Statistical Analysis of Streambed Sediment Grain Size Distributions: Implications for Environmental Management and Regulatory Policy[1]

Brenda Rosser[2] and Matt O'Connor[2]

Abstract

Fish habitat in cold water streams in many northwestern California watersheds has been declared degraded under provisions of the Federal Clean Water Act, contributing to listings of anadromous fish species under the Endangered Species Act. It is believed that past and present land management activities induce erosion that contributes excess sand-size and finer sediment to stream systems, which then causes an increase in the proportion of fine sediment in spawning gravels. The higher proportion of fine sediment can reduce the rate of survival of eggs. Target thresholds for desirable fine sediment concentrations in spawning beds have been identified based on scientific literature and watershed studies. There are few data describing natural or unimpaired sediment size distributions. This is of concern in the region owing to high natural erosion rates.

This study examines data from gravel bed streams collected by McNeil sampling and bulk sediment sampling in northern California (samples typically 25 to 30 kg) and New Zealand (samples typically 50 kg). The McNeil streambed sampling protocol is the preferred method to determine sediment size distributions and stream substrate quality for salmonids in the fisheries literature. Confidence intervals for various percentiles of the grain size distributions were computed from field data using a two-stage sampling approach. Accuracy and precision of data from these sampling programs are considered in relation to the biological/regulatory thresholds as well as the effort required to obtain, process and analyze grain size distributions. Either very large samples, and/or a large number of samples are typically required to obtain data with high precision, suggesting that in many circumstances, it may be difficult to assess whether regulatory thresholds are exceeded.

Key words: fish habitat, sediment sampling, spawning gravel, statistical analysis

Introduction

One of the factors contributing to the decline in salmonid populations in western North America is the impairment of spawning habitat. A primary factor determining spawning habitat availability and quality is determined by the quantity and distribution of suitably sized gravels (Kondolf 2000). One cause of impairment of spawning habitat is sedimentation by sand and fine gravel, from erosion associated with land management. These sediments may be deposited on and mix with

[1] This paper was presented at the Redwood Science Symposium: What does the future hold? March 15-17, 2004, Rohnert Park, California.
[2] O'Connor Environmental, Inc., P.O. Box 794, Healdsburg, CA, (707) 431-2810. email: brendar@oe-i.com and matto@oe-i.com, respectively. website: http://www.oe-i.com

streambed gravels, and can reduce survival of eggs deposited in redds by reducing the flow of oxygenated water and increasing the concentration of metabolic waste. In addition, fine gravel (~ 2 to 8 mm) may impede emergence of salmonid fry from the redds by blocking gravel interstices. The proportion of fine material in the gravel substrate has been linked to the rate of survival of salmonid species (Kondolf and Wolman 1993). Research on the effect of fine sediment (less than about one mm diameter) on incubation of salmonid eggs in redds suggests that spawning gravels are in good condition if fine sediment (<1 mm) comprises less than 12 to 14 percent of spawning bed material (Chapman 1988, Kondolf 2000). Similarly, previous research suggests that emergence of fry will not be significantly reduced when fine sediment less than ~3 mm to 6 mm comprises roughly 30 percent or less of spawning gravels (Kondolf 2000).

Regulatory thresholds have been set for percent fines through the U.S. Environmental Protection Agency's Total Maximum Daily Load's (TMDL) process. Targets are set based on literature review of optimal spawning gravel conditions and limited sampling of existing conditions in the watershed. The USEPA sediment TMDL studies for the Navarro and Garcia watersheds in northern California, set target values for percent fines <0.85 mm at 14 percent, and <6.35 mm at 30 percent, and bed material median particle size (D50) at 37 to 69 mm (min & mean) (USEPA 1998, USEPA 2000).

Another regulatory process, implementation of the Pacific Lumber Company Habitat Conservation Plan (HCP) in northern California, includes a set of targets for sediment conditions pertaining to spawning habitat. The fine sediment target in the HCP is 11 to 16 percent sediment <0.85 mm, and 20 to 25 percent sediment <6.35 mm.

This study compares results from three different particle size sampling programs, each representing a different level of sampling intensity. Confidence limits for various particle size fractions are compared for the three levels of sampling intensity. The sampling programs were conducted independently of each other, at different times and with different purposes in mind, however, the particle size statistics obtained serve to illustrate various levels of accuracy and precision that may be achieved with different levels of sampling effort, as well as the implications of statistical and sampling issues for regulatory programs.

