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1991
Journal Article WWRC-91-04

In

North American Journal of Fisheries Management

Volume 11

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North American Journal of Fisheries Management 11:339–346. 1991

Selection of Measures of Substrate Composition to Estimate Survival to Emergence of Salmonids and to Detect Changes in Stream Substrates

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Abstract.—Biologists have attempted to link intragravel survival of juvenile salmonids to changes in stream substrate quality caused by land management, but the failure to standardize measures of substrate composition has hindered this effort. We compared 15 such measures in laboratory tests that evaluated survival to emergence of Colorado River cutthroat trout *Oncorhynchus clarki pleuriticus* in substrates of different composition. We also evaluated the sensitivity of three measures of substrate composition to the modification of stream substrates by spawning brook trout *Salvelinus fontinalis* and to the deposition of sediment in former redds of Colorado River cutthroat trout. Different estimates of the geometric mean particle size accounted for the greatest proportion of the variation in survival to emergence in laboratory tests, but the percentage of substrate less than 0.85 mm in diameter was the most sensitive measure of known changes in substrate composition in the field. We concluded that a single measure of substrate composition may be inadequate to both assess the potential survival to emergence in a substrate and detect changes in substrate composition caused by land use.

It has been demonstrated that fine sediment can reduce survival to emergence (STE) of juvenile salmonids (Tappel and Bjornn 1983) and that certain land management practices can increase the proportion of fine sediment in spawning gravels in streams (Platts et al. 1989). Managers have attempted to link the effects of land management on STE by assessing changes in substrate composition (Stowell et al. 1983); however, the inconsistent definition of substrate composition, in addition to other problems (Chapman 1988: Young et al. 1990), has obscured this linkage.

Two approaches have been widely used to describe substrate composition. In the first, the proportion of substrate particles less than a given size is quantified by weight or volume. Reference particle diameters have included 6.4 mm (Stowell et al. 1983), 4.0 mm (MacCrimmon and Gots 1986), 3.33 mm (Koski 1975; Ringler and Hall 1988), 3.0 mm (Hall and Lantz 1969; Phillips et al. 1975), 2.0 mm (Hausle and Coble 1976; Witzel and MacCrimmon 1983a), 1.0 mm (Crisp and Carling 1989), 0.84 mm (Reiser and White 1988), 0.83 mm (McNeil and Ahnell 1964), and 0.75 mm (Olsson and Persson 1988). In addition, Tappel and Bjornn (1983) used two sizes of sediment (9.5 mm and 0.85 mm) to describe substrate composition (also see Reiser and White 1988).

In the second approach, aspects of the central tendency of the entire particle distribution are described. Such measures include the geometric mean particle size (Platts et al. 1979), fredle index (Lotspeich and Everest 1981), modified fredle index (Beschta 1982), arithmetic mean particle size (Crisp and Carling 1989), median particle size (Witzel and MacCrimmon 1983b), sorting coefficient (Sowden 1983), and skewness (Crisp and Carling 1989). Graphical and mathematical techniques have been used to calculate most of these measures (Shirazi and Seim 1979); however, these techniques produce different estimates for a particular substrate, especially if the distribution of particle sizes in a sample is not lognormal (see Folk and Ward 1957).

We know of no studies of the relation between the several measures of substrate composition and STE. Often, a single measure of substrate composition is arbitrarily selected and related to STE (usually as the percentage of fines less than a given

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[2] The Unit is jointly supported by the University of Wyoming, the Wyoming Game and Fish Department, and the U.S. Fish and Wildlife Service.

size—e.g., Phillips et al. 1975). Occasionally, a measure has been chosen based on theoretical or empirical relations between substrate composition and the intragravel environment (Platts et al. 1979). Although some studies included comparisons of more than one measure of substrate composition (e.g., Tappel and Bjornn 1983), these frequently compared only similar statistics such as the percentage of substrate particles less than 0.84 mm and the percentage of particles from 0.84 to 4.6 mm in diameter (Reiser and White 1988).

