessing the level of sedimentation impact both locally in a given stream spawning site as well as more generally for the entire stream that might be impacted by watershed management activities.

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A STREAM SYSTEMS EVALUATION —-

AN EMPHASIS ON SPAWNING HABITAT FOR SALMONIDS

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DISCLAIMER

FOREWORD

Effective regulatory and enforcement actions by the Environmental Protection Agency would be virtually impossible without sound scientific data on pollutants and their impact on environmental stability and human health. Responsibility for building this data base has been assigned to EPA's Office of Research and Development and its 15 major field installations, one of which is the Corvallis Environmental Research Laboratory (CERL).

The priority mission of the Corvallis Laboratory is research on the effects of environmental pollutants on terrestrial, freshwater, and marine ecosystens; the behavior, effects and control of pollutants in lakes and streams; and the development of predictive models on the movement of pollutants in the biosphere.

This report is the product of a special conference at Gleneden, Oregon June 4-6, 1979, to discuss and rewrite a white paper originally prepared by Shirazi and Seim on development of a united approach for evaluation of spawning habitat. Invited participants are listed below. This report was shaped as the outcome of intensive work sessions directed towards crystalizing a consensus. The senior authors are, of course, indebted to these scientists for their contributions, but they derive greatest satisfaction from the support their work has received.

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ABSTRACT

As a result of silvicultural activities in the Pacific Northwest, various levels of sediment and debris enter the streams, often degrading spawning substrate of salmonid fishes. Simple but reliable procedures are needed to monitor spawning gravels to assess the level of these impacts. This paper presents a preliminary rationale for conducting a monitoring program with the objective of assessing the level of sedimentation impact both locally in a given stream spawning site as well as more generally for the entire stream that might be impacted by watershed management activities.

CONTENTS

INTRODUCTION

Nonpoint source pollution (NFS) is recognized as a serious problem in the United States and throughout the world. Water quality management programs conducted under state and federal legislation have identified nonpoint sources of pollution as a significant obstacle to attaining the 1983 goal of water quality adequate for fish, wildlife and recreation. Stream sedimentation is one of the greatest NFS pollution problems, primarily because widespread activities such as agriculture, logging, livestock grazing and road construction are major sources of increased sediment loading. For example, logging and road construction in the Pacific Northwest introduces various levels of sediments and debris into streams and rivers. This can result in the degradation of riffle habitats critical for salmonid fish reproduction and for the production of invertebrate food organisms necessary for the rearing of juvenile fish. In mountain streams spawning takes place in riffles where the water velocity is usually 45 to 75 cm/sec (1.5-2.5 ft/sec) and the water depth is 15 to 90 cm (6 to 36 inches). Salmonid reproduction and the production of invertebrate food organisms respond adversely to excessive sedimentation in these areas. A study of spawning habitats could, therefore, provide a relatively simple, sensitive and meaningful indicator of watershed management impacts.

For several decades, fishery biologists have known the general properties of spawning gravels used by salmonids. However, the lack of a relatively simple, reliable and standardized method of characterizing the gravels has hindered quantitative descriptions of changes caused by sedimentation. This paper describes a comprehensive procedure to assess and monitor the effects of watershed management activity on stream spawning habitat, applicable both to individual spawning sites and to an entire stream system. This monitoring program is designed to minimize costs and work effort. It is anticipated that this procedure will provide the groundwork for a serious effort in compiling the comprehensive data base required to evaluate effects of land use on streams over large geographical areas in the United States.

A UNIFYING SUBSTRATE STATISTIC

Fisheries researchers generally agree that excess fine sediments in the spawning gravel of salmonids are a cause for embryo and larval mortality (Iwamoto et. al. 1978). Several measures of substrate fines have been advocated, namely, fractions less than .83 mm, 3.3 mm, or 6.5 mm. Even if there is no consensus on a unified definition of fines, the causal factor of mortality is generally believed to be the filling of spaces within the gravel. This causes substantial reduction in the replacement of metabolite-laden water with oxygen-laden water during the incubation of embryos and alevins and the trapping of alevins during emergence from the gravel.

Since natural spawning substrates contain *a* wide range of particle sizes including silt, sand, gravel and cobble, permeability to flow and thus embryo survival depends not only on fine materials in the sand range, but also on the presence of gravel and cobble. Permeability is a strong function of pore size distribution, which in turn is affected by the size composition of the particles and by their shapes and packing arrangement. Shape angularity of the particles directly influences the packing arrangement. There exists no convenient measure of natural packing of substrate in a stream bottom. Lotspiech (1978} presented convincing arguments that combined measures of central tendency (i.e., the mean) and the sorting coefficient (i.e., the standard deviation) should provide an indirect but adequate measure of potential change in permeability.

In an extensive analysis of the relationship between permeability and gravel composition, and in an attempt to arrive at a logical alternative measure of spawning gravel, Platts et. al. (1979) demonstrated that information on the entire textural composition of the gravel is necessary. They proposed the geometric mean particle diameter (d_g) as an appropriate statistic because

(1) d_g is a conventional statistical measure used in sedimentary petrology and engineering to represent sediment composition.

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

(3) d_g may be calculated from d_{84} and d_{16}, two parameters that may also be used to calculate the standard deviation.

(4) d_g relates to the permeability and porosity of channel sediments and to embryo survival, at least as well as "percent fines.".

(5) d_g is a more complete description of total sediment composition than "percent-fines" and sediment composition evaluations in many cases involve less sampling error using d_g.

(6) d_g relates to porosity and permeability, and thus it is potentially a suitable unifying measure of channel substrate condition as it impacts embryo survival.

In a comprehensive review paper of embryonic survival, Shirazi (unpublished) showed an empirical relationship of survival during different embryo to alevin emergence stages with geometric mean diameter of the spawning substrate (Figure 1). Percent embryo survival is plotted against the geometric mean diameter of the substrate within the redd. The positive trend relating these two variables is unmistakable. To account for minor egg size differences among species, d_g was divided by a value for egg diameter (d_e) for that species in order to produce a more strongly correlated relationship with survival (Figure 2). The utility and the adequacy of a generalized scalar (d_g) are indicated in the figures by the strong correlation it exhibits with embryo survival from diverse sources of data.

There may be justification for further research to obtain a more complete description of the substrate than d_g. Vigorous research will hopefully continue, but for it to be successful and to provide the data base, the full substrate composition must accompany all survival test results. Having this information, d_g, percent fines, or other convenient measures may be readily estimated and correlated with embryo survival studies.