Study Areas

Particle size data were available for three study areas including the Waipaoa River in New Zealand; Soda, Carneros, and Sulphur Creeks in the Napa River watershed, and Green Valley and Salt Hollow Creeks in the Russian River watershed (the North Bay region in northern California); and Freshwater Creek in Humboldt County. All study reaches are gravel-bed streams. The study sites in northern California are known to support salmonid populations, including coho salmon and/or steelhead trout. Green Valley Creek contains one of the few remaining coho salmon populations in the Russian River. Freshwater Creek supports coho and Chinook salmon as well as steelhead and cut-throat trout. The Napa streams are believed to support steelhead. Study reach characteristics are summarized in *table 1.*

Table 1—*Summary of study reach characteristics.*

	Waipaoa River	Napa/Sonoma	Freshwater Creek
Location	East Cape, New Zealand	Northern California	Northern California
Watershed scale	Large – 100 km	Moderate – 2-10 km	Small – 1000 ft
Study objective	Scientific investigation	Spawning gravel study	Aquatic trends monitoring (HCP)
Sampling type	Bulk sediment samples	McNeil samples	Shovel samples
Sampling position	Exposed point bars	Pool tail outs	Riffles
Average subsample size	50 kg	25 kg	5 kg
Number of subsamples	102	22	27
Average D50	4 mm	24 mm	26 mm

Geology of the Waipaoa River, East Cape, New Zealand

The Waipaoa River is a 104 km long gravel-bed river located on the East Cape of New Zealand's North Island. The Waipaoa River is not a fish-bearing stream, however, it was included in this study as an example of an extensive particle size sampling effort—the spatial resolution and extent of the sampling program are unique for a field situation. The Waipaoa River basin is situated within a zone of active deformation associated with the Hikurangi subduction margin (Moore and Mazengarb 1992), which has induced high uplift rates in the ranges at the head of the basin. Sediment supply rates to the river are high; annual suspended sediment yield is 6750 t/km/yr (Hicks and others 2000) and bedload is estimated at one percent of this value (Trafford 1998). The Waipaoa River and its tributaries have been aggrading in response to increased sediment supply rates since the beginning of the twentieth century, when an intense phase of erosion was initiated in the upper watershed following large-scale deforestation, which destabilized the landscape.

Geology of North Bay Region Watersheds, Northern California

Napa Valley and Salt Hollow creek basins are underlain by the Central Belt Franciscan complex. Here, the Franciscan complex includes a mélange of sheared shale and sandstone with some chert, high-grade metamorphic rocks, shattered sandstones and greenstones, and serpentinite. The Franciscan assemblage supports high topography and steep hillslopes, and is notorious for its erosion potential, hence, landslides and other mass movement events are important geomorphic agents in these watersheds. The Franciscan formation is highly fractured and sheared, thus providing a source of fine sediment to the channel when failures occur (Pearce and others 2000). The uppermost headwaters of Carneros Creek, portions of Sulphur Creek and the majority of Soda Creek are underlain by Tertiary Sonoma volcanics, which consists mainly of andesitic and rhyolitic lava flows. Green Valley Creek is located in the coastal range, and is underlain by Coastal Belt Franciscan rocks, which tend to be more stable than Central belt Franciscan rocks. The Napa study areas have drainage basins less than 25 km^2, and Green Valley Creek has a drainage area of 44 km^2. The study site on an unnamed tributary of Salt Hollow Creek has a drainage area of about 1.5 km^2, and is located below on-stream reservoirs.

Geology of Freshwater Creek, Northern California

Freshwater Creek is an 80 km^2 drainage basin located near Eureka, California in Humboldt County. Approximately 77 percent (62 km^2) of the watershed, is owned and managed for timber production by the Pacific Lumber Company (PALCO). The underlying geology present within Freshwater Creek consists primarily of three groups: the Wildcat Group, the Franciscan Central Belt Group, and the Yager Formation (PALCO 2003). The Wildcat Group is composed mostly of mudstone, siltstone, claystone, fine-grained sandstone, and minor conglomerate. The Wildcat formation rocks are inherently erodible and potentially unstable. Gravels in the streambed that are derived from the Wildcat formation are typically very soft and can be broken very easily, and tend to weather quickly into fine particle sizes once in the stream (PALCO 2003). Rates of hillslope erosion and downcutting by major streams within the soft rocks of the Wildcat Formation are geologically rapid (PALCO 2003).

