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Assessing Salmonid Spawning Gravel Quality

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Abstract.—Much of the recent literature on salmonid spawning gravels has been devoted to the search for a single statistic drawn or computed from the streambed particle size distribution to serve as an index of gravel quality. However, a natural gravel mixture cannot be fully described by any single statistic, because gravel requirements of salmonids differ with life stage, and thus the appropriate descriptor will vary with the functions of gravel at each life stage. To assess whether gravels are small enough to be moved by a given salmonid to construct a redd, the size of the framework gravels (the larger gravels that make up the structure of the deposit) is of interest, and the d_{50} or d_{84} of the study gravel (the sizes at which 50% or 84% of the sediments are finer) should be compared with the spawning gravel sizes observed for the species elsewhere. To assess whether the interstitial fine sediment content is so high as to interfere with incubation or emergence, the percentage of fine sediment of the potential spawning gravel should be adjusted for probable cleansing effects during redd construction, and then compared with rough standards drawn from laboratory and field studies of incubation and emergence success. An assessment should also consider that the fine sediment content of gravel can increase during incubation by infiltration, that the gravels may become armored over time, or that downwelling and upwelling currents may be inadequate. These considerations are incorporated in a nine-step, life-stage-specific assessment approach proposed here.

The size of available streambed gravels can limit the success of spawning by salmonids (Groot and Margolis 1991). The bed material may be too coarse for spawning fish to move, a problem particularly common where dams eliminate supplies of smaller, mobile gravels (e.g., Parfitt and Buer 1980). Excessive levels of interstitial fine sediment may clog spawning gravels, effects that have been documented downstream of land uses that increase sediment yields, such as timber harvest and road construction (Cederholm and Salo 1979; Everest et al. 1987; Meehan 1991).

Because of these problems, there is frequently a need to assess the quality of spawning gravels to determine whether gravel size limits spawning success. Any such assessment involves comparison of gravel size on site with information on gravel size suitability from laboratory studies or field observations elsewhere. Although many of the fundamental questions are essentially sedimentological and geomorphological, these disciplines have not been involved in many spawning gravel assessments; instead, such assessments are typically conducted by fish biologists.

In an effort to provide useful measures for evaluating gravels, much of the literature on spawning gravels has concerned single-variable indices of gravel quality, that is, single statistics drawn or computed from the size distribution curves that describe gravel mixtures (e.g., Lotspeich and Everest 1981; Shirazi and Seim 1981, 1982; Beschta 1982). These single-variable statistics are easier to report than full size distributions and provide convenient independent variables against which to compare incubation and emergence success in field and laboratory studies. However, there is no reason to expect that any single statistic can fully represent the attributes of the gravel size distribution relevant to the distinct functions of redd construction, embryo incubation, and fry emergence. Gravel size plays a different role in each life stage, and thus the relevant size attributes differ.

In this paper I consider the gravel requirements of each life stage and the need for comparability among studies, and review size descriptors proposed as indices of gravel quality from a geomorphological and sedimentological viewpoint. I recommend that potential spawning gravel quality assessors consider the distinct requirements for different life stages of salmonids. I also propose a step-by-step procedure for assessing spawning gravel quality and demonstrate the approach with a case study from the Colorado River and tributaries in Grand Canyon National Park.

Attributes of Gravel Size Distributions

Natural streambed gravels consist of a mixture of sizes. If silt and clay are present in the mixture,

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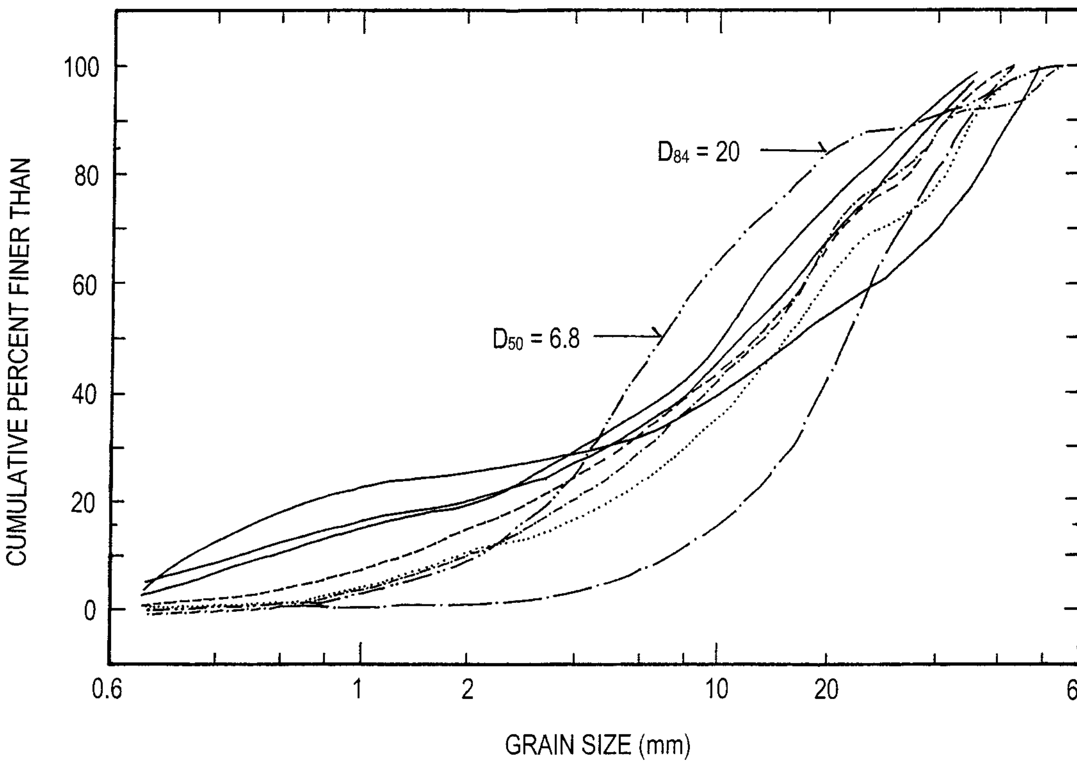

FIGURE 1.—Cumulative size distribution curves for spawning gravels available to rainbow trout *Oncorhynchus mykiss,* drawn from the case study in the main-stem Colorado River (solid lines, three samples) and Nankoweap Creek (broken lines, five samples), a tributary downstream of Glen Canyon Dam. Size descriptors (d_{50}, d_{84}, etc.) are obtained from a curve by reading the grain size corresponding to the indicated percentile. In the example shown, a potential spawning gravel from Nankoweap Creek has a d_{84} of 20 mm and a d_{50} of 6.8 mm (i.e., 84% of grains are smaller than 20 mm and 50% of grains are smaller than 6.8 mm).

particle diameter may range over five orders of magnitude. Many sediments (and sedimentary rocks) are characterized by larger particles that make up the structure of the deposit (the framework grains) with finer sediments filling the pore spaces between the framework grains (the matrix). Some sediments contain so much matrix that most framework grains are not touching and thus are not carrying the weight of the deposit; these are termed ''matrix-supported'' deposits (Williams et al. 1982). The threshold size between matrix sediment and framework gravel should be a function of the pore sizes in the framework. In a bimodal distribution, the distinction between framework and matrix may be straightforward. Otherwise, defining the upper size limit of matrix sediment may be arbitrary.

The range of sizes present in natural gravels is typically presented in cumulative size distribution curves (Figure 1). Although these cumulative size distribution curves provide complete information on the range of sizes present in a given gravel, it is unwieldy to use them to compare gravels, and it is impossible to present more than a few similar distributions on the same graph because the lines overlap and obscure characteristics of individual size distributions. Size distributions can also be presented as modified box-and-whisker plots (Tukey 1977; Kondolf and Wolman 1993), which permit summarization of multiple distributions on the same graph without overlap (Figure 2).