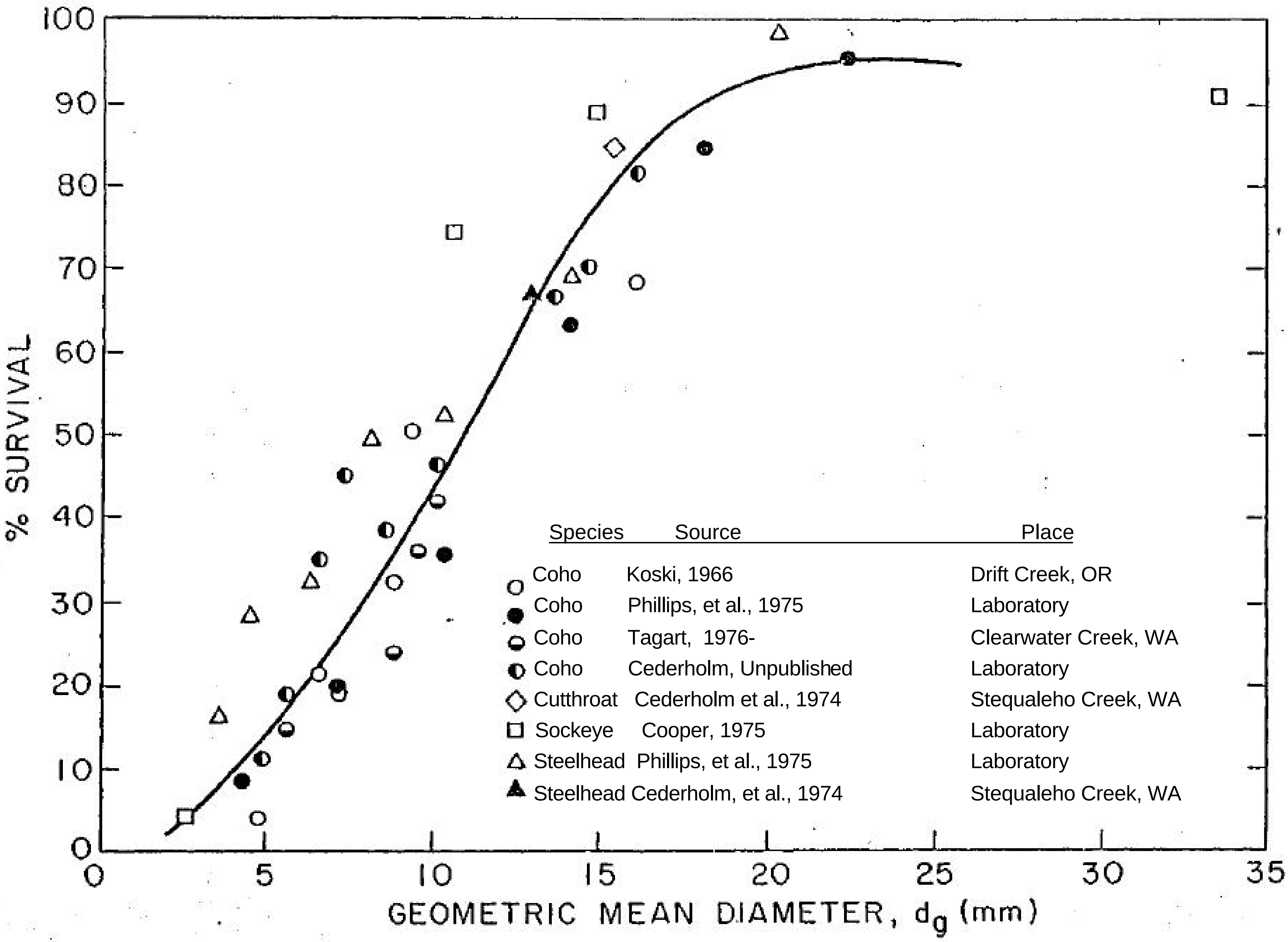

Figure 1. Relationship between percent embryo survival and substrate composition expressed in geometric mean diameter.

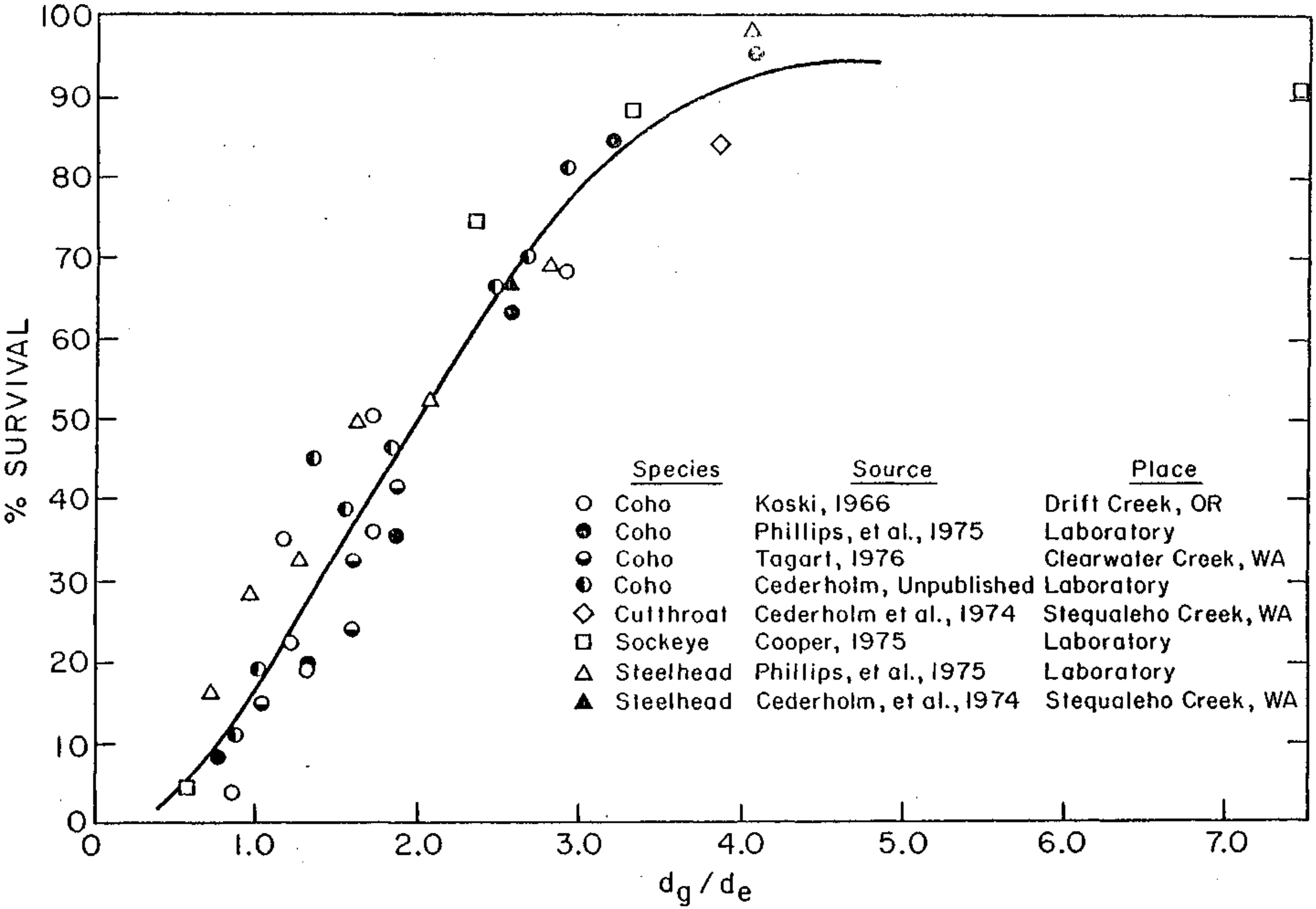

Figure 2. Relationship between percent embryo survival and substrate composition in multiples of egg diameter.

VISUAL ESTIMATION OF SUBSTRATE COMPOSITION AND NUMBER OF SAMPLES

To accomplish the objective of monitoring and assessing stream gravel composition, the following facts must be considered:

(a) Substrate composition varies both horizontally and vertically at a given time and location.

(b) Substrate composition changes through time because of bed form movement (e.g., bar progression) and the entrainment and deposition of fine material.

(c) Within a given stream reach, bed forms and channel patterns tend to repeat as similar geomorphic conditions are encountered (e.g.a sequence of pool-riffle complexes).

Because of the natural variability of stream gravel composition in time and space, a rapid stratification of the gravel environment would be desirable to reduce the overall sampling effort. It must be remembered that site assessment (gravel composition) must be coupled with area determination to establish net gravel quality and quantity within a stream reach or system. The experiment described here addresses gravel composition differences at typical spawning sites within an area, each site on the order of ten to several hundred square meters. This experiment tested the ability to estimate visually relative differences in the composition of two neighboring gravel patches. No attempt was made to delineate the boundaries of these patches even though the composition at times appears to change continually between these patches. A variety of spawning substrates was sampled, including streams in the Siuslaw National Forest in Oregon, a segment of the Rogue River in Oregon and a small salmon stream in southeast Alaska. The sampling team initially had no experience in matching visual composition with the results of sieve analysis.

At each location, the areal extent of the spawning gravels was visually stratified into three groupings (based on apparent composition of the surface gravels): A for coarse, C for fine, and B for intermediate. Channel form was indirectly included by associating the relative coarseness of gravels with flow velocities; coarse gravels are typically found under relatively faster waters. A single 12" core sample was collected within each area and field-sieved.

Subsequent analysis of the field data indicated that when mean particle diameter in bed material differed by about 10% for any two samples at a site, the visual procedure was capable of correctly identifying the coarser material 87% of the time (Table 1). When differences were about 20%, the visual estimation of relatively coarser material was correct 93% of the time. To get an idea of the differences in the compositions of A, B, and C, the reader should refer to the analysis of a typical site sample collected in Indian Creek (Figure 3a).

These results indicate that visual estimation procedures may be useful for characterizing the relative composition of the underlying bed material at a particular site. Canadian experience (Chamberlin, pers. comm.) suggests that trained observers can estimate percentage of fine (< 2mm), gravel (2-64 mm) and larger material to ± 10% in test gravels. Such a capability would allow a relatively rapid assessment of quality and quantity of potential spawning gravels along a particular stream reach. However, detailed gravel measurements would be necessary at specific sites for evaluating composition changes along the stream or through time. It may be useful to speculate on how accurately observers can visually assess gravel characteristics in comparison to the variability in the area determinations which are necessary for overall reach or system assessment. If precise area measurements are difficult (as in mobile bed rivers) then rapid visual estimates of bed composition referenced to a few quantitative samples may provide useful monitoring information.

As a consequence of visual stratification of gravels, sample sizes may be adjusted to reflect the degree of variability within the sites of interest. The presence of broad zones of homogenous material suggest fewer sample points than would a mosaic of widely different bed material compositions.