Failure to standardize measurement of substrate composition has plagued the assessment of land management effects on stream substrates. To evaluate the effects of logging and road construction on spawning areas in the South Fork Salmon River, Platts and Megahan (1975) visually estimated the amount of fine sediment less than 4.7 mm in diameter. Alternatively, Shirazi and Seim (1981) favored the geometric mean to monitor changes in substrate composition, and Beschta (1982) suggested that not all substrate measures were equally sensitive to changes in substrate composition caused by logging.

Because of the array of substrate statistics and the variety of techniques for determining some of them, we questioned whether these substrate measures were equally proficient at accounting for the variation in STE or detecting the alteration of stream substrates. Therefore, we performed laboratory tests to determine the relation between STE and 15 substrate statistics used previously for such analyses. Furthermore, we examined the sensitivity of a subset of these statistics to known changes in substrate composition in the field.

Methods

We conducted experiments at the University of Wyoming's Red Buttes Environmental Biology Laboratory 16 km south of Laramie. We used experimental aquaria equipped with a horizontal-flow system. Test substrate was placed between porous baffles in glass-walled, plexiglass-bottomed aquaria 50.8 cm long, 25.4 cm wide, and 30.5 cm deep. Baffles, made of a plexiglass frame covered with fiberglass screen, were placed 7.5 cm from each end of an aquarium. Flow splitters (Mount and Brungs 1967) maintained constant flows of 1 L/min of 9°C well water, at or near oxygen saturation, to each aquarium. An adjustable standpipe inside a venturi standpipe controlled water depth; the venturi standpipe drew water from the lower one-third of the aquarium.

We filled each aquarium with substrate to a depth of 10 cm and constructed a centrum of three or four 25-mm gravel particles (Chapman 1988). Next, we began filling each tank with water; when the water level exceeded the depth of the substrate, we poured 100 eyed eggs onto the centrum and gently added the remaining substrate and continued filling each tank with water. The rear standpipe maintained a water depth of 3 cm over the substrate.

We monitored the aquaria weekly until emergence began, then collected emerging fry with a suction device every 1–3 d until emergence ended. To estimate STE for a nongravel control, we placed 300 eggs in incubation trays for each test.

From 1988 to 1989, we completed two STE experiments with Colorado River cutthroat trout *Oncorhynchus clarki pleuriticus*. We devised 31 treatment substrates of various compositions (Table 1) and tested at least three replicates of each substrate.

To assess the relation of the various measures of substrate composition to STE, we created skewed, uniform, and geometric distributions of sediment less than 3.35 mm in diameter in each test substrate (Table 1). For example, the test substrates composed of 30% sediment less than 3.35 mm in diameter contained essentially no sediment less than 1.7 mm in diameter (skewed), roughly equal proportions of sediment from 1.7 mm to less than 0.212 mm (uniform), or increasing proportions of sediment from less than 0.212 mm to 1.7 mm (geometric).

To obtain substrates of different size-classes, we dried material and then sorted it on a mechanical shaker through sieves of 10 mesh sizes (mm): 50, 25, 12.5, 9.5, 6.3, 3.35, 1.70, 0.85, 0.425, and 0.212; smaller particles were collected on a pan attached to the last sieve. Finally, we weighed the material retained by each sieve and the pan. All substrate consisted of material collected from a stream supporting a naturally reproducing population of Colorado River cutthroat trout.

For each substrate we calculated six statistics that represent different measures of central tendency. Three measures relate to the geometric mean. To calculate the geometric mean by a method of moments, we used the formula of Lotspeich and Everest (1981):

$$D_g = D_a^{P_a} \times D_b^{P_b} \times \ldots \times D_i^{P_i};$$

D_g = the geometric mean (mm);

D_i = the mean diameter (mm) of material retained on sieve i;

TABLE 1.—Percentages by weight of each substrate size-class in the treatment substrates. Type is the general description of each treatment substrate; the first and second numbers define the approximate percentage of substrate less than a given size (mm), and the letter defines the distribution (dist) of this fine substrate as skewed (s), uniform (u), or geometric (g).