To facilitate comparison among size distributions, we commonly develop statistics from the curves. For example, the median particle diameter, d_{50}, is commonly used in hydrology, geomorphology, and engineering as a measure of central tendency of the distribution because it is easily read from distributions and unambiguously interpreted (Inman 1952; Vanoni 1975). Also commonly reported are the d_{16} and d_{84}, the sizes at which 16% and 84% of the sample, respectively, are finer. The range of sizes in natural gravels is

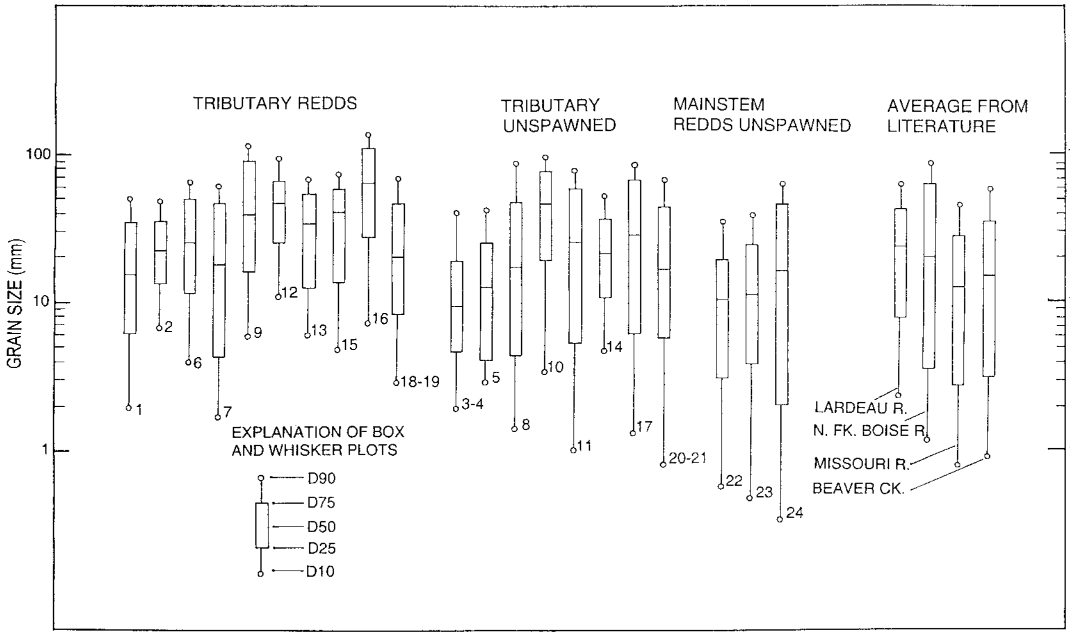

FIGURE 2.—Box-and-whisker plots for rainbow trout spawning gravels from the case study in the Colorado River and tributaries downstream of Glen Canyon Dam, and averages for other rainbow trout spawning gravels. (Summary numerical values are given in Table 2). For each sample, the rectangle (box) encompasses the middle 50% of the sample, from the d_{25} to d_{75} values, termed the ''hinges.'' The median diameter, d_{50}, is represented by a horizontal line through the box. Above and below the box are lines (whiskers) extending to the d_{90} and d_{10} values, a modification of the standard box-and-whisker plot of Tukey (1977). Numbers below the plots refer to samples in Kondolf et al. (1989). Box-and-whisker plots are easier to read than cumulative size distribution curves when several similar distributions are plotted on the same graph.

so great that data are usually log-transformed (or plotted on log-transformed graph paper). Gravel size distributions tend to resemble log-transformed normal, gamma, or Weibull distributions rather than untransformed normal distributions (Kondolf and Adhikari, in press). In lieu of an arithmetic mean, sedimentologists have used the geometric mean, $d_g = (d_{84} \cdot d_{16})^{0.5}$ (Inman 1952), which is another measure of central tendency, but one more influenced by extremes of the distribution than the median.

Other commonly reported attributes of size distributions are sorting and skewness. Sorting, or dispersion, refers to the degree to which fluvial processes have collected similarly sized particles together. In downstream reaches of larger river systems, some deposits may be entirely of gravel, others entirely of sand. These deposits would be considered ''well sorted'' with low dispersion. Sorting is commonly reported as the geometric sorting coefficient, $s_g = (d_{84}/d_{16})^{0.5}$, which increases with dispersion (and thus decreases with sorting). Skewness refers to how much the distribution is skewed off a normal or lognormal distribution. It is commonly calculated as the geometric skewness coefficient sk = $[\log_{10}(d_g/d_{50})]/[\log_{10}(s_g)]$ (Inman 1952). Gravel size distributions tend to be positively skewed, whereas log-transformed distributions (as reflected in the values of sk) tend to be negatively skewed, which is reflected in the tendency of geometric mean diameters to be less than median diameters (Kondolf and Wolman 1993).

Gravel Requirements of Salmonids

The spawning gravel requirements of salmonids differ during redd construction, incubation, and emergence (Figure 3). The spawning female must be able to move gravels to excavate a depression in the bed to create the redd. Fish need not move all rocks present (some larger particles can remain unmoved as a lag deposit), but most of the particles present must be movable or the redd cannot be excavated. Thus, most framework grains should be movable, a requirement that effectively sets an upper size limit to suitable spawning gravels.

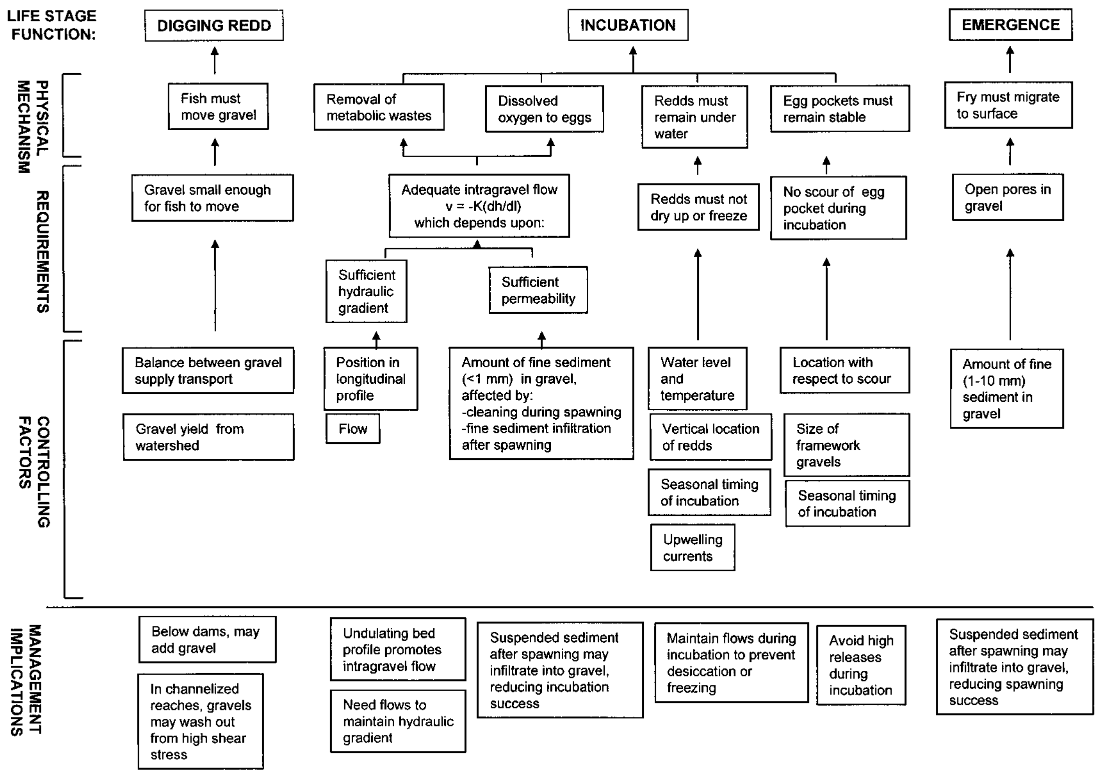

FIGURE 3.—Flow chart showing gravel requirements of salmonids during redd construction, incubation, and emergence. The intragravel flow equation is defined in Figure 5.

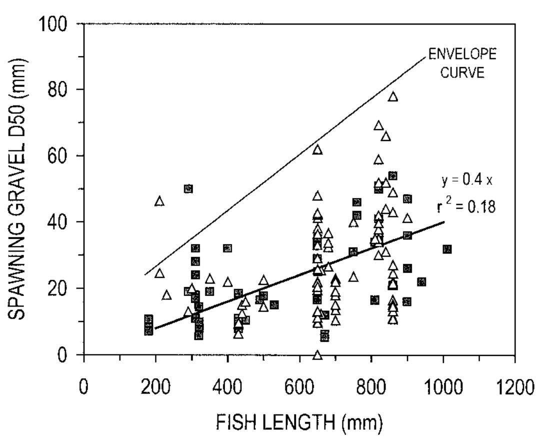

FIGURE 4.—Median diameter (d_{50}) of spawning gravel plotted against body length of a spawning salmonid. Solid squares denote samples from redds; open triangles are "unspawned gravels," which are potential spawning gravels sampled from the undisturbed bed near redds. (Modified from Kondolf and Wolman 1993.)

