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 $d_{30}$ 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 too high to interfere with incubation or emergence, the percentage of fine sediment of the parent 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., Parfit 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,
### TABLE A.1 — Cumulative size distributions for rainbow trout spawning gravel samples, Colorado River and tributaries.

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Stream or river</th>
<th>Redd or potential</th>
<th>Cumulative percentage of grains finer than (mm):</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.063</td>
</tr>
<tr>
<td>1</td>
<td>Nankoweap</td>
<td>Redd</td>
<td>0.3</td>
</tr>
<tr>
<td>2</td>
<td>Nankoweap</td>
<td>Redd</td>
<td>0.0</td>
</tr>
<tr>
<td>3</td>
<td>Nankoweap</td>
<td>Potential</td>
<td>0.1</td>
</tr>
<tr>
<td>4</td>
<td>Nankoweap</td>
<td>Potential</td>
<td>0.5</td>
</tr>
<tr>
<td>5</td>
<td>Nankoweap</td>
<td>Potential</td>
<td>0.3</td>
</tr>
<tr>
<td>6</td>
<td>Nankoweap fan</td>
<td>Redd</td>
<td>0.1</td>
</tr>
<tr>
<td>7</td>
<td>Clear</td>
<td>Redd</td>
<td>0.7</td>
</tr>
<tr>
<td>8</td>
<td>Clear</td>
<td>Potential</td>
<td>2.0</td>
</tr>
<tr>
<td>9</td>
<td>Clear</td>
<td>Redd</td>
<td>0.1</td>
</tr>
<tr>
<td>10</td>
<td>Clear</td>
<td>Potential</td>
<td>1.3</td>
</tr>
<tr>
<td>11</td>
<td>Bright Angel</td>
<td>Potential</td>
<td>1.1</td>
</tr>
<tr>
<td>12</td>
<td>Crystal</td>
<td>Redd</td>
<td>ND</td>
</tr>
<tr>
<td>13</td>
<td>Crystal</td>
<td>Potential</td>
<td>0.3</td>
</tr>
<tr>
<td>14</td>
<td>Crystal</td>
<td>Potential</td>
<td>0.5</td>
</tr>
<tr>
<td>15</td>
<td>Shinumo</td>
<td>Redd</td>
<td>0.1</td>
</tr>
<tr>
<td>16</td>
<td>Shinumo</td>
<td>Redd</td>
<td>0.0</td>
</tr>
<tr>
<td>17</td>
<td>Shinumo</td>
<td>Potential</td>
<td>0.9</td>
</tr>
<tr>
<td>18</td>
<td>Tapeats</td>
<td>Redd</td>
<td>0.0</td>
</tr>
<tr>
<td>19</td>
<td>Tapeats</td>
<td>Redd</td>
<td>0.1</td>
</tr>
<tr>
<td>20</td>
<td>Tapeats</td>
<td>Potential</td>
<td>0.6</td>
</tr>
<tr>
<td>21</td>
<td>Tapeats</td>
<td>Potential</td>
<td>0.4</td>
</tr>
</tbody>
</table>

### Footnotes

* Tributary creeks for samples 1–21.
* "Redd" denotes actual use; "potential" denotes undisturbed gravel near redds.
* ND means "no data."
* Four-mile bar.
* Eight-mile bar.
* Twelve-mile bar.
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 1.** Cumulative size distribution curves for spawning gravels available to rainbow trout Oncorhyncus 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 ($d_{16}$, $d_{50}$, 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 $d_{16}$ 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).
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, \( d_g = (d_{10}\cdot d_{10})^{0.5} \) (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, \( s_g = (d_{50}/d_{10})^{0.5} \), 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 \( sk = [\log_{10}(d/d_{50})]/[\log_{10}(d)] \) (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 2](image-url)
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. 1970).
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ing 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 be­
tween 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 else­
where. When only one (or a few) summary statis­

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firmed 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 re­

quires connected pore space through which the al­
evins 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 in­
tensive studies of egg pockets. Such studies would no doubt prove helpful in better understanding pro­
cesses 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 spawn­
ing 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 else­
where. When only one (or a few) summary statis­

tics 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
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 relating 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, $d_{50}$) 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, whereas 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.