Substrate type (%-mm-dist)	Sieve size (mm) 50	25	12.5	9.5	6.3	3.35	1.70	0.85	0.42	0.21	Pan
1988 Colorado River cutthroat trout test											
5-0.85-s	2.0	27.2	35.8	7.8	11.2	5.7	3.3	2.0	5.0	0.0	0.0
5-0.85-u	2.0	27.2	35.8	7.8	11.2	5.7	3.3	2.0	1.7	1.7	1.7
5-0.85-g	2.0	27.2	35.8	7.8	11.2	5.7	3.3	2.0	2.8	1.5	0.7
10-0.85-s	1.8	25.7	34.0	7.3	10.7	5.3	3.2	1.8	10.0	0.0	0.0
10-0.85-u	1.8	25.7	34.0	7.3	10.7	5.3	3.2	1.8	3.3	3.3	3.3
10-0.85-g	1.8	25.7	34.0	7.3	10.7	5.3	3.2	1.8	5.7	2.8	1.5
10-1.70-s	1.8	26.2	34.7	7.5	10.8	5.5	3.3	10.0	0.0	0.0	0.0
10-1.70-u	1.8	26.2	34.7	7.5	10.8	5.5	3.3	2.5	2.5	2.5	2.5
10-1.70-g	1.8	26.2	34.7	7.5	10.8	5.5	3.3	5.3	2.7	1.3	0.7
20-1.70-s	1.7	23.3	30.8	6.7	9.7	4.8	2.8	20.0	0.0	0.0	0.0
20-1.70-u	1.7	23.3	30.8	6.7	9.7	4.8	2.8	5.0	5.0	5.0	5.0
20-1.70-g	1.7	23.3	30.8	6.7	9.7	4.8	2.8	10.7	5.3	2.7	1.3
30-3.35-s	1.5	21.2	28.0	6.2	8.8	4.3	30.0	0.0	0.0	0.0	0.0
30-3.35-u	1.5	21.2	28.0	6.2	8.8	4.3	6.0	6.0	6.0	6.0	6.0
30-3.35-g	1.5	21.2	28.0	6.2	8.8	4.3	15.5	7.7	3.8	2.0	1.0
1989 Colorado River cutthroat trout test											
0-1.7-s	2.1	29.2	38.5	8.4	12.1	6.1	3.6	0.0	0.0	0.0	0.0
7.5-0.85-s	1.8	26.5	34.8	7.7	11.0	5.5	3.3	1.8	7.5	0.0	0.0
7.5-0.85-u	1.8	26.5	34.8	7.7	11.0	5.5	3.3	1.8	2.5	2.5	2.5
7.5-0.85-g	1.8	26.5	34.8	7.7	11.0	5.5	3.3	1.8	4.3	2.1	1.1
15-1.70-s	1.8	24.9	32.7	7.1	10.3	5.1	3.1	15.0	0.0	0.0	0.0
15-1.70-u	1.8	24.9	32.7	7.1	10.3	5.1	3.1	3.8	3.8	3.8	3.8
15-1.70-g	1.8	24.9	32.7	7.1	10.3	5.1	3.1	8.0	4.0	2.0	1.0
20-3.35-s	1.7	24.2	32.0	7.0	10.1	5.0	20.0	0.0	0.0	0.0	0.0
20-3.35-u	1.7	24.2	32.0	7.0	10.1	5.0	4.0	4.0	4.0	4.0	4.0
20-3.35-g	1.7	24.2	32.0	7.0	10.1	5.0	10.3	5.2	2.6	1.3	0.6
25-3.35-s	1.6	22.7	30.0	6.7	9.4	4.7	25.0	0.0	0.0	0.0	0.0
25-3.35-u	1.6	22.7	30.0	6.7	9.4	4.7	5.0	5.0	5.0	5.0	5.0
25-3.35-g	1.6	22.7	30.0	6.7	9.4	4.7	12.9	6.4	3.2	1.6	0.8
40-3.35-s	1.3	18.1	24.0	5.3	7.6	3.7	40.0	0.0	0.0	0.0	0.0
40-3.35-u	1.3	18.1	24.0	5.3	7.6	3.7	8.0	8.0	8.0	8.0	8.0
40-3.35-g	1.3	18.1	24.0	5.3	7.6	3.7	20.6	10.3	5.2	2.6	1.3