Larger fish are capable of moving larger rocks, so this upper size limit varies with fish size (Figure 4) (Kondolf and Wolman 1993).

Human impacts may also affect spawning habitat. Trapping of gravel in reservoirs and release of clear water downstream may cause the winnowing of smaller, mobile grains from beds below dams, leaving only progressively coarser particles. This process, termed armoring, may result in gravels becoming too coarse for use by spawning salmon, as documented on the Sacramento, Shasta, and Klamath rivers in California (Parfitt and Buer 1980; Buer et al. 1981).

For successful incubation, gravel must be sufficiently free of fine sediment that the flow of water through the gravel is adequate to bring dissolved oxygen (DO) to eggs and carry off metabolic wastes (see discussions in Chevalier et al. 1984 and Groot and Margolis 1991). Studies relating intragravel water properties to emergence success indicate that *minimum* levels of DO necessary for survival vary (with temperature, in part), but generally fall between 2 and 8 mg/L (Alderdice et al. 1958; Coble 1961; Shumway et al. 1964; Silver et al. 1965; Davis 1975; Chevalier et al. 1984). Other studies have shown that interstitial fine sediment can reduce gravel permeability and lead to less intragravel flow, which can result in lower levels of DO and suffocation of embryos (McNeil and Ahnell 1964; Cooper 1965; Koski 1966; Chevalier et al. 1984). Thus, for successful incubation, the lower limits of acceptable spawning gravel size are defined not by framework size, but by the amount of interstitial matrix present (and its effect on permeability).

Chinook salmon *Oncorhynchus tshawytscha* (and some other salmonids) have been observed to preferentially spawn where stream water downwells into the gravel bed (e.g., Vronskiy 1972); chum salmon *O. keta* (and some other species) often spawn where water upwells from the gravel bed into the water column (e.g., Tautz and Groot 1975). As emphasized by Healey (1991), the absence of downwelling or upwelling currents may be an important reason why spawning fish do not use many seemingly excellent spawning gravels (e.g., Burner 1951).

Dye studies in the field and laboratory have confirmed that irregularities in the bed profile tend to promote exchanges of water between the stream and the interstices of the gravel bed (Cooper 1965; Vaux 1968). These patterns can be explained by a fundamental equation of groundwater flow, Darcy's Law, which states that the rate of groundwater flow (or Darcy velocity, V) is the product of the permeability (or hydraulic conductivity, K) and the hydraulic gradient dh/dl (Figure 5) (Freeze and Cherry 1979). The lower elevation of the water surface in the riffle creates a hydraulic gradient that induces downwelling at the tail of the pool. The redd mound (or tailspill) produces a similar effect at a smaller scale, inducing inflow of stream water into the mound. (Darcy's law also illustrates the importance of the matrix sediment, because it affects the hydraulic conductivity, K).

After hatching, alevins live in the intragravel environment for a period, then migrate through the gravel to the surface. Successful emergence requires connected pore space through which the alevins can pass. Field and laboratory studies have demonstrated that, in some gravels, although eggs may incubate successfully and alevins hatch and live in the intragravel environment, alevins cannot migrate upward to the surface because fine sediment blocks intragravel pore spaces (e.g., Phillips et al. 1975; Hawke 1978). The sediment sizes held responsible for blocking emergence are typically between 1 and 10 mm (Bjornn 1969; Phillips et al. 1975; Harshbarger and Porter 1982), and those blamed for reducing permeability are finer than 1 mm (McNeil and Ahnell 1964; Cederholm and Salo 1979; Tagart 1984). Thus, emergence requirements set another limit to interstitial fine sediment, but of a coarser caliber than those of concern for incubation.

Laboratory and field researchers have attempted to relate fine sediment content to incubation and emergence success, producing a wide range of results (Table 1). In a comprehensive and influential review, Chapman (1988) suggested that this variability resulted from poor understanding of the structure of the egg pocket (the small area within the redd containing the eggs) and argued for intensive studies of egg pockets. Such studies would no doubt prove helpful in better understanding processes within the redd; however, study results might have only limited direct application to the common problem of evaluating the suitability of potential spawning gravels because, by definition, no egg pockets yet exist to be sampled. In a thoughtful comment, Young et al. (1990) noted that variations in female fecundity and egg viability can affect the results of relations between egg survival and gravel size.

Comparability of Assessment Methods and Attributes

Studies relating gravel size to successful spawning or survival to emergence are useful only to the extent that the data can later be applied to gravels elsewhere. Similarly, to assess gravel quality at a new site, we must be able to apply relations between gravel size and spawning derived elsewhere. This transfer of information cannot be effected without comparability in methods of sampling and reporting of data. When full size distributions are reported, subsequent workers can compute a statistic of choice for comparison with results elsewhere. When only one (or a few) summary statistics are reported, comparisons are impossible unless the same statistics have been reported in all studies.

Comparability also requires recognition of the distinction between redd gravels and potential spawning gravels being sampled to determine their suitability. As females construct redds, they winnow fine sediment from the gravel. The gravel within the redd typically has less fine sediment than it did before redd construction (Figures 6, 7). The reduction in fine sediment during spawning depends largely on the amount of fine sediment initially present, and the reduction can in some

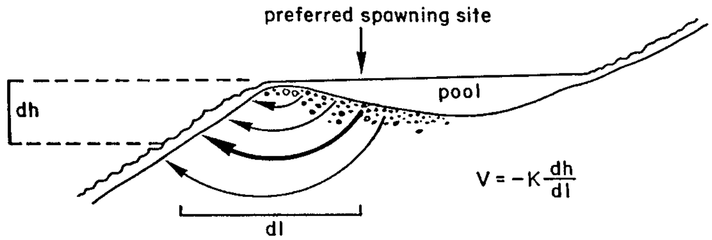

FIGURE 5.—Diagram of groundwater flow through the tail of a pool. The lower elevation of the water surface in the riffle creates a hydraulic gradient that induces downwelling at the tail of the pool; *V* is Darcy velocity and *K* is hydraulic conductivity. Vertical scale is greatly exaggerated. (From Keller and Kondolf 1990.)

cases transform unsuitable gravels into suitable gravels (Kondolf et al. 1993). Montgomery et al. (1996) have suggested that mass spawning may change sediment characteristics and bed form such that the bed is less subject to scour.

Laboratory and field emergence studies attempt to represent conditions in redds, so before relations from these studies are applied to potential spawning gravels, the fine sediment content of the potential spawning gravels should be adjusted for the probable cleaning effect of spawning. Moreover, as noted by Chapman (1988), the redd structure of coarse lag gravels encountered in many redds may not be reflected in the homogenized sediment mixtures typically used in laboratory studies.

Sampling Spawning Gravels

Various techniques have been used to sample spawning gravels, and they range widely in the effort and cost required to use them. Most sampling methods involve obtaining a gravel sample, which is then passed through a series of sieves to determine the proportions of the sample in various size classes. The more expensive and seemingly sophisticated techniques are not necessarily better. The selection of sampling technique should be driven by the purpose of the study, adequacy of sample size, and comparability of results.

Sampling methods for gravels (and specifically for spawning gravels) have been described in detail by various authors, including Kellerhals and Bray (1971), Lisle and Eads (1991), and Young et al. (1991). Here, I briefly review some popular sampling methods after considering issues of surface versus subsurface layers, exclusion of large rocks, and sample size.

Surface versus Subsurface Layers

The surface layer of gravel on river beds (here defined as the depth of one grain diameter, d_{84}) is typically coarser than the underlying, subsurface layers, whose size distribution is commonly similar to that of the transported bed load (Parker and Klingeman 1982). The framework grains of the surface are generally not larger than those of the underlying sediment, but the surface layer is typically deficient in the finer fractions of the distribution. In part, this can be explained by selective transport of finer grains exposed on the surface at flows too low to mobilize the entire bed. However, some coarse surface layers are active features in that they persist (or reform) despite frequent mobilization of the bed. By contrast, some coarse surface layers are inactive, being mobilized only by infrequent flows, developing downstream of dams or in other situations of decreased sediment supply. Parker and Klingeman (1982) termed the active surface layers pavements and the inactive ones armor layers, whereras Gomez (1984) argued that the terms should be used in the opposite sense.

The potential paucity of interstitial fine sediment in the surface layer implies that framework size can be estimated by sampling the surface layer, but matrix assessment requires subsurface sampling.

