SEDIMENT AND STREAMBED MONITORING PLAN FOR LAGUNITAS CREEK

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Contents

1. Introduction

The Sediment and Streambed Monitoring Plan (the Plan) describes sediment monitoring goals and how they relate to District fisheries and riparian management plans. Prior monitoring methods are reviewed in relation to proposed future monitoring. The Plan describes monitoring parameters and methods, including details pertaining to sampling methods, sample size and analytical methods. The Plan is suitable for implementation, however, it may be adapted over time.

1.1. Monitoring Goals

The Plan is intended to provide data and analytical methods that can achieve the following goals.

- Document sediment and streambed conditions in Lagunitas Creek, including its major tributaries San Geronimo Creek and Devils Gulch.
- Provide a means to evaluate the efficacy of sediment management efforts implemented within the Lagunitas Creek watershed.
- Integrate hydrologic and geomorphologic characteristics of Lagunitas Creek with its biological components in an attempt to reveal how stream flow, sediment and streambed conditions influence fish and shrimp populations.

The monitoring goals above are related to District fisheries management goals in Lagunitas Creek:

- Reduce the quantity of fine sediment that enters Lagunitas Creek and enhance the streambed habitat conditions of the creek, for the benefit of coho, steelhead, and California freshwater shrimp.
- Improve and enhance rearing habitat for salmonids and enhance the condition of the riparian corridor to benefit all fishery resources of the Lagunitas Creek watershed.

1.2. Hypotheses

Monitoring data will be used to conduct formal hypothesis testing using appropriate sampling statistics as described in this plan. The principal hypotheses to be tested are:

- *Sediment size distributions are uniform throughout Lagunitas Creek; alternatively, sediment size distributions vary between stream reaches*. Channel gradient and sediment supply, among other factors, are expected to influence sediment size distributions, hence there is reason to believe that sediment size distributions will differ among stream reaches.
- *Sediment size distributions are uniform over time; alternatively, sediment size distributions vary over time.* Prior monitoring observations suggest that storm history and proximity to watershed sediment sources affect temporal patterns of change in sediment size. This plan will test whether there are statistically significant time trends in sediment size distribution.

This study design is based on prior sampling studies (described below) that focused on surface sediment size distributions. Data from prior studies enabled the development of a sampling design with specified sample size and expected sampling error for surface sediment size distributions. Sediment size distributions will be statistically evaluated in terms of percentiles of the size distribution (e.g. median diameter-d50, d16, d84, etc.) and the proportion of the size distribution considered to be “fine” sediment (e.g. < 4 mm diameter). Hypothesis testing will be followed by examination of confidence intervals around percentiles and proportions of interest in the sediment size distribution.

Additional data relating to size distributions of subsurface sediment, sedimentation processes, suspended sediment transport, large woody debris and fish habitat will be evaluated using descriptive statistics and confidence intervals as well as statistical tests presented in the Plan. These analyses will guide development of additional hypotheses and determination of appropriate sample sizes. Modifications to monitoring specified in the Plan may be considered based on statistical power, sample size requirements, and sampling efficiency.

2. Monitoring Plan Overview

The Plan includes several discrete monitoring parameters distributed among broadly defined stream reaches in the Lagunitas Creek watershed as summarized below (Figure 1). The Plan is designed to evaluate trends in sediment conditions over time using sampling methods and analytical techniques that can distinguish between statistically-verified trends and random variation. In support of fish habitat monitoring by District biologists, the Plan will also provide quantitative and qualitative data relevant to the quality and quantity of aquatic habitat.

2.1. Channel Reach Framework for Monitoring Sites

Monitoring sites will be distributed within distinct reaches of the Lagunitas Creek mainstem and its tributaries. Three mainstem reaches have been identified

(Figure 1) based on data from prior studies (Table 1) pertaining to sediment size, geomorphology and channel slope:

- Hwy 1 to Tocaloma Bridge (reach M1),
- Tocaloma Bridge to Devils Gulch (reach M2), and
- Devils Gulch to Shafter Bridge (reach M3).

Two tributaries will be monitored:
- Devils Gulch (reach T1) and
- San Geronimo Creek (reach T2).

Monitoring data will be collected and analyzed within each of these five reaches as they represent distinctive portions of Lagunitas Creek that have significantly different characteristics such as channel slope and width (Table 1), as well as differences in stream flow and sediment supply controlled by both natural conditions and the effects of Kent Lake[1]. Time trend analysis of channel conditions will be made more effective by collecting and analyzing monitoring data in this spatial framework because inherent variability between reaches will not be confused with change over time.

Table 1. Summary of reach characteristics and sampled area.

Reach	Length[a] (miles)	Mean Slope (ft/ft)	Typical Bankfull Width (ft)	Estimated Total Sample Length[e] with 4 Sites (ft)	Estimated % of Reach Sampled
M1: Tocaloma Bridge to Hwy 1	5.8	0.002[c]	40	3,200	10
M2: Devils Gl. to Tocaloma Br.	2.7	0.003[c]	50	4,000	28
M3: Shafter Bridge to Devils Gl.	3.1	0.004[b]	60	4,800	29
T1: Devils Gulch	1.4	0.02[d]	20	1,600	22
T2: San Geronimo Creek	4.6	0.007[b]	30	2,400	10

Notes:
a. Reach lengths from MMWD (2008) Lagunitas Creek Habitat Typing Survey 2006 Analysis, Table 2.
b. Slope estimated from longitudinal profile surveyed by SFBRWQCB.
c. Slope estimated from preliminary analysis of 2009 LiDAR data.
d. Slope estimated from USGS topographic data.
e. Sample length refers to the systematic sampling reaches.
f. See Figure 1 for reach locations.

[1] O'Connor Environmental, Inc. 2006. Lagunitas Creek Fine Sediment Investigation. p 14-15.