Table 1. GEOMETRIC MEAN DIAMETER d_g (mm) OF SUBSTRATE CATEGORIES (A, B, AND C) SHOWING SCORES FOR 10% AND 20% DIFFERENCE IN RELATIVE COARSENESS ESTIMATION.

	Coarse A	Intermediate B	Fine C	Score[a] 10%	Score[a] 20%
1	46.4	14.5	14.2	3	3
2	22.5	16.7	18.9	2	3
3	31.0	27.5	22.6	3	3
4	24.7	22.1	9.6	3	3
5	23.1	14.4	13.3	3	3
6A	27.6	13.9	8.5	3	3
6B	23.9	23.3	16.9	3	3
7	20.2	23.7	14.9	2	3
8A	24.4	16.9	14.4	3	3
8B	12.5	11.8	6.2	3	3
9A	51.4	13.2	6.8	3	3
9B	26.5	22.4	26.4	2	3
10	25.8	19.0	26.1	2	2
11	35.1	38.9	18.8	3	3
12	83.1	62.9	25.1	3	3
ISA	39.0	39.7	15.2	3	3
15B	41.9	20.5	17.4	3	3
14B	59.0	30.9	17.3	3	3
14C	21.8	18.6	48.4	1	1
14D	58.7	58.8	65.5	1	3
15	22.2	22.6	19.5	3	3
16A	6.5		8.7	1	1
16B	8.7	6.4	7.9	2	2
17	28.3	23.1	19.4	3	3
18	16.0	10.3	4.3	3	3
19	33.8	22.5	32.7	2	2
Possible Score		76		66	71
Rating Success %				87	93

[a] A full score of 5 was assigned if A was coarser than B and C, and B coarser than C.

To determine the number of samples to be taken in an area consisting of tens of hundreds of sites, one must combine the visual information on variability of the composition in the site with the desire to attain a certain level of resolution. This procedure allows enough flexibility to assess either as small an area as that occupied by a redd or an entire riffle of several hundred square meters. In both instances taking only three samples may be adequate, with obvious implications on the accuracy attained in each case. To assess reaches of an entire stream system stretching several kilometers, the level of resolution need not be too demanding. For example, the authors surveyed a two-kilometer reach of Canal Creek in nearly four hours. They combined results of this visual survey with two site estimates of gravel composition (Items 8A and 8B in Table 1) to obtain the results shown in Table 2.

Table 2. STREAM REACH EVALUATION OF SPAWNING GRAVEL COMPOSITION IN IN CANAL CREEK, JUNE 29, 1975.

Relative coarseness	Approx. mean diameter (nm)	Approx. gravel area in m^2	Percent of total
Cl	6	24	1
C	9	672	24
B	12	1191	43
A	18	768	27
Al	26	137	5
Total :		2792	100

Total stream length surveyed: 2130 m

Total stream reach covered as a result of beaver dam: 400 m

Approximate stream width: 2.5 m

Approximate spawning area: 50% of the reach

It appears that this level of effort may be entirely adequate in many cases and should provide a general assessment of quality of substrate with attached areal extent for the stream reach.

THE ADEQUACY OF A SAMPLE WEIGHT

The question of sample weight must be addressed in terms of its adequacy to assess a spawning site for the effects of sediments on success of reproduction and development of salmonid fishes. It is evident that there is considerable variability in data relating survival to geometric mean. For example, at 50% survival (Figure 1), the mean geometric diameter is 10 mm, but, due to the scatter in the data, a range of diameters from 7.5 mm to 12.5 mm could also lead to the same result. The level of variation is more pronounced in the midrange of d_g. The true source of variation can only partially be related to the procedural difficulties in assessing the gravel composition. Natural variability within bed material at spawning sites and within egg packets has been documented by Koski (1966), Tagart (1976), Platts (1974, 1979), and Corely and Burmeister (1978). Two-fold variation in the geometric mean even within a single redd is not unusual. That alone can cause the scatter under natural conditions. Difficulties in accurately estimating the number of eggs deposited and enumerating emergent fry further contribute to possible sources of errors. Consequently, the margin of error attributed to d_g is probably rather small.

The problem of adequate sample weight may now be evaluated as follows. If a gravel patch has a true mean geometric diameter equal to d_{gt}, how large a sample weight should we analyze to estimate d_{gt} with reasonable accuracy, say to within ± 10%? An experiment was conducted in Oak Creek using a frame sampler 30x30x30 cm. Gravel was extracted and placed randomly in five different containers marked 1 through 5. The contents of each container were dried, sieved and analyzed. Results were compiled for sample 1, samples 1 and 2, samples 1, 2 and 3, etc., each time increasing the sample weight, with the idea of attaining a limit as the weight increased. Unfortunately, we did not take a sample too small to be totally inadequate. Nevertheless, in this experiment, d_g fluctuated mildly and tended to approach a limit, hopefully approximating the true value of d_{gt}, as the sample weight became very large.

More specifically, these values were 14.4, 14.9, 14.7, 15.3, and 15.1 mm.

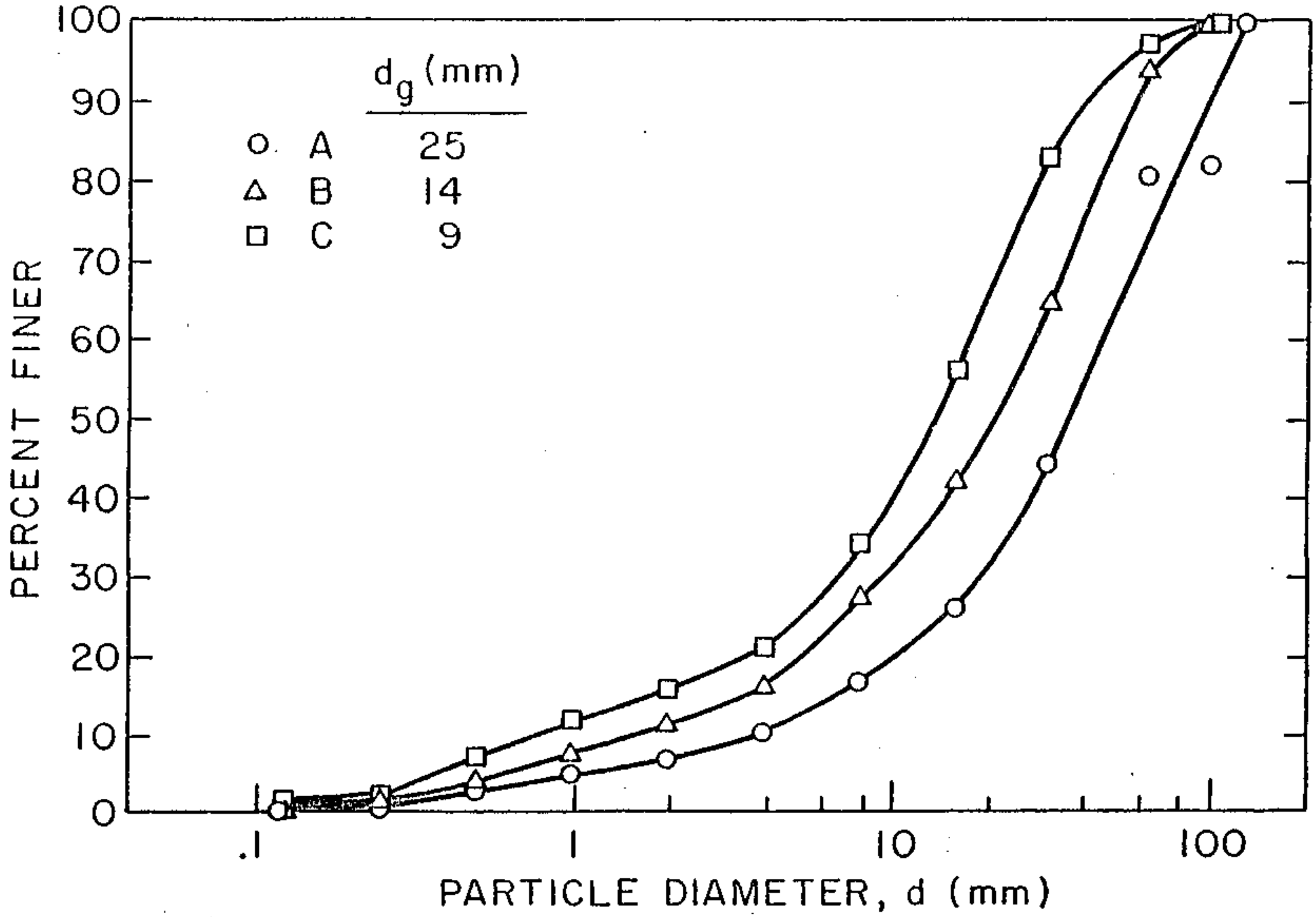

Figure 3a. Particle size distribution for spawning gravels in Indian Creek, Siuslaw National Forest, Oregon.

