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SEDIMENT PARTICLE SIZES USED BY SALMON FOR SPAWNING WITH METHODS FOR EVALUATION

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ABSTRACT

The size composition of substrates used by chinook salmon for spawning in the South Fork Salmon River, the main Salmon River and tributaries of the Middle Fork Salmon River, Idaho, was determined. Substrates used by resident trout were analyzed for streams in the Boise and Payette River drainages. These analyses were made over time to determine particle sizes preferred by spawning salmon, yearly differences in sizes used by these salmon, the size differences used by spring and summer chinook salmon, and differences between channel sediments used by chinook salmon for spawning and those substrates occupied by trout.

The use of the geometric mean particle diameter method is presented as a companion measurement to "percent fines" for a more complete analysis of sediments used for spawning. The geometric mean particle diameter is more adaptive to statistical analysis than the more common method of using "percent fines." The geometric mean diameter of the sediment particle size distribution is used for analyzing channel sediments. The relationship between the geometric mean particle diameter and "percent fines," substrate permeability, and substrate porosity is established. The strongest correlation between the two methods of analysis, "percent fines" and geometric mean diameter, was for fine sediments below 0.88 in (2 mm) in particle size.

Chinook salmon selected sediments for spawning that were mainly between 28 and .79 in (7.0 to 20 mm) in geometric mean particle diameter, regardless of stream selected. This is a narrow range considering that the mean particle diameters for streambed sediments available for chinook salmon to spawn in vary from less than 0.02 in (.5 mm) to well over 3.94 in (100 mm). The composition of spawning sediments selected by chinook salmon each year between 1966 and 1976 were quite uniform. Sediments used for spawning in the South Fork Salmon River decreased in particle size in a downstream direction. Geometric mean diameters 35 miles below the headwaters averaged .35 in (8.8 mm); particles 10 miles below the headwaters averaged .58 in (14.7 mm).

INTRODUCTION

Most stream fishes require channel sediments having a variety of particle size mixes for survival. This is especially true for salmonids which deposit their eggs in sediments of a particular size class. However, studies have demonstrated that the redd sediments must be of the proper particle size class and composition for high embryo survival. Large increases in fine sediment loads into stream channels can create intolerable channel modifications in salmonid spawning areas (Platts and Megahan 1975). Hall and Lantz (1969), in their Alsea, Oregon logging studies, found that an increase of 5 percent in fine sediment smaller than 0.033 in (.83 mm) in diameter in redds decreased survival of emergent coho salmon fry (Oncorhynchus kisutch Walbaum). Other authors have demonstrated that fine sediment particles deposited in the streambed reduce permeability and thus cause higher egg-to-fry mortality (McNeil and Ahnell 1964). The literature supports the statement that fine sediments can limit fish productivity. However, there is a dearth of literature identifying and evaluating the effect of different mixtures of sediment sizes on fish health and survival in the actual stream environment.

During their evolutionary period salmon and trout adapted to the natural channel sediments. Salmonids need sediment for spawning, rearing their young, and providing for their food. However, the mix of sediment particle sizes for optimum fish productivity is not clear. Probably no single particle size group (i.e., boulder, rubble, gravel or fine sediment) will create the type of environment salmonids require for growth and survival. More likely, a complex mixture of sediment sizes is needed in combination with certain hydraulic conditions to provide the ideal channel environment.

Since streams offer a wide variety of sediment sizes, salmon entering virtually any river area can select any particle size for spawning. Stream channel substrates are available from 100 percent fine sediments to channels that are all boulder or rubble. The fish seldom find channels composed entirely of gravel because gravels are usually mixed with fine sediment and small rubble. However, some hydraulic environments such as heads of riffles may sort out most of the fine sediments. Throughout their evolution, it is probable that those salmon that spawned in fine sediments, rubble or boulders failed to survive as well as salmon that spawned in predominantly gravel. Somewhere between the extremes of fine sediment and rubble is the optimum composition composed mainly of gravel mixed with smaller amounts of fine sediment and small rubble.

Most salmon become riffle spawners because embryo survival requires specific conditions such as water velocities, water depths, sufficient dissolved oxygen and embryo metabolic waste removal. The hydraulic conditions that build and maintain these spawning riffles are widespread and persistent enough so that through time and over space, salmon were able to develop habitual spawning areas. Although there may be some minor changes in riffle location from year to year they are usually slight enough to cause no problems to salmon homing. Thus, each year salmon usually seek a predetermined area for deposition of their eggs. Salmon usually select areas where the hydraulic controls on the stream channel provide a substrate almost devoid of boulders because fish can't move them, low in fine sediments because of the need for subsurface water permeability, and high in gravel and small rubble which they can form into a cover that protects the eggs and alevins. This particle size distribution provides an egg cover that win withstand most of the velocities the stream exerts without sediment movement damaging the embryos. It is interesting that the fish do not choose channel substrates completely devoid of fine sediments, even though such areas exist. Thus, it is possible that fine sediments in the correct amounts can be important to embryo survival. Possibly, and this is based only on intuitive thinking, proper amounts of fine sediments could protect the eggs from predators, keep organic materials in the stream flow from settling on the eggs, keep eggs from being buffeted by high sub-surface flows, and help keep eggs and alevins in the substrate during floods until time for their emergence.

A confounding factor to us in determining why salmon choose a certain spawning area is that the quality of the surrounding rearing environment that guarantees survival of their young must also be a major factor in spawning site selection. We believe salmon select spawning sites by ocular selection of desirable sediment size classes, a feel for the required surface water velocities to drive the needed subsurface flows for the embryos and alevins, and a strong homing instinct that places them in an area in which their young have a good chance to survive.

Although salmonids have survived sedimentation from the watershed over the past million years, the literature indicates that their ability to cope with sudden increases in channel sedimentation may not be very good. Thus certain questions relating to watershed management need better answers: Have stream channel sediment size classes changed because of man's influences? Has there been a resulting change in the spawning success of salmonids? Can salmonids adjust to changes in the quality of channel sediments over time? Have fish evolved to survive only within narrow ranges of channel sedimentation or can they survive under wide variations? Do we know what channel sediment particle sizes and particle size composition fish need for good health and survival? If so, how closely do we need to be able to measure this composition for optimum fisheries management?

This report contributes some answers for these questions by describing channel sediment particle size mixtures chinook salmon (Oncorhynchus tshawytscha Walbaum) use for spawning over broad streambed areas. Methods for the analysis and evaluation of those sediments selected are discussed.

STUDY AREA

The Salmon River drainage supports most of the chinook salmon that enter Idaho to spawn. These waters are usually low in mineral content because of the predominance of granitic bedrock. A major part of the Salmon River watershed is within the 16,000-square-mile (6,150 km^2) Idaho Bathotith, an area of granitic bedrock much of which is characterized by steep slopes, erosion-prone soils, and severe climatic stresses. Soil disturbances, such as those associated with logging and road construction, can accelerate soil erosion many times over natural rates on such lands. Part of the Salmon River drainage lies in the Belt Series which is not granitic, and other bedrock types such as vplcanics and sedimentaries occupy relatively small sections.

The Salmon River drainage (Figures 1 and 2) ranges from over 12,000 feet (3600 m) above sea level in headwater areas to about 1500 feet (450 m) at its confluence with the Snake River. Most of the spawning areas occur between 5000 and 7000 feet (1650-2100 m), which corresponds to some important sediment dumps formed by glaciers during the Pleistocene epoch. These streams formed themselves in these extensive Pleistocene glacial deposits. This sediment was transplanted from higher elevations by glaciers and deposited in moraines and outwash trains. Subsequently, stream channels have reworked this sediment and evolved to their present morphology in quasi-equilibrium with climatic change. Part of the reason chinook salmon and steelhead trout (Salmo gairdneri Richardson) spawn and rear on these glacial dumps is because of the abundant supply of suitable sediment particle sizes at elevations creating cool water temperatures.

The Boise River drainage (Figure 3) ranges from over 10,000 feet (2048 m) to about 2600 feet (792 m) at its confluence with the Snake River. This river also drains an area of granitic bedrock.

This study was mainly conducted in the Salmon River drainage including its two major tributaries, the South Fork Salmon River and the Middle Fork Salmon River. The South Fork drains a 1,270-square-mile (660 km^2) watershed representative of the forested mountainous terrain found in central Idaho. The Middle Fork is a larger drainage that depends on its tributaries for the spawning of chinook salmon and steelhead trout. The South Fork channel con-tains the necessary sediment particle sizes required for spawning white the Middle Fork channel does not. The stream power in the Middle Fork is too high to allow sufficient quantities of gravel and fine sediment to remain in the channel. Therefore, salmon move into the tributaries to find the size of channel materials they need for spawning. In the South Fork there are channel reaches with low enough stream power to allow accumulation and containment of gravels and fine sediment. However, salmon use the tributaries in the South Fork much less than in the Middle Fork. The main river has large channel areas composed of gravel and fine sediments.