Exclusion of Large Rocks

Many workers have excluded large rocks from their gravel samples, because individual large rocks can constitute a large percentage of the total sample weight and thus might ''bias'' the distribution. There may be arguments for excluding rocks above some threshold size when only fine sediment content is compared (Church et al. 1987), but the complete size distribution (including large rocks) should be reported to permit assessment of framework size as well. Exclusion of large rocks reduces the coarser fraction of the sample and thus increases the remaining finer fractions as a percentage of the total sample. At the very least, the decision to exclude large rocks from the sample should be reported; this has not always been done,

TABLE 1.—Fine sediment percentages corresponding to 50% emergence of salmonids in various studies.

Reference or statistic	Species[a]	Maximum percentage of grains finer than: 0.83 mm	2.0 mm	3.35 mm	6.35 mm	9.5 mm
Hausle and Coble (1976)	Brook trout		10			
Weaver and White (1985)	Bull trout					16, 40
Bjornn (1969)	Chinook salmon				15, 26	
Tappel and Bjornn (1983)	Chinook salmon				40	
McCuddin (1977)	Chinook salmon				30, 35	
Koski (1975, 1981)	Chum salmon			27		
Cederholm and Salo (1979)	Coho salmon	7.5, 17				
Koski (1966)	Coho salmon	21		30		
Phillips et al. (1975)	Coho salmon			36		
Tagart (1984)	Coho salmon	11				
Irving and Bjornn (1984)	Cutthroat trout				20	
Irving and Bjornn (1984)	Kokanee				33	
Irving and Bjornn (1984)	Rainbow trout				30	
NCASI (1984)	Rainbow trout	12			40	
Bjornn (1969)	Steelhead				25	
Tappel and Bjornn (1983)	Steelhead				39	
McCuddin (1977)	Steelhead				27	
Phillips et al. (1975)	Steelhead			25		
Mean		13.7	10.0	29.5	30.3	28.0
SD		4.7	0.0	4.2	7.4	12.0

[a] Scientific names: brook trout *Salvelinus fontinalis*; bull trout *S. confluentus*; chinook salmon *Oncorhynchus tshawytscha*; chum salmon *O. keta*; coho salmon *O. kisutch*; cutthroat trout *O. clarki*; kokanee *O. nerka*; rainbow trout (nonadromous) and steelhead (anadromous) *O. mykiss.*

casting doubt on the comparability of some studies.

Sample Size

Adequate sample size increases with particle size. Church et al. (1987) noted that ''the largest class of grains present in the sample should define the sample size since they will be the fewest in number, hence least well represented.'' They reviewed sample size requirements, noted that for typical river gravels, more than 200 kg are required to obtain truly representative samples, and proposed a simple rule that the largest particle should not constitute more than 1% of the total sample weight. The pebble count method (described below) was proposed by Wolman (1954) as an alternative to large bulk samples for estimating surface grain size distributions; however, Wolman's principal interest was in estimating grain rough-

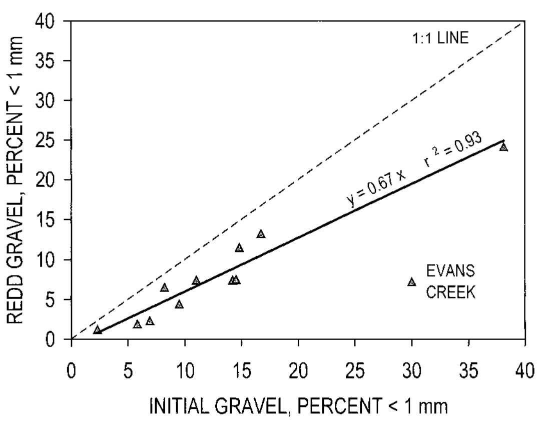

FIGURE 6.—Percentage of sediment finer than 1 mm in redds and potential (comparable, unspawned) gravels. The data point for Evans Creek is excluded from the regression. (See Kondolf et al. 1993 for sources of data.)

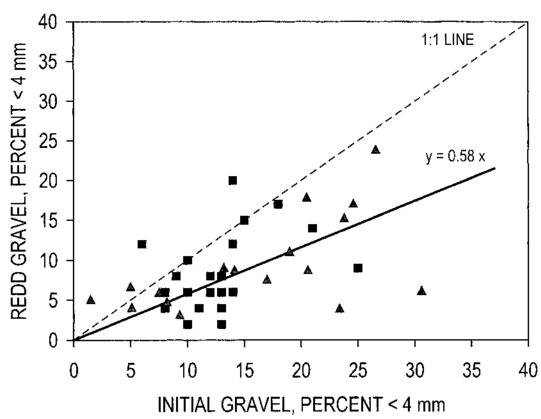

FIGURE 7.—Percentage of sediment finer than 4 mm from pairs of redd and potential spawning gravel sampled by Chambers et al. (1954) (squares) and by Kondolf et al. (1993) (triangles).

ness, not in determining interstitial fine sediment content.

Many trout redds, especially those constructed in pocket gravels in steep channels, do not contain enough gravel to satisfy sample size requirements, which poses a fundamental problem in attempting to apply minimum size requirements to sampling spawning gravels. In such cases, obtaining as large a size as possible from the site is probably the best approach.

Sampling Methods

Pebble counts and visual estimates provide a measure of the surficial grain size only, and cannot measure fine sediment content of the subsurface gravel. Visual estimates (''ocular assessments'') are widely employed by fish biologists and are typically used as input to the PHABSIM fish habitat model (Bovee 1982). However, there is no evidence that these subjective estimates of percentages of various size classes in the bed are reproducible among different investigators. Moreover, the results are usually reported in the form of ''dominant'' and ''subdominant'' size-classes or as percentages of classes such as ''80% cobble, 10% sand, and 10% silt.'' Even if these estimates are accurate, they are not reported in a form that can be readily compared with sediment sizes reported in the engineering and geomorphic literature, in which statistics are drawn from standard size distributions.

The pebble count method (Wolman 1954; Kondolf 1997) involves measurement of the diameter of 100 stones randomly selected from specific geomorphic features on the bed surface. Pebble counts provide reproducible surface grain size distributions and can be readily adapted for use in fish habitat studies as an alternative to visual estimates (Kondolf and Li 1992). A recent modification, the zigzag count (Bevenger and King 1995), should be avoided because it mixes sample points from many different channel features (i.e., this method would typically mix data from spawning riffles, intervening pools, and banks), does not yield adequate sample sizes for individual populations of gravel, and does not yield reproducible size distributions. Thus, the zigzag count (and similar modifications) are not true pebble counts and are not good methods for assessing spawning gravel quality (Kondolf 1997).

Bulk core sampling involves driving a cylindrical core sampler into the bed and removing (by hand) the material within it down to a predetermined depth. Drums 50 cm in diameter, with the top and bottom removed (and usually shortened to permit the operator's arms to reach the bottom of the sampler), have been used (e.g., Chambers et al. 1954, 1955; Orcutt et al. 1968). Other variants of cylindrical core samplers have included a 60-cm length of 46-cm-diameter well casing with a serrated lower edge and handles attached to the top (Horton and Rogers 1969), a 53-cm length of 35-cm-diameter pipe with a serrated lower edge (W. F. Van Woert and E. J. Smith, California Department of Fish and Game, unpublished), a 25-cm-diameter Hess-type core sampler (Shirazi et al. 1981), a 25-cm-diameter ''bottomless bucket'' (Kondolf et al. 1989), and a 75-cm length of 15-cm-diameter galvanized stove pipe (Peterson 1978).

The most popular bulk core sampler among fish biologists has been the FRI or McNeil sampler, constructed from a 50-cm drum with a 15- to 30-cm-diameter pipe welded on the bottom. The smaller pipe is worked into the bed, the gravel is removed by hand, and the muddy water within the sampler is retained to sample suspended fine sediments (McNeil and Ahnell 1964). Geomorphologists have used bottomless 50-cm oil drums in various forms to obtain sufficiently large samples, such as the 140–240-kg samples collected by Wilcock et al. (1996). The ''cookie-cutter'' sampler is a 50-cm drum sampler with an underwater sample box that has a screen to collect fine material washed downstream (Klingeman and Emmett 1982), and the ''barrel'' sampler is a 46-cm drum sampler fitted with a 152-cm-long hood of filter mesh to collect fine sediment (Milhous et al. 1995). When gravel is removed from drum samplers, it is possible to remove the surface layer first and analyze it separately. Curtin (1978) fitted a hood on a shovel to retain fine sediment. In the event the gravel is exposed on a bar (usually not the case for spawning gravels), it can be easily sampled by shovel or backhoe.

