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Protecting sediment-sensitive aquatic species in mountain streams through the application of biologically based streambed sediment criteria

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Abstract. We evaluated several lines of evidence to identify bedded fine sediment levels that should protect and maintain self-sustaining populations of native, sediment-sensitive aquatic species in the western US. To identify these potential criterion values for streambed sediments $\leq$0.06 mm (fines) and $\leq$2 mm (sand and fines) diameter, we examined: 1) the range of areal % fines and areal % sand and fines values at 169 least-disturbed reference sites in our sample, 2) sediment tolerance values calculated for a selection of sediment-sensitive aquatic vertebrate and macroinvertebrate taxa for both particle size ranges, 3) quantile regression predictions of the declines in vertebrate and macroinvertebrate Indices of Biotic Integrity (IBIs) at progressively higher ambient levels of streambed sediment from synoptic survey data acquired in 557 mountain stream sampling sites in 12 western states, 4) a literature review of the effects of sand and fines on the survival of salmonid eggs to hatching, and 5) a literature review of studies that quantitatively linked macroinvertebrate response to the pertinent size ranges of streambed sediment in mountain streams. Predicted maximum vertebrate Index of Biotic Integrity (IBI) declined 4.4 points (SE = 1.0) and macroinvertebrate IBI declined 4.0 points (SE = 0.60) for each 10% increase in % fines. Similarly, for each 10% increase in % sand and fines, the predicted maximum vertebrate IBI decreased 3.7 points (SE = 0.50) and macroinvertebrate IBI decreased 3.0 points (SE = 0.50). Combining all lines of evidence, we concluded that for sediment-sensitive aquatic vertebrates, minimum-effect sediment levels were 5% and 13% for % fines and % sand and fines, respectively, both expressed as areal percentages of the wetted streambed surface. For aquatic macroinvertebrates, minimum-effect levels for the 2 sediment size classes were 3% and 10%, respectively. We encourage managers to consider these biologically based minimum-effect values when developing sediment criteria for mountain streams. Quantifying and comparing both vertebrate and macroinvertebrate assemblage responses to streambed sedimentation informs the criteria-setting process and allows managers to set stream restoration priorities.

Key words: sediment criteria, stream physical habitat, fine sediment, silt, sand, habitat quality, quantile regression, index of biotic integrity, IBI.

Sediment has long been recognized as a leading cause of biological impairment in rivers and streams of the US (Iwamoto et al. 1978, Judy et al. 1984, Wood and Armitage 1997, USEPA 2000). A given percentage of streambed fine sediments (fines) in a particular ecoregion might be seen as deficient, optimum, or excessive, depending on differences in stream size, slope, basin lithology, and the degree of human disturbance (Kaufmann et al. 1999, 2009). We might not have a clear understanding of regionally appropriate (natural) levels of fine sediment in streams, but we do recognize that human activities, such as road-building, agriculture, mining, and logging, increase the delivery of fine sediments to streams where they cause impairment to habitats and aquatic life (Waters 1995, Wood and Armitage 1997, Nietch et al. 2005). Fine sediments affect fish food sources, growth rates, migration, and reproduction (Berkman and Rabeni 1987, Everest et al. 1987, Chapman 1988, Meehan 1991, Bjornn and Reiser 1991, Spence et al. 1996, Suttle et al.

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2004). Fine sediments fill interstices among coarse gravel and cobble surfaces to interfere with the anchoring, feeding, and respiration of benthic macroinvertebrates and larval amphibians (Lemly 1982, Minshall 1984, Waters 1995, Wood and Armitage 1997, Cantilli et al. 2006).

Federal and state agencies recently increased their commitment to the development of biologically based sediment criteria (Cantilli et al. 2006, Cormier et al. 2008). The term *biologically based* indicates that biological data are used to set sediment criteria that protect and maintain populations of native, sediment-sensitive species. Biologically based sediment criteria assume that a level of fine sediment accumulation exists beyond which sediment-sensitive assemblages are no longer self-sustaining (Bryce et al. 2008). Rational and defensible criterion values are a prerequisite to imposing management prescriptions for excess sediment in streams.

We must quantitatively link sediment effects with biotic responses to develop sediment criteria that are protective of aquatic life. Presumably, excess sediment accumulation reaches a level where the numbers of aquatic species are reduced and their assemblage and guild structures are altered, signifying ecosystem impairment. Multimetric indices of biological integrity (IBIs), developed for both aquatic vertebrates and benthic macroinvertebrates, document assemblage changes with increasing human disturbance (Kerans and Karr 1994, Fore et al. 1996, Moyle and Marchetti 1999, Klemm et al. 2002, Hughes et al. 2004, Stoddard et al. 2005b, Whittier et al. 2007b). IBI metrics respond to sedimentation (Mebane et al. 2003, Kaufmann and Hughes 2006), one of the major disturbances to aquatic ecosystems, and to alterations in flow, temperature, O_2 content, and habitat structure. In our study, we were concerned with reductions in species richness and abundance and with alterations in assemblage structure and function caused by fine sediment accumulation in stream beds. We show that, although IBIs respond to multiple, synergistic perturbations, sediment is a major factor limiting IBI potential in many streams and that examination of a regional data set allows us to quantify this limiting relationship. This focus on the limiting relationship, in combination with other information concerning sediment tolerances, adds to a weight of evidence that advances the development of fine sediment criteria for mountain stream beds.

In a previous paper (Bryce et al. 2008), we used a weight-of-evidence approach to suggest a sediment criterion for aquatic vertebrates for fines $\leq$0.06 mm in diameter (silt and finer) in mountain streams of the western US. We concluded that streambed areal surficial fine sediment levels of $\leq$5% fines retain full habitat potential for sediment-sensitive aquatic vertebrates in mountain streams. Here, our objectives are to expand the overview of our first effort to include salmonid response to larger particles (sand and fines $\leq$2 mm) and to examine the response of another commonly sampled assemblage, aquatic macroinvertebrates, to particles in both size ranges ($\leq$0.06 mm and $\leq$2 mm). As we did in our previous paper (Bryce et al. 2008), we determined an upper limit of streambed surficial fine sediment levels for each assemblage that ensured the continued presence of sediment-sensitive aquatic species. Quantifying and comparing assemblage-specific responses to streambed sedimentation informs the criteria-setting process. Water resource managers need to know if these 2 interdependent stream taxa respond similarly to accumulations of fine sediment and whether common sediment criteria would protect sensitive members in both groups.