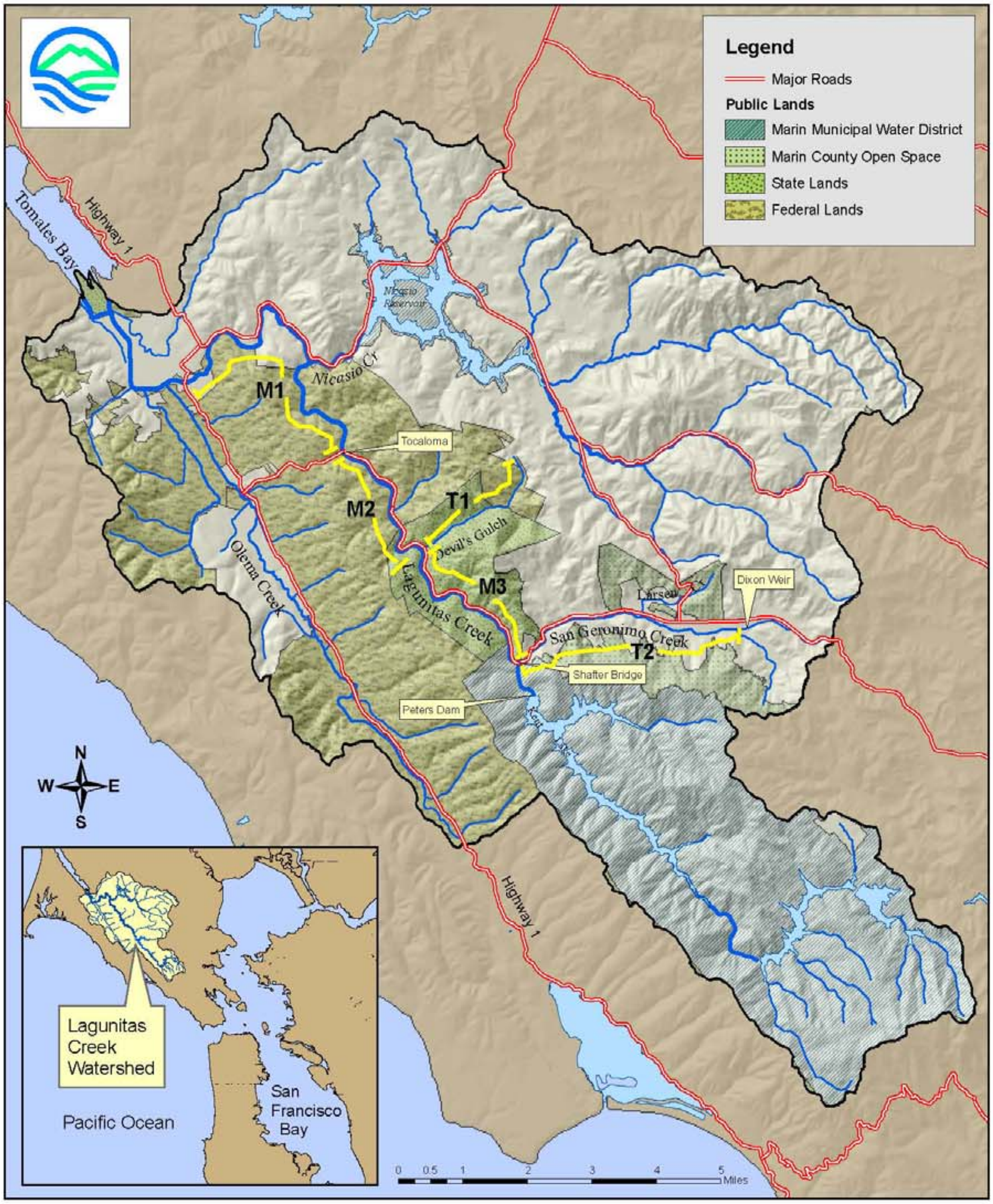

Figure 1. Map of the Lagunitas Creek Watershed Sediment and Streambed Monitoring Reaches

2.2. Systematic Streambed Surface Sampling

A systematic sampling framework will be used to guide data collection in the field and data analysis. The systematic sampling approach will be used to determine the streambed surface sediment size distribution and other characteristics of interest, such as distribution of habitat types and sediment patches (facies), depth of fine sediment deposits, and large woody debris.

A systematic random grid (Figure 2) will be established within the lateral limits of the bankfull channel to conduct this sampling procedure. Transverse transects spaced at intervals of one-half bankfull width will be sampled at ten equally-spaced points across the transect over a portion of channel twenty bankfull widths in length. This sampling grid will yield 400 data points from forty transects; this design provides relatively high accuracy while limiting the extent (and cost) of sampling. Data to be collected using the systematic sampling grid include:

- the size distribution of sediment on the surface of the streambed,
- the size distribution of sediment in the subsurface of the streambed,
- the proportion of the channel bed occupied by fine sediment including characteristic sediment mixtures distributed in “patches” (sediment facies),
- proportions of habitat types (pool, run, glide, riffle and cascade)
- depth and size distribution of fine sediment deposits (this data may be subsampled to improve efficiency based on analysis of preliminary data), and
- volume and characteristics of large woody debris (measured on grid transects)

2.3. Systematic Streambed Subsurface Sampling

Sampling and analysis of size distributions of the sediment underlying the streambed surface where salmonids are likely to spawn will provide data describing spawning habitat quality and the sedimentation status of the bed.

2.3.1. Spawning Gravel Condition

A random spawning habitat site within each grid will be selected for subsurface sediment sampling and analysis to determine the size distribution of spawning gravel. Material will be collected in bulk to a depth of about one foot using a “McNeil sampler”. Only locations where spawning is likely to occur