Freeze core sampling involves driving steel probes into the bed, discharging a cooling agent (such as liquid CO_2 or nitrogen) into the probes to freeze the interstitial water adjacent to the probe, and withdrawing the probes (with gravel samples frozen to them) from the bed with a tripod-mounted winch (Everest et al. 1980). The method was developed to obtain gravel samples that preserved vertical stratification of the sediments, although laboratory experiments have shown that driving the probes into the bed can disrupt the existing stratification (Beschta and Jackson 1979). Freeze core samples tend to have a ''ragged edge'' with larger particles protruding from the frozen mass, implying that all fractions of the distribution are not sampled proportionately. Most importantly, however, freeze core samples are typically less than 10 kg, too small to accurately represent gravels that include particles 64 mm and greater (Church et al. 1987).

Bulk core sampling is simple (although labor-intensive), can yield large samples, and does not suffer from the ''ragged edge'' of freeze core sampling. In a comparison of shovel, bulk core (McNeil), and freeze-core sampling, Young et al. (1991) found that the bulk core samples most frequently approximately the true substrate composition.

Standpipes can be used to directly measure permeability, intragravel flow velocity, and DO in situ. The most widely used type is the standpipe of Terhune (1958) or later variants, such as the substitution of stainless steel for aluminum by Barnard and McBain (1994). The pipe, perforated to allow seepage of water from the adjacent gravel into the pipe, is inserted into the gravel bed to the depth at which the permeability measurement is desired. Water is pumped from the standpipe, maintaining a constant hydraulic gradient into the pipe, and the rate at which water flows into the pipe is measured and used as a basis to compute permeability. The dissolved oxygen content of the inflowing water can also be measured.

Size Descriptors Proposed as Indices of Gravel Quality

Once obtained, gravel samples are usually sieved and weighed to yield a size distribution. Because these size distributions are unwieldy, statistics drawn (or computed) from the distributions have been used as indices of gravel quality and as the independent variables against which the dependent variables of incubation or emergence success are plotted in laboratory studies. Because these indices are so widely employed with so little discussion of their relation to the complete size distribution, a review of the evolution of these indices and their attributes may be useful.

Percent Fines

In general, the literature suggests that interstitial sediments finer than about 1 mm reduce the permeability of the gravel and can prevent intragravel flow from providing sufficient oxygen to embryos and removing metabolic wastes. Sediments in the 1–10-mm size range have been implicated in blocking fry emergence through intragravel pores (Everest et al. 1987).

The use of ''percent fines'' in the fish biology literature originated with a study relating incubation success to gravel size by McNeil and Ahnell (1964), who found incubation success was inversely related to the percentage finer than 0.83 mm. The value of 0.83 mm was an arbitrary cutoff, simply an artifact of the set of Tyler sieves used in the study. It is not a physically significant threshold, nor does it correspond to a break in size-classes on the standard Wentworth scale (Vanoni 1975). However, many subsequent authors apparently accepted 0.83 (or 0.85) mm as a physically significant size threshold. It is preferable to use sieves sized in whole mm, and to round 0.83 or 0.85 mm to 1 mm.

Tappel and Bjornn (1983) proposed that the quality of spawning gravel be assessed based on the percentages finer than 0.83 mm and finer than 9.5 mm out of the portion of the size distribution finer than 25.4 mm. This approach is an improvement over simple percent-fines measures in that it offers a more complete description of the percentage of fine sediment, albeit one in which the influence of framework particles greater than 25 mm is explicitly ignored.

The percentage of fine sediment below a given size is influenced not only by the amount of fine sediment, but by the other sizes present as well, because it is simply a percentage of the total. Thus, exclusion of large grains artificially increases the percentage of remaining, finer fractions, and we could expect a given amount of fine sediment to have different effects on permeability of gravels depending on framework size.

Geometric Mean Diameter and Fredle Index

In response to shortcomings in the ''percent fines'' measure, Shirazi and Seim (1981) proposed the geometric mean diameter, d_g, as an index of gravel quality and a ''unifying substrate statistic,'' because it reflected the complete size distribution and because emergence success in laboratory experiments was found to be related to d_g. However, the experimental gravels differed principally in the fine sediment content added, so lower values of d_g reflected greater fine sediment contents. Lotspeich and Everest (1981) proposed the fredle index (f_i), which combined a measure of central tendency (d_g) with a measure of dispersion. The fredle index is calculated as $F_i = d_g/S_T$, where S_T is the Trask sorting coefficient, given by $S_T = [(d_{75})/(d_{25})]^{0.5}$ (Inman 1952), where d_{75} and d_{25} are the sizes at which 75 and 25% of the distribution, respectively, are finer.

The geometric mean can be similar for very different gravel mixtures because a large d_{84} can offset a small d_{16} if it contains some very coarse framework gravels (and thus a large d_{84}). A gravel mixture with a large content of fine sediment (and thus a small d_{16}) could have a d_g similar to a gravel mixture with little fine sediment. Large chinook salmon have spawned in gravels with median diameters of over 50 mm, but they also spawn in smaller gravels (Kondolf and Wolman 1993). Thus, suitable spawning gravels (i.e., movable by fish and free of fine sediment) could have very different values of d_g solely because of different framework sizes, implying nothing about fine sediment content.

As with the geometric mean, similar values of fredle index could derive from a wide range of different size distributions, so it is similarly unsuitable as a unifying substrate statistic. The fredle index has other disadvantages as follows.

(1) There is no physical reason to expect a measure of central tendency divided by a measure of dispersion (sorting) to yield a meaningful index of gravel quality. The fredle index is effectively an inverse coefficient of variation with dimensions of length.
(2) The measure of central tendency, d_g, is calculated from d_{84} and d_{16} and is thus influenced by the extremes of the distribution. A more robust and preferable measure of central tendency would be the median size, d_{50}.
(3) The measure of dispersion, S_T is calculated from d_{75} and d_{25} and thus reflects the spread of only the middle 50% of the distribution, and is thus insensitive to ecologically significant differences in fine sediment contents less than 25%.
(4) The fredle index has no physical reality, unlike the median diameter or percentage finer than 1 mm. Because it is more complicated and harder to comprehend, it may appear more sophisticated than (and thus preferable to) simpler, more straightforward, descriptors of gravel size.

Gravel quality is by nature complex, due to various meanings of quality (Figure 3) and the natural complexity of sediments, so it is unreasonable to expect any single-variable descriptor to be a good index.

Gravel Quality Criteria Drawn from Emergence Studies

Compilation of Laboratory and Field Study Results

Results of laboratory and field experiments of incubation and emergence success have generally been presented as plots relating percent fine sediment content to percent successful incubation or emergence. Table 1 presents fine sediment percentages corresponding to 50% emergence drawn from such plots from 2 field studies (Koski 1966; Tagart 1984) and 11 laboratory trough studies. The choice of 50% emergence is arbitrary, but can be justified because redds with at least 50% emergence success would probably be considered as productive by most biologists. Moreover, the range of emergence reported in these studies always encompassed 50%, but not necessarily lower or higher emergence values (i.e., some studies had no emergence values less than 20%, and some had none more than 80%). However, it is worth noting that in some streams with successful natural reproduction, emergence measured in natural redds is considerably less than 50% (see NCASI 1984 for a review).

One of the most striking features of Table 1 is the variation among studies in the definition of ''fine sediment,'' which ranges from 0.83 mm to 9.5 mm. In some cases, ''fine sediment'' was defined based on the sieve size that best correlated to emergence; in other cases it was defined at the outset of the study, and experimental gravel mixtures were prepared with varying percentages of sediment smaller than this size. Gravel mixtures varied among studies, and some size distribution curves were atypical for natural spawning gravels (Figure 8).

Gravel Quality Criteria

Gravel quality criteria were inconsistent among these studies (and even among replicates of the same studies), so to define precise thresholds for fine sediment content is probably not justified. However, it is possible to generalize from these studies. The percentage finer than 1 mm (or 0.83 mm) was about 14% for 50% emergence, close to the standard of 12% indicated by McNeil and Ahnell (1964) and from extensive field observations by J. Cederholm (Washington Department of Natural Resources, personal communication 1986).