The Franciscan Central Belt is composed of metasedimentary rocks that consist of a matrix of fine sediments with included blocks of harder metamorphic rocks (PALCO 2003). Like the Wildcat Group, this group weathers rapidly to sand, silt, and clay; however, it has a higher fraction of larger rocks that weather more slowly. The Yager Complex consists of dark gray indurated mudstones, shales, graywackes, siltstones, and conglomerates, with interbedded limey siltstones. Rocks from the Yager Formation are much harder and generate larger classes of gravel and cobble (PALCO 2003).

Particle Size Sampling

A two-stage sampling approach was used which involved collecting several subsamples per reach and determining statistics for the pooled sediment sample data (Bunte and Abt 2001). Bunte and Abt (2001) recommend collecting bed material samples that are large enough so that the mass of the largest particle in each subsample is generally less than three percent of the total sample mass. The less than three percent criterion was not achieved for all samples (particularly the Freshwater samples).

In the Waipaoa River, bulk sediment samples were obtained from exposed bars, near the channel centerline (Rosser 1997). The surface and subsurface sediment populations were sampled separately. Sample weights for the Waipaoa River samples were typically >50 kg, and the weight of the largest particle was typically less than two percent of the total sample weight. A total of 104 subsurface sediment samples were obtained at 1 km intervals along the mainstem, which included seven reaches within the river. Each study reach represented a different channel morphology, where the river has responded to different types and rates of sediment supply and sediment transport processes.

All particle size samples from the North Bay streams were obtained using a McNeil sampler, and applying a modified version of the method described by McNeil and Ahnell (1964). Under laboratory conditions, Schuett-Hames and others (1996) found the McNeil sampler to produce samples that most closely represented the composition of test gravel mixtures based on comparison of particles by individual size classes. In the North Bay study reaches, samples were taken from the thalweg in pool tail out positions and were intended to represent potential salmonid spawning sites. Research has shown that female salmonids appear to select spawning sites where flow conditions within the gravel are favorable for the successful incubation of eggs and alevin (Schuett-Hames and Pleus 1996). Favorable subsurface flow conditions exist where surface water infiltrates into the bed material, and is enhanced by a combination of surface water velocity, convex bed profile (such as in pool tail outs and riffle crests) and high gravel permeability (Vaux 1962). Bed material samples included the surface particles as well as subsurface particles. Sample weights from the North Bay region streams were typically 20 to 30 kg; the largest particle within each sample was generally three to 10 percent of the total sample weight.

Bed material samples from Freshwater Creek were obtained using a shovel technique. Data were provided by PALCO. Samples were obtained from the thalweg in pool tail crest positions within the channel. Individual subsample weights from Freshwater Creek were typically five to 15 kg. The particle size statistics were obtained by pooling the statistics from the three subsamples per reach. Schuett-Hames and others (1996) found that shovel based sampling techniques produced samples similar to the McNeil sampler, and that McNeil and shovel samples did not differ significantly in composition. Samples were collected facing upstream, and were taken from within the wetted channel in flowing water. Fine sediment may have been suspended when the bed material was disturbed during sampling. For this reason, the percentage of fine sediment in spawning sites in Freshwater Creek may have been underestimated by this sampling technique. The proportional volume of the smallest size category (<0.106 mm in their experiments) was found by Schuett-Hames and others (1996) to be significantly different between McNeil and shovel samples.

Statistical Analysis

A two stage sampling approach involved collecting several subsamples per study reach, analyzing each subsample separately, then computing statistics using the mean particle size parameters from all pooled subsamples, and assuming a normal distribution of sample means. Sampling precision was estimated by calculating the 95 and 80 percent confidence intervals for the D_{25} and D_{16} percentiles for each reach according to method in Bunte & Abt (2001, p. 303). The mean, standard deviation and standard error were calculated for the D_{16} and D_{25} in each study reach. The confidence intervals represent the range within which the true population mean is expected to occur at the stated level of probability.