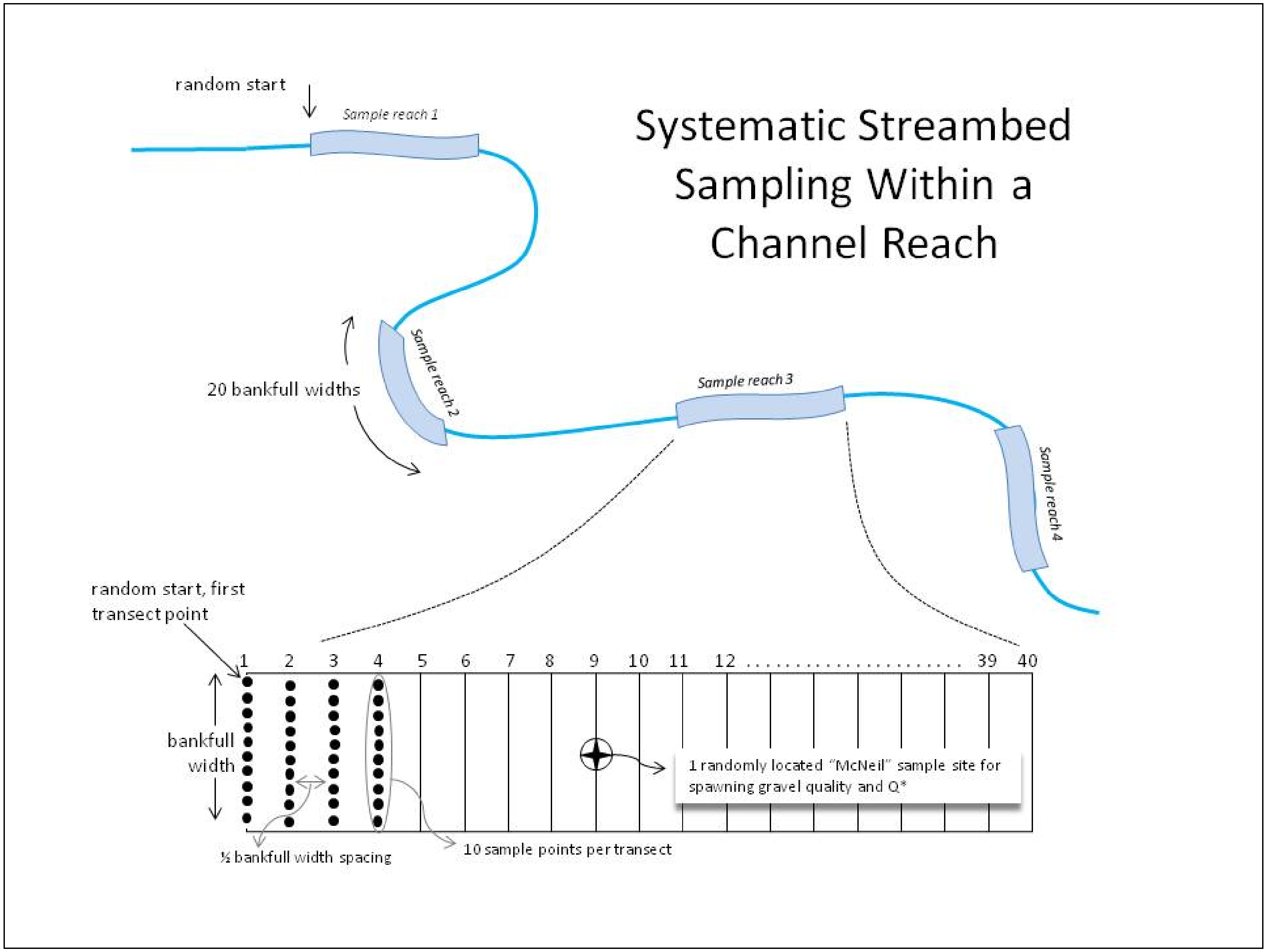

Figure 2. Schematic representation of streambed sampling.

(typically near the transition between a pool and downstream riffle) will be selected for sampling. The sediment size distributions will characterize spawning habitat quality and spatial variability. The data will also be compared to earlier data sets to evaluate changes over time.

2.3.2. Sediment Supply and Transport Capacity-The q* Index

Spawning gravel size distributions will simultaneously be used to calculate a geomorphic index representing the relationship between sediment transport capacity and sediment supply (q_*). The size distribution of the streambed surface at the sampling location and local bed shear stress at bankfull flow will also be required.

2.4. Sediment Patches

The distribution of sediment patches (facies) will be systematically sampled on the grid. Sediment facies previously described in the study area include well sorted sand, fine gravel and sand, gravel with pockets of sand, gravel dominant and cobble dominant. Observation and monitoring of sediment facies is expected to provide insights into sedimentation processes, and patch distribution will be evaluated in relation to other sedimentation and habitat monitoring parameters.

2.5. Habitat Types

The distribution of habitat types will be systematically sampled on the grid. Aquatic habitat types previously used for Lagunitas Creek include pool, run, glide, riffle and cascade. Observation and monitoring of habitat types is expected to provide insights regarding sedimentation processes as they relate to fish habitat.

2.6. Depth of Fine Sediment Patches

The depth of fine sediment facies will be subsampled on the grid. In addition, the size distribution of these fine sediment deposits will be subsampled. Observation and monitoring of the depth of fine sediment facies will permit estimation of the quantity of fine sediment and its distribution in Lagunitas Creek.

2.7. Large Woody Debris (LWD)

Systematic random streambed sampling will include measurements of LWD on sample transects established for the sampling grid (Figure 2). LWD is a component of fish habitat that contributes cover and may interact with streamflow to create pools and depositional features. Prior studies of Lagunitas Creek suggested that streambed sediment sizes tend to be finer in the vicinity of LWD. Observations and monitoring of LWD will help characterize the role of LWD in habitat, and permit evaluation of the effect of LWD on sediment size distributions.

2.8. Streambed Elevation and Topography

Topographic surveys will be conducted periodically at two monitoring sites each in the reaches M1, M2 and M3. The primary product of the survey will be a digital elevation model from which topographic maps and cross-sections can be produced. Elevation data from a systematic sampling grid will also be produced to test for changes in mean bed elevation over time. This type of monitoring will produce quantitative data and analyses, along with process observations and quantitative analysis of trends that will provide continuity with monitoring that began in 1992.

Monitoring sites will coincide with prior established monitoring reaches KB (reach M3), KC (reach M3), KD (reach M2) and KF (reach M2). Two new monitoring sites will be established in reach M1. It is intended that these monitoring sites will coincide with monitoring sites used for systematic sampling of sediment described above, including q_* sites. Maps will be developed for bed topography, woody debris, sediment patches, and other morphologic features. These are intended to provide descriptive monitoring data in a three-dimensional map context distinct from the numerical two-dimensional data obtained through systematic sampling.

2.9. Turbidity Threshold Sampling

An effective method of quantifying fine sediment delivery from management activities dispersed over a group of sites or an entire watershed is to measure suspended sediment loads (SSL) at key locations. Turbidity Threshold Sampling (TTS) is an accurate and cost effective SSL monitoring system that estimates loads by sampling suspended sediment (SS) in conjunction with continuous turbidity (an optical property of water) and streamflow measurements. [2] Determination of SSL for individual storm events will provide highly accurate estimates of sediment flux at locations of interest over a variety of time intervals for trend analysis.

TTS monitoring sites are proposed at three locations: San Geronimo Creek gauge site (existing station operated by Balance Hydrologics), Samuel P. Taylor State Park gauge site (existing station operated by USGS), and Devils Gulch (gauging station to be established). These monitoring data will provide the District with direct measures of sediment yield that can be used to evaluate the effectiveness of the District's erosion control management efforts as well as trends over time. This data set will be particularly valuable in that it provides direct continuous

[2] Lewis J and Eads R (2009). Implementation guide for turbidity threshold sampling: principles, procedures, and analysis. Gen. Tech. Rep. PSW-GTR-212. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 87 p.

measurements of sediment yield that will complement indirect measures of erosion and sedimentation from streambed monitoring.

2.10. Limitations

Proposed methods may require modification for the Tocaloma to Hwy. 1 reach (M1) owing to the prevailing depth of water and the prevalence of finer-grained channel substrate. The final monitoring plan for reach M1 will be determined following a pilot study to test the applicability of Plan methods in this reach. Feasible alternative methods would be selected as appropriate.