P_i = the proportion by weight of the entire sample made up of material retained on sieve i.

Platts et al. (1979) graphed substrate composition on log-probability paper to calculate the graphic geometric mean:

$$D_{gg} = (D_{84}D_{16})^{0.5};$$

D_{84}, D_{16} = the substrate diameters below which 84% and 16% of the sample lie.

In addition, Shirazi and Seim (1979) demonstrated a least-squares regression technique to determine the geometric mean. We refer to this statistic as D_{gr}. The sample median, D_{50}, was also determined from graphs.

To calculate the fredle index of each substrate, we used the formula

$$F_i = D_g/S_o;$$

S_o = a sorting coefficient, $(D_{75}/D_{25})^{0.5}$;

D_{75}, D_{25} = the substrate diameters below which 75% and 25% of the sample lie.

Beschta (1982) suggested that the fredle index could be improved by using the standard deviation of the geometric mean rather than a sorting coefficient. Shirazi and Seim (1979) provided a method-of-moments formula for determining the geometric standard deviation. We referred to the geometric mean divided by its standard deviation as the modified fredle index (F_m).

Using regression analysis (SPSS^x, SPSS 1986), we related STE to substrate composition. For each substrate treatment we calculated the aforementioned measures of central tendency, the log transformations of three of these measures (D_g, F_i, and F_m), and the percentages of fine sediment less than 6.3 mm, 3.35 mm, 1.70 mm, 0.85 mm, 0.425 mm, and 0.212 mm in diameter. Before making any analyses we normalized STE with the arcsine transformation (Zar 1984: 286). For all analyses we adopted $P < 0.05$ as significant.

We used indicator variables in regression analyses (Neter et al. 1983:343) of STE and substrate composition to determine whether data from different years could be combined. Based on these analyses, we separately analyzed the two experiments involving Colorado River cutthroat trout.

Tests of the sensitivity of substrate measures to known changes in stream substrate relied on data from two sources. First, we reexamined the data on modification of substrate composition by spawning brook trout *Salvelinus fontinalis* (Young et al. 1989). To assess that modification, we collected freeze-core samples of substrate from egg pockets, from other locations in the redd, and from locations next to redds. After stratifying the samples into upper and lower layers (representing substrates altered and unaltered by spawning fish), we dried, sieved, and weighed the substrates as described above. Because of possible biases associated with the sampling technique (Adams and Beschta 1980; Chapman et al. 1986), we excluded the substrate retained on the 50-mm and 25-mm sieves. We then compared the ability of D_g, F_m, and the percentage of fine sediment less than 0.85 mm in diameter to detect the anticipated differences in substrate composition among upper-stratum samples and among unstratified (recombined) samples. Based on our previous work, we expected to find differences among all three locations from the upper-stratum samples, and between egg pockets and outside redds from unstratified samples. We used the Wilcoxon signed-rank test to compare locations (Sokal and Rohlf 1981) and considered the level of significance to be an indicator of sensitivity to changes in substrate composition.