Sample bias was evaluated by comparison of the mass of the largest particle in the subsample to the total subsample mass. To avoid bias towards larger particles, Bunte and Abt (2001) recommend that the weight of the largest particle should be less than three percent of the total sample weight. Samples in which the weight of the largest particle exceeded 3 percent of the total sample weight were considered to be biased and should be treated with caution.

Results

Cumulative particle size distribution curves for each of the study reaches are shown in *figure 2*. The distribution curves are composites for each study reach, and were constructed by combining the individual particle size fraction weights from all samples within a reach, and recalculating the percent finer values for each reach. The one mm threshold, representing the particle size that significantly reduces permeability and oxygen flow in redds, can be represented by a D_{16} that is one mm or coarser (in other words, the upper bound of the 11 to 16 percent target for fines in the PL HCP). In *figure 3,* mean D_{16} values that fall above the 1 mm threshold represent spawning gravels where incubation of eggs in redds is not threatened by excess fine sediment. The PL HCP target range for <6.35 mm sediment (particles that may block emergence of alevins) is 25 to 30 percent in the PFC matrix. Therefore the D_{16} and D_{25} can be used to test fine sediment thresholds.

Although the Waipaoa River is not a fish-bearing stream, the same fine sediment target thresholds were applied for purposes of evaluating sediment sampling techniques. The D_{16} threshold value of one mm appears to be met in four of seven reaches at the 95 percent confidence level. The D_{25} threshold of 6.35 mm was not met in any reach. Confidence intervals about the mean D_{16} and D_{25} values were ±0.22 mm and ±0.47 mm for the 95 percent confidence level.

The D_{16} target value of one mm appears to be met by all sampled North Bay (Napa, Sonoma, Mendocino) streams at the 80 percent confidence level. However, at the 95 percent confidence level we were unable to determine if the target value for D_{16} was met. The only stream that met the target for D_{16} at the 95 percent confidence level was Green Valley Creek. The D_{25} target of 6.35 mm was not achieved for Salt Hollow and Green Valley Creeks at the 95 percent confidence level. The target value appears to be met in Soda Creek at the 80 percent confidence level. We were unable to determine if the target value was met for Sulphur or Carneros Creeks at the 95 percent and 80 percent confidence level.

The smaller volume bed material samples collected from Freshwater Creek indicate that the D_{16} target value was met for five of nine reaches at the 80 percent confidence level. We were unable to determine if targets were met at the 95 percent confidence level for all but one reach, where the target was definitely met (reach 32). Mean D_{25} values indicate that HCP targets were met in most reaches in Freshwater Creek, however, considering the 95 percent and 80 percent confidence intervals we were unable to determine if the targets were met or not. The D_{25} target was not met in one (reach 135) at both 95 percent and 80 percent confidence levels.

Discussion

The accuracy of a sediment sample is defined as how closely the sample distribution represents the true distribution of sediment sizes in the channel, and sample precision refers to the size of the deviations from the sample mean to the mean value obtained by repeated sampling (Bunte and Abt 2001). For a specified sampling accuracy and precision, sample size should increase as the variability of the parent population increases (in other words, as the sorting becomes poorer or the standard deviation becomes larger). By consistently sampling the same position within the channel, or habitat unit, the variability of particle sizes within a single stream reach should be minimized. However, the northern California data were collected exclusively from pool tail-out positions (potential spawning sites), and illustrate the high degree of variability within a single habitat unit and stream reach. The data also indicate that either a larger number of replicate samples, or larger individual samples are required to assess if fine sediment thresholds are met or not.