Methods

Study area

We used fish, macroinvertebrate, and physical-habitat data from a survey of wadable streams in the western US: the US Environmental Protection Agency's Environmental Monitoring and Assessment Program (EPA EMAP-West; Stoddard et al. 2005a, b). For EMAP-West, a stratified, unequal probability survey design (50 sites/state and additional sites in 5 intensive study areas) was used to select sites from all streams and river segments coded as perennial in the EPA digital Reach File Version 3 (RF3; Clifford et al. 1993). These sites comprise a regionally representative probability sample of the network of wadable perennial streams in the 12 western states (Washington, Oregon, California, Idaho, Montana, North Dakota, South Dakota, Wyoming, Nevada, Colorado, Utah, and Arizona; Fig. 1) surveyed during the 2000 to 2004 EMAP-West survey. The probability sample permits statistically unbiased, regional estimates of stream condition (Stevens 1997, Olsen et al. 1999). Documenting physical and chemical characteristics, the status of stream biota, and stream and riparian stressors at sample reaches evaluates the degree to which each site deviates from one that possesses biointegrity (i.e., with a species composition, diversity, and functional organization expected in minimally disturbed natural habitats of the region) (Frey 1977, Karr and Dudley 1981, Stoddard et al. 2005b).

We supplemented the EMAP-West database with data from a previous study conducted in the mid-1990s in the Coast Range of Oregon and Washington

FIG. 1. US Environmental Protection Agency Environmental Monitoring and Assessment Program (EMAP)-West sample stream reaches in the Mountains ecoregion in 12 western US states.

(Herger and Hayslip 2000). Sediment is a major stressor in the Coast Range where other stressors, such as nutrient enrichment, toxic chemicals, or flow modifications that accompany agriculture, mining operations, and urbanization, are limited in extent compared to the rest of the western states.

The reporting framework for EMAP-West divides the western US survey area into 3 geoclimatic regions (Mountains, Plains, and Xeric). Each of these regions is large enough to ensure a sufficient sample size for statistical rigor. We focused our analyses on wadable streams in the Mountains region (an aggregate region based on the Omernik ecoregion framework; Omernik 1987, 1995; Fig. 1). The database consisted of 557 site visits across the Mountains region over the 5-y time frame of the survey. Sample sizes vary in our analyses depending on the number of sites successfully sampled for a sediment metric or particular assemblage—aquatic vertebrate or aquatic macroinvertebrate. These mountainous areas span a wide geo-

Table 1. Sample distributions of selected basin, channel, and riparian characteristics of the stream reaches used in our study. dbh = diameter breast height.

Variable	Median	Range
Drainage area (km^2)	25	0.19–14,180
Elevation at sample reach (m)	1385	10–3660
Mean slope of reach water surface (%)	3.0	0–35
Mean wetted width (m)	3.8	0–42
Mean depth at thalweg (m)	0.26	0.007–1.55
Mean riparian tree + shrub + ground woody cover (%)[a]	80	0–223
Mean canopy density (densiometer at mid-channel) (%)	63	0–100
Mean riparian canopy cover: trees $<$ 0.3m dbh + trees $>$ 0.3m dbh (%)[a]	28	0–114
Mean riparian tree canopy cover: trees $>$ 0.3m dbh (%)	10	0–79
Riparian human disturbance (proximity-weighted observations per plot)	0.38	0–5.9
Road density in basin (km/km^2)	0.6	0–3.7
Large wood volume (m^3 wood/m^2 bankfull channel area)	0.005	0–0.4
Substrate fines (% $\leq$ 0.06 mm diameter)	3.8	0–100
Substrate sand + fines (% $\leq$ 2 mm diameter)	15	0–100
Substrate % bedrock	0	0–74
Substrate D_{gm} (geometric mean diameter) (mm)	30	0.008–2500
LRBS = Log_{10}(relative bed stability)	−0.55	−4.0–1.4
Conductivity (μS/cm)	121	1.6–2757
pH	7.8	6.1–9.2
Acid neutralizing capacity (μeq/L)	1123	2.8–7028
Dissolved organic C (mg/L)	1.3	0.1–20
Cl^- (μeq/L)	21	0–6810
Total N (μg N/L)	119	11–3720
Total P (μg P/L)	12	0–593
Turbidity (Nephelometric Turbidity Units)	0.38	0.05–214

[a] Overlapping strata can create totals $>$ 100%

graphic range and subsume much regional variability, but they share similar physical characteristics (e.g., steep slopes, shallow soils, high stream gradients, and cooler temperatures), and they provide cool to cold oxygenated water and coarse relatively silt-free substrates for fish and macroinvertebrate assemblages (Table 1). Mountain streams in our survey were predominantly coarse-bedded. More than ½ of the sample stream reaches had geometric mean bed surface particle diameter (D_{gm}) $>$ 30 mm and 85% had $D_{gm} > 3$ mm.

Field methods

Between 1 April and 30 September of 2000 to 2004, field crews sampled physical habitat, water quality, fish, aquatic amphibians, aquatic macroinvertebrates, and periphyton at selected stream reaches. Physical habitat measurements and biotic assemblage samples were collected systematically along sample reach lengths that were 40× their mean wetted channel width with a minimum length of 150 m (Peck et al. 2006, Hughes and Peck 2008). A reach length of forty wetted widths (Lyons 1992, Angermeier and Smogor 1995, Patton et al. 2000, Reynolds et al. 2003) or slightly longer (Paller 1995, Dauwalter and Pert 2003a, b) is adequate for capturing all but the rarest aquatic vertebrate species and for obtaining repeatable measures of indices of biotic integrity (Reynolds et al. 2003) in many parts of the US.

Field crews sampled longitudinal streambed profiles and measured fish cover, large woody debris, riparian vegetation structure, and surficial substrate at 21 evenly spaced, cross-sectional transects within the wetted channel margin (Kaufmann et al. 1999, Peck et al. 2006). On each of the stream cross sections, at 5 equally spaced stations across the wetted width of the stream channel, a particle was selected and assigned to 1 of 7 particle size classes (total 105 particles per reach). For sand and smaller particles ($\leq$2 mm diameter), field crews determined the dominant size class (sand or silt) of particles in the pinch of fine particles between their fingers. For our study, we focused on 2 particle size classes: % fines ($\leq$0.06 mm) and % sand and fines ($\leq$2 mm), expressed as the areal % of streambed surface particles. The % fines particle class is composed primarily of silt-sized particles. The 2-mm diameter maximum for the sand and fines size class is the upper limit of sand in the Wentworth (1922) classification scale. Particles >2 mm were classified as fine gravel. Hereafter, *fines* refers to particles $\leq$0.06 mm and *sand and fines* refers to particles ≤2 mm unless otherwise stated.