Only summer chinook use the South Fork Salmon River for spawning; spring chinook are the primary species using the Middle Pork drainage and the main Salmon River.

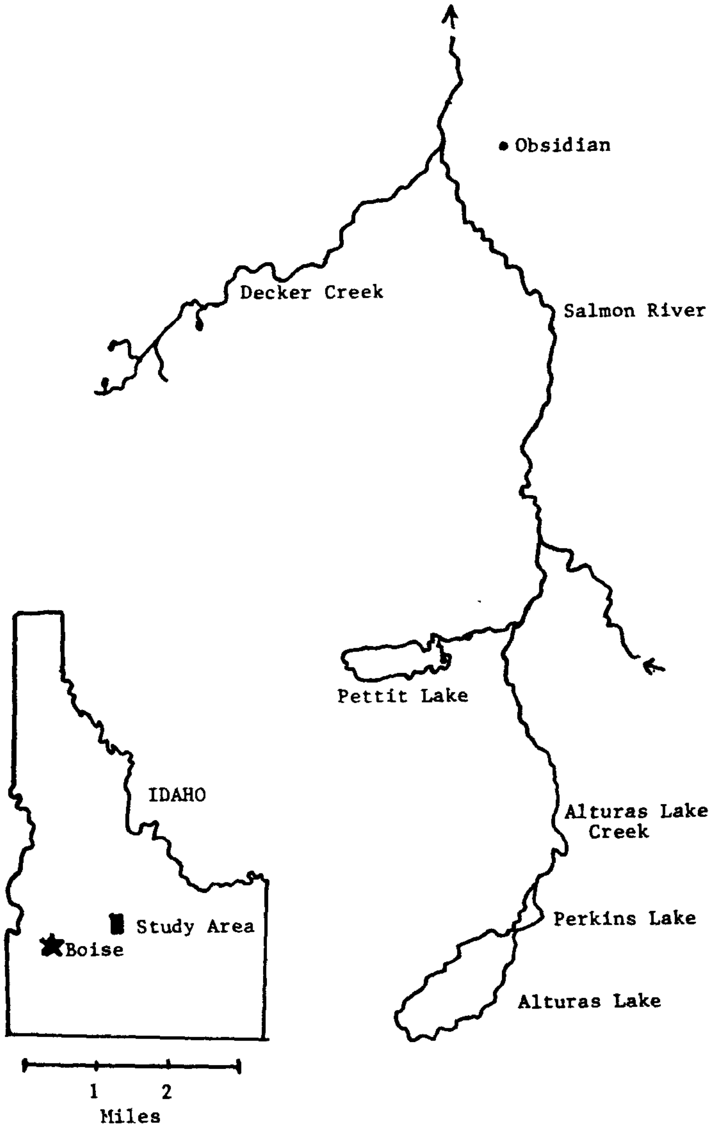

Figure 1. Study sites in the headwaters area of the Salmon River.

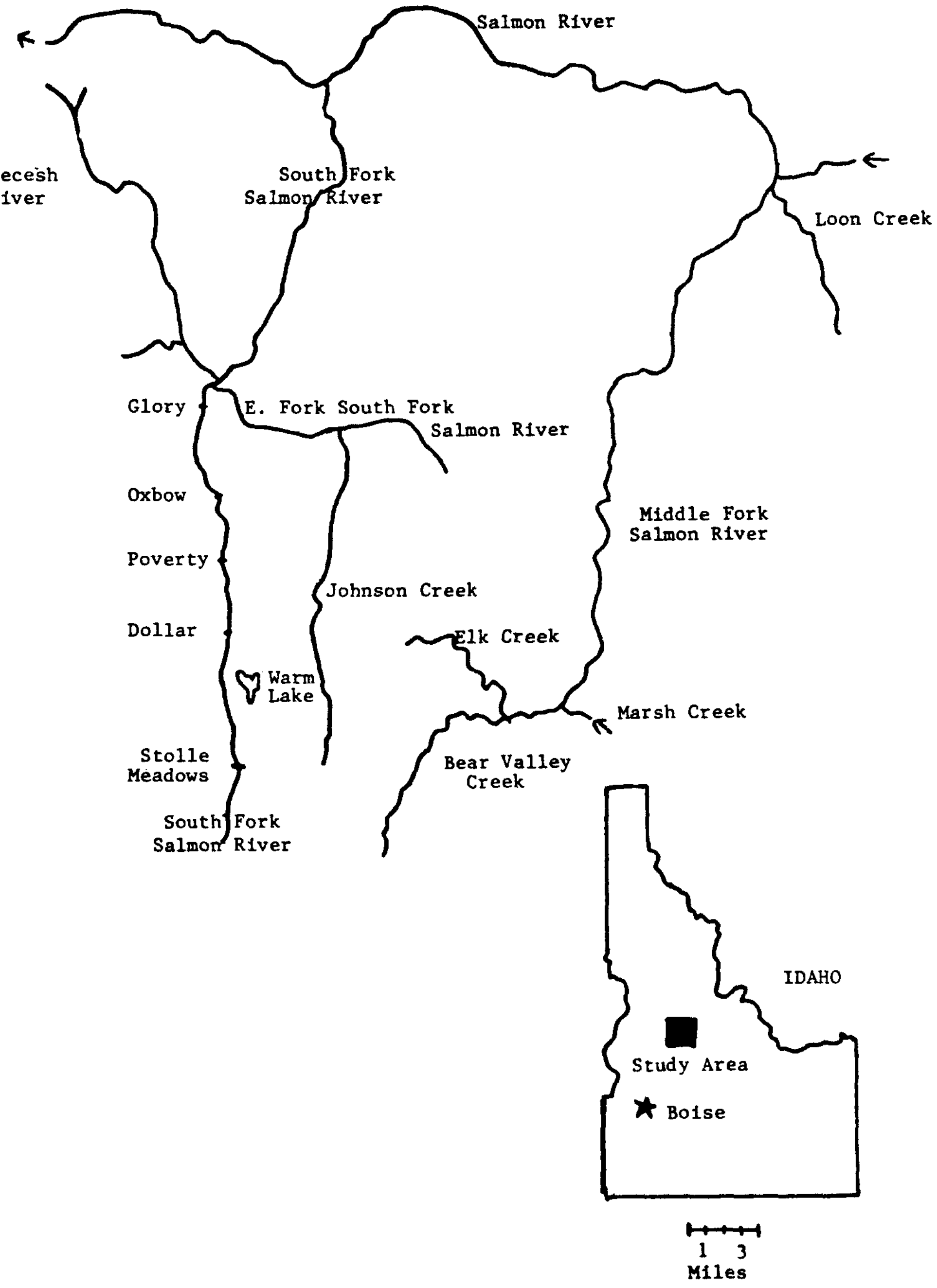

Figure 2. Streams studied in the Salmon River drainage.