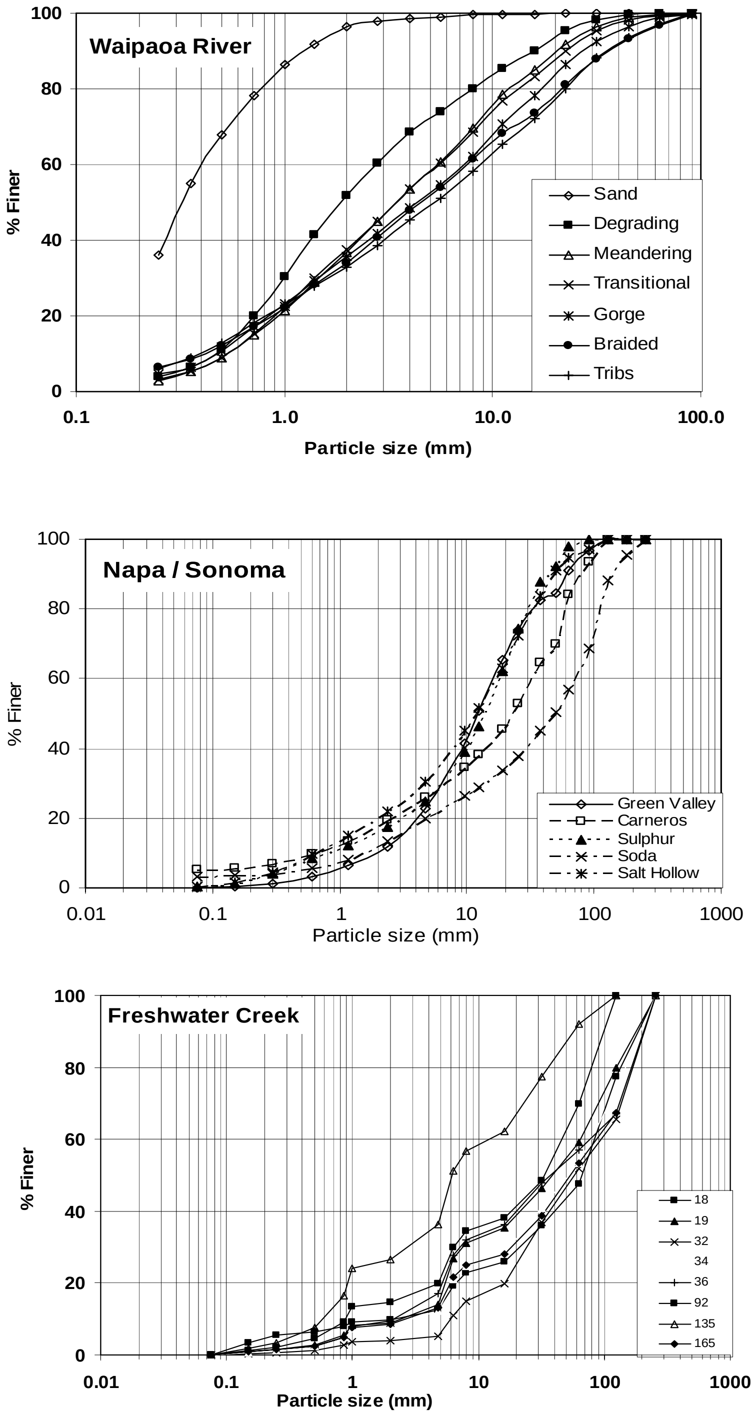

Figure 2—Cumulative particle size distribution curves showing composite samples from the 3 study areas.