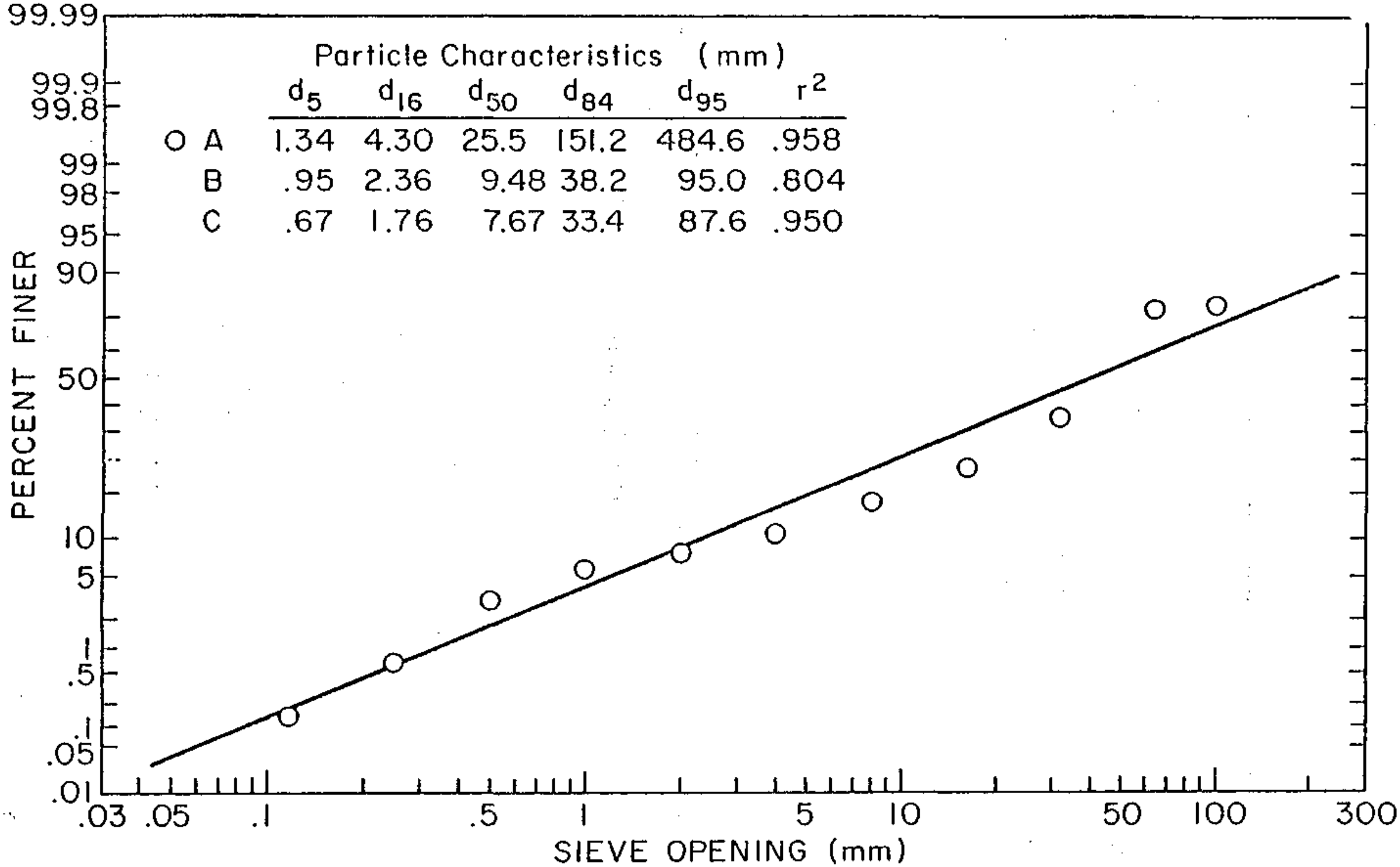

Figure 3b. Gravel composition in Indian Creek showing three textures.

The results suggest that a sample size of 5 to 10 kg produced the desired accuracy. Other important observations are (a) the patch was indeed fairly homogenous as evidenced from analysis of individual samples, (b) the size fraction between 50 to 76 mm was on the order of 5 to 10% of the total sample weight, and (c) an equivalent sample size can be obtained with 6" core FRI (McNeil) sampler.

Because of these observations and the widespread use of FRI samplers, one can generalize the experimental results as follows: (a) core diameter should be two to three times the *size* of largest particles sampled, and (b) the weight fraction of the largest particles (or the content of the coarsest sieve when appropriate) should be on the order of 5 to 10% of the total weight.

The adequacy of the sample weight obtained with a freezecore method is discussed in the next sections. In general, it is determined by the radial extent of the frozen core relative to the size of the largest particles attached and by the ability to extract the core without losing excessive amount of particles.

For application to a coarser substrate, a large core diameter must be used. Gravel patches are seldom homogenous. There are pockets of fine and coarse particles appearing randomly with depth and areal directions. Therefore, the above rule must be applied in combination with the visual estimation procedure discussed earlier.

The following experiments will demonstrate the heterogenous nature of gravel patches in the Poverty spawning area in the South Fork Salmon River, Idaho, and will also give an idea of adequate sample weight. The Poverty area has been monitored for more than a decade using various methods. Corley's data for 1976 show that the mean diameter is 13.5 mm (corrected for the effects of wet sieving) and the range for mean diameter is 7 mm to 23.7 mm. We compared 1978 measurements taken by Corley in the Poverty area with the largest gravel sample ever taken in that area or elsewhere by Platts (Figure 4). Platts[1] sample size of 620 kg, which consisted of a typical redd, gives d_g ~23.3 mm. Corley's

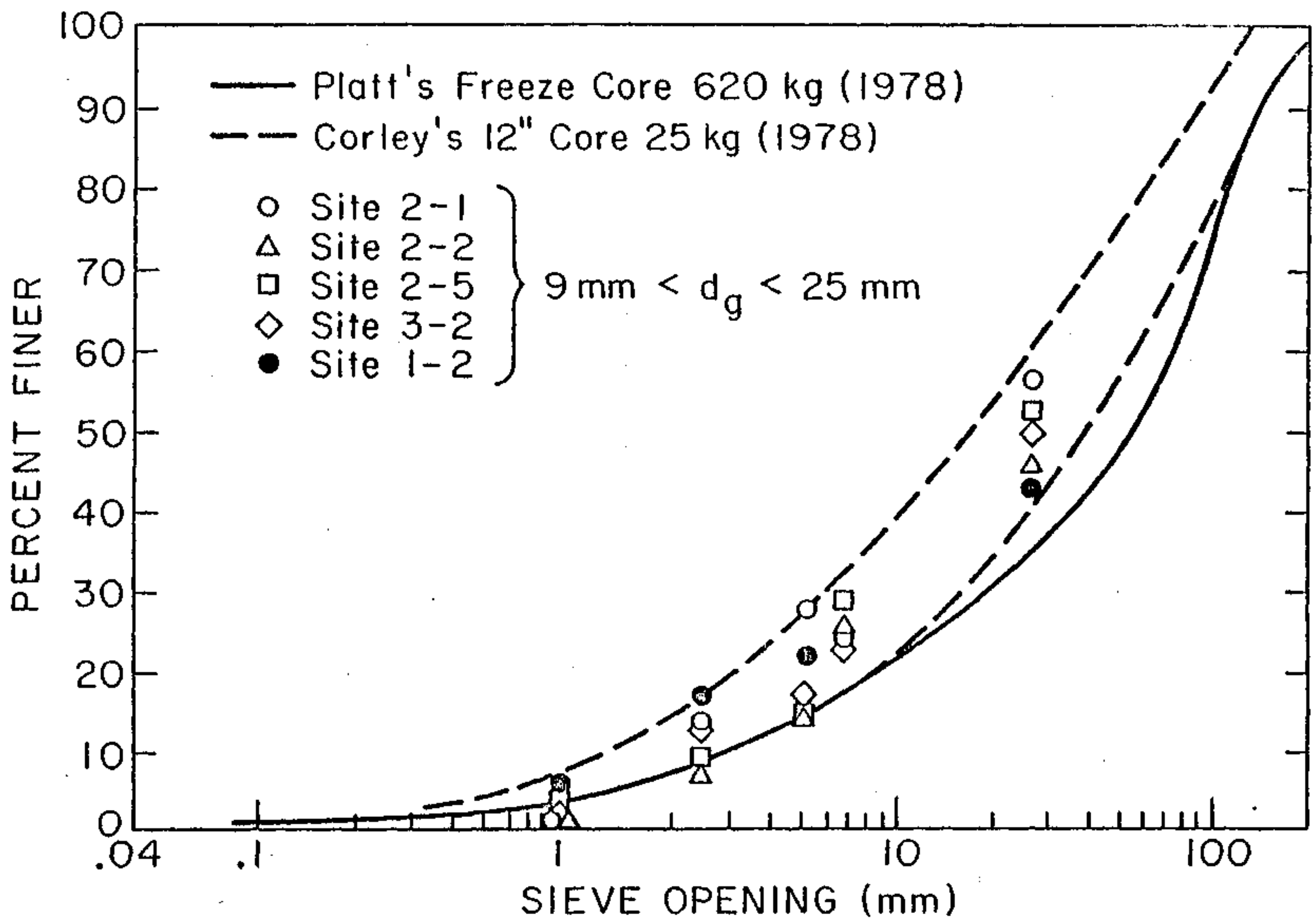

Figure 4. Comparison between compositions of an entire redd and 12 inch core samples near redd.