The recommended approach to monitoring depth and size distribution of fine sediment deposits is similar to methodology using the metric “v_*“ to systematically monitor the volume of pools occupied by fine sediment.[3] The proposed adaptation of the method for use in Lagunitas Creek is feasible but has not been tested to evaluate the expected precision of sampling. The proposed approach is expected to provide quantitative estimates of the volume of fine sediment stored on the channel bed that will be useful for evaluating sedimentation impacts on fish habitat as well as trend analysis related to effectiveness of watershed management to control erosion.

2.11. Frequency of Monitoring

Frequency of monitoring in the Plan is variable (Table 2). Annual sampling of all monitoring sites for all parameters is not recommended. Rather, a fixed minimum sampling frequency is proposed that may be modified by high magnitude flow events in Lagunitas Creek. Sampling at the full complement of systematic streambed monitoring sites would occur at a maximum interval of three years. Sampling would also occur during the summer following a peak flow event exceeding 3,000 cfs at Samuel P. Taylor State Park (USGS gauge 11460400). Sampling would occur again the third summer following, assuming that no additional 3,000 cfs events occur. Based on the period of record 1980-2006, monitoring would have occurred in 13 of 27 years using these criteria. Sampling would have occurred in consecutive years during the intervals 1985 to 1986 (2 consecutive years) and 1995 to 1998 (4 consecutive years).

Annual monitoring would be conducted for a limited set of systematic streambed monitoring parameters (size distribution, proportion of fine sediment and patch type, and habitat type) from a subset of sites comprised of one monitoring site in each of the five reaches of Lagunitas Creek. Fine sediment depth and woody

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[3] Lisle T and Hilton S (1999). Fine bed material in pools of natural gravel bed channels. Water Resources Research 35(4):1291-1304. and
Hilton, S. and Lisle, T.E. 1993. Measuring the fraction of pool volume filled with fine sediment. Research Note PSW-RN-414, 11 pp. USDA For. Serv., Albany, Calif.

debris would be excluded from annual monitoring. TTS monitoring at stream gaging stations will combine routine maintenance and flow observations with continuous automated sampling during the rainy season.

Table 2. Summary of monitoring program sampling frequency (see also Table 3 for expanded list of monitoring tasks within the Systematic Sampling monitoring element).

	Frequency of Monitoring		
Monitoring Element	3 years OR after > 3,000 cfs peak flow	Annual	Annual Rainy Season (Oct.-April)
Systematic Sampling	5 reaches, 4 sites per reach	5 reaches, 1 site per reach	n.a.
Streambed Elevation & Topography	3 reaches, 2 sites per reach	n.a.	n.a.
Turbidity Threshold Sampling	n.a.	n.a.	3 reaches, 1 site per reach

2.12. Number of Monitoring Sites

Methods for grid sampling of surface sediment size distributions and data sets available from OEI's 2006 study of fine sediment in Lagunitas Creek were used to design the systematic random sampling and McNeil sampling. Details of the monitoring design are described in the following sections.

Monitoring site reaches are designed to be twenty bankfull width units in length, so typical monitoring reaches in Lagunitas Creek would likely be on the order of 1,000 ft long (Table 1). Each site would be comprised of forty sampling transects perpendicular to flow and spaced at intervals of one-half bankfull width (Figure 2). Each transect would contain ten evenly spaced sample points; locations would be subject to a random start in each transect. The Plan includes four monitoring site reaches within each of the five reaches of Lagunitas Creek and its tributaries identified above. Hence, the Plan proposes to establish twenty monitoring site reaches. Sampling to monitor spawning habitat also comprises twenty sampling sites to be co-located with systematic streambed monitoring reaches. Monitoring activities under the Plan are summarized in Table 3.

Table 3. Summary of monitoring program sampling.

		Sample Reach					
Monitoring Element	Monitoring Task	M1	M2	M3	T1	T2	Total
Systematic Sampling	Surface Sampling	X	X	X	X	X	
	Sites/Reach	4	4	4	4	4	20
	Transects/Site	40	40	40	40	40	200
	Samples/Transect	10	10	10	10	10	50
	Total Samples	1600	1600	1600	1600	1600	8000
	Subsurface (McNeil) Sampling	X	X	X	X	X	
	Sites/Reach	4	4	4	4	4	20
	Samples/Site	1	1	1	1	1	
	Total Samples	4	4	4	4	4	20
	Large Woody Debris Sampling	X	X	X	X	X	
	Sites/Reach	4	4	4	4	4	20
	Transects/Site	40	40	40	40	40	200
	Total Samples	160	160	160	160	160	800
Streambed Elevation & Topography	Bed Topography Survey (Total Station)	X	X	X			
	Sites/Reach	2	2	2			6
Turbidity Threshold Sampling (TTS)	TTS Monitoring Stations			X	X	X	
Analyses	Sediment Size Analysis	X	X	X	X	X	
	Woody Debris Volumes	X	X	X	X	X	
	q* calculations	X	X	X	X	X	
	Digital Elevation Models (DEMs)	X	X	X			
	Mean Bed Elevation	X	X	X			
	TTS Analyses			X	X	X	

3. Prior Monitoring Program

The prior monitoring program[4] measured streambed parameters of interest with respect to sediment conditions as they affect fish habitat. The Plan proposes substantial changes in the approach to monitoring relative to prior monitoring; however, these changes do not represent a radical departure from the prior monitoring program with respect to monitoring parameters. Continuity with selected elements of the prior monitoring program will be maintained. Prior monitoring analyses of monitoring data did not utilize formal hypothesis testing procedures. Following is a brief summary of the prior monitoring program including a description of how prior monitoring program elements will be handled under the Plan. *Elements of the prior monitoring program for which further consideration is recommended are emphasized with italics.*

Annual Reconnaissance Survey. This survey was conducted to provide geomorphic perspective on annual channel changes at a broader spatial scale within Lagunitas Creek. It provided insights regarding annual variation of in-stream processes and channel condition. The Plan will not continue this reconnaissance survey in its current form.

The Plan is expected to document significant changes at the scale of monitoring reaches (M1, M2, M3, T1 and T2). The proportion of channel to be sampled in four monitoring sites per reach is shown in Table 1. The Plan assumes that significant systemic changes would be detected in this framework. Local variations detected in the spatially comprehensive reconnaissance surveys may not be individually represented in the Plan.

Systematic photo point monitoring within sampling reaches will be conducted to provide supplemental descriptive information. Successive photos can be compared to qualitatively evaluate change over time. Particular areas of interest that are not within the sampling reaches will be identified (e.g. the Big Bend area where sediment storage and bank erosion dynamics appear to be of greater significance), and comparable photo points established.