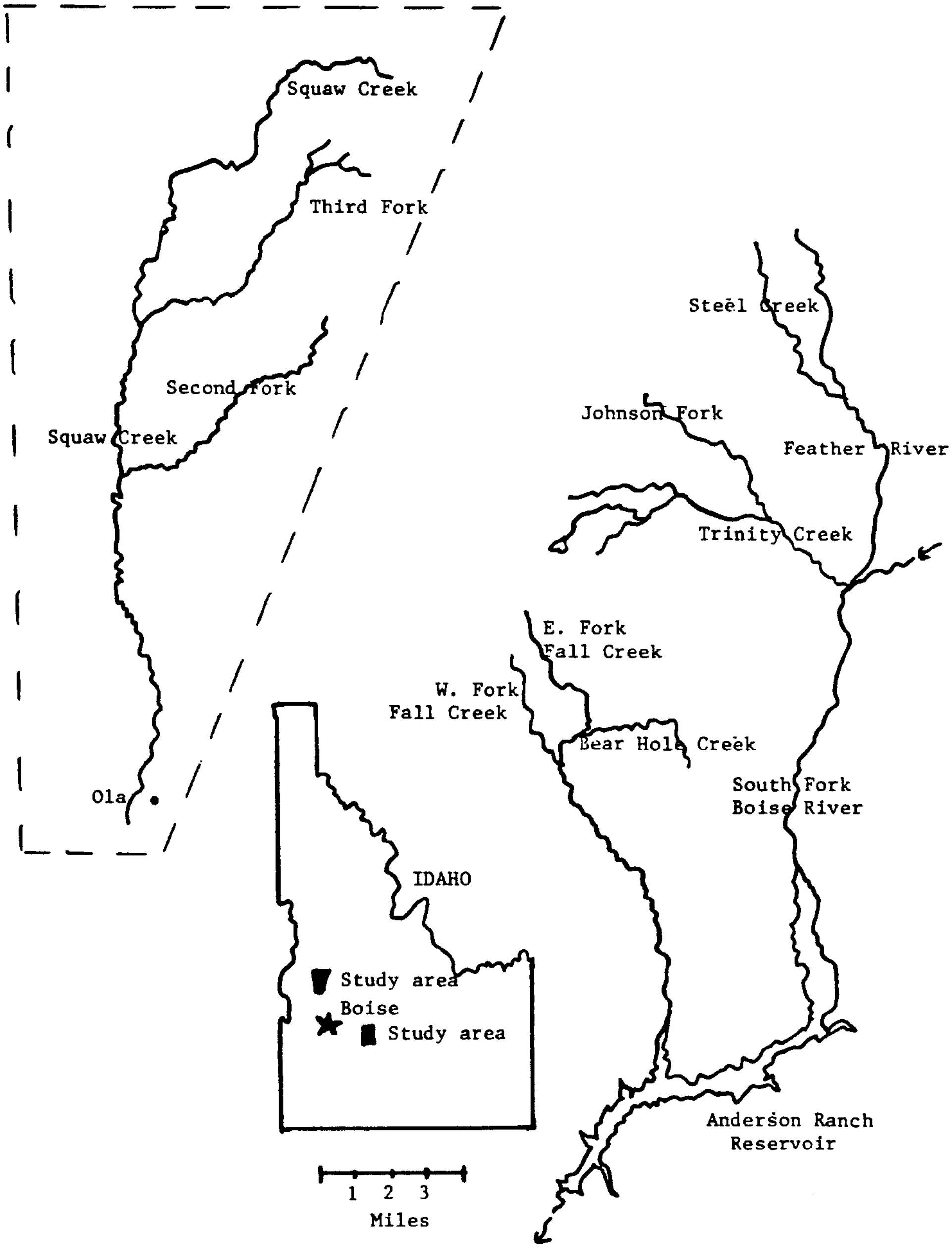

Figure 3. Study areas in the Squaw Creek and South Fork Boise River drainages.

METHODS FOR DESCRIBING SPAWNING SEDIMENTS

Sediments with different particle size compositions can be compared using the respective particle size-cumulative distribution curves. Data for these curves can be obtained through standard particle size analysis with percent of sediment by weight that is finer or coarser than a given sieve size plotted against that opening size. The use of logarithmic abscissa is desirable because natural sediments have an extremely wide range of grain sizes spreading over three or more cycles (i.e., factors of 10). Furthermore, natural sediments frequently exhibit lognormal distributions, i.e., when the logarithm of the particle size (instead of the particle size itself) is used, the distribution is nearly normal. Such nearly lognormal distributions show more symmetrical patterns on semi-log papers and their cumulative distributions are close to straight lines on log probability papers.

Following a conventional statistical approach, it is possible to compare two different sediment samples by some representation of the particle size-cumulative distribution curves in place of the entire curves. For example, if the curves were truly lognormal, the means and variances of the cumulative distributions could be the only information needed to define the curve. If the curves are skewed, additional information is required to show the skewed effects. The use of mean and variance simplify the comparison considerably, even when the distributions are not truly lognormal.

Numerical integration procedures for calculation of the mean, variance or skewness are available and can be applied to the data once the particle size cumulative distribution is known. Because this is tedious, graphical approaches are better suited for estimating such standard parameters as the mean and variance. For example, the median particle size, d_{50}, is picked up from the graph of the cumulative distribution curve directly to represent the particle diameter for which 50 percent dry weight of the sediment is coarser or finer. If the distribution is lognormal, this is exactly equal to the geometric mean of the distribution. For normal distributions, one standard deviation on either side of the mean diameter is approximately d_{16} and d_{84}, respectively, and the 2.5 and 97.5 percentiles are two standard deviations on either side of the mean. Once the cumulative distribution curve of a sediment composition is plotted, all such parameters can be directly picked up from the curves with no further calculation.

When the distribution is not symmetrical or lognormal, Innman (1952) following the classic work of Otto, recommended using the geometric mean of the particle diameters corresponding to the 16th and 84th percentiles (i.e., d_{16} and d_{84}). This has now become a standard procedure (Vanoni 1977). That is, the geometric mean diameter obtained from d_{16} and d_{84} is used even if the distribution deviates from lognormal. The geometric mean diameter, d_g is obtained from d_{16} and d_{84} as follows:

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

An estimate of the standard deviation, σ_g , is obtained by:

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

The mean diameter d_g is a useful measure, since it can be manipulated algebraically (Innman 19%). For example, the mean particle size of several combined samples is equal to the average of the means of those samples; this is not true for the median, i.e., d_{50}.

It is interesting to note that small values of σ_g are usually associated with small d_g values, frequently in large streams. In the case of coarse sediments, i.e., when d_g is relatively large, the geometric standard deviation is also relatively large (Bogardi 1974). This suggests that d_g is both a convenient and sufficient way to describe substrate composition.

Innman (1952) reported on Yule and Kendall's calculations showing that, for a normal curve, sampling error is greatly increased below 5 and above 95 percentiles of the distribution. The errors are tolerable for 16 and 84 percentiles. This is an important practical consideration when sampling for substrate composition and will be discussed further.

Fishery scientists have characterized stream channel sediments by "percent fines", which is defined as the mass fraction below a suitable selected particle size. There has been considerable debate (Iwamoto et a1. 1978) on the choice of the suitable particle size as it relates to egg and alevin mortality. Common particle sizes fishery scientists use to identify "percent fines" are .03 in (0.83 mm), .13 in (3.3 mm), .19 in (4.7 mm), and .25 in (6.3 mm). This has rendered comparison of research results difficult if not impossible. There are reasons why fishery scientists have used different particle size limits to define fine sediments. One reason is that salmon spawning areas in the Pacific Northwest exhibit different particle size graduations and researchers concerned with these areas observe different dominant features affecting embryo survival. A second reason is that mortality has been intrinsically associated with excess fine particles because of (a) the adverse effects very fine particles have on permeability and (b) the entrapment of embryos that can be caused by presence of particles of intermediate fineness, say, 2 mm-6 mm.

Note the difference in emphasis between the "percent fines" and the percentile approach. With the "percent fines" the particle diameter is selected and then the fraction of the sample which is finer is determined. With the percentile method, the percent passing is selected and the sample analyzed to find the corresponding particle diameter. The inherent disadvantages of the "percent fines" approach is that the probability of occurrence of these quantities, e.g., percent by weight less than .03 in (.83 mm), etc., vary from one composition to another. This means that if the sediment composition is coarse, it would be more difficult to evaluate its "percent fine" by sampling than if the sediment composition is fine. The percentile approach always results in the same sample size.

For example, the channel substrate in the Dollar and Poverty spawning areas on the South Fork Salmon River contains 5 and 14 percent, respectively, "percent fines" less than .03 in (.83 mm). Therefore, because of smaller "percent fines" in the Dollar area, the sampling error associated with its determination is expected to be greater than for the Poverty area. To attain comparable accuracies while using the same sampling procedures in the two areas, "percent fines" in the Dollar area must be based on .08 in (2 mm) particles where 14% of the substrate is finer. This presents an intolerable paradox; how do we know in advance what basis (i.e., particle diameter) for percent fines to choose? Measures based on geometric mean avoid this particular difficulty because the independent variable, i.e., the particle size, is not predetermined and it may vary, as it actually would from one sediment sample to another. Also, if it is desirable to determine the smaller particle sizes, thereby placing more emphasis on the amount of fines, then such quantities as d_{16}, d_5, $d_{2.5}$ etc., are more suitable than "percent fines". These d levels can then be used to determine degree and causes of mortality in embryos and alevins.

The intuitive appeal of "percent fines" in fisheries studies stems from its long association with impacts on egg survival (Iwamoto et at. 1978). As stated earlier, it has been verified that intergravel flow of water and oxygen is strongly related to percent fines and thus to spawning success. This is a very important and legitimate argument. Our studies show that as a measure of intergravel flow, the geometric mean is at least as good a measure as "percent fines".

Cooper (1965), presents data relating survival of eyed sockeye salmon (*Oncorhynchus nerka* Walbaum) eggs with intragravel water flow (Table 1).

TABLE 1. RELATION BETWEEN RATE OF WATER FLOW THROUGH A GRAVEL BED AND THE SURVIVAL OF EYED SOCKEYE EGGS IN THE GRAVEL[1].

Apparent velocity (cm/sec)[2] through spawning sediments	Percent egg survival
.0338	89.3
.0112	78.3
.00542	68.3
.00261	59.0
.00136	36.3
.000945	26.5
.000668	15.6
.000389	1.9

[1] Taken from Cooper (1965).

[2] Apparent velocity equals discharge divided by total cross sectional area of voids and solids.