data taken near that sample give a range 9 mm < d_g < 24.5 mm. Corley's samples were on the order of 25 to 45 kg taken with a 12" core. Detailed vertical analyses of Platts' sample demonstrate that the patch was coarse throughout and, thus, perhaps an upper limit of gravel composition in Poverty area. Unfortunately, Corley did not use a sieve greater than 25 mm opening and thus his data were extrapolated to obtain d_g in Figure 2.

Now, according to Platts, particles were all smaller than 203 mm, and less than 7% were greater than 127 mm. Corley's sampler, therefore, satisfies the size selection rule stated above even if it captures the stated proportion of large particles. On the other hand, the use of a 6" core would be only marginally adequate, if not actually inadequate.

METHODS OF OBTAINING GRAVEL SAMPLES

The primary purpose of developing these procedures is to obtain a representative sample of the substrate to a depth used by spawning salmonids. Theoretically, we wish to extract an undisturbed core of gravel. The two most common methods are frozen core samples developed separately by Ryan (1970) and Walkotton (1976) and grab (or manual) sampling techniques designed by McNeil and Ahnell (1960).

In the freezecore method a metallic tube about one inch in diameter,is driven into the gravel. Liquid carbon dioxide (CO_2) is throttled into the tube through a bank of small nozzles. The expansion of the gas rapidly freezes interstitial water outside the tube, thereby attaching a solid core of substrate materials to the tube, which is then extracted for analysis. The dimensions of the core and the total size of the sample can be varied by a combination of (a) depth of tube penetration into the gravel, (b) length of time CO_2 is applied and (c) use of more than one tube in a given area. Freezing efficiency is inversely related to gravel density. Efficiency declines rapidly beyond about 4 minutes of application of CO_2.

The manual sampling method consists of inserting a large diameter tube (4 to 12 inches) into the gravel bed to a depth of 4 to 12 inches and extracting by hand or scoop the gravel and sand inside the pipe. An estimate of the suspended material that escapes the gravel sample is obtained by retaining, for subsequent analysis, a subsample of the water column in the pipe, once the contained water is thoroughly mixed.

A photographic method analyzing surface (or armor) material visible through clear water was developed by Ritter and Helley (1969). Photographic prints of a stream bottom segment are analyzed with specialized scanning equipment. These devices incorporate computation facilities that enable counting, sizing, and even particle size distribution. Once the system is set up and calibrated, photographic records of hundreds of particles can be analyzed in a matter of minutes.

This method is good for extremely large quantities of work but is restricted to the analysis of the surface layer of gravel, hence the utility of this method is limited.

The main advantages of the freezecore method are (a) the ability to sample in deep water or under ice on frozen streams, (b) the routine application of uniform procedures, i.e., duration of CO_2 application and depth of core, and (c) the ability to analyze samples from different depths within the substrate. Disadvantages are (a) the equipment weight and field transport problems, (b) the cost of CO_2 recharge, (c) the difficulty of sampling in gravel coarser than 32 to 64 mm in diameter with a single probe, and (d) inability to sample from dry gravel patches, and (e) disturbance during probe insertion and loss of particles during probe removal.

Advantages of manual sampling are (a) simplicity of equipment and procedure, (b) flexibility in modifying sample diameter with respect to gravel characteristics, and (c) possibility of combining with benthic invertebrate sampling. Disadvantages are (a) bias associated with different operators who might extract the gravel selectively, including the suspended fines segment, (b) difficulty in sampling in deep water, and (c) difficulty of inserting the core into a coarse gravel bed.

The disadvantages of freezecore and manual sampling may be reduced to acceptable levels. For example, Lotspiech and Reid (1979) used steel tubes instead of copper to reduce problems of tube bending during insertion and extraction of the frozen core. They also used aluminum CO_2 tanks to minimize carrying weight while increasing refrigerant capacity. To minimize operator bias with manual sampling all substrate components must be removed to a pre-determined depth. A scoop should be used when possible.

This discussion relates primarily to the mechanical advantages and disadvantages of various sampling methods. Some sampling bias can be reduced by taking a very large sample. Obviously all attempts to minimize bias should be made before increasing sample size. Increasing sample size should not be used to disguise problems inherent in the sampler itself.

The following case studies are presented to enable comparison of results from freezecore with FRI samplers.:

1) Berry Creek near Corvallis, Oregon has a very coarse substrate. Five samples were taken in the following manner. After a spot was chosen in the stream, a 12" diameter sampler was placed on the spot and a single freezecore sample was extracted from within the 12" core sample, then the remaining material was extracted. The data were analyzed separately for the freezecore sample and in combination with the remaining parts of the 12" core sample. Theoretically, the freezecore represented a subsample of the 12" core sample. The experiment should demonstrate a direct comparison of the two methods (Table 3).

Table 3. COMPARISON OF RESULTS FROM FREEZING FRI (McNEIL) SAMPLES.

	d_g mm	
Sample #	Freezecore	12" core
1	9.7	32.7
2	42	43.5
3	42	43.0
4	33.9	27.0
5	37	66
Mean	32.9	42.4

On the average, samples taken by the two methods are within 25% of one another; individually they may differ by a factor greater than 3. The 12" core samples averaged 25 kg each, the freezecore samples were about 5 kg.

2) In a second experiment with a coarse substrate in the Rogue River, 12" diameter core samples and tri-tube freeze samples (Lotspeich

and Reid 1979) were obtained side by side. Eleven such samples were collected and analyzed. The average weights of the tri-tube samples and 12" cores were 13.3 and 25.4 kg with a standard deviation of 6.9 and 3.2 kg, respectively (Table 4).

Table 4. COMPARISON OF TRI-TUBE FREEZECORE AND 12" 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 Mean	A	15.6	22.9
	C	19.3	19.5
		32.1	35.0

On the average samples differed only about 10%. The tri-tube presents a significant improvement over single tube freezecore, even though the Rogue River presented a severe test of the system. Note that the difference in the results of the methods is not always in the same direction. Calculations presented by Lotspeich and Reid (1979) differ slightly from those given here due to different estimation procedures. The same 10% difference appears using their method as well.

3) Platts (1979) obtained 15 single freezecore samples in South Fork Salmon River, Poverty area during 1977. There were considerable variations in the sample weights as well as the geometric means. The average sample weight was 5.1 kg with a standard deviation of 3.7 kg. The average of the 15 geometric mean diameters was 34.6 mm with a 20.6 mm deviation from

this mean. We attribute this difficulty to the inconsistency of sampling with a freezecore in a relatively coarse substrate. Because of this scatter, the size fractions from all samples were combined to obtain an average geometric mean equal to 20.4 mm. This is within the range of results ($7 < d_g < 23.7$ mm and average = 13.3 mm) obtained by Corley using 12" core samples in 1976. Platts' freezecore samples were obtained in egg pockets and this may explain the difference between the two means. The aggregates of Platts' single freezecore samples in egg pockets during 1977 agree well with the entire redd sample taken in 1978.

4) There have been many attempts to directly compare freezecore samples with 6" core samples. Among these are the unpublished work of Cederholm and yet to be published work of Koski. Both works were restricted to relatively fine artificial gravel mixes. Both indicate single freeze-cores produced satisfactory results under these conditions.

Ringler (1970) in his Master's thesis compared freezecore samples with 6" core samples both obtained from redds in Drift Creek. He found that the freezecore nearly always underestimated the fines smaller than 85 mm and 3.3 mm.

We will conclude, based on the analysis of the foregoing case studies, that: (a) by combining the analysis of many freezecore samples taken from a spawning site, a reasonable estimate of the mean composition of that site is obtainable, (b) single freezecore samples, particularly if taken in a coarse substrate with a single tube nay not be a good representation of a gravel patch, and (c) it is expected that a good representation of the patch over the range of grain size up to 100 mm substrate is obtained by a tri-core method.