For analysis, we reduced each particle count to a whole-reach substrate characterization by calculating percentages of the 105 observations within the stated size classes. Because the collection points were systematically spaced, we interpreted these percentiles as surficial areal estimates of the substrate characteristics of each sampled stream reach (Kaufmann et al. 1999). Each individual classification of particle size made at the subreach scale with the visual/tactile method of particle size estimation is not as precise as the volume or mass measures used for streambed substrate sampling in many detailed, smaller-scale studies, including some that we reference in our paper. However, this method is appropriate for broad multistate survey efforts because reach-scale characterizations of acceptable precision can be obtained with a practical level of effort at a large number of sites (Faustini and Kaufmann 2007). The practicality and rigor of this method has resulted in metrics that can be associated with aquatic species distributions and biotic response.

Field crews sampled fish and amphibians with backpack electrofishers. They fished the sample reach in an upstream direction in a single pass without using block nets (Reynolds et al. 2003, Peck et al. 2006). Crews identified, tallied, and measured fish, crayfish, and amphibians. They retained voucher specimens for taxonomic verification by the National Museum of Natural History and released the remaining animals. Crews used kick nets to collect benthic macroinvertebrates from a 0.09-m^2 area at 11 of the 21 cross-sectional transects. Samples collected at each of the 11 transects were combined into a single composite to represent benthic macroinvertebrate species composition and relative abundance in the entire reach (Peck et al. 2006). At least 300 macroinvertebrates, randomly drawn from the composite sample (maximum 500 individuals), were identified to the finest taxonomic level possible and formed each site's subsample for macroinvertebrate index development (Peck et al. 2006). EMAP-West fish and macroinvertebrate data are available on request from the EPA National Health and Environmental Effects Research Laboratory (NHEERL), Western Ecology Division.

Reference site screening

We modified the methods of Stoddard et al. (2005a, b) and Herlihy et al. (2008) to screen a subset of 169 least-disturbed reference sites from the EMAP-West sample. We used chemical, physical, and riparian habitat variables, including nutrients, Cl^-, pH, riparian canopy density, and riparian human disturbances collected or observed at each site. Screening criteria for reference status were established from predetermined ranges of these variables considered characteristic of least-disturbed conditions (Stoddard et al. 2005b). Sedimentation was one of the screening criteria for selecting reference sites to be used in biological analyses, but to avoid circularity, we did not use sediment as a criterion in selecting reference sites for our study. To hypothesize a regional expectation for fine sediments in mountain streams, we used the 75th percentile of the reference distribution of areal % fines and areal % sand and fines values at reference sites. We chose the 75th percentile as a reference value to allow for natural variability in fines accumulations but also to recognize that those reference sites with the highest accumulations of fines probably had natural or anthropogenic watershed disturbances that were not captured by the other criteria in the reference-site screening process.

Quantile regression

We associated a fish IBI (Whittier et al. 2007b) and macroinvertebrate IBI (Stoddard et al. 2005a, b) developed from EMAP-West survey data with % fines and % sand and fines. Exploratory analyses together with evidence from the literature suggested that accumulated fine streambed sediment was a limiting factor for both assemblages in many of the sample streams. Quantile regression is an appropriate analytical tool for defining limiting relationships from data that typically appear as wedge-shaped distributions in plots of biotic response vs some stressor or habitat element (Terrell et al. 1996, Cade et al. 1999, Dunham et al. 2002). Whereas ordinary least squares regression emphasizes the center of a distribution, quantile regression procedures model associations near the upper edge of a wedge-shaped distribution where the variable of interest (sediment in this case) is the active limiting constraint (Terrell et al. 1996, Cade et al. 1999, Dunham et al. 2002).

We used quantile regression (Blossom statistical software, Version W2005.08.26, 2005; US Geological Survey, Fort Collins, Colorado) to estimate the decline in fish and macroinvertebrate IBI as a function of accumulating areal % fines and % sand and fines. In our earlier quantile regression analysis of the association of fish IBI with sediment fines ≤ 0.06 mm (Bryce et al. 2008), we tested slope variances for continuous quantiles between 2 and 98 and modeled the 90th quantile, because it was the largest quantile with low uncertainty for regression slope (Cade et al. 1999, Cade and Noon 2003). Above the 90th quantile, confidence intervals widened abruptly. For the present paper, we used the same quantile to model the limiting relationship for consistency in comparisons among particle size classes and fish or macroinvertebrate assemblage responses. We derived 4 regression equations describing potential fish or macroinvertebrate IBI as a function of % fines or % sand and fines.

Sediment tolerance values

To establish fish and macroinvertebrate species tolerance values for the 2 sediment particle size classes addressed in our study, we applied a weighted-averaging technique based on fish and macroinvertebrate species' relative abundances (ter Braak and Barendregt 1986, Huff et al. 2005, Whittier et al. 2007a). For each species, we calculated the weighted average as:

$$\frac{\sum([\text{relative abundance}][\text{proportion of fines}])}{\sum(\text{relative abundance})}$$

where relative abundance is the number of individuals of a species/total number of individuals of all species at a site, proportion of fines (or proportion of sand and fines) is the proportion of fine sediment at a site.

The weighted average, or optimum tolerance value, identified the sediment value at which the highest abundances occurred. The optimum tolerance value + 1 standard deviation defined the upper tolerance value for each species (above which relative abundances dropped dramatically). We reasoned that high relative abundances indicated the suitability of sediment conditions for that species, and that conditions at upper tolerance values were no longer suitable for sustaining the species.

We calculated optimum sediment tolerance values for each of the 59 fish and amphibian species sampled and the hundreds of aquatic macroinvertebrate taxa identified in the EMAP-West survey. For the present study, we focused on 4 sediment-sensitive fish species in the Mountains region—Chinook salmon (*Oncorhynchus tshawytscha*), bull trout (*Salvelinus confluentus*), rainbow trout (*Oncorhynchus mykiss*), and cutthroat trout (*Oncorhynchus clarkii*)—and a group of 8 sediment-sensitive aquatic macroinvertebrates representing the orders Ephemeroptera, Plecoptera, and Trichoptera (EPT; listed in Table 2). We selected the salmonid species because of their importance to managers and the public and because information about their reproductive success and general response to sediment was available in the literature. We chose the 8 macroinvertebrate species because their sensitivity to fine sediment was corroborated in available macrobenthos literature (Relyea et al. 2000, Carlisle et al. 2007). We did not include amphibians in the rest of our analysis or literature review, but we did list optimum sediment tolerance values for the 6 most sediment-sensitive amphibians in our database (Table 2) to allow comparison with the other taxa highlighted in our study.

TABLE 2. Optimum sediment tolerance values and medians for areal % fines ($\leq$0.06 mm) and areal % sand and fines ($\leq$2 mm) for selected sediment-sensitive species. Percent fines for salmonids were first presented in Bryce et al. (2008).