The positive relationship is unmistakable with these low velocities. However, as velocities continue to increase above those reported here, there would be a level where egg survival would start to decrease because of the pressures or buffeting from surface flows. Cooper conducted numerous tests with gravels of different compositions and showed that apparent velocity is a function of gravel porosity and permeability for a given hydraulic head. That is,

$$V = f(s, e. \beta).$$

where,

V = velocity
s = hydraulic head
e = porosity
β = permeability

Our analysis of Cooper's data demonstrates a strong correlation between geometric mean diameter of the appropriate gravels used and their respective measured porosity e and computed permeability β. These results are shown in Table 2 and Figures 4 and 5. Accordingly, a single measure of gravel composition, d_g, provides the link between apparent subsurface water velocity and egg survival.

Alternatively, "percent fines" also are related to porosity with reasonably high correlation, but a choice has to be made for a proper definition of "percent fines". Table 3 shows the comparison of porosity as a function of d_g, percent fines, and $\Sigma^p/_d$. The latter factor appears in the definition of permeability β as reported by Cooper (1965). It is the sum of the fraction P of particles by weight of diameter d divided by the diameter. The table was prepared for correlation of e and β with d_g, "percent fines", etc. Linear correlations were best suited for e but power functions of the type Ax^b were more appropriate for β. This table is not intended for use of these empirical correlations. The degrees of fit also are not used here to show conclusively which are the best parameters. We are dealing only with one set of data and caution should be exercised in reading too much into the result. Table 3, however, does serve one important function, i.e., to show that for this set of data the geometric mean particle diameter competes in representativeness with other measures.

There is also an excellent correlation between $\Sigma^p/_d$, and p, since I. Has been used in the definition and calculation of β. $\Sigma^p/_d$ does appear to be a very good measure, even though it is less conventional and more difficult to calculate than d_g. There is, however, a strong correlation between $\Sigma^p/_d$ and d_g. Calculations are not presented in the table, but the coefficient of representation r^2 of a power function of the type Ax^b was found to be 0.89.

The high correlation between "percent fines" for the 6.3 mm particle size and less and β has a curious explanation associated with the specific nature of gravel used in the work. For the 15 gravel compositions used, "percent fines" below 6.3 mm averaged 15 percent. This is very closely related to die used in calculation of d_g. The rationale for the strong correlation becomes y

TABLE 2. POROSITY AND PERMEABILITY OF SPAWNING GRAVEL AND ITS RELATION TO GRAVEL COMPOSITION[1]

		% Finer than		Porosity, e			Permeability, β			Gravel Sample[1]	
d_g (cm)		.83 (mm)	6.3 (mm)	Loose bed	Compact bed	Mean e	Loose bed	Compact bed	Mean β	ID	Symbol used in Figures 4 and 5
1.61	2.66	2.0	19.4	0.278	0.200	0.244	0.025	0.015	0.020	1	θ
1.73	1.88	3.5	20.9	0.298	0.232	0.265	0.037	0.025	0.031	2	
3.24	3.84	7.9	27.6	0.233	0.111	0.172	0.013	0.005	0.009	3	
3.35	0.77	1.0	9.2	0.305	0.254	0.280	0.093	0.069	0.081	4	
6.90	0.41	0.4	4.4	0.412	0.382	0.397	0.283	0.238	0.261	5	
1.60	4.35	6.7	25.9	0.235	0.186	0.211	0.012	0.008	0.010	A	Λ
2.09	3.93	5.2	18.8	0.269	0.235	0.252	0.015	0.012	0.014	B	
2.97	1.54	3.5	12.6	0.295	0.248	0.272	0.045	0.089	0.067	C	
4.60	0.58	1.7	7.4	0.316	0.283	0.300	0.130	0.106	0.118	D	
6.26	0.40	0.2	4.9	0.371	0.334	0.353	0.238	0.193	0.216	E	
6.57	0.40	0.2	5.0			0.327			0.200	14	□
4.13	1.12	2.4	9.0			0.278			0.053	15	
3.12	1.93	4.0	12.5			0.240			0.027	16	
2.12	3.07	5.2	17.5			0.217			0.014	17	
1.30	4.67	6.7	27.5			0.206			0.009	18	

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[1] based on data from Cooper (1965); ID column allows data in this table to be related to that of Cooper.

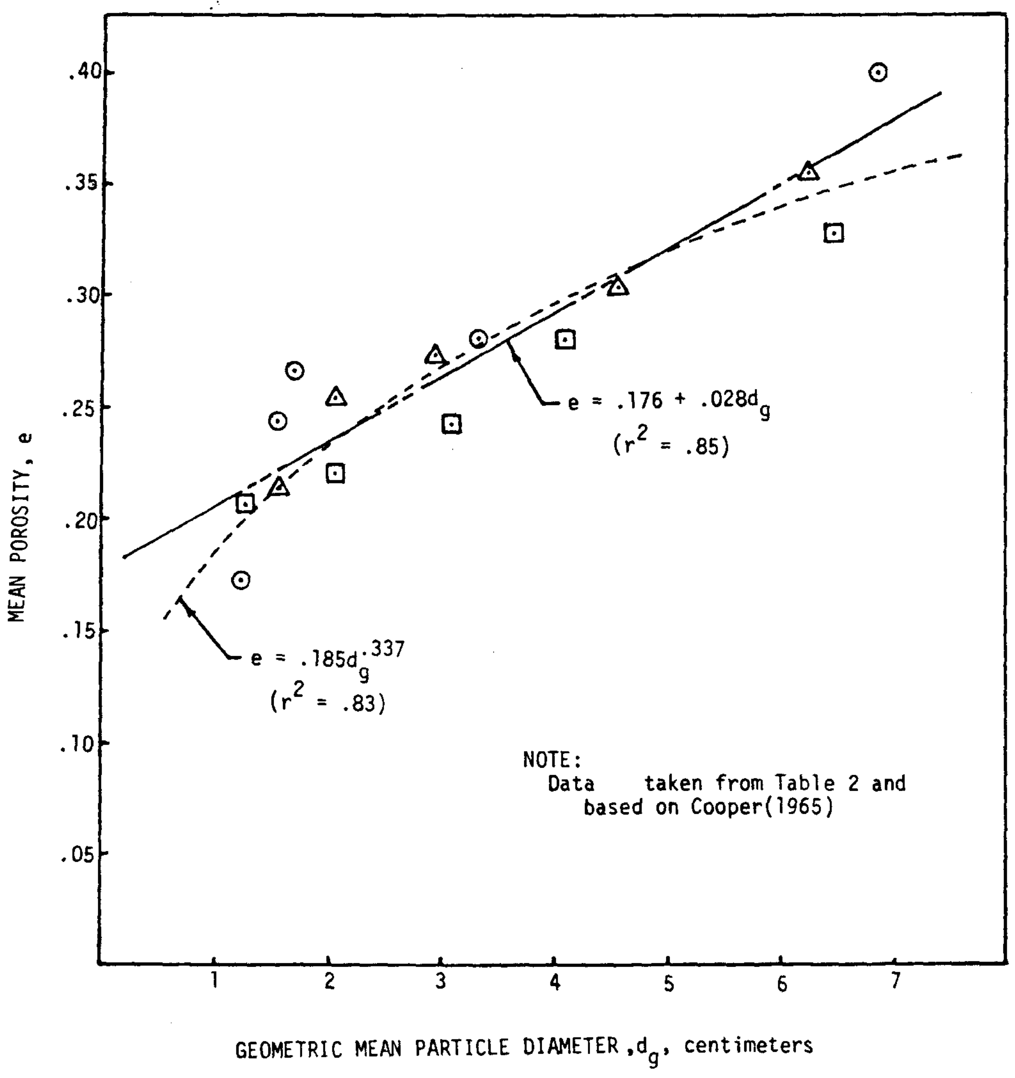

Figure 4. Relationship between sediment porosity and geometric mean sediment particle diameter.