ANALYSIS OF GRAVEL—WET SIEVING

Access to spawning areas with motorized vehicles is not always possible and transporting large gravel samples from the stream bank to the vehicle often presents a problem. Therefore, serious consideration should be given to on-site analysis by wet sieving the gravel.

Equipment required for wet sieving includes a set of sieves, a bucket with an overflow nozzle and a graduated cylinder. In general, it is desirable that the sieve sizes should represent a geometric progression (e.g. 128, 64, 32, 16, 8, ... 0.064 mm). However, the specific sizes chosen will depend upon the actual stream being sampled and the need to maintain consistency of sizes with past sampling or other comparative work. If, for the selected sieve series, a large proportion of the material collects on one sieve, an additional, coarser sieve may be added to facilitate the sieving process.

The content of the 4-mm and coarser sieves can be wet sieved and analyzed volumetrically in the field using the bucket and graduated cylinder. Particles retained on all sieves on will also contain some interstitial and surface water. The amount will vary with particle size and become quite significant at sizes below 4 mm. To avoid introducing excessive errors in the volumetric determination, the sieved samples should be allowed to drain before the volumetric measurements are made (draining with sieves inclined and the material periodically turned over will expedite this process). The contents of the fine sieves, i.e. size ranges less than 4 mm, may be either processed in the field or taken to the laboratory for dry weight analysis. This also applies to particles passing the smallest sieve used. The error introduced by wet sieving, because of the water present, can be corrected by using data in Table 5.

If dry sieving is used for particles smaller than 4 mm, the two sets of data must be combined. Combining the volumetric and gravimetric analysis requires knowledge of average gravel density. For this purpose, the dry contents of the 2 mm sieve should be used for rock density

Table 5. WATER GAINED IN A WET SIEVING PROCESS AND CORRECTION FACTOR FOR VOLUMETRIC DATA.*

Sieve size		Gram water gained / Gram dry gravel			Correction factor applied to wet sieved gravel		
inches	mm	p=2.2	p=2.6	p=2.9	p=2.2	p=2.6	p=2.9
3	76.2	.02	.01	.01	.97	.96	.96
	64	.02	.02	.01	.96	.96	.96
2	50.8	.02	.02	.02	.96	.96	.95
	32	.02	.02	.02	.95	.95	.94
1	25.4	.03	.02	.02	.94	.94	.94
	16	.03	.03	.03	.93	.93	.92
1/2	12.7	.04	.03	.03	.92	.92	.91
	8	.05	.04	.04	.91	.90	.89
1/4	6.35	.05	.05	.05	.89	.88	.88
	4	.07	.06	.06	.87	.86	.85
1/8	3.18	.08	.07	.07	.86	.85	.84
	2.0	.10	.09	.08	.83	.81	.81
1/16	1.59	.11	.10	.09	.81	.80	.79
	1.0	.13	.12	.12	.77	.76	.75
1/32	.79	.15	.14	.13	.75	.73	.72
	.5	.19	.18	.17	.70	.69	.67
1/64	.40	.21	.20	.19	.68	.66	.65
	.25	.27	.25	.23	.63	.61	.59
1/128	.20	.30	.28	.26	.60	.58	.57
	.125	.38	.35	.33	.54	.52	.51
1/512	.10	.43	.39	.37	.52	.50	.48
	.063	.54	.49	.47	.46	.44	.42

* The values in this table have been obtained from detailed analysis of substrate ranging from 0.63 mm to large gravel based on unpublished work of Thompkins, Shirazi, and Klingeman. Example: The volumetric displacement of a 2-mm sieve is 300 cm^3. From prior analysis, the estimate of the gravel density is known to be 2.69 g/cm^3. The dry weight of the gravel according to the table is 300 x .81 = 243 g.

determination by simply dividing the dry weight of the material in grams by its displaced volume of water in cubic centimeters. This requires bringing a sample of such material to the laboratory for analysis. Unpublished data from Klingeraan show that the choice of 2 mm for density determination is reasonable, although there is a slight change of density with particle sizes used. The error is on the order of one percent of the mean for a range of 14 sieve sizes. Correspondence of the density of 2 mm and larger particles should be confirmed where likelihood of difference is apparent.

CALCULATION OF SUBSTRATE STATISTICS

Examples of three procedures for calculating the geometric mean diameter and the geometric variance of two samples of gravel are given in this section for the purpose of demonstrating the relative effort needed and the relative accuracy obtainable with each procedure. The gravel samples A, B, and C were obtained from Indian Creek. They are plotted on semi-logarithmic scales in Figure 3a.

LEAST SQUARES GRAPHICAL METHOD

The graph of sample A is shown replotted in Figure 3b on a log-probability paper. The straight line passing through the data is the least squares fit with a coefficient of determination r^2 equal to 0.958 which can be interpreted as the test of lognormality. The average r^2 for 100 samples was 93 which is very good indication that spawning gravel is lognormally distributed. The data for sample B are not shown on the plot to avoid crowding. The coefficient of determination for the least squares linear fit to that set of data is 0.804.

The details of this procedure are listed in Table 6. Columns one and two are the original data listed in terms of weight percentiles. Column three (designated X) is the log transform of column one. Column four (designated Y) is the inverse probability transform of column two. The latter can be obtained from tabulated standardized normal distribution function available in textbooks of statistics. They also can be calculated with small programmable calculators. Next, Y is regressed over X. The linear equation now can be used to obtain all statistics as listed. Note that the percent fines, for example, less than 3.3 mm can be calculated from the equation, thereby relating that point statistically to the entire distribution. The procedure reduces the variability, otherwise unavoidable, if the data were used directly. This method yields the following:

$d_{g_A} = 25.5$ mm $\qquad \sigma_{g_A} = 5.93$

$d_{g_B} = 9.48$ mm $\qquad \sigma_{g_B} = 4.02$

Table 6. ILLUSTRATIVE EXAMPLE OF LEAST SQUARE/GRAPHICAL PROCEDURE FOR SAMPLE A IN INDIAN CREEK, OREGON.

Sieve opening d mm (1)	Percent finer F(d) (2)	$\log_{10} d$ X (3)	$\hat{O}^{-1}[F(d)]$* Y (4)
127	100		
102	82.6	2.009	.938
64	80.6	1.806	.863
32	44.0	1.505	-.151
16	26.6	1.204	-.625
8	16.8	.909	-.962
4	10.3	.602	-1.265
2	7.53	.301	-1.458
1	5.60	0	-1.590
.5	3.01	-.301	-1.880
.25	.67	-.602	-2.475
.125	.17	-.902	-2.929
.063	0		

$$X = 1.407 + .777\,Y \quad r^2 = .958$$

$d_5 = 1.34$ mm

$d_{16} = 4.30$ mm

$d_{50} = 25.50$ mm

$d_{84} = 151.21$ mm

$d_{95} = 484.33$ mm

$d_g = d_{50} = 25.5$ m

$$\acute{o}_g = \frac{d_{84}}{d_{50}} = 5.93$$

% Fines < 3.3 is 13% becuase:

$\log_{10} 3.3 = 5.19$

Y = 1.143

F (3.3) = 13%

* Ö is the standardized normal distribution function

QUANTILE GRAPHICAL METHOD

A common, simple graphical procedure consists of estimating directly from the data the diameters at the 84th percentile (i.e. d_{84}) and at the 16th percentile (i.e. d_{16}) of the distribution. The geometric mean and the geometric variance is then:

$$d_g = \sqrt{d_{84}\, d_{16}}$$

$$\sigma_g = \sqrt{d_{84}/d_{16}}$$

For the two samples given above, we have

METHODS OF MOMENTS

$d_{g_A} = 104 \times 7.4 = 27.7$ $\qquad$ $\sigma_{g_A} = 104/7.4 = 3.8$

$d_{g_B} = 50 \times 3.8 = 13.8$ $\qquad$ $\sigma_{g_B} = 50/3.8 = 3.6$

The details of this method are described in Table 7. It consists of taking the n^{th} root of the product of n numbers as required by definition of the geometric mean. The procedure for calculating the geometric variance is also given. For the two samples

$d_{g_A} = 25.5$ mm $\qquad$ $\sigma_{g_A} = 4.0$

$d_{g_B} = 14.7$ mm $\qquad$ $\sigma_{g_B} = 4.1$

CHOICE OF METHODS

Considering both the adequacy of the theoretical basis as well as the simplicity in procedure, the quantile graphical method should be favored over the others. The least squares method is more precise in calculating the geometric variance than the second method, however, it is difficult to assess the theoretical adequacy of the third method from this aspect. At times it might be necessary to obtain a systematic estimation of the geometric variance so that the entire distribution, including back-calculation of percent fine becomes possible. In that case the first procedure is recommended. For monitoring and assessment objectives the quantile graphical method of calculation is quite adequate (if d_g is needed) and is the suggested procedure.