Taxon	% fines	% sand and fines
Sediment-sensitive salmonids		
Chinook salmon *Oncorhynchus tshawytscha*	4	11
Bull trout *Salvelinus confluentus*	6	11
Rainbow trout *Oncorhynchus mykiss*	7	16
Cutthroat trout *Oncorhynchus clarkii*	8	19
Median values	6.5	13
Sediment-sensitive amphibians		
Foothill yellow-legged frog *Rana boylii*	2	11
Tailed frog *Ascaphus truei*	3	7
Pacific giant salamander *Dicamptodon tenebrosus*	9	14
Rough-skinned newt *Taricha granulosa*	9	14
Red-legged frog *Rana aurora*	10	17
Cascades frog *Rana cascadae*	11	15
Median values	9	14
Sediment-sensitive macroinvertebrates		
Ecclisomyia sp. Trichoptera	1.6	7.3
Epeorus grandis Ephemeroptera	1.7	9.1
Caudatella hystrix Ephemeroptera	2.5	12.3
Pteronarcys sp. Plecoptera	2.6	8.2
Oligophlebodes sp. Trichoptera	3.0	8.8
Arctopsyche grandis Trichoptera	3.6	10.2
Epeorus longimanus Ephemeroptera	3.9	11.4
Megarcys sp. Plecoptera	4.3	11.4
Median values	2.8	9.7

Determining minimal-effect sediment levels

The objective of a biologically based sediment criterion for streams is to protect and maintain self-sustaining populations of native, sediment-sensitive aquatic species. We attempted to identify allowable surficial streambed sediment amounts with a minimum effect on the long-term sustainability of sediment-sensitive aquatic biota. For our weight-of-evidence approach, we used multiple sources of information. From the EMAP-West database, we derived the quantile regression models, reference values for the 2 sediment particle size ranges, and

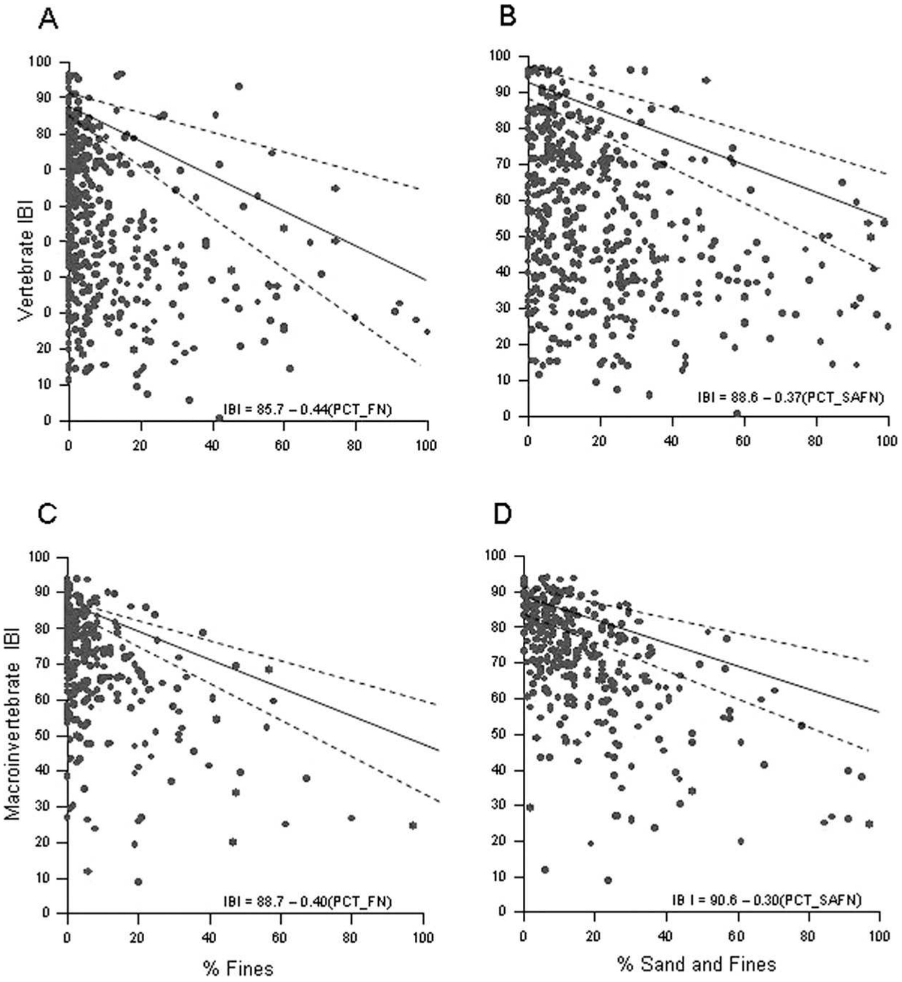

FIG. 2. Quantile regressions (90th quantile) for aquatic vertebrate Index of Biotic Integrity (IBI) against % fines (PCT_FN; ≤0.06 mm) (A), aquatic vertebrate IBI against % sand and fines (PCT_SAFN; ≤2 mm) (B), aquatic macroinvertebrate IBI against % fines (C), and aquatic macroinvertebrate IBI against % sand and fines (D), with equations and confidence intervals for each. All sediment measures are reach-wide % areal cover of wetted streambed obtained from systematic particle counts.

sediment tolerance values for selected fish and macroinvertebrate species. We sought additional evidence to corroborate the aquatic species' sediment tolerance values from 2 literature reviews: 1) a literature review of field and laboratory research quantifying the effects of sand and fines on the survival of salmonid eggs, and 2) a review seeking evidence of a quantifiable macroinvertebrate response to accumulated fine sediment in both particle size ranges in cold-water mountain stream beds. By combining this information, we hoped to identify specific sediment levels below which impairment was unlikely.

Results and Discussion

Quantile regression

We regressed the 90th quantile for 4 associations: aquatic vertebrate IBI and aquatic macroinvertebrate IBI against % fines and % sand and fines (Fig. 2A–D, Table 3). Statistical significance of quantile regression slope is indicated by the choice of the largest quantile that could be estimated with high precision (having narrow confidence intervals) and by confidence intervals that do not contain 0 (Cade et al. 1999). The quantiles near the outer edge of the distribution (the 90th quantile in this case) have slope estimates that represent reductions in IBI caused by the limiting effects of accumulating fine sediments in stream beds. The scatter of IBI scores below the upper quantiles represent scores that are reduced by factors other than (or in addition to) sediment (Fig. 2A–D).

For each indicator and each particle size class, we applied the 90th quantile regression equation describing the decline in IBI potential with increasing fine sediments.