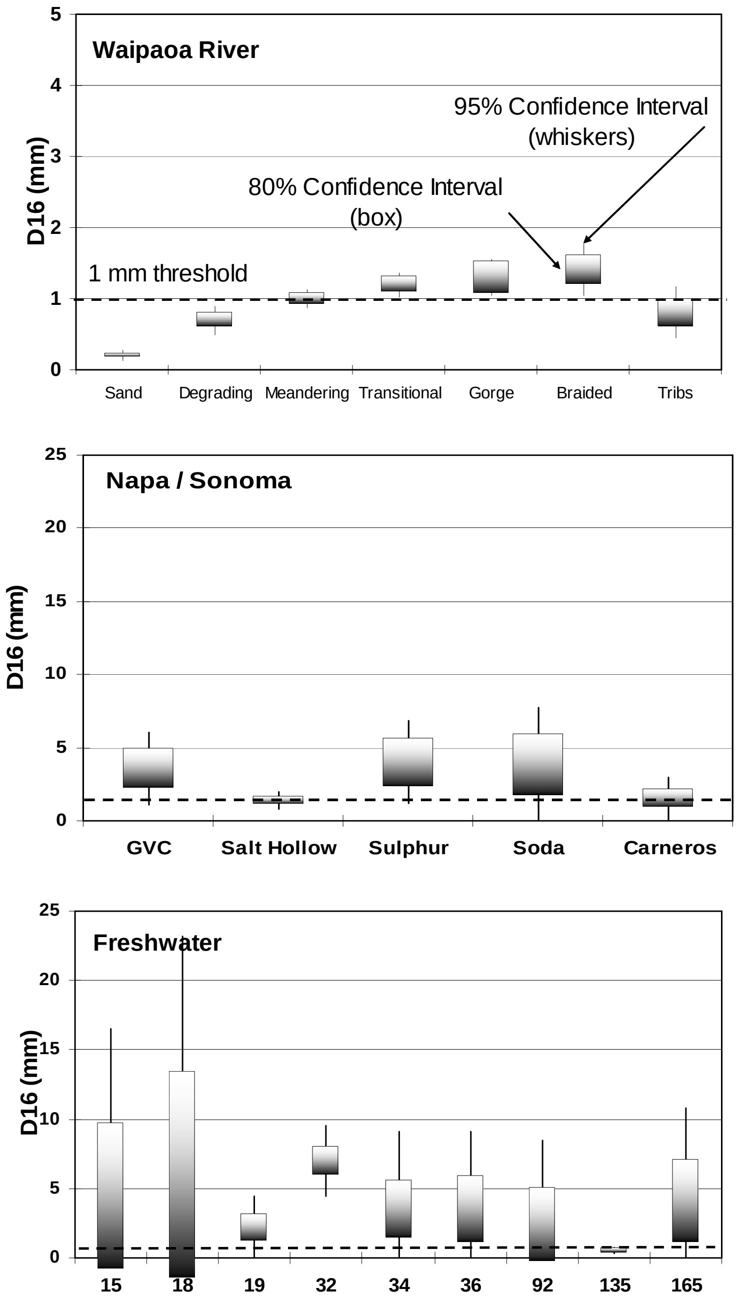

Figure 3—Box and whisker plots showing the 95 percent confidence intervals (whiskers) and the 80 percent confidence intervals (box) around the mean D_{16} percentile values. When the mean value is below the threshold value, the implication is that the "properly functioning conditions" are <u>not</u> met.