Bed Elevation and Channel Configuration. Topographic cross-sections of relatively short reaches containing representative riffles, pools and glides have been used to document changes in bed elevation and channel configuration over time. This prior monitoring established that channel patterns and bed elevations are relatively stable over a period of years with modest variability from year to year. *The Plan proposes to retain this fundamental approach, with substantial revisions to the methods of surveying and the frequency of data collection.*

[4] Balance Hydrologics 2008. Lagunitas Creek Sediment and Riparian Management Plan, Marin County, California: Streambed Monitoring Report, 1995-2007.

The Plan proposes to produce three-dimensional maps of selected portions of monitoring reaches using a Total Station survey instrument to develop a digital elevation model (DEM) of the selected portion of the reach. DEM's will then be used to create topographic maps to document conditions and assess changes in the channel between surveys. Both qualitative and quantitative analyses will be performed. Bed elevation changes in relation to habitat units and prior cross-section locations from the prior monitoring program can continue to be observed.

Particle-size Distribution of Bed Surface. The prior monitoring program focused sampling intensity on relatively short monitoring reaches. The Plan utilizes a similar method (surface point counts on a systematic grid), but over a larger area and at wider intervals. Existing monitoring data and proposed monitoring data from the Plan would be generally comparable, but may not be directly comparable.

Embeddedness of Cobbles and Boulders. The Plan eliminates this monitoring parameter. Alternative methods are proposed to measure accumulations of fine sediment on the bed. *Embeddedness is primarily a fish habitat metric. We suggest that District fisheries staff consider including this measure of cover habitat be retained in fish habitat monitoring protocols.*

Abundance of Cobbles and Boulders. The Plan will continue to provide data on the abundance of cobbles and boulders through the measurement of particle size distributions on the bed surface.

Percent of Bed Covered by Fine Sediment. The Plan will continue to provide data on the abundance of fine sediment through the measurement of particle size distributions on the bed surface.

Particle-size Distribution of Bed Subsurface. The prior monitoring program obtained samples of subsurface sediment from pool tails. The Plan proposes an alternative method focusing on spawning habitat that will produce data on size distribution of subsurface sediment. McNeil samples of subsurface sediment in pool-tail and riffle crest transitions demonstrated in a prior study[5] provides comparable information regarding sediment conditions in addition to direct measures of habitat quality.

Lithology of Fine Sediment Deposits. Distinctive rock types found in different portions of the Lagunitas Creek watershed enabled utilization of this technique to provide information on the relative magnitude of sediment source areas in the watershed. More direct studies of sediment sources have been conducted and

[5] O'Connor Environmental, Inc. 2006. Lagunitas Creek Fine Sediment Investigation.

are proposed since the inception of this analysis. The Plan does not propose to continue routine measurement of this parameter.

San Geronimo Creek Stream Gauge. Hydrologic data from San Geronimo Creek are extremely useful. *It is recommended that stream gauging activity at this site should be continued.* Bedload sediment transport measurements are of considerable value. These data provide observations pertaining to bed sediment in San Geronimo Creek, a primary source area for sediment delivered to Lagunitas Creek. The utility of these data with respect to inferences that can be made regarding changes in transport rates over time is limited by the variability of the data. *Bedload transport data should be analyzed to determine the accuracy of the inferences that may be made.* The existing data are extremely useful in that they establish a relationship between stream discharge and bedload transport rate in San Geronimo Creek.

4. Monitoring Plan Methods and Analysis Techniques

In this section, details regarding data collection and analytical techniques, along with study design considerations, are described in greater detail.

4.1. Study Design for Systematic Streambed Sampling

A systematic random grid sampling procedure will be used to collect the following data:

- the size distribution of sediment on the surface of the streambed,
- the proportion of the channel bed occupied by fine sediment including characteristic sediment mixtures distributed in "patches" (sediment facies),
- proportions of habitat types (pool, run, glide, riffle and cascade)
- depth and size distribution of fine sediment deposits (this data may be subsampled to improve efficiency based on analysis of preliminary data), and
- volume and characteristics of large woody debris (measured on grid transects)

The design for systematic sampling was guided by sample data from prior studies that used a comparable design.[6] The primary monitoring parameter considered is the size distribution of sediment, and it is upon these parameters that the analysis of sampling design was based. Consideration was given both to sampling objectives and sampling efficiency. The recommended sampling grid for monitoring sites contains transverse transects (oriented perpendicular to flow), spaced at intervals of one-half bankfull width with sample points at ten equally-spaced locations across the transect over a portion of channel twenty bankfull widths in length. This sampling grid will yield 400 data points from forty transects.

A generalized depiction of the distribution of sampling units within a stream reach is shown in Figure 2. Sampling locations would be determined once; these same sample units would be re-sampled during all successive sampling events.

Based on sampling data from 2005 streambed surveys of the bankfull channel width, sampling precision over a range of the number of transects was estimated assuming transects spaced at intervals of one bankfull width. Additional analyses were conducted to evaluate transect spacing greater than one bankfull width, however the efficiency of sampling declines (i.e. the cost of sampling increases) as transect spacing increases hence the analysis presented focuses on an interval of one bankfull width.

[6] O'Connor Environmental, Inc. 2006. Lagunitas Creek Fine Sediment Investigation.

Sampling precision is evaluated in terms of the mean of the size distribution measured in “psi” units (sediment size classes based on log_2 units, e.g. 1 mm = 0 , 2 mm =1, 4 mm = 2, 8 mm =3, and so on) and in terms of the proportion of the streambed sediment size distribution finer than 4 mm. Figures 3 and 4 on the following page summarize these relationships.

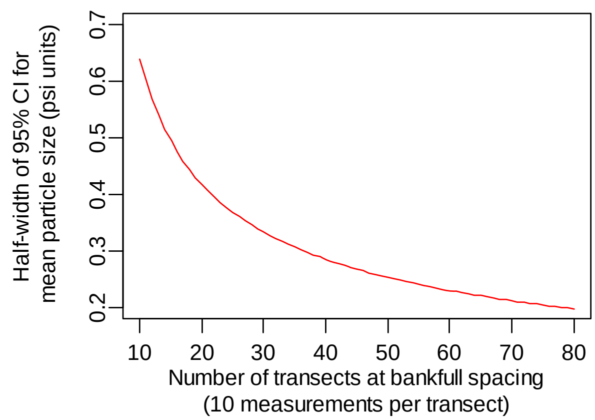

Figure 3. Relationship between number of transects at bankfull width spacing and sampling precision for an estimate of the mean of the sediment size distribution.