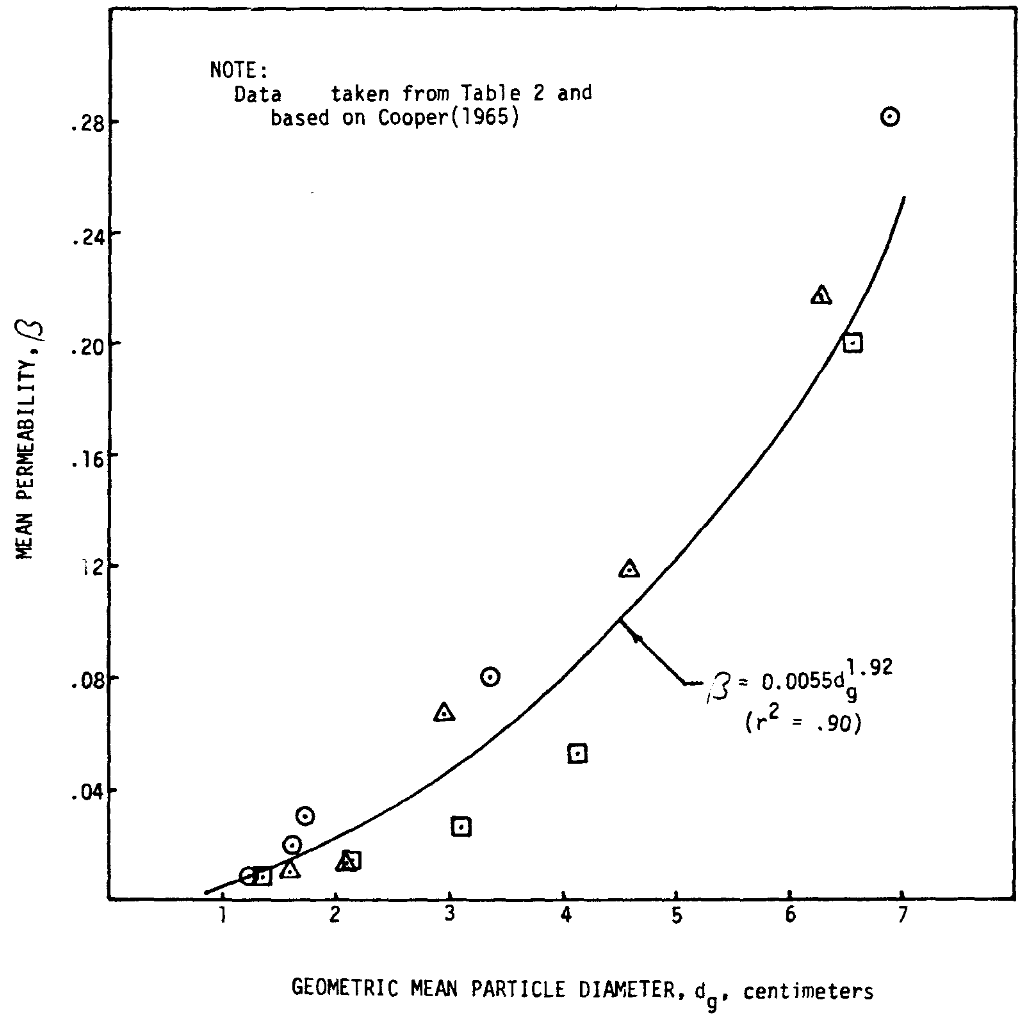

Figure 5. Relationship between gravel permeability β, and geometric mean sediment particle diameter.

obvious if we recall the definition of d_{16} i.e., the size below which 16 percent of the gravel is finer. Naturally we should not always expect that 6.3 mm and d_{16} coincide as it did in this case.

TABLE 3. COEFFICIENT OF DETERMINATION BETWEEN PERMEABILITY AND POROSITY AND INDICES OF GRAVEL COMPOSITION d_g, $\Sigma^p/_d$ AND PERCENT FINES USING LINEAR AND POWER FITTING FUNCTIONS

Sediment property	d_g	$\Sigma^p/_d$	Percent fines less than	
			.83 mm	6.3 mm
Porosity, e	.85	.71	.79	.77
Permeability, β	.90	.97	.82	.93

In summary, the geometric mean diameter is recommended as a standard measure for substrate characterization in fisheries work for the following reasons:

(1) d_g is a conventional statistical measure being used by several disciplines 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 is calculated from d_{84} and d_{16}, two parameters that can 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) Because d_g relates to porosity and permeability, it is potentially a suitable unifying measure of channel substrate condition as it impacts embryo survival.

PROCEDURES

Three investigators determined the sediment composition of selected spawning areas from 1966 to 1977 in the Salmon River drainage. They used at least three different procedures in site selection, method of collection, equipment and analysis.

The data collected by Ortmann (1968) for 1966 and Platts (1968. 1970 and 1972) for 1967-1974 were obtained using the McNeil method with 6-inch (153 mm) diameter cores. The USDA Forest Service Materials Testing Laboratory, Salt Lake City, Utah, heat-dried, screened, and weighed the selected particle size groups of the samples collected by Platts. Platts collected cores along permanent stratified random transects crossing spawning areas. Two samples were taken, one each at 1/4 and 3/4 intervals across each transect. Occasionally a third sample was taken mid-point on the transect.

Corley (1975a, 1975b and 1978) collected samples from 1975 through 1977 with a 12-inch (305 mm) core sampler. About 5 gallons (18.9 liters) of sediment was collected with each sample. The sediment samples of Ortman and Corley were sieved wet and analyzed in the field using standard sorting screens for sediment separation. Weights of the selected sediment size groups were determined using the volumetric water displacement method suggested by McNeil (1964).

Corley selected gravel areas from 25 x 25 foot (7.63 x 7.63 m) square grids laid out within known spawning riffles. Ten core samples were selected randomly within the designated 625 ft^2 (58.1 m^2) square. Four riffles, all located within the spawning area, were selected to represent the complete spawning site.

Very fine particle sizes, on the order of .0025 in (63 microns) and less, were analyzed by Cortey using an Imhoff cone and by Platts using a hydrometer. The mass fraction of these small particles per sample was much less than 1 percent.

The treatment of very large sediment particles was more difficult and depended on the core diameters used. Frequently large particles were found obstructing the 6-in (153 mm) core sampler, in which case they were added to the sample. The use of a 12-in (305 mm) core sampler may present a smaller sampling bias. Since the total volume from a 6-in core sampler is smaller than that taken from a 12-in core sample, the presence of large particles in the small sample could skew the distribution, biasing it toward coarse composition. This would cause larger fluctuations in the results. Also, in the process of digging out the channel materials within the core sampler, fine sediments are more readily collected than large size particles.

Data obtained by Platts were presented for 3-in (76.2 mm) size particles and less, i.e., that fraction of the sample passing the 3-in sieve. All materials above 3 in were grouped into one size class. Cortey's 1975 and 1977 data are analyzed only for sediment particles 1-in (25.4 mm) and less. The composition above 1 in and below 3 in was not sorted, except for 1976 data.

RESULTS AND CONCLUSIONS

Data describing the particle size distributions for various spawning areas are summarized in Tables 4-7. Because of the differences in screen size selection by the different authors, the tables do not show directly-measured data for all sieve sizes. Instead, interpolated values (shown within parentheses) are inserted for convenience. The interpolations were made by graphing the particle size frequency distribution curve for each sample and taking the interpolated number from its respective place on the curve.

The substrate compositions of chinook spawning areas located in the South Fork Salmon River, Middle Fork Salmon River tributaries, and the Salmon River and one of its tributaries are shown in Tables 4 and 5. Each spawning area listed represents from 5 to 130 core samples collected from that site. In addition, averages for all chinook spawning areas located within each of the three river drainages are presented, and, finally, a grand average for all chinook salmon spawning areas is given. The preference for the sediment composition chosen by spawning salmon is reflected by the d_g averages of .28 to .79 in (7 to 20 mm), depending on the river reaches sampled. The narrow range salmon find acceptable for spawning becomes apparent when the average sediment particle size found in spawning areas is compared with other channel reaches of similar size they could have selected for spawning, e.g., they could have selected fine sand with d_g less than 0.04 in (1 mm) or areas of predominant rubble with d_g greater than 3.99 in (100 mm).

Orcutt et al. (1968) listed the preferred substrate size used by spawning steelhead trout in Idaho as between .25 in (6.7 mm) and 4.0 in (101.6 mm).

Based on the 815 samples taken from the 12 most important salmon spawning areas in Idaho, channels used for spawning averaged only 8 percent fine sediments below .03 in (.83 mm) in particle size. However, these areas averaged 30 percent in sediment particle size less than .19 in (4.7 mm). This indicates that entrapment of atevins by fine sediments may be more of a problem in the Salmon River drainage than embryo or alevin mortality caused by low dissolved oxygen in the subsurface flows. About 93 percent of the sediments are less than 3 in (76.1 mm) in particle diameter, which shows salmon are not looking for large sediments for spawning. Actually, the majority of the sediments they are using are less than .75 in (19 mm) in particle size.

There are differences in sediment sizes used for spawning between streams or areas within streams, but these are not major differences. The change in procedures from year to year and person to person may have some effect on these differences.

TABLE 4. CHANNEL SUBSTRATE COMPOSITION BY YEARLY AVERAGES BY SEDIMENT PARTICLE SIZE IN SAMPLES TAKEN FROM CHINOOK SALMON SPAWNING AREAS.