TABLE 3. Regression model parameter estimates (90th quantile) and standard error (SE) for predicted potential maximum vertebrate and macroinvertebrate Indices of Biotic Integrity (IBIs) from reach-wide streambed surface % fines (≤0.06 mm) and % sand and fines (≤2 mm). The 95% confidence intervals (CIs) for each parameter (estimate ± 2SE) are listed in parentheses. Quantile regression equations for each taxon and each sediment type follow the pattern: Vertebrate (or Macroinvertebrate) IBI = intercept + (regression slope) × (% sediment).

Biotic group	Sediment type	Intercept ± SE (CI)	Slope ± SE (CI)
Vertebrate	% fines	85.7 ± 1.51 (82.8–88.7)	−0.44 ± 0.10 (−0.65–−0.24)
	% sand and fines	88.6 ± 1.72 (85.2–92.0)	−0.37 ± 0.05 (−0.47–−0.27)
Macroinvertebrate	% fines	88.7 ± 0.85 (87.0–90.3)	−0.40 ± 0.06 (−0.52–−0.29)
	% sand and fines	90.6 ± 1.08 (88.5–92.7)	−0.30 ± 0.05 (−0.39–−0.21)

$$\text{Potential IBI} = \text{intercept} + (\text{regression slope})(\%\ \text{sediment})$$

For each 10% increase in areal % fines (≤0.06 mm), the predicted potential maximum vertebrate IBI declined 4.4 points (SE = 1.0) and macroinvertebrate IBI declined 4.0 points (SE = 0.60). Similarly, for each 10% increase in % sand and fines (≤2 mm), the predicted potential maximum vertebrate IBI decreased 3.7 points (SE = 0.50) and macroinvertebrate IBI decreased 3.0 points (SE = 0.50). The quantile regression models clearly indicated declines in the potential maximum aquatic vertebrate and macroinvertebrate IBIs with increasing amounts of streambed sediments, but these linear model relationships alone do not suggest a specific threshold level of % fines or % sand and fines above which impairment is evident.

Our earlier study (Bryce et al. 2008) indicated on the basis of a literature review that IBIs of 80 to 100 reflected conditions that were considered protective of sensitive fish assemblages found in least-disturbed, cold-water reference streams throughout the US. Bryce et al. (2008) also demonstrated with a quantile regression model that an IBI of 80 corresponded to a silt level of 16%, clearly higher than the 5% fines that they concluded would be protective of sediment-sensitive species. This apparent inconsistency suggests that although IBIs typically incorporate ≥1 sensitive-taxon metrics that show strong responses to sediment, they also contain metrics that capture assemblage response to other stressors. As a result, choosing an IBI score considered *good* (e.g., 80) and matching it with its corresponding % fine sediment on a quantile regression plot of IBI vs % fines does not ensure a limit (or criterion value) that will be protective of sediment-intolerant species within the aquatic assemblage. Rather, we show that a method of sediment criteria development that focuses on identifying minimum-effect sediment levels is more likely to be protective of sediment-sensitive aquatic species. In the following sections, we use sediment-related information in a weight-of-evidence approach to identify allowable sediment levels that avoid the negative effects of excess streambed % fines and % sand and fines on aquatic vertebrates and aquatic macroinvertebrates.

Aquatic vertebrate response to sand and fines

We examined 3 sources of evidence concerning aquatic vertebrate responses to bedded fine sediment: 1) the distribution of areal streambed surficial sand and fines in least-disturbed reference sites in the EMAP-West database, 2) aquatic vertebrate sediment tolerance values for sand and fines calculated from taxon–sediment distributions in the EMAP-West survey, and 3) a literature review of the effects of % sand and fines on the survival of salmonid eggs to hatching.

Sand and fines in reference sites.—The 75th percentile of the distribution of areal % streambed surface sand and fines at least-disturbed reference sites in our database was 17%, with a median of 10% and a range of 0 to 66%.

Aquatic vertebrate sediment tolerance values for sand and fines.—The weighted-averaging process revealed species-level tolerances along the gradient of increasing % sand and fines (Fig. 3). Optimum reachwide sediment tolerance values for the 4 selected sediment-sensitive salmonid species common in mountain streams varied from 11 to 19% sand and fines with an average of 14% and a median of 13% (Table 2). The species' sediment tolerance values for % fines (≤0.06 mm) calculated for our earlier study (Bryce et al. 2008) are included in Table 2 for comparison. We did not do a literature review for amphibians sampled from streams, but we did calculate their sediment tolerances. Six of the most sediment-sensitive amphibian species had optimum tolerance values within the range of the 4 selected salmonid species. Tailed frog and foothills yellow-legged frogs had optimum tolerance values ≤ those of the most sediment-sensitive salmonids (Table 2, Fig. 3).

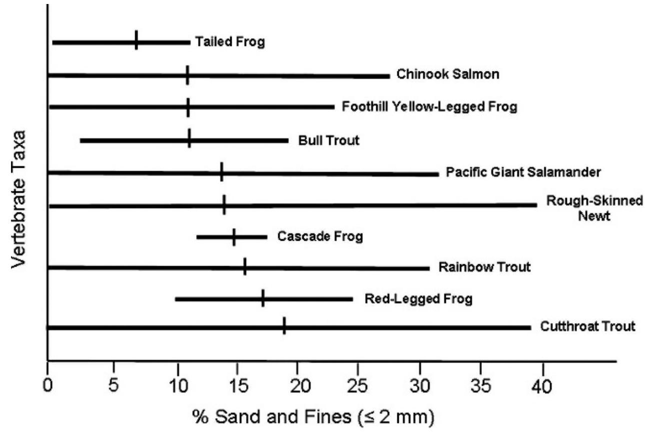

FIG. 3. An example of the output for sediment tolerance values for 10 sediment-sensitive salmonid and amphibian species. The vertical hatch marks on the lines represent the weighted average, or optimum tolerance value, identified as the sediment value at which the highest abundances occurred. The right-hand extent of each line represents the optimum tolerance value + 1 standard deviation, defined as the upper tolerance value for each species. Several species with sediment optima <20% sand and fines have relatively broad sediment tolerance ranges (for example, cutthroat trout with 0–39% sand and fines). However, in every case, beyond the upper tolerance value, relative abundances dropped dramatically.

Literature review for sediment effects on salmonid egg survival.—A number of field and laboratory studies clearly demonstrated that the survival of salmonid eggs declined as amounts of fine sediment increased in spawning gravels. However, it was difficult to find quantitative information for our particular range of particle size classes. Fines as defined in the fish literature often corresponded to a size class of <0.85 mm, but particles labeled fines in the literature also ranged from >0.85 mm to particles as large as 3.3 mm (Koski 1966), 6.4 mm (Bennett et al. 2003), or even 9.5 mm (Tappel and Bjornn 1983). Our literature review yielded a small number of applicable studies addressing particle size classes of <0.85 mm and <2 mm.