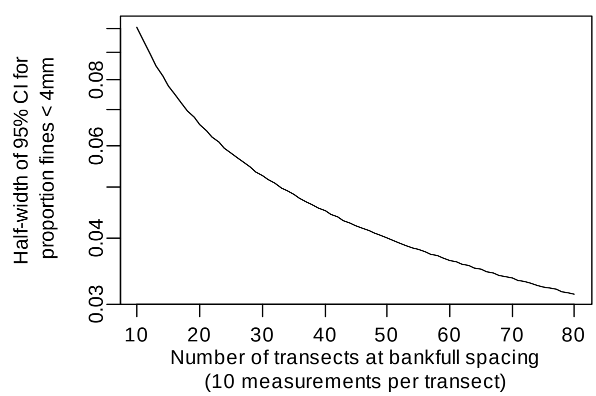

Figure 4. Relationship between number of transects at bankfull width spacing and sampling precision for an estimate of the proportion of the sediment size distribution finer than 4 mm.

The recommended monitoring approach will have a transect spacing of one-half bankfull width, a scenario that could not be evaluated with the available sample data. The closer spacing of transects is expected to provide improved sampling precision within monitoring sites owing to spatial autocorrelation of sediment sizes, hence the precision estimates portrayed in Figure 3 and 4 are conservative estimates.

The recommended monitoring approach specifies sampling of 40 transects at each monitoring site. Figure 3 indicates that the half width of the 95% confidence interval with 40 transects will be about 0.3 phi units. Table 4 provides the confidence interval converted to measurement units of mm over a range of likely values observed in Lagunitas Creek.

Table 4. Representative confidence intervals in measurement units for mean sediment diameter.

Sediment Diameter (phi units)	Sediment Diameter (mm)	Lower Bound 95% Confidence Interval (mm)	Upper Bound 95% Confidence Interval (mm)
2	8	6.5	9.8
3	16	13.0	19.7
4	32	26.0	39.4

With respect to proportion of sediment finer than 4 mm on the streambed, the recommended monitoring approach is expected to produce a 95% confidence interval of +/- 5%. In other words, for a mean estimate of 15% of the streambed occupied by sediment finer than 4 mm it is 95% certain that the true proportion lies between 10 and 20%.

Sampling precision with respect to the sediment size distribution may also be conveniently expressed in relation to percentiles of a cumulative size distribution such as that determined by simple random streambed sampling[7]. Such a relationship is displayed in Figure 5. The expected precision from the proposed sampling approach is expected to be greater because of spatial autocorrelation of sediment size data in systematic random sampling. Figure 5 therefore represents a conservative estimate of sampling precision.

The recommended sample grid within each monitoring site would contain 400 sample points. As shown in Figure 5, for n = 400 the 95% confidence interval around the 5th and 95th percentiles of the distribution would about +/- 2.2%. For the 16th and 84th percentiles, the confidence interval would be about +/- 4.2%, and for the 50th percentile (the median), the 95% confidence interval is +/- 5%. In other words, there would be 95% certain that the true median grain size would be between the 45th and 55th percentile of the sample distribution.

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

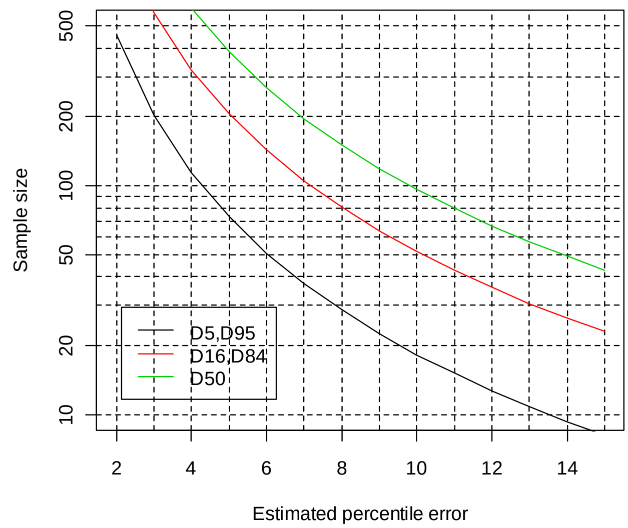

Figure 5. Estimated percentile error for specified percentiles of the cumulative sediment size distribution after Bunte and Abt (2001).

The relationship between sampling precision and the number of monitoring sites sampled in each monitoring reach of Lagunitas Creek (Table 4) was determined based on sample data from prior monitoring studies[8]. This analysis likely overestimates error because it is based on sample variance for sites extending from Shafter Bridge to Nicasio Creek, encompassing monitoring reaches M2, M3 and part of M1. Both surface sediment size distributions (2005 data) and subsurface sediment size distributions (pooled data from 2004 and 2005) were analyzed.

Figure 6 presents the estimated standard error for the mean value of various surface and subsurface sediment size parameters of interest. Figure 7 presents the estimated standard error of the mean value of percentage of cumulative sediment size distributions less than particular diameters of interest for both surface and subsurface sediment. The curves represent sampling precision as a function of the number of monitoring sites per reach. Four sites per reach were judged to provide the appropriate balance between sampling precision and sampling efficiency (cost).

[8] O'Connor Environmental, Inc. 2006. Lagunitas Creek Fine Sediment Investigation.

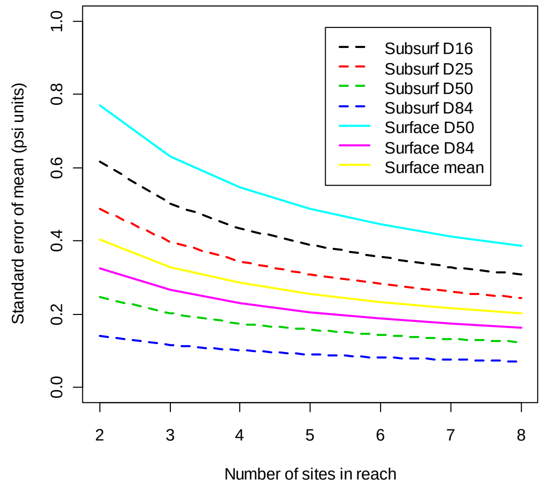

Figure 6. Relationship between number of monitoring sites per monitoring reach and sampling precision for an estimate of the mean of various percentiles and the mean of the sediment size distribution.