Results for the effect of coarser fine sediment on emergence are less consistent. Values associated with 50% emergence averaged about 30% for

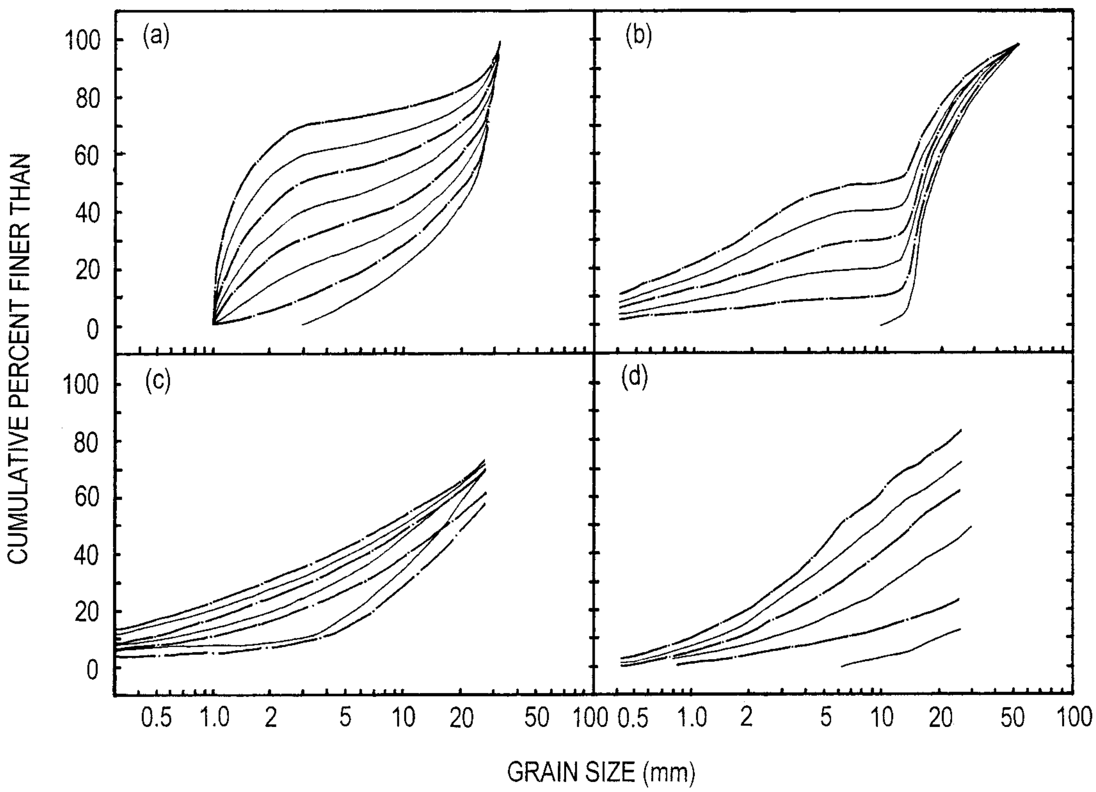

FIGURE 8.—Cumulative size distribution plots of some gravels used in emergence studies: **(a)** Phillips et al. (1975); **(b)** Tappel and Bjornn (1983) and Irving and Bjornn (1984), mixtures 0:0–50:20; **(c)** Cederholm and Salo (1979), 1975 experiments, troughs 6–12; **(d)** Weaver and White (1985). (From Kondolf 1988.)

sediment finer than both 3.35 mm and 6.35 mm. (We might expect that more of the coarser fine sediment could be present before negatively affecting gravel quality, but in the artificial gravel mixtures used in most of these studies, 3-mm and 6-mm sediment may have similar effects in blocking pore space.)

Influence of Fish Size

While the framework size movable by a fish will depend on the size of the fish, the effect of fine sediment on gravel permeability should be a function of the physics of groundwater flow, which would be independent of fish size. However, larger eggs (of larger fish) may require more irrigation, potentially making them more sensitive to reduced permeability. For emergence, larger alevins may have more difficulty than smaller alevins in passing through intragravel pore spaces decreased by interstitial fine sediments, but they may also be stronger (Phillips et al. 1975; Tappel and Bjornn 1983).

Changes in Gravel Size over Time

Gravel size can change seasonally and from year to year, affecting the applicability of observed gravel sizes to actual conditions during incubation or emergence. The amount of interstitial fine sediment can increase during the incubation period by infiltration into the redd (Carling and McCahon 1987; Sear 1993) or by scour and fill (Lisle 1989). Thus, the timing of sediment transport in the channel in relation to incubation of salmonid embryos is very important in determining spawning success. Timing may be especially important with fine sediment inputs from human activities, because these may occur during low flows in the channel. Most naturally produced fine sediment enters the channel during high flows, when there is adequate stream power to transport and disperse it. However, anthropogenic sources (such as irrigation return flow) may occur during base flow, when the fine sediment is more likely to settle out and infiltrate.

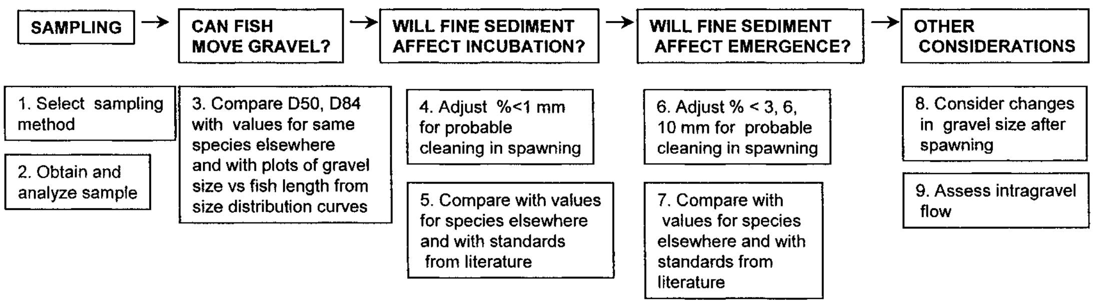

FIGURE 9.—Flow chart illustrating nine discrete steps in evaluating salmonid spawning gravel quality.

The framework sizes of gravel may also undergo changes, more likely on a longer timescale of years to decades, as a result of changes in coarse sediment supply or local shear stress. For example, at spawning areas downstream of dams, the bed may coarsen due to decreased supply of sand and gravel from upstream, such that size distributions may no longer be valid several years after their measurement. Similarly, channel straightening, levee construction, or upstream urbanization could increase local shear stress and thus lead to a coarser bed material.

A Procedure to Assess Spawning Gravel Quality

Gravel requirements should be considered separately for redd construction, incubation, and emergence, and gravel size distribution curves should be examined for information relevant to the specific requirements of these life stages. As indicated in Figure 9 and discussed below, this life-stage-specific approach can be broken down into nine discrete steps.

Sample the Gravel and Develop a Size Distribution (Steps 1–2)

The sampling method depends upon the purpose of the assessment. If the concerns are limited to whether the fish can move the gravels, pebble counts may be adequate, although such values (obtained from the surface layer) may be larger than those from bulk samples, because the latter would be influenced by interstitial fine sediment in the subsurface. More commonly, however, the fine sediment content is also of concern, in which case subsurface samples must be obtained. Because of the drawbacks of freeze core sampling discussed earlier, bulk core samples (of adequate size) are preferable. Pebble counts directly yield size distributions, but bulk subsurface samples must be passed through sieves and weighed to obtain size distributions (Vanoni 1975). In either case, the size distribution should be plotted as a cumulative frequency curve; to compare multiple distributions, box-and-whisker plots can be plotted from percentile values drawn from the cumulative distributions.

Determine Whether Gravel Is Movable by Spawning Fish (Step 3)

Whether the framework gravels are too large for the fish to move can be determined by comparing the d_{50} or d_{84} with those reported for the species elsewhere and with the maximum movable size predicted by Figure 4, which suggests that spawning fish can move gravels with a median diameter up to about 10% of their body length. In some channels, gravels may be compacted or cemented, rendering otherwise suitable sizes unsuitable. No widely accepted or easily applied method has been developed to quantify this phenomenon, so it should be evaluated qualitatively.

Determine Whether Fine Sediment Content Is Excessive for Incubation (Steps 4–5).

The question is whether the amount of sediment finer than 1 mm is so great that gravel permeability, and thus intragravel flow, is negatively affected. The percentage finer than 1 mm should be drawn from the grain size distribution curves and adjusted downward (using Figure 6) to reflect the probable cleaning effect of redd construction before fine sediment content is evaluated.