The second source of field data consisted of substrate samples collected with shovels from new and former redds of Colorado River cutthroat trout. We obtained these samples from two second-order streams in south-central Wyoming, Green Timber Creek and Harrison Creek, that contain naturally reproducing populations of this subspecies. In July 1987, all samples represented egg pockets. We measured the distance from each sample location to a marker on the nearest streambank. During May 1988, over 1,500 m^3 of fine sediment were deposited in Green Timber Greek when a transbasin water pipeline failed (R. N. Schmal, U.S. Forest Service, personal communication). In July 1988 and 1989, we resampled most of these former redds (some were not sampled because markers were lost). Again, all samples were dried, sieved, and weighed, and particles larger than 25 mm were excluded from further analyses. After calculating the D_g, F_m, and percentage of fine sediment less than 0.85 mm for each sample, we used these statistics to compare the substrates between years and streams. We expected to find no differences between streams in 1987 (only egg pockets were sampled); but because of the sediment spill, we anticipated that 1987 samples from Green Timber Creek would differ from those collected in 1988 and 1989, and that samples from Harrison Creek would differ from those collected in Green Timber Creek in 1988 and 1989. We used the Wilcoxon signed-rank test to compare between years for each stream and the Mann–Whitney U-test to compare between streams for each year (Sokal and Rohlf 1981). Again, the level of significance was considered an indicator of sensitivity to change.

Results

Forms of the geometric mean particle size accounted for the greatest proportion of variation in STE for both 1988 and 1989 experiments (Table 2). In the 1988 test, the graphic geometric mean had the largest coefficient of determination. In the 1989 test, the geometric mean calculated by the method of moments had the largest value. Gen-

TABLE 2.—Coefficients of determination between the arcsine transformation of survival to emergence of Colorado River cutthroat trout and various measures of substrate composition for laboratory experiments in 1988 ($N = 45$) and 1989 ($N = 57$). D_g is the geometric mean particle size (mm), D_{gr} is the least-squares geometric mean (mm), D_{gg} is the graphic geometric mean (mm), D_{50} is the median (mm), F_i is the fredle index, F_m is the modified fredle index, and percent fines is the percentage of sediment less than a given size.

	Coefficient of determination	
Independent variable	1988	1989
D_g	0.65	0.58
D_{gr}	0.56	0.53
D_{gg}	0.67	0.45
D_{50}	0.51	0.42
F_i	0.63	0.54
F_m	0.60	0.47
Log(D_g)	0.64	0.57
Log(F_i)	0.58	0.53
Log(F_m)	0.58	0.54
Percent fines		
<6.3 mm	0.52	0.46
<3.35 mm	0.52	0.46
<1.70 mm	0.48	0.33
<0.85 mm	0.14	0.33
<0.425 mm	0.25	0.26
<0.212 mm	0.22	0.22

erally, the percentage of substrate less than any given size did not perform as well as the measures of central tendency.

We found significant differences between the STE equations for the 1988 and 1989 laboratory tests with Colorado River cutthroat trout (Figure 1). In addition, the mean STE in incubator trays was 93% (SD, 0%) in 1988 but 71% (17%) in 1989.

The percentage of fine sediment less than 0.85 mm was the most sensitive indicator of the alteration of substrates by spawning brook trout; five of six comparisons were significant (Table 3). Furthermore, the modified fredle index was a better indicator of change than was the geometric mean for both upper-stratum and unstratified samples.

Similarly, the percentage of fine sediment less than 0.85 mm was the most sensitive indicator of change in substrate composition due to the sediment spill in Green Timber Creek (Tables 4, 5). When using either the modified fredle index or the geometric mean, we failed to detect all of the anticipated differences between streams and years.