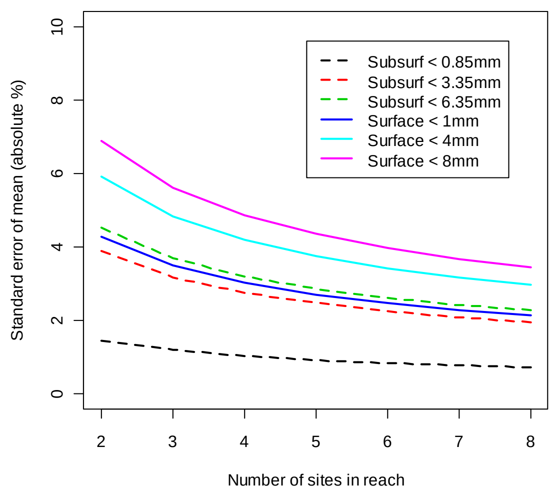

Figure 7. Relationship between number of monitoring sites per monitoring reach and sampling precision for an estimate of the mean percentage of cumulative sediment size distributions less than particular diameters of interest for both surface and subsurface sediment size distributions.

4.2. Study Design for Systematic Streambed Subsurface Sampling

Monitoring of subsurface sediment size distributions and the size distribution and volume of fine sediment deposits will be implemented using the sampling framework developed in the study design for surface sediment sampling. Data were insufficient to develop a similar design for subsurface sediment and fine sediment using statistical power and sampling efficiency concepts.

Two elements of the Plan are discussed below. First is the sampling of subsurface sediment in bulk (McNeil samples) at likely spawning sites to monitor spawning gravel quality and the geomorphic metric q_*. Second is a new approach to monitoring fine sediment by measuring the depth and size distribution of pockets or patches (facies) of fine sediment.

Sampling subsurface sediment at likely spawning sites has been conducted in Lagunitas Creek with some consistency, and has provided data that can be used to evaluate spawning habitat quality[9]. The metric q_* is a theoretical fluvial geomorphologic index of the state of sediment supply in relation to sediment transport capacity[10]. This metric was analyzed in a prior study in Lagunitas Creek and showed considerable potential interpretative value.[11] It can be computed at all sites where McNeil samples are collected and supplemented by local data for channel slope, cross-section geometry, and surface sediment size distribution. These data are needed to estimate bed shear stress at the sampling location. The channel geometry data will be obtained from topographic survey data collected to monitor bed form and elevation when and where available, otherwise specific local measurements will be necessary. In addition, local surface sediment median diameter should be measured by conducting a small scale systematic sample of the bed surface size in the immediate vicinity of the McNeil sample site. This additional surface sediment size data would be collected in conjunction with McNeil sample collection.

Measurement of depth and size distribution of fine sediment deposits at points on the sampling grid has not been performed in prior studies of Lagunitas Creek, hence there are no estimates of sample size or precision for this portion of the monitoring plan. Based on sample data to be collected during the initial

[9] O'Connor Environmental, Inc. 2006. Lagunitas Creek Fine Sediment Investigation. pp 44-47.
[10] Dietrich WE, Kirchner JW, Ikeda H, and Iseya F. 1989. Sediment supply and the development of the coarse surface layer in gravel-bedded rivers. Nature 340:215-217.
[11] O'Connor Environmental, Inc. 2006. Lagunitas Creek Fine Sediment Investigation. pp 24-25, 51-52.

implementation of this monitoring element, a determination regarding the number of pools or patches sampled in subsequent monitoring events is to be determined using power analysis for a two-sample t-test, (assuming spatial autocorrelation is not an issue between fine sediment patches). The sediment size range of particular interest is sediment < 4 mm diameter based on prior studies indicating that sediment between about 1 and 4 mm diameter is expected to be retained in temporary storage on the streambed.[12] This size fraction is transported in intermittent suspension, and may be relatively responsive to variations in sediment supply and streamflow. These data will be evaluated regarding potential correlation with measures of streamflow and suspended sediment yield.

4.3. Field Methods

Following is a detailed description of sampling methods to be employed for both systematic sampling of the streambed surface and subsurface, including fine sediment facies.

The sampling grid will be established at a random start point within a systematic framework to locate monitoring sites within monitoring reaches. The locations of the random start points will be established relative to a semi-permanent monument established on the floodplain for each monitoring site. The monument will also be located using a GPS receiver. Once established, the random start points and transect locations are to be recorded so that future surveys are repeated allowing two-sample matched-pairs statistical analyses to be employed. During the initial survey, ten bankfull width measurements will be collected at intervals equivalent to twice the bankfull width to establish the nominal bankfull width for transect spacing. (The bankfull width in this context is that associated with flow conditions approximately equal to the 1.5 yr recurrence interval flow as demonstrated in prior studies.[13])

The start point in each transect will be randomly determined. The location of sample points on transects will be determined by dividing the bankfull width (w) at each transect by 10. A random number between 0 and w/10 will be chosen to establish the location of the first point, with successive points spaced at intervals of w/10.

Measurements at individual sample points will include observation of individual sediment grains on transect sample points. Transects will be temporarily located using a flexible fiberglass tape or equivalent. To select a sediment grain for measurement, a sharp-tipped object such as a pencil will be located adjacent to

[12] IBID. pp 56-58.
[13] O'Connor Environmental, Inc. 2006. Lagunitas Creek Fine Sediment Investigation. p 51.

the appropriate point on the flexible tape and then lowered to touch the bed; the sediment grain touched will be picked up for measurement. A sediment measurement template may be used, or a ruler, to determine the width of the intermediate or b-axis of the sediment grain. The measured dimension is equivalent to the sieve mesh that the grain would catch on. Grain diameters are to be measured at half psi intervals (4, 5.6, 8, 11.2, 16, 22, 32, 45, 64, 90, 128, 180, 256 mm and so on). Sediment finer than 4 mm is classified as < 4 mm. Sediment size distributions are analyzed as the proportion of grain sizes finer than a given diameter. Touches on bedrock or organic material will be recorded as such and excluded from the sediment size analysis. Data are to be recorded so that the spatial relationship of sample points in the grid is preserved.

At each sample location on the transect, additional descriptors pertaining to the local sediment facies and channel morphology pertaining to fish habitat will be recorded. Sediment facies previously described include well sorted sand, fine gravel and sand, gravel with pockets of sand, gravel dominant and cobble dominant.[14] Fish habitat morphology at sample points in the wetted channel will be classified as pool, run, glide, riffle and cascade as used by District fisheries biologists.[15] Dry portions of the channel may be classified as either bar or bank as appropriate.