The resulting values can be compared with values reported from redds elsewhere and with standards drawn from laboratory and field studies of incubation and emergence in Table 1 (showing values for 50% survival). They also can be evaluated against conclusions drawn from field observations by McNeil and Ahnell (1964) and Cederholm and Salo (1979) that less than 12–14% of gravels

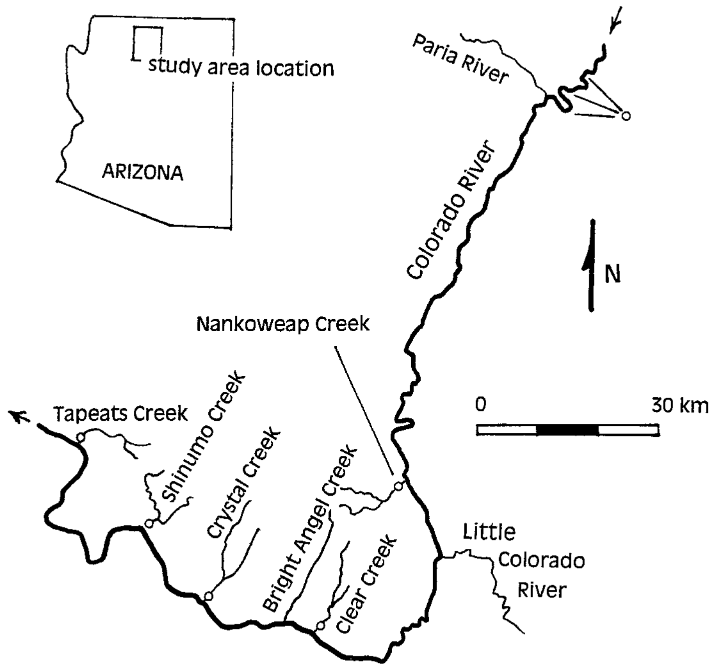

FIGURE 10.—Location map of Colorado River and tributaries, Grand Canyon National Park, Arizona. Spawning gravel sample locations (on Nankoweap, Clear, Crystal, Shinumo, and Tapeats creeks, and on the main stem) are shown in open circles. Other important tributaries also shown for reference. (Adapted from Kondolf et al. 1989.)

should be finer than 1 mm (or 0.83 mm) for successful incubation.

Determine Whether Fine Sediment Content Is Excessive for Emergence (Steps 6–7)

To assess whether the fine sediment will block the upward migration of fry, the percentage finer than 3, 6, or 10 mm can be compared with values reported from redds elsewhere and with standards drawn from laboratory and field studies of incubation and emergence. However, although the fine sediment (<1 mm) threshold for incubation effects can be estimated at 12–14%, the upper limits of the (larger) fine sediments affecting emergence (percentages less than 3–10 mm) are more difficult to select, showing considerable variability (Table 1).

As with the percentage of sediment less than 1 mm, the percentages less than 3, 6, or 10 mm should be adjusted downward to reflect the probable cleaning effect of redd construction, but the effects of redd building on these sizes are more variable than they are upon the percentage finer than 1 mm (Figure 7) (Kondolf et al. 1993).

Consider Changes in Gravel Size after Spawning (Step 8)

Potential changes in sediment yield and local sediment transport capacity should be evaluated at the watershed scale to identify potential sources of fine sediment during the incubation period and to evaluate the potential for bed scour or coarsening. Field studies to monitor changes in fine sediment percentages over the course of the incubation season (Adams and Beschta 1980; Lisle and Eads 1991) may be appropriate. Because the future applicability of gravel size data collected may be compromised by long-term changes in bed material size, monitoring of bed material sizes in future years may also be appropriate.

Evaluate Intragravel Flow Conditions (Step 9)

Intragravel flow depends both on the gravel permeability and the hydraulic gradient. The former is affected by fine sediment content and thus is partly addressed in steps 4–5. The hydraulic gradient is more complex to evaluate because it depends on flow level, channel bed geometry, and possibly on large-scale groundwater circulation patterns. Standpipe measurements, dye studies, or

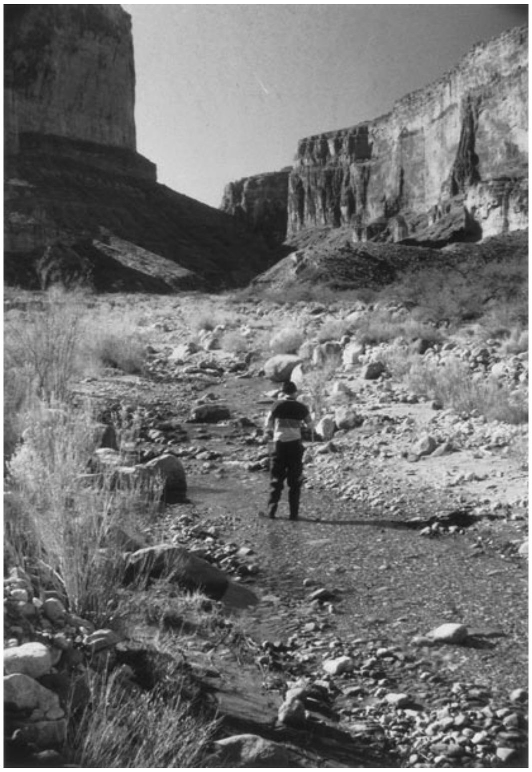

FIGURE 11.—Lower reaches of Nankoweap Creek, looking upstream from right bank, about 50 m upstream from the confluence with the Colorado River. (Photograph by author, December 1985.)

examination of the channel bed geometry could all be used to shed light on intragravel flow conditions.

A Case Study: Assessing Spawning Gravels for Rainbow Trout in the Colorado River and Tributaries below Glen Canyon Dam

Case Study Site Description

Since closure of Glen Canyon Dam on the Colorado River in 1963, a popular sport fishery for rainbow trout has developed in the Colorado River downstream in Grand Canyon National Park. The fishery is especially productive in the tailwater reach between the dam and the Paria River confluence (Figure 10), where consistently cold-water releases have produced a nearly complete change in species composition from native warmwater fishes to introduced rainbow trout. The trout spawn both in the main stem and in tributaries. Spawning habitat is limited to some large main-stem gravel bars and to gravel deposits in tributary reaches downstream of migration barriers (Figure 11), many of which are ''pocket gravels'' within boulder-dominated channels (Figure 12). The quality of these spawning gravels had not been assessed prior to the study described here.

Case Study Methods

As part of a larger research effort to examine the fish resources (native and exotic) of the Col-

FIGURE 12.—Pocket gravel on lower Nankoweap Creek, view from right bank. (Photograph by author, December 1985.)

TABLE 2.—Grain size statistics for rainbow trout spawning gravels reported in the literature and in the Colorado River and tributaries (from Kondolf et al. 1989).

Location[a]	Reference	Fish size (cm)	N	Partical size (mm): Median (d_{50})	Partical size (mm): Geometric mean (d_g)	Geometric sorting coeffi-cient (s_g)	Geometric skew-ness coeffi-cient (sk)	Percentage of grains finer than: 0.85 mm	Percentage of grains finer than: 3.4 mm[b]
Lardeau River, British Columbia	Hartman and Galbraith (1970)	75	6	23.5	14.7	3.6	−0.37	6.3	15.2
North Fork Boise River, Idaho	Platts et al. (1979)	30	45	20	12.4	6.5	−0.25	7	24
Missouri River, Montana	Spoon (1985)	44	27	12.5	8.3	4.6	−0.27	11.1	ND
Beaver Creek, Montana	Spoon (1985)	44	19	15	9.3	4.9	−0.3	9.8	ND
Colorado River, Arizona	Kondolf et al. (1989)								
Tributary, redds		40	9	33.4	24.5	3.04	−0.27	1.5	7.7
Tributary, unspawned		40	8	21.9	14.9	4.21	−0.25	6.5	17.8
Main stem, redds		45	2	10.5	5.6	5.4	−0.4	6.8	15.2
Main stem, unspawned		45	1	16	5.2	10.5	−0.47	15	25

[a] See Figure 2 for box-and-whisker plots by site.
[b] ND means "no data."

orado River system in the Grand Canyon and the effects of fluctuating flows upon them (Maddux et al. 1987), Kondolf et al. (1989) sampled trout redds and potential spawning gravels in the Colorado River and tributaries below Glen Canyon Dam in 1985 (Figure 10). Main-stem gravels were sampled by shovel from three gravel bars exposed by low river levels, removed to the laboratory, dried, and sieved. Tributary samples were obtained within a few hundred meters of the Colorado River confluence with a 25-cm polyvinyl chloride bucket with the bottom removed. The latter sampling method was dictated by logistics of the remote tributary sites, the small size of the trout redds, and the often limited extent of gravel deposits in which they occurred. Samples were obtained from both redd and potential spawning gravels, dried by sun or campfire, and sieved and weighed on site, except for subsamples of the fine fraction retained for laboratory sieving.

Case Study Results

Cumulative size distributions for all samples are reported in Appendix Table A.1, curves for main-stem and Nankoweap Creek gravels are shown in Figure 1, and box-and-whisker plots of all samples in Figure 2. These distributions illustrate the wider range of gravel sizes in the tributaries, reflecting greater variability in hydraulic conditions. These distributions also illustrate the larger percentage of fine sediments in the main-stem gravels, as reflected in the fine tails of the main-stem distributions.