Most of the pertinent studies consisted of laboratory tests based on incubation of salmonid eggs in artificial redds, which typically are filled with suitably sized spawning gravel measured by volume or mass, and then injected with varying amounts of finer particles. Cederholm et al. (1981), Hall (1986), and Reiser and White (1988) used this method, and all reported steep declines in survival of Chinook (*O. tshawytscha*) and coho (*O. kisutch*) salmon eggs between 0 and 10% fines (≤0.84 mm) measured by mass or volume (Table 4).

TABLE 4. Results of laboratory investigations on the survival rates of Chinook (*Oncorhynchus tshawytscha*) and coho (*Oncorhynchus kisutch*) salmon eggs at various levels of fine sediments (<0.84 mm) added to incubation gravel.

		Mean % survival		
Fish	% fines (<0.84 mm)	Cederholm[a] (1981)	Hall[b] (1986)	Reiser and White[a] (1988)
Chinook	0		77.5	68.0
	5		53.0[c]	38.0[c]
	10		28.5	10.0
Coho	0		68.5	
	5		40.0[c]	
	10		7.0	
	<10	58.9[c]		
	>10	20.5[c]		

[a] Substrate measured by volume
[b] Substrate measured by mass
[c] Estimated or averaged point values from graphs

Reiser and White (1988) also tested the survival of newly fertilized Chinook salmon eggs at larger particle sizes of 0.84 to 4.6 mm measured by volume. They found that declines in survival were delayed as fines were progressively added until % fines in the incubation gravel was >10% by volume, after which declines began and continued unabated. As injected sediments (0.85–4.6 mm) increased from 10 to 30%, newly fertilized Chinook salmon egg survival declined from 63% to 25%. Fudge et al. (2008) randomly distributed a combination of sand and silt (<2 mm) and coarser sand (2–4 mm) among 20 redd chambers to represent 4 treatment levels of 0%, 4.6%, 8.2%, and 11.2% of the volume of particles <2 mm to test the effects on the emergence of rainbow trout fry. At reference (0%), low (4.6%), and medium (8.2%) levels of sediment, total emergence was between 85% and 90%. Emergence decreased to 78.5% when sediment was increased to 11.2% by volume. The sediment loadings also resulted in a number of nonemergent fry that were trapped beneath the sediment. The numbers of nonemergent (trapped) fry were significantly greater ($p < 0.05$) at medium and high amounts of sediments (8.2% and 11.2%, respectively) than they were at low and reference levels (4.6% and 0%, respectively; Fudge et al. 2008).

We found a limited number of survival-to-emergence studies done on natural redds, and only 2 of them met our particle size constraints. Cederholm et al. (1981) surveyed 19 redds in the Clearwater River of Washington state. The graphed relationship between % fines (<0.85 mm) measured by volume and coho salmon egg survival to emergence indicated a threshold at ~18% fines (<0.85 mm). Above 18% fines (<0.85 mm), coho salmon egg survival to emergence showed little variability in emergence success and did not exceed ~23%, whereas survivals at sites with <18% fines (<0.85 mm) accumulation varied from 15 to 77%. Mean survival in the group of redds with <18% (<0.85 mm) fines was 34%, whereas mean survival in redds with >18% fines (<0.85 mm) was 15%.

Magee et al. (1996) conducted a field study of cutthroat trout embryo survival in erodible volcanic and sedimentary geology in 2 headwater watersheds of the Taylor Fork basin in Montana. Predicted embryo survival, averaged over 16 stream reaches, was just 8.5% at 26% sand and fines (≤2.36 mm) measured by mass. In a study of Yellowstone cutthroat trout redds on a tributary of the Snake River in Idaho, Thurow and King (1994) did not measure emergence, but they did assess the proportion of various particle size classes sorted by mass in the substrate adjacent to 10 sample redds in suitable spawning habitat. They found that particles <2 mm ranged from 2.3 to 17.7%, with a mean of 9.6%; particles <0.85 mm ranged from 0.7 to 10.6%, with a mean of 5.0%; and particles <0.06 mm ranged from 0.1 to 1.2%, with a mean of 0.7%, all expressed as % by mass.

Peterson et al. (1992) conducted a review of 13 salmonid survival-to-emergence studies using artificial or natural redds (including the ones already mentioned above from the 1980s) and recorded the reductions in survival at 11% and 16% fines (<0.85 mm) for each study. They also reviewed studies on natural levels of particles in the <0.85 size class in Washington, Alaska, and British Columbia and found that they varied from 6 to 14%. Weighing the available evidence from the studies, but relying more on the range of natural levels of particles in unmanaged watersheds, Peterson et al. (1992) selected 11% as an acceptable maximum level for particles <0.85 mm in Pacific Northwest mountain streams.

Minimum-effect sediment levels for aquatic vertebrates.—The literature review provided few useable results, but it did frame the range of salmonid egg survival at various levels of accumulated fine streambed sediment as a percentage of the mass or volume of streambed sediments in natural or artificial spawning redds. Our results are based on % areal cover of fine particles over the surface of the entire wetted stream channel. For these reasons, the literature results cannot be directly related to ours. However, in spite of the differing sampling protocols and measurements of fine sediments, the results of these other studies paralleled ours in documenting declines of sediment-sensitive species with progressive increases in fine sediments. They suggest that hatching success will decline to unsustainable levels when bedded sand and fines are between 11% and 18% by volume or mass. Whether the correspondence of results between the 2 methods is real or serendipitous, the literature review studies produced a range of % sand and fines values very similar to the range of values that we derived by other means.

We concluded after reviewing the evidence from our study that streambed areal surficial fine sediment levels of ≤13% sand and fines (≤2 mm) would retain habitat potential for sediment-sensitive aquatic vertebrates in mountain streams. Thirteen percent was the median sediment tolerance value for the 4 focal sediment-sensitive salmonid species in our paper (Table 2). This value is also at the lower end of the 11–18% range suggested by the literature review. Even though the reference value for % sand and fines for least-disturbed sites was 17%, and calculated sediment tolerance values ranged as high as 19% sand and fines for cutthroat trout, our intent was to choose a criterion value that would protect the most sediment-sensitive aquatic species. Many other species would be protected by a 13% minimum-effect sediment level. Of the 59 species of fish and amphibians that were sampled in EMAP-West, 19 had optimum sediment tolerance values of ≤13% sand and fines. A minimum-effect sediment level of 13% (at the lower end of the 11–19% range) also would protect against the tendency of sand and fines to create a cap or seal over substrate gravels to entrap or entomb emerging fry. The sealing of substrate gravels by sand and fines and subsequent entrapment of emerged fry has been reported with particles as small as 0.5 mm (Beschta and Jackson 1979) and as large as 6 mm (Waters 1995).