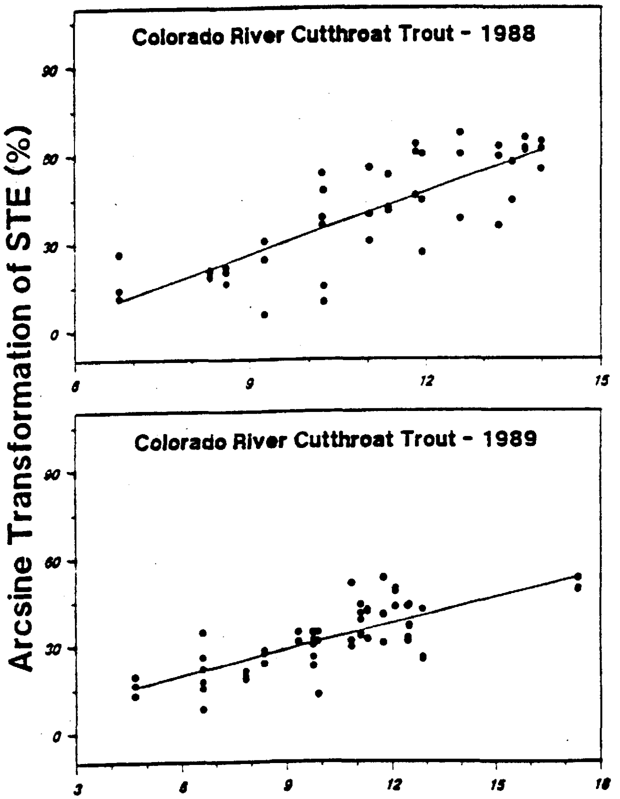

FIGURE 1.—Relation between survival to emergence (STE) of cutthroat trout and the geometric mean substrate particle size (GM, mm) in two laboratory tests. For 1988, arcsine(STE) = 7.01 (GM) − 36.89; $F = 81.39$, $r^2 = 0.65$, $P < 0.0001$, $N = 45$. For 1989, arcsine (STE) = 2.98 (GM) + 1.67; $F = 75.09$, $r^2 = 0.58$, $P < 0.0001$, $N = 57$.

TABLE 3.—Levels of significance from the Wilcoxon signed-rank test on substrate samples from in or near brook trout redds for three measures of substrate composition. Comparisons are of upper-stratum samples or unstratified samples from inside and outside redds (IR–OR; $N = 12$), egg pockets and inside redds (EP–IR; $N = 13$), and egg pockets and outside redds (EP–OR; $N = 28$). D_g is the geometric mean particle size (mm), F_m is the modified fredle index, and percent fines is the percentage of sediment less than 0.85 mm.

Sample and substrate measure	Comparison		
	IR–OR	EP–IR	EP–OR
Upper strata			
D_g	0.023	0.055	0.001
F_m	0.008	0.039	<0.001
Percent fines	0.005	0.007	<0.001
Unstratified			
D_g	0.117	0.075	0.002
F_m	0.071	0.055	<0.001
Percent fines	0.071	0.033	<0.001

Discussion

Overall, our laboratory studies indicated that the geometric mean particle size was the best predictor of STE. Furthermore, measures of central tendency based on the entire particle distribution (e.g., D_g, F_i, and F_m) typically performed better than measures that relied on only a portion of the distribution. Based on the reanalysis of other data, Chapman (1988) preferred the log transformation of the fredle index to the geometric mean, but our analyses of the same data indicated that the two measures accounted for almost equal proportions of the variation in STE for several species (Young et al. 1990). Sowden and Power (1985) found that the modified fredle index was significantly correlated with survival of rainbow trout *Oncorhynchus mykiss* to a stage shortly after hatching, whereas the geometric mean was not. However, the authors relied on a small sample of redds ($N = 5$), and they estimated survival only during a portion of the intragravel phase.

Predicting STE from the percentage of substrate less than a given size proved unsatisfactory, seemingly because survival was sensitive to the distribution of sediment size within the target range. In the 1989 test with Colorado River cutthroat trout, for example, the treatments in which 25% of the substrate was less than 3.35 mm produced mean STEs of 39, 25, and 11% from the skewed, geometric, and uniform distributions of that substrate. Consequently, we question the use of models that estimate STE from the percentage of fine sediment in a substrate (e.g., Stowell et al. 1983).