Because most samples were taken at or adjacent to redds, the ability of the fish to move the gravels was generally not at issue. The d_{50}s were similar to those reported in the literature for rainbow trout elsewhere (Figure 2; Table 2) and fall within the range of d_{50}s expected for these spawning females, which average 40–45 cm long (Figure 4).

In assessing the fine sediment content, the potential spawning gravels had less than 7% finer than 1 mm, and the redds even less, values well below the standard from laboratory studies and other values reported for rainbow trout even before adjustments were made for the probable cleaning effect of redd digging (Table 2). In the main stem, redd gravels had less than 7% finer than 1 mm, but one sample of potential spawning gravel had 15% finer than 1 mm. This would exceed the standard of 12%, but with the expected effects of spawning taken into account (Figure 6), the percentage of fine sediment in the redd gravels would be less than 10%. Thus, the quality of these gravels was quite good.

Case Study Discussion

Although potential spawning gravels had good quality, their extent was limited. Tributary spawning gravels were limited because of the small size of the channels and the often patchy distribution of gravels. Some of these gravels may be inaccessible at low river stage because of migration barriers. Main-stem gravels were limited at the time of sampling (1985), and the extent of suitable gravel bars probably continues to decrease and the grain size to coarsen as smaller, mobile gravels are transported from the reach by high flows without replacement from upstream. In repeated visual observations over 2 years, Maddux et al. (1987) noted large variations in the fine sediment content of tributary gravels, presumably reflecting changes wrought by flash floods. Thus, repeated gravel sampling might be warranted here. We did not evaluate intragravel flow conditions.

Conclusion

The literature on spawning gravels contains much debate over the best single-variable descriptor for gravel quality (e.g., Lotspeich and Everest 1981; Shirazi and Seim 1981, 1982; Beschta 1982; Chapman 1988, 1990; Young et al. 1990), but there can be no single statistic that measures all aspects of gravel quality. The gravel requirements of salmonids differ with life stage as the role of gravel changes. Rather than seek a single index that can capture all characteristics relevant to salmon spawning success, assessment of gravel quality is more profitably approached by recognizing that the appropriate measures depend on the questions being asked.

To determine if the fish can dig redds in the gravel, the framework size is important and can be compared with framework sizes of gravels utilized by the same sized fish elsewhere. To determine if the gravel contains too much fine sediment, the percentage of fine sediment can be compared with values for the species elsewhere and with threshold from laboratory studies, although the percentage of fine sediment measured in potential spawning gravels should be adjusted downward to account for the cleaning effect of the spawning fish.

When gravel sizes are reported, the full size distribution should be included (or made readily available) so that later workers can independently calculate size descriptors of choice for purposes of comparison.

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Appendix: Gravel Size Distributions

TABLE A.1.—Cumulative size distributions for rainbow trout spawning gravel samples, Colorado River and tributaries. Size categories differ between tributaries and main stem.

Sample number	Stream or river[a]	Redd or potential[b]	Cumulative percentage of grains finer than (mm):[c]							
			0.063	0.25	0.85	2	4	9.5	12.5	19
1	Nankoweap	Redd	0.3	0.6	3.2	25.8	17.2	34.2	42.5	58.4
2	Nankoweap	Redd	0.0	0.1	0.3	4.6	4.0	15.1	22.0	40.1
3	Nankoweap	Potential	0.1	0.2	1.6	31.1	25.7	62.9	71.5	83.9
4	Nankoweap	Potential	0.5	1.0	3.4	29.2	21.1	41.6	48.8	65.5
5	Nankoweap	Potential	0.3	1.0	6.6	38.3	24.6	42.4	50.1	64.8
6	Nankoweap fan	Redd	0.1	0.5	2.3	12.8	9.3	21.7	26.5	38.3
7	Clear	Redd	0.7	1.6	4.7	32.5	23.9	39.1	43.4	51.0
8	Clear	Potential	2.0	3.8	6.9	35.7	24.1	38.3	43.0	51.6
9	Clear	Redd	0.1	0.1	1.2	9.3	6.8	16.3	19.9	29.3
10	Clear	Potential	1.3	2.2	4.9	17.8	10.7	14.8	18.3	25.2
11	Bright Angel	Potential	1.1	2.5	8.4	36.3	22.1	32.5	36.7	44.6
12	Crystal	Redd	ND	ND	ND	ND	3.7	9.1	11.4	17.0
13	Crystal	Redd	0.3	0.5	0.8	4.3	4.2	18.3	25.1	36.3
14	Crystal	Potential	0.5	1.9	3.7	11.9	8.2	22.4	29.3	45.5
15	Shinumo	Redd	0.1	0.2	1.0	11.0	8.4	18.3	22.8	31.2
16	Shinumo	Redd	0.0	0.1	0.5	7.4	5.7	12.1	14.8	20.2
17	Shinumo	Potential	0.9	2.4	6.8	32.7	20.6	31.2	35.6	43.2
18	Tapeats	Redd	0.0	0.4	2.3	14.0	10.8	28.9	35.5	47.6
19	Tapeats	Redd	0.1	0.5	2.3	14.5	11.4	30.6	37.9	49.9
20	Tapeats	Potential	0.6	3.9	10.6	32.2	19.3	39.8	45.4	57.0
21	Tapeats	Potential	0.4	3.7	10.1	30.5	18.6	34.6	39.8	53.0

Sample	Stream or river[a]	Redd or potential[b]	Cumulative percentage at grains finer than (mm):[c]						
			25.4	32	45	64	90	128	180
1	Nankoweap	Redd	69.2	72.2	84.4	97.3	100.0	100.0	100.0
2	Nankoweap	Redd	57.4	69.9	86.6	100.0	100.0	100.0	100.0
3	Nankoweap	Potential	88.0	88.8	92.2	100.0	100.0	100.0	100.0
4	Nankoweap	Potential	76.5	80.4	91.5	93.1	100.0	100.0	100.0
5	Nankoweap	Potential	74.6	78.8	92.8	100.0	100.0	100.0	100.0
6	Nankoweap fan	Redd	50.6	54.9	69.6	88.1	100.0	100.0	100.0
7	Clear	Redd	58.8	61.8	72.8	91.2	100.0	100.0	100.0
8	Clear	Potential	61.7	64.6	72.8	84.5	90.3	100.0	100.0
9	Clear	Redd	36.9	44.5	54.6	71.3	75.0	100.0	100.0
10	Clear	Potential	33.6	38.2	49.4	68.9	80.9	100.0	100.0
11	Bright Angel	Potential	50.5	54.1	66.0	79.4	100.0	100.0	100.0
12	Crystal	Redd	24.1	29.8	46.1	72.5	88.6	100.0	100.0
13	Crystal	Redd	45.0	49.3	58.1	88.0	88.0	100.0	100.0
14	Crystal	Potential	61.3	71.6	84.7	100.0	100.0	100.0	100.0
15	Shinumo	Redd	35.3	40.7	57.2	82.5	100.0	100.0	100.0
16	Shinumo	Redd	24.6	26.5	37.9	50.4	65.1	86.0	100.0
17	Shinumo	Potential	48.9	51.9	60.8	74.6	100.0	100.0	100.0
18	Tapeats	Redd	57.6	64.4	77.6	83.7	100.0	100.0	100.0
19	Tapeats	Redd	56.0	59.4	65.9	83.6	100.0	100.0	100.0
20	Tapeats	Potential	63.7	66.7	76.0	85.5	100.0	100.0	100.0
21	Tapeats	Potential	62.5	66.5	77.7	93.6	100.0	100.0	100.0

Sample number	Stream or river	Redd or potential	Cumulative percentage of grains finer than (mm):									
			0.045	0.25	0.5	1	1.7	3	6	11	22	51
22	Main stem[d]	Redd	0.0	3.0	9.0	14.9	18.3	24.6	36.8	53.5	78.6	100.0
23	Main stem[e]	Redd	0.1	5.2	11.2	16.6	19.1	23.6	34.3	49.8	72.3	100.0
24	Main stem[f]	Potential	0.2	4.0	16.0	22.7	24.5	27.6	32.8	41.8	57.6	79.2

[a] Tributary creeks for samples 1–21.
[b] "Redd" denotes actual use; "potential" denotes undisturbed gravel near redds.
[c] ND means "no data."
[d] Four-mile bar.
[e] Eight-mile bar.
[f] Twelve-mile bar.