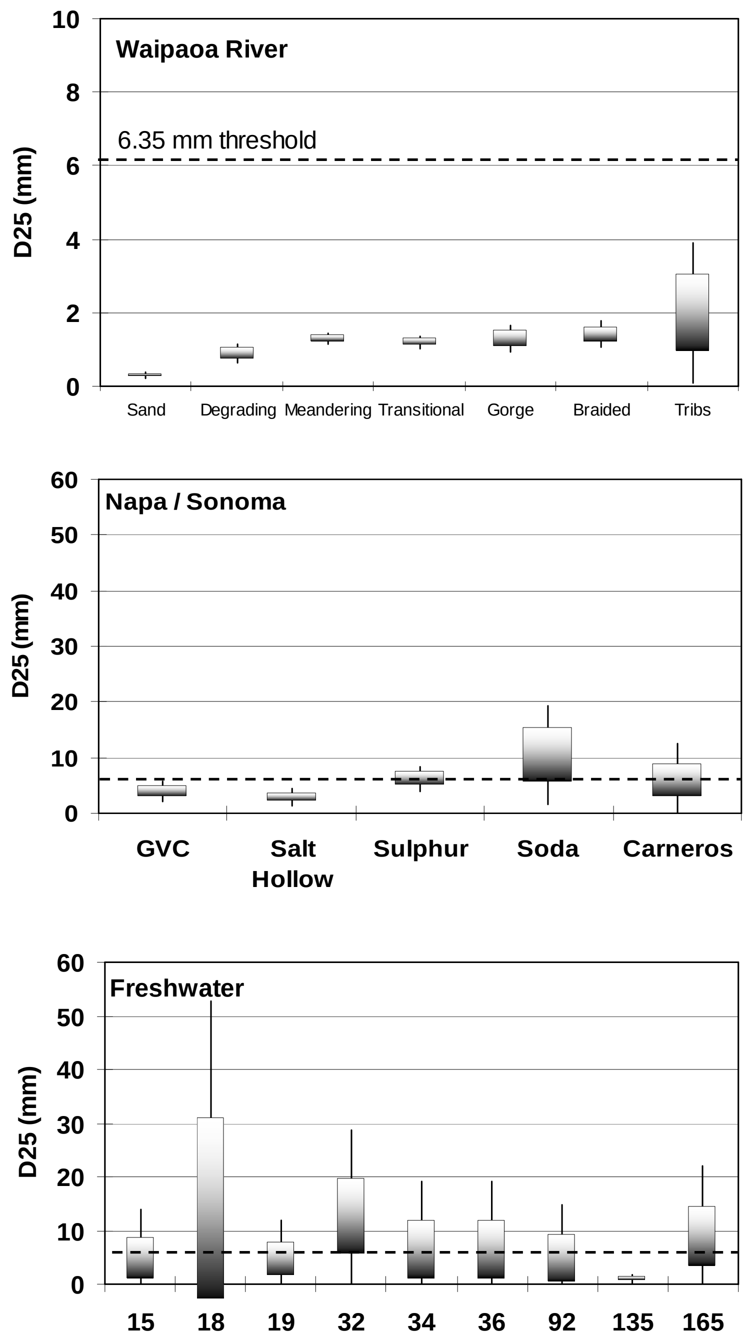

Figure 4—Box and whisker plots showing the 95 percent confidence intervals (whiskers) and the 80 percent confidence intervals (box) around the mean D_{25} percentile values. When the mean value is below the threshold value, the implication is that the "properly functioning conditions" are <u>not</u> met.

The Waipaoa River does not support a salmonid population because of the characteristics of the bed material. There is abundant fine material supplied to the river by large active gullies in the upper basin. The very narrow (±0.22 mm mean value for 95 percent confidence level) confidence intervals for bed material samples from the Waipaoa River likely reflects the large number of large unbiased samples collected, the fine particle size distribution of the bed material, and a sampling scheme that was designed for the physical conditions in the river. If a large number of unbiased samples are collected, the confidence intervals around the mean D_{16} and D_{25} values are small and we can say with greater certainty that fine sediment thresholds have been met or not (in the case of the Waipaoa River, not met). However, this level of sampling intensity is generally not necessary or achievable for most practical situations where spawning gravel composition is to be assessed.The majority of the sampled reaches in the North Bay region are known to support salmonid populations, predominantly steelhead trout except for Green Valley Creek. These streams were sampled using the standard technique for determining spawning gravel composition in the Pacific Northwest, using a McNeil sampler at pool tail-out postions within the channel. Most of the samples stream reaches appeared to meet the D_{16} target value at the 80 percent confidence level. We were unable to determine if the target value was met for Sulphur or Carneros at the 95 percent and 80 percent confidence level. The volume of material collected with a McNeil sampler is often not large enough to exclude sample bias caused by unrepresentative sampling of the larger size classes. A larger number of subsamples is required to achieve greater sample accuracy and precision. However, due to the small areal extent of potential spawning sites, particularly in small streams, it may not be practical to take larger samples.

The large spread of confidence intervals for bed material samples from Freshwater Creek likely reflects the variability and coarse nature of the bed material, the small amount of sediment in the subsamples, and the small number of subsamples used to characterize each reach (n = 3). The uneven shape of the cumulative distribution curves *(fig. 2A)* is indicative of the bias caused by the high proportion of larger grains in the sample. Larger samples are required to reduce the bias of larger particles and to produce smooth representative size distribution curves.

If regulatory targets are to be set with respect to percent fines, the required confidence intervals should also be stated so that sample sizes and the number of replicates required can be calculated. There may be a need to relax standard statistical confidence levels from the standard value of $\alpha = 0.05$ when dealing with natural resource applications to take into account the highly variable nature of riverbed sediments and the level of effort required to collect and analyze samples. The given examples represent fairly intensive sampling efforts, yet do not produce very precise estimates of the particle size percentiles of interest.

Conclusions and Implications

To determine if streambed material meets specified regulatory targets with respect to salmonid spawning habitat quality, bed material sampling efforts should be tailored to the specific study reach under investigation. Sampling technique, including sample size, and number of samples, should reflect the physical characteristics of the study reach. Any particle size sampling program should consider the level of accuracy that will be achieved, and whether the chosen sampling scheme will produce results that will determine if regulatory thresholds are met or not. A critical step is collection of sample data to calculate sample variances used to predict requisite sample mass and number of samples required to achieve an acceptable level of precision. Statistical power should also be considered.