<table>
<thead>
<tr>
<th>Reference or statistic</th>
<th>Species*</th>
<th>Maximum percentage of grains finer than:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.83 mm</td>
</tr>
<tr>
<td>Hausle and Coble (1976)</td>
<td>Brook trout</td>
<td>10</td>
</tr>
<tr>
<td>Weaver and White (1985)</td>
<td>Bull trout</td>
<td></td>
</tr>
<tr>
<td>Bjornn (1969)</td>
<td>Chinook salmon</td>
<td>15.26</td>
</tr>
<tr>
<td>Tappel and Bjornn (1983)</td>
<td>Chinook salmon</td>
<td>40</td>
</tr>
<tr>
<td>McCudden (1977)</td>
<td>Chinook salmon</td>
<td></td>
</tr>
<tr>
<td>Cederholm and Salo (1979)</td>
<td>Coho salmon</td>
<td>7.5, 17</td>
</tr>
<tr>
<td>Koski (1966)</td>
<td>Coho salmon</td>
<td>21</td>
</tr>
<tr>
<td>Phillips et al. (1975)</td>
<td>Coho salmon</td>
<td>21</td>
</tr>
<tr>
<td>Taggart (1984)</td>
<td>Coho salmon</td>
<td>11</td>
</tr>
<tr>
<td>Irving and Bjornn (1984)</td>
<td>Cutthroat trout</td>
<td></td>
</tr>
<tr>
<td>Irving and Bjornn (1984)</td>
<td>Kokanee</td>
<td>33</td>
</tr>
<tr>
<td>Irving and Bjornn (1984)</td>
<td>Rainbow trout</td>
<td>30</td>
</tr>
<tr>
<td>Bjornn (1969)</td>
<td>Steelhead</td>
<td>35</td>
</tr>
<tr>
<td>Tappel and Bjornn (1983)</td>
<td>Steelhead</td>
<td>39</td>
</tr>
<tr>
<td>McCudden (1977)</td>
<td>Steelhead</td>
<td>27</td>
</tr>
<tr>
<td>Phillips et al. (1975)</td>
<td>Steelhead</td>
<td>20</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>13.7</td>
</tr>
<tr>
<td>SD</td>
<td></td>
<td>4.7</td>
</tr>
</tbody>
</table>

* 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-
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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 sediments (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 CO₂ 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 reserved 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 Bjorndal (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 \( f \), which combined a measure of central tendency \( d_{10} \) with a measure of dispersion. The fredle index is calculated as \( f = \frac{d_{15}}{d_{25}} \), where \( S_p \) is the Trask sorting coefficient, given by \( S_p = \left( \frac{d_{15}}{d_{25}} \right)^{0.5} \) (Inman 1952), where \( d_{15}, d_{25} \) are the sizes at...
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 I 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 I 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

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.
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.
ASSESSING 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 weighted 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 d50 or d84 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...
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...
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-
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) not-
ed 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., Loetsch 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.

Acknowledgments

I have benefited greatly from conversations on these topics with M. G. Wolman, M. J. Sale, J. G. Williams, S. Li, K. Vyverberg, L. B. Leopold, and others. The manuscript was much improved by review comments of S. Railtack, D. Chapman, and two anonymous reviewers. This publication is based in part on work performed at Oak Ridge National Laboratory in the Laboratory Graduate Participation Program under contract DE-AC05-76OR00033 between the U.S. Department of Energy and Oak Ridge Associated Universities. Manuscript preparation was supported in part by the Beatrix Farrand Fund of the Department of Landscape Architecture and Environmental Plan-ning, and by the Center for Environmental Design Research, both at the University of California, Berkeley.

References


Carling, P. A., and C. F. McCahon. 1987. Natural situa-

Koski, K. V. 1966. The survival of coho salmon (Oncorhynchus kisutch) from egg deposition to emergence in three Oregon coastal streams. Master's thesis, Oregon State University, Corvallis.
Silver, J. C. E. Warren, and P. Duodoroff. 1965. Dissolved oxygen requirements of developing steel-
head and chinook salmon embryos at different water velocities. Transactions of the American Fisheries Society 92:327-343.