Table 7. CALCULATION OF GEOMETRIC MEANS AND GEOMETRIC VARIANCE BY THE METHOD OF MOMENTS.

Sieve Size		Sample A				Sample B			
Range (1) d mm	Midpoint (2) dm mm	(3) f	(4) p % finer	(5) f(ln d_m)	(6) f(ln d_m)	(7) f	(8) p % finer	(9) f(ln d_m)	(10) f(ln d_m)2
127			100.0						
102-127	114.5	.1737	82.63	.823	3.904		100.0		
64-102	83.0	.0201	80.63	.089	.392	.0540	94.60	.239	1.054
32-64	48.0	.3660	44.02	1.417	5.485	.3010	64.50	1.165	4.511
16-32	24.0	.1744	26.59	.554	1.761	.2260	41.90	.718	2.283
8.0-16	12.0	.0983	16.76	.244	.607	.1490	27.0	.370	.920
4.0-8.0	6.0	.0650	10.26	.116	.209	.1070	16.30	.192	.344
2.0-4.0	3.0	.0272	7.53	.030	.033	.0480	11.50	.053	.058
1.0-2.0	1.50	.0194	5.60	.008	.003	.0360	7.90	.015	.006
.5-1.0	.750	.0258	3.01	-.007	.002	.0349	4.41	-.010	.003
.25-.5	.375	.0235	0.67	-.023	.023	.0335	1.06	-.033	.032
.125-.25	.188	.0050	0.17	-.008	.014	.0083	.23	-.014	.023
0.63-.125	.094	.0017	--	-.004	.010	.0023	--	-.005	.013
		1.000		Ó$_5$=3.239	Ó$_5$=12.442	1.000		Óg=2.689	Ó$_{10}$=9.246

$$d_{g_A} = e_5 = e^{3.239}$$
$$= 25.508 \text{ mm}$$

$$d_{g_B} = e_9 = e^{2.689}$$
$$= 14.720 \text{ mm}$$

$$\sigma_{g_A} = \exp\ (\Sigma_6 - \Sigma_5^2)^{1/2}$$
$$= e^{1.951} = 4.042$$

$$\sigma_{g_B} = \exp\ (\Sigma_{10} - \Sigma_9^2)^{1/2}$$
$$= e^{2.016} = 4.136$$

ESTIMATING LOCALIZED AND STREAMWIDE IMPACTS

The ultimate goals of substrate monitoring are to relate watershed processes and land use to substrate conditions and to assess the possible impact of accelerated erosion on spawning habitat, both locally in one or more riffles as well as more extensively for an entire stream system. The parameters used as measures of this impact can be classified in the categories: (a) changes in the area of spawning gravel, i.e. the change in the available habitat, and (b) changes in the composition of the gravel, i.e. the quality of the habitat. For the latter measure the, geometric mean diameter d_g is assumed to be a sufficient indicator.

The extent of actual and potential spawning areas for the species of interest can be obtained through visual inspection and areal measurement in the stream reach. The quality of these spawning areas can then be determined by using the sampling procedures previously outlined in this document.

To demonstrate how this information can be used to assess stream-wide impacts examine Table 8 which contains hypothetical data for spawning gravel quality and quantity in areas on Dream Creek prior to a landslide in 1966. Throughout the 4 miles of this creek the spawning gravel, totaling 510 m^2, had a mean d_g of 12.5 mm, equivalent to predicted average egg survival of 62%. Table 8 also shows the same type of information obtained by monitoring after the landslide. Note that, though the quality of the gravel was reduced (d_g = 8.3 mm), the total available spawning area was increased from 510 m^2 to 540 m^2 and the overall predicted average survival was reduced to 33%. If the number of spawning fish and number of eggs deposited in Dream Creek remained approximately the same after the landslide, the 34% reduction in d_g corresponds to a 47% reduction in the number of emerging fry produced by the system.

Table 8. SPAWNING GRAVEL AREA AND QUALITY BEFORE AND AFTER LANDSLIDE OF 1966 IN DREAM CREEK.*

	Area m^2		d_g mm		% Survival	
Mile Post	Before	After	Before	After	Before	After
1	100	60	13	6	66	19
2	300	300	10	8	45	31
3	50	100	12	9	58	38
4	60	80	15	10	79	45
Total or mean	510	540	12.5	8.3	62	33

* hypothetical data

EVALUATION OF STREAM SYSTEMS

The geology and morphology of watersheds strongly influence substrate composition in the stream systems draining them. For this reason one would not expect all spawning gravels in streams unaffected by cultural activities to be of the highest quality. A hypothetical example is provided by Figure 5, which demonstrates the areal extent of gravels of different quality as determined by measurements of d_g. All of these stream systems are relatively undisturbed by man, yet the total stream area suitable for salmonid spawning (that expected to yield less than 50% egg survival) varies from approximately 8% in Cascadia Creek to approximately 77% in Flynn Creek.

Three important qualifications must be introduced in this interpretation to complete the picture. One is that the total area of spawning gravel of a particular quality in one system could be many times greater than the second system, even if percentages are alike. Thus, an additional column supplementing this information must be provided in the real situation to enable comparison of one system with another. The second qualification is that the adequacy of the habitat differs with the species using the habitat. An important aspect of species differences relating to survival is size. For this reason, interpretation of quality is best made

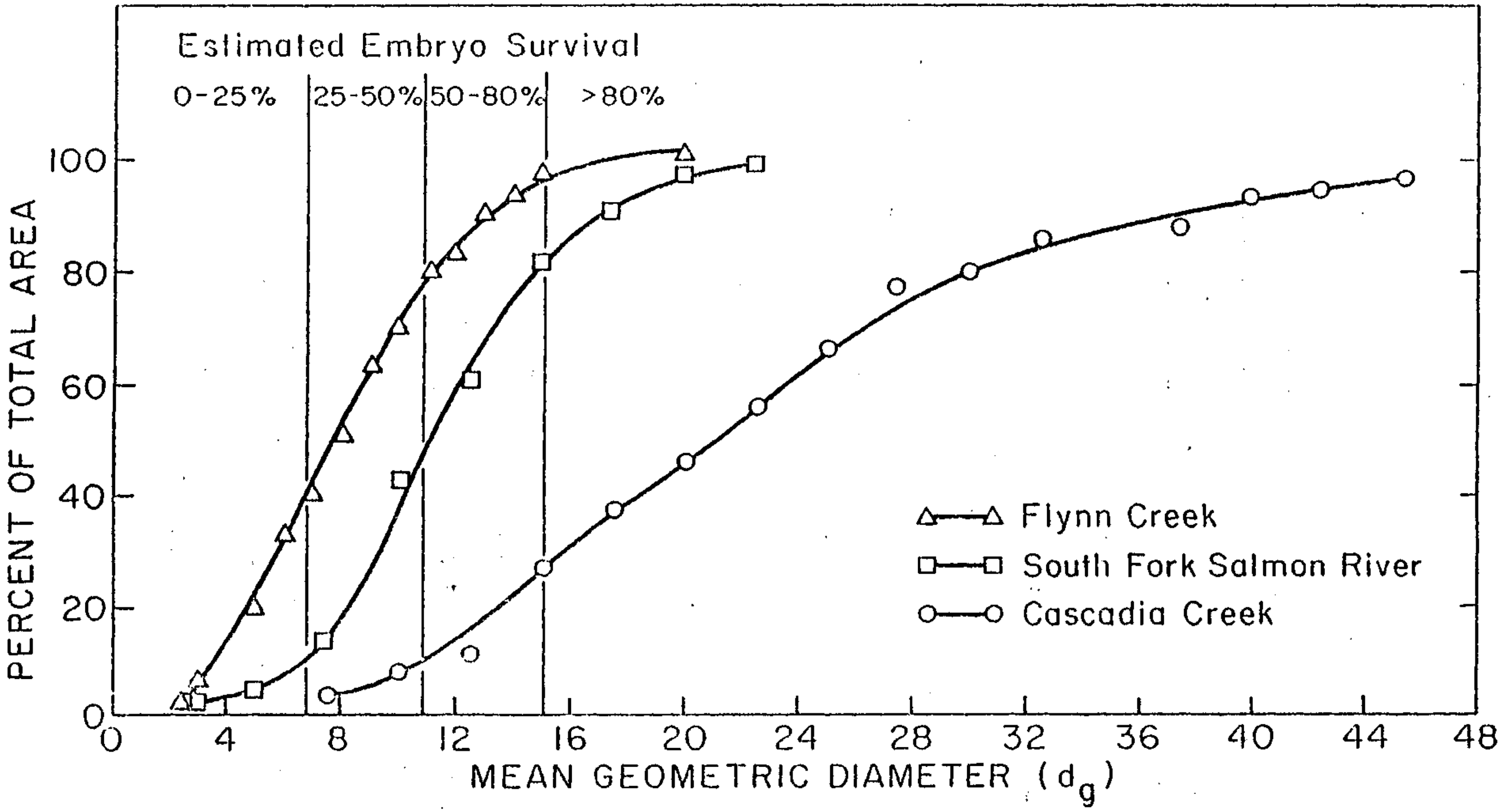

Figure 5. Hypothetical assessment of quality and quantity of spawning habitat in three stream-watershed systems.

with respect to a transformed scalar d_g / d_e , i.e. in terns of multiples of egg diameter d_e , such as in Figure 2. The third, and perhaps the most important qualification is that any implied adequacy of quality of habitat must relate to a baseline condition in the absence of accelerated erosion. It is not unusual to find a natural substrate of small mean diameter producing low survival. In this case, the baseline that can be used for comparison is, as expected, rather low as well. In some stream systems the salmonids, successfully adapting to the existing local environment, may maintain relatively high population levels in the presence of rather low embryo survival rates which are the result of the long term existence of marginal baseline substrate conditions. Additional mortalities caused by reducing baseline conditions is expected to be deleterious to the population, however.