			Substrate Particle Size by Groups Representing Percent Volume Through Sieve of the Designated Size (mm) Passing[1]																			
Stream or Area	Sample Size	Time Period	76.1	50.8	38.1	25.4	19.0	12.7	9.51	6.35	4.76	2.83	2.38	2.00	1.00	.83	.42	.25	.21	.10	.07	.05
<u>South Fork Salmon River</u>																						
Stolle Meadows Area	145	1966 to 1975	92	79	71	53	48	42	38	34	30	26	(23)	19	15	11	6	2	1	.6	.1	0
Dollar Area	40	1975	--	--	--	49	(44)	(40)	(35)	31	28	(23)	(19)	(14)	(10)	5	(4)	(2)	.5	(.5)	(.4)	0.4
Poverty Area	310	1966 to 1976	93	84	77	68	60	52	47	42	37	33	28	23	18	14	7	4	2	1	0	0
Oxbow Area	50	1975	--	--	--	74	(68)	(63)	(58)	53	48	(41)	(33)	(25)	(17)	9	(7)	(4)	1	(1)	(0)	0
Glory Area	80	1966 to 1975	93	82	70	57	52	46	41	36	31	(28)	(24)	20	(15)	5	12	2	1	1	.5	.5
Johnson Creek	100	1966 to 1976	86	74	(63)	51	(44)	38	(33)	28	25	21	17	(14)	10	8	(5)	(3)	1	(1)	(0)	0
<u>Middle Fork Salmon River</u>																						
Bear Valley Creek	20	1968	98	90	82	72	63	53	48	(42)	37	(33)	(28)	24	(18)	12	5	1	(1)	0	0	0
Elk Creek	20	1968	100	98	89	71	58	45	39	(34)	28	(24)	(19)	15	(10)	5	3	.5	(.5)	0	0	0
Loon Creek	20	1969	94	76	67	55	47	38	32	(27)	22	(20)	(17)	15	(11)	7	2	1	(1)	0	0	0
<u>Salmon River</u>																						
Lower Decker Area	5	1969	82	62	56	49	43	37	32	(26)	21	(18)	(15)	12	(9)	6	3	1	(1)	0	0	0
Upper Decker Area	5	1969	96	85	78	67	59	49	42	(35)	28	(23)	(19)	14	(10)	5	1	0	0	0	0	0
Alturas Creek	20	1969	95	77	66	54	46	38	33	(27)	24	(22)	(17)	14	(10)	6	3	1	(1)	0	0	0
Combined Average			93	81	72	60	53	45	40	34	30	26	22	17	13	8	4	2	0.9	0.4	0.1	0.1
Total Sample Size 815																						

[1] Values in parentheses are interpolated by graphing the particle size distribution curve and selecting the percent passing from the intersection of the group size with the curve.

TABLE 5. CHANNEL SUBSTRATE COMPOSITION BY DRAINAGE BY SEDIMENT PARTICLE SIZE IN SAMPLES TAKEN FROM CHINOOK SALMON SPAWNING AREAS.

		Substrate Particle Size by Groups Representing Percent Volume Passing[1] Through Sieve of the Designated Size (mm)																			
Drainage	Sample Size	76.1	50.8	38.1	25.4	19.0	12.7	9.51	6.35	4.76	2.83	2.28	2.00	1.00	.83	.42	.25	.21	.10	.07	.05
South Fork Salmon R.	725	91	80	70	59	53	47	42	37	33	29	24	19	14	10	6	3	1	0.8	0.2	0.2
Middle Fork Salmon R.	60	97	88	79	66	56	45	40	(34)!	29	(26)	(21)	18	(13)	8	3	0.8	(0.8)	0	0	0
Main Salmon River	30	91	75	67	57	49	41	36	(29)	24	(21)	(17)	13	(10)	6	2	0.7	(0.7)	0	0	0

[1] Values in parentheses are interpolated by graphing the particle size distribution curve and selecting the percent passing from the intersection of the group size with the curve.

In comparing particle sizes used by salmon between the three major drainages, the differences were again not substantial. There was a difference of 4 percent at .03 in (.83 mm) and less in particle size, 9 percent at the .19 in (4.7 mm) particle size, and 6 percent at the 3 in (76.1 mm) particle size. Salmon are not searching out major differences in sediment particle sizes for spawning regardless of the drainage, stream or stream area. However, studies have shown that an increase from 5 percent to 15 percent in fine sediments less than .03 in (.83 mm) in particle size can result in a change from low mortality to high mortality. Therefore, salmon have to search out sediments within narrow particle size distribution limits because the survival requirements of the embryo and alevin are so demanding.

In an attempt to find a best correlation between various definitions of "percent fines" and geometric mean diameter for chinook spawning substrate in the Salmon River, a power curve fitting procedure of the form

$$(\text{percent} < d) = A(d_g)^b$$

was used, where d is the appropriate particle diameter below which the mass fraction percentile is finer, and A and b are constants. This formula was repeatedly applied to the core data and the coefficient of determination, r^2 was calculated.

"Percent fines" less than .08 in (2 mm) provides the best fit (Figure 6). Possibly this is because .08 in (2 mm) coincides with the mean of the 16 percentiles of the entire data sample for the spawning substrate in the Salmon River drainage.

The curves in Figure 6 might be used as a summary and as rough estimates of "percent fines" in spawning areas in the Salmon River drainage. The figure provides a good illustration of the value of d_g in synthesizing apparently unrelated results. A vertical line drawn through a d_g of .24 in (6 mm), for example, shows that this d_g is equivalent to each of-the following "percent fines" specifications: 22 percent less than .04 in (1 mm), 26 percent less than .08 in (2 mm), 31 percent less than .09 in (2.38 mm), 36 percent less than .11 in (2.83 mm), and 39 percent less than .19 in (4.76 mm). It should be emphasized, however, that use of Figure 6 is restricted to obtaining an estimate of fine sediments for this specific data set. Figure 6 should not be used to determine a general relationship for other spawning substrates.

The average substrate composition for spawning areas located in each of the three drainages listed in Table 4 is plotted using semi-log axes in Figure 7. The consistently coarser structure of substrates used by spawning salmon in the Salmon River and its tributary, Alturas Creek, relative to those areas used in its two major tributaries, the Middle Fork Salmon River and the South Fork Salmon River, is clearly shown. The upper Salmon River as well as the Middle Fork Salmon River are used mainly by spring chinook salmon. There is some indication that spring chinook salmon spawning areas in Idaho consist of a coarser substrate. However, the data alone cannot be used to substantiate this because the South Fork Salmon River (used by summer chinook) may still be affected by past logging operations.

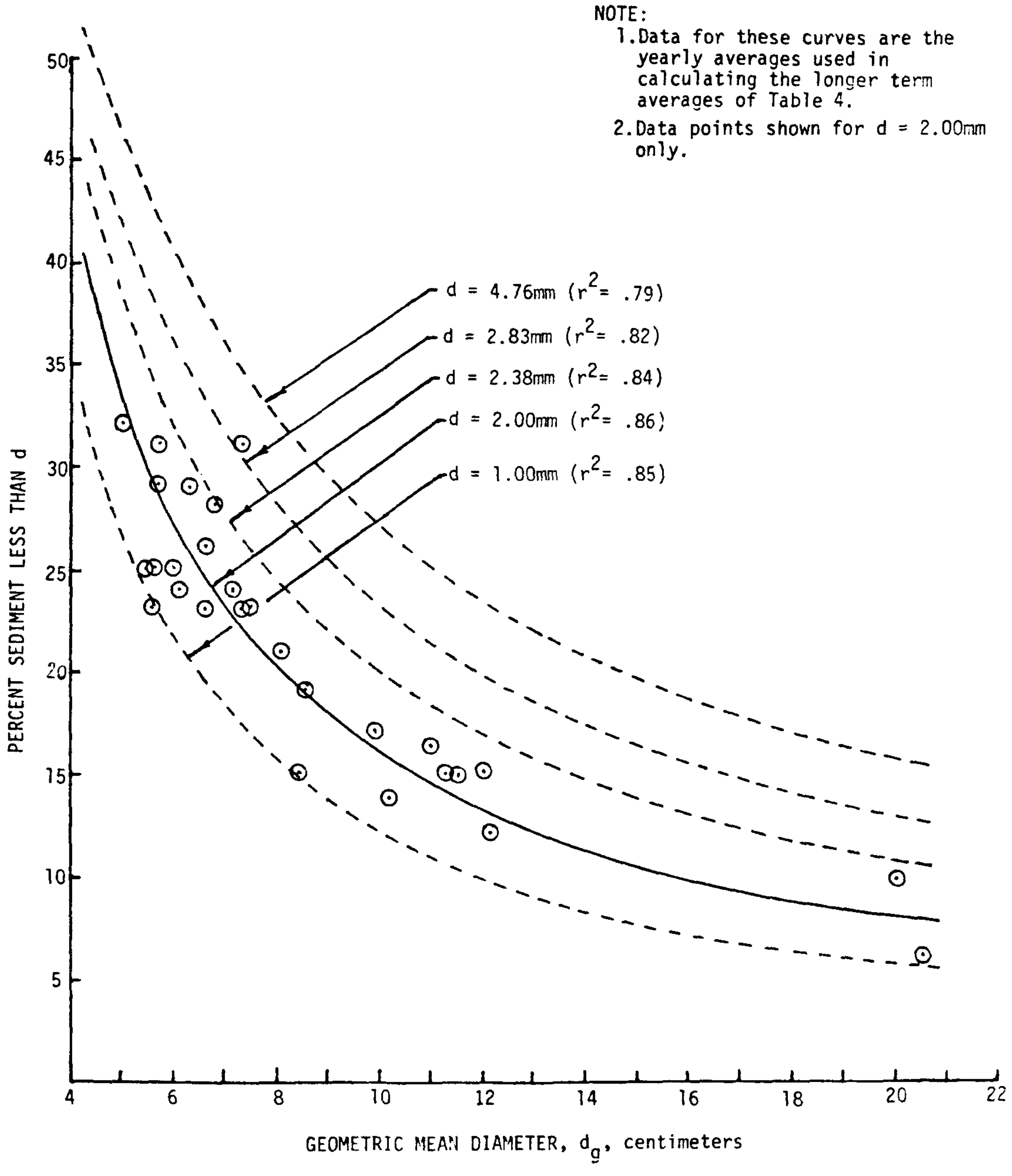

Figure 6. Relationship between geometric mean diameter and percent fines.