By applying the quantile regression equation for aquatic vertebrate IBI vs sand and fines, we find that an areal % sand and fines level of ≤13% corresponds to a vertebrate IBI value of ≥83.8 (SE = 1.7). In other words, excess sand and fines is not likely to be a problem for sediment-sensitive taxa in mountain streams with vertebrate IBI scores >~84 (based on the vertebrate IBI developed for EMAP-West [Whittier et al. 2007b] or a comparable IBI formulation).

Aquatic macroinvertebrate response to sediment

We followed the same 3-step process for aquatic macroinvertebrates, deriving sediment reference values, sediment tolerance values, and evidence from literature reviews to search for evidence of a quantitative macroinvertebrate response to the areal accumulation of streambed % fines and % sand and fines.

Sediment reference values.—The 75th percentiles of the distributions of streambed surface % fines and % sand and fines at least-disturbed reference sites in our database were 5% and 17%, respectively.

Macroinvertebrate sediment tolerance values.—We applied the weighted averaging technique described earlier to the hundreds of taxa listed for the Mountains region in the EMAP-West macroinvertebrate database. We selected 8 taxa that were highly intolerant of sediment and widely distributed throughout the mountainous West (Table 2). Six of the 8 taxa had been identified by Relyea et al. (2000) as very intolerant to fine sediment, and we were able to corroborate their findings. The 8 taxa include representatives of the orders Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies) (EPT). Optimum sediment tolerance values for the 8 taxa for areal % fines ranged from 1.6% to 4.3% fines with a median of 2.8%; and optima for areal % sand and fines varied from 7.3% to 11.4% with a median of 9.7% (Table 2).

Literature review for macroinvertebrate quantitative sediment response.—The literature review for macroinvertebrates yielded a small number of studies that quantitatively linked macroinvertebrate response to particular size ranges of streambed sediment in mountain or highland streams. A larger number of studies reported correlations or general changes in macroinvertebrate assemblages with increased sedimentation resulting from various landuse regimes (Mebane 2001, Gage et al. 2004, Herlihy et al. 2005).

Carlisle et al. (2007) developed indicator values similar to sediment tolerance values for macroinvertebrate genera and families for sediment fines <2 mm. However, only 2 of the genera listed in their study were included in our list. We were in agreement with Carlisle et al. (2007) that the genus *Epeorus* (Ephemeroptera:Heptageniidae) is very sensitive to fine sediment, but they found *Pteronarcys* (Plecoptera:Pteronarcyidae) to be more tolerant of fine sediment than we did (score: 7 of 10, with 10 being most tolerant). The sediment tolerance value for *Pteronarcys* in EMAP-West calculated from optimum abundances was lower (indicating *Pteronarcys* was more sensitive to fine sediment ≤2 mm) than the scores for 2 species of the sediment-sensitive *Epeorus* (Table 2).

Kaller and Hartman (2004) sampled 7 Appalachian streams to study the effects on macroinvertebrates of fine sediments from streamside roads (<0.125 mm; close in size to the smaller silt-sized particles sampled in our study). Sampling occurred in spring and autumn over 2 y. They found that EPT taxon richness declined significantly ($p < 0.05$) when fine substrates were >0.8–0.9% of riffle substrate composition (by mass). EPT taxon richness declined only in the seasons when a stream exceeded these fine sediment amounts, and taxon richness remained constant when fine sediment levels were <0.8 or 0.9%.

Cormier et al. (2008) used EPA EMAP data from a mid-1990s survey of the mid-Atlantic Highlands in the eastern US to associate number of EPT taxa with a silt-sized particle class (≤0.06 mm). They tested 8 methods for developing sediment criteria, including a quantile regression method. They used as their benchmark a 5% decrease in number of EPT taxa from the quantile regression y-intercept value. In their quantile regression model, the reduced number of EPT taxa corresponded to a % fines (≤0.06 mm) value of 5.8%, higher than our calculations of sediment tolerance values or values from the literature. However, Cormier et al. (2008) sought a sediment value that would maintain aquatic life use in cold-water streams. Their objective differed from ours, which was to determine a % fines value to protect the most sediment-sensitive species of macroinvertebrates.

At the larger particle size range (<2 mm), Zweig and Rabeni (2001) studied the response of macroinvertebrates to accumulated sand and fines. They sampled 73 moderate-velocity glide habitats in 4 streams in the Missouri Ozark Highlands. Substrate conditions were assessed initially by an areal visual estimate at each site, followed by sieving and weighing an additional substrate sample to separate it into representative size classes. Taxon richness significantly declined in 3 of the 4 streams, rare taxa were eliminated, and EPT richness and density were significantly negatively correlated with deposited sediment across all 4 streams. Zweig and Rabeni (2001) observed 50% reductions in 21 macroinvertebrate taxa between 0 and 15% deposited sediment by mass. Using the same data set, Rabeni et al. (2005) examined the response of macroinvertebrate functional groups to fine sediments. Of the feeding groups, filterers were the most intolerant of sand and fines (<2 mm) accumulation in stream gravels; only 10% of all individuals encountered were at sites with >20% sediment (by mass) in this size range. In the habit group, clingers were most intolerant of sediment. Sixty-five percent of individuals in this group occurred where sediment accumulations were <10%. All 8 of our sediment-sensitive macroinvertebrate taxa were in the clinger habit group.

Relyea et al. (2000) used existing data from several regional EMAP surveys that sampled 562 stream sites in 4 northwestern states; in all these surveys, substrate

Table 5. Minimum-effect sediment levels for aquatic vertebrates and aquatic macroinvertebrates for reach-wide wetted streambed areal % fines ($\leq$0.06 mm) and areal % sand and fines ($\leq$2 mm).

Aquatic indicator	% fines ($\leq$0.06mm)	% sand and fines ($\leq$2 mm)
Aquatic vertebrates[a]	5%	13%
Aquatic macroinvertebrates	3%	10%

[a] Fish and amphibians

sampling was conducted using areal % cover estimates for a particle size range of $\leq$2 mm (the same method as in our study). Relyea et al. (2000) reported species-specific responses to fine sediment in streams. They found that the traditional metric, %EPT, declined steadily with increasing fine sediment, and they also discriminated the effects of fine sediments on individual taxa at 10% increments. They identified 7 intolerant taxa that declined to near 0 relative abundance by the time sediment levels reached 30% areal fines.