CONCLUSIONS AND RECOMMENDATION

The study of salmonid spawning habitats or habitats potentially usable for spawning may provide a meaningful indicator of watershed characteristics because stream substrate conditions integrate many aspects of climate, vegetation, soil type, land form and human activities. This paper provides a unifying methodology for sampling stream substrates and applying that methodology to the monitoring of substrate quality and quantity. The mean geometric particle diameter (d_g) provides a convenient and theoretically sound parameter that expresses the entire range of the particle distribution and effectively relates particle size to salmonid embryo survival. Thus d_g is preferred to percent fines because it is biologically meaningful, sensitive to changes in distribution and, most important, provides a theoretical basis for substrate analysis by considering the entire spectrum of size composition. In this respect particle size distribution is taken as tending toward log-normality. Either manual core or freezecore samplers may be adequate when used properly. Sampling recommendations include the following:

(1) The range of coarseness of spawning or potentially adequate spawning substrates can be identified visually as a basis for selecting sample locations.

(2) Either manual core or freeze core samples provide adequate samples when used properly.

(3) The diameter of FRI (McNeil) type samplers should be two to three times the diameter of the largest particle sampled. The 12-inch (30 cm) is suitable for a broad range of typical substrate coarseness.

(4) Single freeze cores or manual cores less than 15 cm in diameter may give inadequate sample size in coarse substrates.

(5) For relatively fine substrates, 5-10 kg sample size is adequate but this value should be increased when increasing coarseness is encountered.

(6) Sample depth should be 25 cm.

(7) The number of samples taken depends on variability and extent of area sampled. For many smaller spawning streams a single riffle area may often be well represented by one sample from each of three categories of coarseness.

(8) Sieve series should follow the series in mm from 64, 32, 16, 8, etc. down to .063. Where finer particles comprise an important fraction they should be retained and determined by any of the several standardized methods.

(9) Water retention on sieved portions should be reduced by draining prior to volumetric analysis.

(10) On-site wet sieving is recommended for size groups greater than 4 mm followed by volume determination using the water displacement technique.

(11) Particle size should be expressed as d_g and determined by

$d_g = \sqrt{d_{84}d_{16}}$ or other suitable methods as described in the text on the investigator's objectives.

(12) By combining visual estimation and actual sampling the quality and areal extent of the various categories of coarseness may be estimated for a single riffle, a stream section, or an entire stream system, depending

(13) For example, assessment of habitat quality and quantity of spawning gravels could be made on the basis of the d_g categories of greater than 15.25, 15.25 to 10.75, 10.75 to 7.0 and 7.0 mm, respectively, rated in terms of embryo survival estimates of 80 or greater, 80-50, 50-25 and 25 percent or less. Comparison between existing and the expected normal background sediment characteristics will provide the basis to assess extent and quality of spawning habitats.

In conclusion, it remains to be stated and emphasized that spawning habitat analysis and assessment is studied here as an avenue to better understanding of the more general driving elements that cause and maintain the spawning habitat. These elements have their roots in the watershed itself. Fish habitat and therefore fish populations and the assemblage of other organisms dependent on the gravel environment respond to these driving forces, but may be adversely influenced by man's activities on them. Programs to monitor stream gravel conditions can therefore be a significant aspect in linking the watershed and the stream environments.

REFERENCES

Cederholm, C.J. and L.C. Lestelle. 1974. Observations on the effects of landslide siltation on salmon and trout resources of the Clear Water River, Jefferson County, Washington, 1972-1973, Final Report, Part I, FRI-UW-7404, April 1974. Fisheries Research Inst., Univ. Washington, Seattle. 133 pp.

Cederholm, C.J., W.J. Scarlett, and E.O. Salo. 1977. Salmon spawning gravel composition data summary from the Clearwater River and tributaries, Jefferson County, Washington, 1972-1976. Fisheries Research Inst. Circ. 77-1, Univ. Washington, Seattle. 135 pp.

Cooper, A.C. 1969. The effect of transported stream sediments on the survival of sockeye and pink salmon eggs and alevin. Internat. Pac. Salmon Fish. Comm. Bull. XVIII, New Westminster, B.C., Canada. 71 pp.

Corley, D.R., and L.A. Burmeister. 1978. Fishery habitat survey of the South Fork Salmon River, 1977. Boise & Payette National Forests, U.S. For. Serv., 1075 Park Blvd., Boise, ID 83706. 90 pp.

Iwamoto, R.N., E.O. Salo, M.A. Madej, and R.L. McComas. 1978. Sediment and water quality: A review of the literature including a suggested approach for water quality criteria, EPA 910/9-78-048, USEPA Region X, 1200 Sixth Ave., Seattle, Wash., Feb. 1978. 150 pp.

Koski, K.V. 1966. The survival of coho salmon from egg deposition to emergence in three Oregon coastal streams. M.S. Thesis, Oregon State Univ., Corvallis. 84 pp.

Lotspeich, F. 1978. Biological significance of fluvial processes in the lotic environment. USEPA, Corvallis Environmental Research Laboratory Working Paper CERL-042. Corvallis, Oregon.

Lotspeich, F., and B. Reid. 1979. A tri-tube freezecore procedure for sampling stream gravels. Submitted to Prog. Fish-Cult. 12 pp.

McNeil, W.J., and W.R. Ahnell. 1960. Measurement of gravel composition of salmon stream beds, College of Fisheries Circ. #120, Univ. Washington, Seattle.

Phillips, R.W., R.L. Lantz, E.W. Claire, and J.R. Moring. 1975. Some effects of gravel mixtures on emergence of coho salmon and steelhead trout fry. Trans. Am. Fish. Soc. 104(3):461-466.

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Platts, W. S. 1974. Geomorphic and aquatic conditions influencing salmonids and stream classification—with application to ecosystem classification. USDA, For. Serv., Surface Environ, and Mining Proj. R. Billings, Montana. 200 pp.

Platts, W.S., M.A. Shirazi, and D.H. Lewis. 1979. Sediment particle sizes used by salmon for spawning, and methods for evaluation. EPA-600/3-79-043. April 1979. USEPA, Corvallis Environmental Research Laboratory, Corvallis, Oregon. 32 pp.

Ringler, N.H. 1970. Effects of logging in the spawning bed environment in two Oregon coastal streams. M.S. Thesis, Oregon State Univ.,Corvallis. 96 pp.

Ritter, J.R., and E.J. Kelley. 1969. Optical method for determining particle size of coarse sediment. Techniques of Water Resources Investigation, U.S. Geol. Surv. Book 5.

Ryan, P. 1970. Design and operation of an in situ frozen core gravel sampler Dept. Fisheries and Forestry, Pacific Station, Canada.

Shirazi, M.A. 1979. A unified analysis of embryonic survival of salmonids. Unpublished.

Shirazi, M.A., D.H. Lewis, and W.K. Seim. 1979. Monitoring spawning gravel in managed forested watersheds, a proposed procedure. EPA-600/5-79-014. Feb. 1979. USEPA, Corvallis Environmental Research Laboratory, Corvallis, Oregon. 13 pp.

Tagart, J.V. 1976. The survival from egg deposition to emergence of coho salmon in the Clear Water River, Jefferson County, Washington. M.S. Thesis, Univ. Washington, Seattle. 101 pp.

Thompkins, C., M.A. Shirazi, and P. Klingeman. 1979. Correction to a wet-sieving analysis of gravel. Unpublished.

Walkotten, W.J. 1976. An improved technique for freeze sampling streambed sediments. USDA For. Serv. Res. Note PNW-281, Pacific Northwest For. and Range Exp. Stn., Portland. 11 pp.