Particle size sampling is a substantial undertaking. Users of particle size data, including regulatory agencies and landowners, should be conscious of the statistical constraints involved with bed material sampling if numeric targets are to be set and assessed.

Acknowledgments

Lester McKee, Sarah Pearce–San Francisco Estuary Institute; Ron Benkert–Sonoma County Water Agency; Ulysses Lolonis and Greg Lolonis–Lolonis Vineyards, Inc; Gretchen Oliver, Kate Sullivan, Jeff Barrett–Pacific Lumber Company; Basil Gomez –Indiana State University; Dave Peacock–Gisborne District Council; Andrea Rosser, Vaughan Griffin, Claire Guthrie–visiting Kiwi field assistants.

The particle size data from the Waipaoa River were collected as part of a MSc thesis (Gomez and others 2001, Rosser 1997), with funding from the Gisborne District Council. Data for Freshwater Creek were provided by the Pacific Lumber Company. Data from Soda, Carneros and Sulphur Creeks were collected as part of a Cal-Fed funded study under contract with the San Francisco Estuary Institute. Data from Green Valley Creek was collected under contract with the Sonoma Water County Agency. Data from Salt Hollow Creek was collected for Lolonis Vineyards, Inc.

References

Bunte, K.; Abt, S.R. 2001. **Sampling surface and subsurface particle-size distribution in wadable gravel- and cobble-bed streams for analyses in sediment transport, hydraulics, and streambed monitoring.** Gen. Tech. Rep. RMRS-GTR-74. Fort Collins, CO: Rocky Mountain Research Station, Forest Service, U.S. Department of Agriculture; 428 p.

Chapman, D.W. 1988. **Critical review of variables used to define effects of fines in redds of large salmonids.** Transactions of the American Fisheries Society 117: 1-21.

Gomez, B.; Rosser, B.; Peacock, D.; Hicks, M.; Palmer, J. 2001. **Downstream fining in a rapidly aggrading gravel bed river**. Water Resources Research 37: 1813-1823.

Hicks, D.M.; Gomez, B.; Trustrum, N.A. 2000. **Erosion thresholds and suspended sediment yields: Waipaoa River basin, New Zealand**. Water Resources Research 36: 1129-1142.

Kondolf, G.M. 2000. **Assessing salmonid spawning gravel quality**. Transactions of the American Fisheries Society 129: 262-281.

Kondolf, G.M.; Wolman, M.G. 1993. **The sizes of salmonid spawning gravels**. Water Resources Research 29: 2275-2285.

McNeil, W.J.; Ahnell, W.H. 1964. **Measurement of gravel composition of salmon stream beds**. Circular No. 120. Seattle, WA: University of Washington, Fisheries Research Institute.

Moore, P.R.; Mazengarb, C. 1992. **Geology and landforms of the Raukumara Peninsula**. In: Soons, J.; Selby, M.J., eds. Landforms of New Zealand. Reading, MA: Addison-Wesley-Longman; 334-343.

Pearce, S.; O'Connor, M.; Grossinger, R.; McKee, L. 2002. **Napa River TMDL baseline study: geomorphic processes and habitat form and function in Soda Creek**, a technical report of the Regional Watershed Program. SFEI Contribution 63. Oakland, CA: San Francisco Estuary Institute.

Rosser, B. 1997. **Downstream fining in the Waipaoa River; an aggrading gravel-bed river, East Coast, New Zealand.** Palmerston North, New Zealand: Massey University. M.S. thesis.

Schuett-Hames, D.; Conrad, B.; Pleus, A.; Smith, D. 1996. **Field comparison of the McNeil sampler with three shovel-based methods used to sample spawning substrate composition in small streams**. Timber Fish and Wildlife Ambient Monitoring Program Report TFW-AM 9-96-005.

Trafford, J.A. 1998. **Bedload transport at Kanakania, Waipaoa River, East Coast, New Zealand**. Auckland, New Zealand: University of Auckland. M.S. thesis.

Valentine, B.E. 1995. **Stream substrate quality for salmonids: guidelines for sampling, processing, and analysis**. Santa Rosa, CA: California Department of Forestry and Fire Protection, Coast Cascade Regional Office.

Vaux, W.G. 1962. **Interchange of stream and intragravel water in a salmon spawning riffle**. Special Science Report, Fisheries No. 405. Washington, DC: USDI Fish and Wildlife Service.