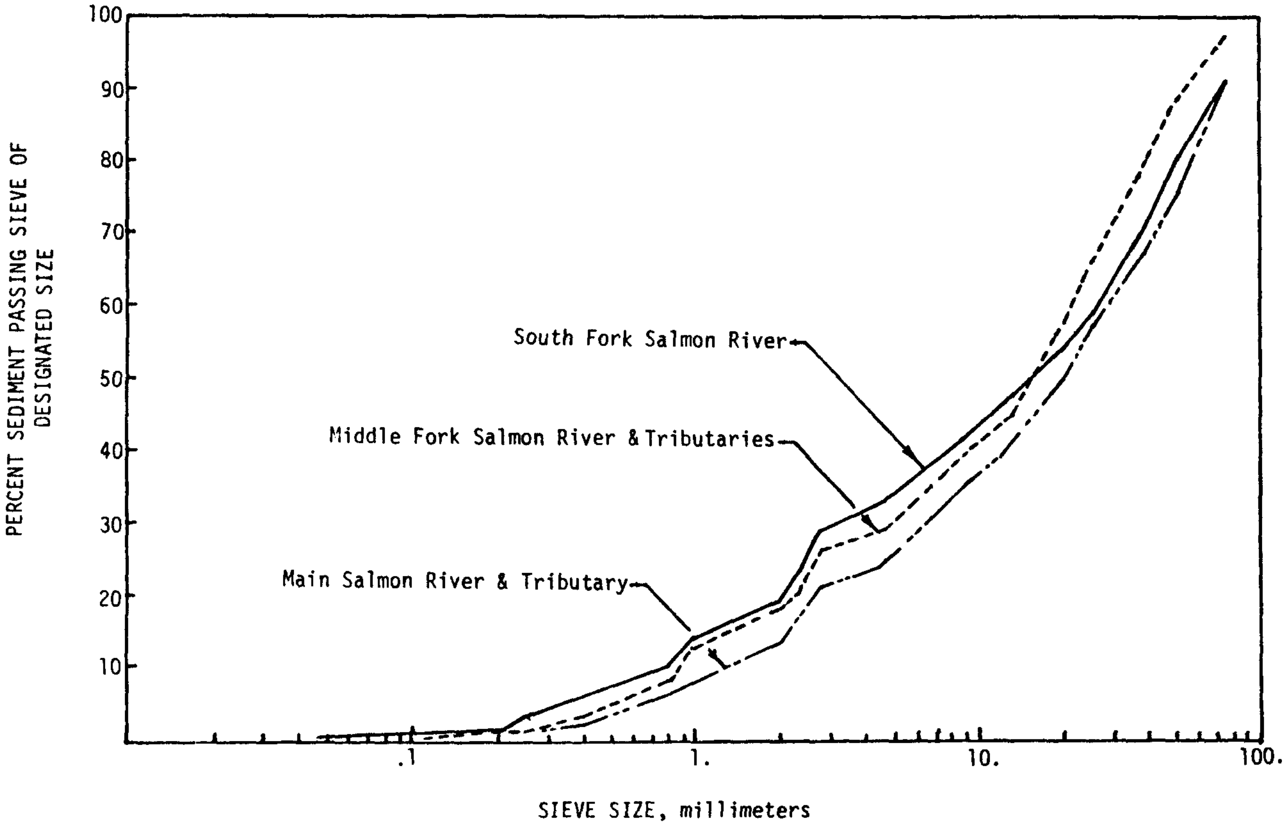

Figure 7. Particle size distributions for chinook salmon spawning areas.

It is difficult to provide a systematic comparison showing substrate composition differences between the streams, spawning areas and stream reaches sampled. The main difficulty arises because of the change in procedures and equipment from year to year and person to person. Therefore, some of the variability and differences indicated by the data might be procedural in nature and not a reflection of the true situation. Taking into consideration this problem, an attempt is made to compare these variabilities. Thus, the data sets are selected to avoid some of the more obvious problems.

A detailed look at a single spawning area (Poverty area) on the South Fork Salmon River is given in Table 6. Four sites were sampled and five samples were taken at each site. The geometric mean particle diameter and to some extent "percent fines" within each site as well as between sites varies by a two-fold magnitude. Thus, there is some variability between each site within the spawning area. This was expected as the upper end of the Poverty spawning area is composed mainly of rubble with gravel in the downstream direction to gravel mixed with fine sediments at the lower end of the spawning area.

TABLE 6. VARIATION OF GEOMETRIC MEAN PARTICLE DIAMETER OF SPAWNING SEDIMENTS IN THE POVERTY AREA AMONG SAMPLES COLLECTED IN 1976.

		Percent fines <6.3 mm		d_g mm	
Site	Point		Average		Average
1	1	6.7		8.5	
	2	7.7		11.7	
	3	6.7		7.8	
	4	8.3		8.5	
	5	9.0		6.9	
			7.7		8.4
2	All points	10.6		6.4	
3		8.3		8.1	
4		10.8		12.0	
			9.4		8.4

Particle size distributions for sediment collected from areas used by trout spawning and rearing are listed in Table 7. These sample areas were distributed over a much larger portion of the stream channel than were the samples collected in the salmon spawning areas discussed earlier. Each horizontal line in Table 7 represents the average for several individual samples taken from each stream. Overall averages for tributaries within the three major rivers and a grand average for a11 three areas are presented. Because of the lack of the upper portion (i.e., particles larger than 1 in (25.4 mm))

TABLE 7. CHANNEL SUBSTRATE COMPOSITION BY YEARLY AVERAGES BY SEDIMENT PARTICLE SIZE CLASS IN SAMPLES TAKEN FROM TROUT SPAWNING AND REARING AREAS.

Drainage Stream	Sample Size	Year	Substrate Particle Size by Groups Representing Percent Volume Passing[1] Through Sieve of the Designated Size (mm)																			
			76.1	50.8	38.1	25.4	19.0	12.7	9.51	6.35	4.76	2.83	2.38	2.00	1.00	.83	.42	.25	.21	.10	.07	.05
South Fork Boise River	70	1975				44	(39)	(35)	(31)	27	24	(20)	(17)	(13)	(10)	6	(5)	(3)	1	(1)	(1)	1
Fall Creek	10	1975				40	(37)	(34)	(31)	28	26	(22)	(19)	(15)	(12)	8	(7)	(5)	3	(3)	(2)	2
E.F. Fall Creek	5	1975				32	(28)	(24)	(20)	16	14	(12)	(10)	(8)	(6)	3	(2)	(1)	0			
W.F. Fall Creek	5	1975				50	(47)	(43)	(40)	36	33	(28)	(23)	(18)	(13)	8	(7)	(5)	3	(3)	(2)	2
Bear Hole Creek	15	1975				58	(53)	(47)	(41)	35	32	(27)	(23)	(18)	(14)	9	(7)	(5)	3	(3)	(2)	2
Trinity Creek	15	1975				35	(30)	(26)	(22)	18	16	(13)	(11)	(8)	(5)	2	(2)	(1)	0			
Spring Creek	5	1975				55	(49)	(44)	(39)	34	30	(25)	(20)	(15)	(10)	5	(4)	(3)	2	(2)	(1)	1
Spring Creek Johnson Fork	5	1975				37	(33)	(29)	(25)	21	19	(15)	(12)	(9)	(6)	3	(3)	(2)	1	(1)	(0)	0
Steel Creek	10	1975				36	(33)	(29)	(25)	21	18	(15)	(12)	(9)	(6)	4	(3)	(2)	1	(1)	(0)	0
North Pork Boise River																						
N.F. Boise River	45	1976	81	(72)	(63)	54	(48)	43	(37)	32	29	(24)	19	(15)	(11)	7	(5)	(3)	1	(1)	(0)	0
Payette River	40	1974	60	(53)	(46)	(40)	(33)	27	(25)	(22)	19	(18)	(17)	16	(14)	(12)	(9)	(7)	(4)	(2)	0	
Squaw Creek	15	1974	54	(47)	(40)	(34)	(27)	21	(19)	(16)	13	(11)	(10)	8	(6)	(5)	(4)	(3)	(2)	(1)	0	
Second Fk. Creek	10	1974	59	(51)	(43)	(36)	(28)	21	(19)	(17)	15	(13)	(12)	10	(9)	(7)	(6)	(4)	(3)	(1)	0	
Third Fk. Creek	15	1974	66	(60)	(54)	(48)	(42)	36	(34)	(31)	28	(26)	(24)	22	(18)	(15)	(12)	(9)	(6)	(3)	0	
Combined Average by Stream			65	(58)	(50)	43	(38)	33	(29)	25	23	(19)	16	13	10	6	(5)	(4)	2	(2)	0.6	0.6
Total Sample Size 155																						