TABLE 4.—Levels of significance from the Wilcoxon signed-rank test for three measures of substrate composition in new or former egg pockets of Colorado River cutthroat trout collected from two streams in 3 years. For Green Timber Creek, $N = 7$ for the 1987–1988 comparison, $N = 5$ for 1988 versus 1989, and $N = 5$ for 1987 versus 1989. For Harrison Creek, $N = 12$ for 1987–1988, 11 for 1988–1989, and 12 for 1987–1989. D_g is the geometric mean particle size (mm), F_m is the modified fredle index, and percent fines is the percentage of sediment less than 0.85 mm.

Stream and substrate measure	Comparison		
	1987–1988	1988–1989	1987–1989
Green Timber Creek			
D_g	0.128	0.345	0.043
F_m	0.028	0.225	0.043
Percent fines	0.018	0.500	0.043
Harrison Creek			
D_g	0.480	0.155	0.239
F_m	0.689	0.131	0.182
Percent fines	0.845	0.168	0.038

TABLE 5.—Levels of significance from the Mann-Whitney U-test for three measures of substrate composition in new or former egg pockets of Colorado River cutthroat trout collected from Green Timber and Harrison creeks in 1987 ($N = 20$), 1988 ($N = 19$), and 1989 ($N = 17$). Comparisons are between streams; D_g is the geometric mean particle size (mm), F_m is the modified fredle index, and percent fines is the percentage of sediment less than 0.85 mm.

Substrate measure	Comparison		
	1987	1988	1989
D_g	0.438	0.385	0.009
F_m	0.438	0.083	0.006
Percent fines	0.275	0.001	0.009

Chapman (1988) noted that evaluations of measures of substrate composition "have produced results that are quantitatively inconsistent among and usually within fish species." He contended that this was largely due to a lack of understanding of the structure of egg pockets. However, we have suggested that these inconsistencies may also be created by variation in the inherent viability of eggs from different stocks in different years (Young et al. 1990). We believe that the significant differences between regression coefficients from the data for STE of Colorado River cutthroat trout in 1988 and 1989, as well as the differences in STE in the nongravel control in those years, support this conclusion.

In the field the expected changes in substrate composition were revealed more frequently by the percentage of substrate less than 0.85 mm than by the geometric mean particle size or the modified fredle index. Beschta (1982) also noted that the percentage of fine sediment was better than the geometric mean as an indicator of the intensity of land use. He speculated that the modified fredle index might be the best statistic for describing the composition of spawning gravels, implying that this index might be the best predictor of STE and the most sensitive to changes in substrate composition. But in our study, the modified fredle index was outperformed in both contexts by other statistics.

We believe that the percentage of substrate less than a given size was the best indicator of changes in field substrate composition because it measured the portion of the particle size distribution that was modified. Thus, the way in which stream substrates are disturbed may dictate the most appropriate measure of substrate composition. For example, debris torrents deeply scour stream channels and alter the proportion of many sizes of substrate; these changes might best be detected by using a measure of central tendency (R. Marston, University of Wyoming, personal communication). In contrast, bank erosion of floodplain alluvium introduces predominantly fine sediment; such changes might best be detected by using the percentage of substrate less than a given size.

Sheridan et al. (1984) asked for the standardization of measures of substrate composition in western North America and hoped that a single measure would be selected. However, we have demonstrated that a single measure would be inadequate to both describe potential STE in a substrate and detect alteration of that substrate by land management or spawning fish.

Acknowledgments

We thank P. Anderson, J. Bobbitt, P. Guenther, D. Lanning, and B. Rhodine for assisting with the laboratory and field studies; T. Annear, H. Bergman, D. Chapman, P. Eschmeyer, R. Marston, W. Platts, F. Rahel, M. Stone, and R. Wiley for reviewing the manuscript; and the U.S. Forest Service, the Wyoming Game and Fish Department, the U.S. Fish and Wildlife Service, and the Wyoming Water Research Center for funding this research.

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