Minimum-effect sediment levels for aquatic macroinvertebrates.—The number of appropriate articles was sparse, but the literature review corroborated macroinvertebrate sensitivity to excess sediment. Kaller and Hartman (2004) suggested that a minimum-effect sediment level for macroinvertebrates for the smaller particle size ($\leq$0.06 mm) would be low, near 1% by mass, and Rabeni et al. (2005) found that a minimum-effect level for the larger particle size would probably be <10% by mass. These findings only loosely frame the effects of the 2 particle size classes on macroinvertebrates, but the literature review and our analyses suggest that sediment-sensitive macroinvertebrate taxa are more sensitive to accumulated fines in either particle size class than the most sediment-sensitive salmonids.

More research is needed to quantify macroinvertebrate response to various sediment size ranges. Given the lack of evidence in the literature, we used the median macroinvertebrate sediment tolerance values calculated for the 8 selected macroinvertebrate species (Table 5)—2.8% (rounded up to 3%) for areal % fines ($\leq$0.06 mm) and 9.7% (rounded up to 10%) for areal % sand and fines ($\leq$2 mm)—to serve as minimum-effect sediment levels for the most sediment-sensitive macroinvertebrates in mountain streams. Applying these sediment levels to the quantile regression predictions shows that, when using the macroinvertebrate IBI developed for EMAP-West (Stoddard et al. 2005a, b) or a comparable IBI, streams with IBI scores $\geq$88 (SE = 0.85 for % fines and SE = 1.08 for % sand and fines) are not likely to have a sediment problem that will affect sediment-sensitive macroinvertebrates.

Management implications.—The value of using multiple indicators in bioassessments lies in relating multiple assemblage-specific responses to human disturbances. Multiple indicators corroborate expected responses or provide information when a commonly used indicator is absent or not sampled. Macroinvertebrates, for instance, provide ecological condition information when fish are absent in steep, small, or ephemeral streams or when field crews are not allowed to sample protected fish stocks.

The choice and application of sediment criteria could be problematic when various biological indicators, such as fish or macroinvertebrates, respond differently to sediments. It is clear from our results that sediment criteria based on the more charismatic and economically important aquatic vertebrates would not protect the more sediment-sensitive macroinvertebrate assemblage. Should managers apply more stringent criteria to protect the most sensitive organisms, in this case macroinvertebrates, even though the public might not value macroinvertebrates as highly as it does fish? From an ecological perspective, if sediment-sensitive macroinvertebrates declined or disappeared, how would their absence affect salmonids' macroinvertebrate food base in low-sediment streams? Such questions provide a fertile area for future research.

The scale of application of sediment criteria also will require evaluation. Most of the literature information was based on sediment within targeted habitats within a reach (e.g., spawning redds or riffles). In contrast, synoptic sampling efforts like EMAP sample whole stream reaches and summarize results across a large region. Future stream sediment criteria might be applied by administrative region at a state, basin, or watershed level or even modeled for individual streams. In an earlier study (Bryce et al. 2008), we evaluated the possibility of subregional differences in biotic response to sediment by comparing aquatic vertebrate response from the west-wide survey in the Mountains ecoregion with that from a separate survey conducted >10 y earlier in a portion of the full survey area, the Coast Range of Oregon. The quantile regression results for fines ($\leq$0.06 mm) for the smaller subregion were very similar to the equation for mountain streams in the full survey area. These results indicated that IBIs calculated for the same stream type, although generated using somewhat different methods at different regional scales and sample sizes, yielded very similar predictions for the potential response of IBI to fine sediments. Perhaps sediment criteria could be set and applied across the mountainous West, but they would have to be evaluated regionally and adjusted in basins having local native fauna that are extremely sensitive (or insensitive) to fine sediments. Similarly, adjustments might be appropriate for streams that receive a naturally high sediment load, for example in areas with shale or mudstone geology.

Peterson et al. (1992) suggested that managers become familiar with the dominant sizes and ranges of small particles in their region and with the class of particles that is actively changing. In our earlier paper (Bryce et al. 2008), we stated that 2 sediment criteria, one for % fines and one for % sand and fines, might be needed for mountain streams, particularly in areas where silt is a significant component of the sediment load derived from natural and anthropogenic sources. As stated earlier, sand and fines >0.5 mm can create a cap or seal over redds, entrapping emerging fry (Beschta and Jackson 1979). Silt, on the other hand, infiltrates interstitial spaces in redds to smother the eggs directly. Therefore, it is important to consider the interactive and additive negative effects of silt and sand, when both are present, on successful emergence of salmonid fry and the foraging ability and physical stability of macroinvertebrates. In areas where silt might have negative effects in addition to those produced by sand-sized particles, 2 sediment criteria might be necessary.

Once the range and distribution of substrate particle sizes is known, elements of a pragmatic management strategy might include applying more restrictive criteria to protect a representative number of minimally disturbed reference streams, where low sediment levels protect both aquatic vertebrates and macroinvertebrates and in areas harboring threatened and endangered aquatic species. For example, using our results for sand and fines, regional managers might propose a 13% criterion for sand and fines, but apply a more restrictive 11% criterion to critical spawning areas for the more sediment-sensitive bull trout or Chinook salmon.

Conclusions

We might expect various biotic assemblages to differ in their sensitivity to fine sediments, but it is instructive to quantify and compare their various responses. After evaluating the available information, we concluded that minimum-effect bedded surficial sediment levels for aquatic vertebrates (fish and amphibians) were 5% and 13%, respectively, for % fines ($\leq$0.06 mm) and % sand and fines ($\leq$2 mm) sampled as a systematic particle count and expressed as whole-reach areal percentage estimates. For aquatic macroinvertebrates, minimum-effect levels were 3% and 10%, respectively, for the 2 particle size ranges (Table 5).

The protective criteria suggested from our analyses might appear restrictive at first glance. However, population estimates from the EMAP-West survey showed that ~55% (±7%) of stream length in mountainous areas of the western US already has a surficial areal % fines value $\leq$5% (Stoddard et al. 2005a). The same survey showed that ~45% (±5%) of stream length in mountainous areas already has a surficial areal % sand and fines value <13% (Stoddard et al. 2005a). The large number of streams already meeting these criteria suggests that a systematic improvement of mountain stream condition under such criteria might be achievable. It is reasonable to think that some proportion of the 50% of mountain streams that exceed the criteria could be restored to support native sediment-intolerant aquatic vertebrates and macroinvertebrates. Guided by knowledge of the range of sediment levels in the management area and by the reference values of the minimum-effect sediment levels, managers will be able to prioritize streams that are candidates for restoration and implement changes to landuse activities in those watersheds to reduce fine sediment input.

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