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[1] Values in parentheses are interpolated by graphing the particle size distribution curve and selecting the percent passing from the intersection of the group size with the curve.

of particle size distribution, geometric mean diameters for trout areas could not be calculated. However, to provide a comparison, the particle size distributions averaged for all chinook spawning areas vs. all samples collected in trout channels used for rearing and possible spawning are presented in Figure 8. The coarser substrate in resident trout channels is clearly shown. Trout often spawn in small niches within the channel that frequently have finer substrate than the overall riffle areas. Therefore, redds are usually interspersed among areas of much coarser material. The sampling procedure does not take this into account.

Table 8 shows the variation of geometric mean diameter for 1976 for different spawning areas in the South Fork Salmon River. These areas are arranged in order of increasing channel elevation, showing that fish have used persistently coarser spawning gravel in the upstream direction, with d_g = .58 in (14.7 mm) in the upstream reaches compared with d_g = .35 in (8.8 mm) in the downstream reaches of the South Fork Salmon River. Whether this is a reflection of availability or preference for certain sediments is not determined.

An attempt was made to obtain measurements within egg pockets in the Poverty area. Fifteen freeze core samples were collected during the 1977 spawning period. The freeze core rods were driven to a depth of 18 inches in the substrate. Results were analyzed separately for each core sample and in combination. The geometric mean diameter for the combined 15 core samples was 18.4 mm. The geometric mean diameter for top to 6 inches, 6 to 12 inches, and 12 to 18 inches were respectively 20.3 mm, 22.4 mm, 6.5 mm. Unfortunately, the individual analysis of separate core samples revealed unusual scatter. For example, the average d_g for the 15 samples was 34.6 mm with a standard deviation of 20.6 mm from thrs mean.

TABLE 8. VARIATION OF GEOMETRIC MEAN DIAMETER OF SPAWNING SEDIMENTS IN SAMPLES 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		

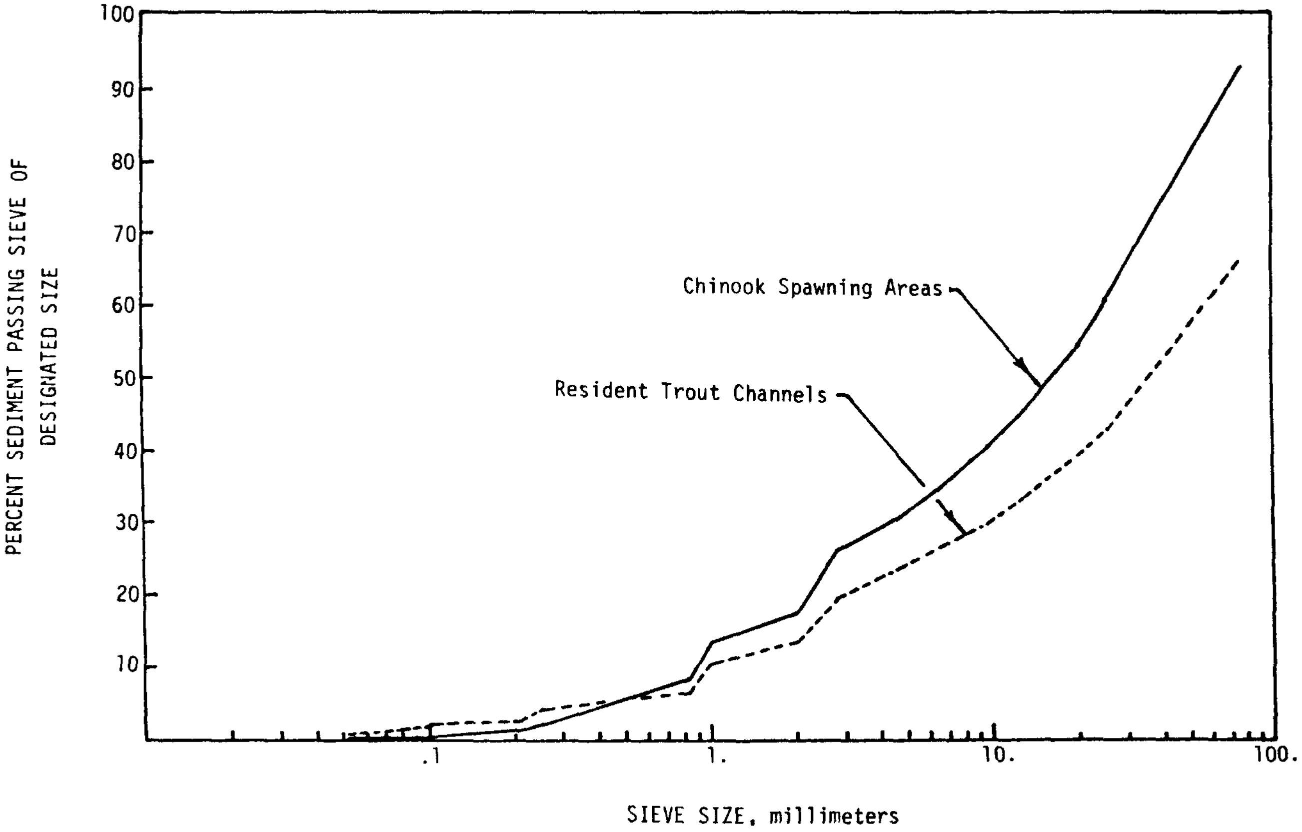

Figure 8. Comparison of particle size distributions for resident trout channels and chinook salmon spawning areas.

Continued attempts to characterize the strata of egg pockets resulted in Table 9 which was obtained from the Poverty area in November 1978. The sample was collected with a battery of freeze cores and an attempt was made to extract an entire redd egg pocket soon after spawning. The dry sample weight was 620 kg and the geometric mean diameter of the redd was 23.3 *mm.* This is somewhat large compared with similar measurements taken by other means both in 1978 and previously.

The difference is attributed to two important factors. The first is that considerable coarsening of the gravel was accomplished by the fish during spawning. The fish was observed digging deep, and covering the eggs with relatively coarse substrate. The digging action released considerable fines thus rendering the texture relatively coarse compared with the surrounding gravel. The second explanation lies in the bias introduced in wet seiving of the 1975 through 1978 gravel samples, even though they were obtained with 12-in core, which is probably an adequate sample size. In this process, the water held within the space between small particles is artificially added to the size fraction. The larger particles do not hold much excess water and thus are relatively unaffected by wet seiving. The method is therefore unduly biased toward smaller particles. An estimate was made of this bias on 1977 data in the Poverty area. The average of 40 samples gave d_g = 8.4 mm without correction. With an approximate correction, d_g = 11.9 mm, i.e., a bias of 42 percent.

Composition of the egg pocket in the vertical shows that the d_g for top to 6 inches, for 6 to 12 inches and 12 to 18 inches are respectively 39.2 mm, 20.1 mm, and 35.2 mm.

TABLE 9. ANALYSIS OF A COMPLETE CHINOOK SALMON EGG POCKET TAKEN IN POVERTY AREA DURING 1978 SPAWNING

Particle size (mm)	Percent fines
203.2	100.0
152.4	98.9
127.0	93.4
101.6	82.2
76.2	62.4
50.8	50.6
25.4	37.4
12.5	25.4
6.3	18.48
4.75	14.98
.84	2.78
.246	0.48
.074	0.08
.074	0

DISCUSSION

While there appears to be a slight difference in the procedures discussed for obtaining samples and presenting data on the description and evaluation of spawning habitat for salmonids, these are minor indeed, compared with our inability to relate these procedures to the effects created by different types of land use, an area of impact evaluation that begs for a better understanding. That goal will be achieved by establishing more unified, scientifically defensible procedures. The authors know of no place in Idaho, for example, where the effects of a land use such as logging and road construction have been accurately related to the reproductive success of a chinook salmon or steelhead trout population. For proper land use and fishery planning and management, this degree of predictability should be attained.

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