Sediment size distributions in spawning gravels will be evaluated using the McNeil sample technique. A modified version of this technique has been tested in Lagunitas Creek and is recommended.[16] Potential sample locations are actual or likely spawning sites in shallow water where the lower edge of an upstream pool transitions to a riffle. The presence of suitable sample locations will be identified in the field at each transect so that a sample site in the reach can be randomly selected. The sample site will be on a transect selected at random from among the population of transects identified as suitable. The precise sample location on the transect will be determined using criteria describing suitability for spawning: evidence of past spawning, sediment size distribution, patch type, and location relative to an upstream pool and downstream riffle crest. These sample sites will be reused in successive surveys to permit analysis of paired samples. If a previously sampled location becomes unsuitable for spawning, it will be replaced by the nearest suitable site. Additional data will be collected at each site to permit calculation of q_{*}, including channel slope, channel cross-section, and local surface sediment median size as per the prior study.

For sample locations with surface sediment diameter < 4 mm and sediment facies described as well sorted sand, fine gravel and sand, or gravel with pockets of sand, the depth of fine sediment deposit will be measured. A thin metal rod

[14] IBID, p. 21; also see photographic examples in Appendix A.
[15] MMWD 2008. Lagunitas Creek Habitat Typing Survey 2006 Analysis.
[16] O'Connor Environmental, Inc. 2006. Lagunitas Creek Fine Sediment Investigation. pp 21-23.

at least 3 ft long will placed on the bed at the sample location and pushed into the bed with consistent force until firm resistance is encountered. The depth of penetration will be observed and recorded as the depth of the fine deposit. The depth of the water column above the sample point will also be observed and recorded. In addition, a small volume subsample of the fine sediment is to be collected for a proportion of sample locations for analysis of grain size distribution. As noted previously, this procedure is similar to that used to measure v_*, but is intended here to be used in all wetted channel habitat types. As described for v_*, the ratio of sediment depth to the sum of sediment depth and water column depth provides a measure of potential habitat space occupied by fine sediment. This is a direct measure characterizing a relationship between fine sediment and aquatic habitat.

4.4. Analysis

Following is a description of statistical methods to be employed for analysis of streambed monitoring data.

Systematic streambed sampling is intended to quantitatively estimate various monitoring parameters pertaining to sediment and habitat and their interrelationships. Monitoring data will be used to produce particle size distributions with confidence bands for mean values and percentiles of the distribution. The streambed area occupied by different habitat types and sediment facies will be estimated, along with the proportion of the streambed influenced by LWD. The mean depth and volume of fines will be estimated with confidence intervals.

The interrelationships that may exist among streambed monitoring parameters will be evaluated by estimating parameter means or percentiles of subpopulations. Quantitative estimates will be developed for sample reaches (M1, M2, M3, T1 and T2) and individual monitoring sites (comprised of the systematic grid over twenty bankfull widths, forty transects and 400 sample points). Quantitative estimates will also be provided for subpopulations by habitat type and sediment facies type.

Data analyses will focus on comparisons of the proportions of fines and particle size percentiles between pairs of surveys. Particle size distributions will be tested for normality using chi-square or Kolmogorov-Smirnov tests. Shifts in distributions may be evaluated using a non-parametric quantile test. The proportion fines (or other size class) may be evaluated using a chi-square contingency table test.

Comparison of fines and particle size percentiles among multiple surveys will be conducted. For the proportion fines (or other size class), a chi-square contingency table test may be used. For analysis of trends, Spearman's rho and Kendall's tau statistics may be used.

Comparison of the areas of given habitat or sediment facies types among surveys will be conducted. For the proportion of points in each class, a chi-square contingency table test may be used.

For subsurface sediment (McNeil samples), the mass of sediment particles will be determined be sieve analysis. Geotechnical laboratories may perform this analysis using ASTM C-136 to produce the required sediment size distributions. The mass of particles will then be derived for half-psi classes. Particle size distributions with confidence bands, mean and percentiles will be produced for each monitoring reach (M1, M2, M3, T1 and T2).

Subsurface sediment analyses will compare percentiles of specified grain diameters of biological significance and particle size percentiles between pairs of surveys. Particle size distributions will be evaluated by chi-square or Kolmogorov-Smirnov tests. Comparisons will be made with paired t-tests. Non-parametric tests will use the Wilcoxon signed-rank test.

Comparison of the percentiles of specified grain diameters of biological significance and particle size percentiles among multiple survey sites will be conducted with 2-way repeated measures ANOVA. A comparable non-parametric test that can be used is Friedman's test. Trends will be evaluated using Spearman's rho and Kendall's tau tests.

Fine sediment depth will be quantified for each monitoring site and for each monitoring reach. Comparisons between surveys can be made with paired t-test. A comparable non-parametric test is the Wilcoxon signed-rank test.

Comparison of fine sediment depth or volume of fines among multiple surveys will be made using 2-way repeated measures ANOVA or using Friedman's test for non-parametric data. Trends will be determined using Spearman's rho and Kendall's tau.

The metric q_* will be quantified for each monitoring site and for each monitoring reach. Comparisons between surveys can be made with paired t-test. A comparable non-parametric test is the Wilcoxon signed-rank test.

Comparison of q_* among multiple surveys will be made using 2-way repeated measures ANOVA or using Friedman's test for non-parametric data. Trends will be determined using Spearman's rho and Kendall's tau.

5. Study Design for Large Woody Debris Sampling

Large woody debris (LWD) is an element of fish habitat that contributes cover and may interact with streamflow to create pools. Prior studies of Lagunitas Creek suggested that streambed sediment sizes tend to be finer in the vicinity of LWD[17]. Consequently, systematic streambed sampling will include measurements of LWD on transects in order that the effect of LWD on sediment size can be evaluated further.

Given this need for LWD observations, it is a relatively simple matter to collect additional data pertaining to LWD so that estimates of LWD volume and other characteristics of interest can be monitored. Prior sampling of LWD in mainstem Lagunitas Creek in 2005 provided sample data that could be used to estimate LWD volume based on measurements of the diameter of LWD pieces intersecting sample transects using line-transect sampling methods. This approach was used in a study of LWD ecology in a coastal stream in Mendocino County to determine the quantity of LWD, the mechanisms delivering it to streams and its relationship to stream hydraulics and fish habitat. [18]

Owing primarily to high natural variability of LWD distribution in streams, the sample data from 2005 produced estimated mean LWD volume with 95% confidence intervals of +/- 70 to 80% of the mean within monitoring reaches with three or four monitoring sites. Because of this high variability, monitoring data are not expected to detect small changes in LWD volume. Some advantage in statistical analysis can be gained by paired sampling where measurements are made on the same sample transects in successive sampling events. In any case, collection of these data will have low marginal cost and will provide quantitative data pertaining to a significant component of the aquatic system contributing to fish habitat. The LWD survey data is expected to provide data on LWD accumulation rates and input processes, as well as details of LWD position and characteristics that will provide perspective regarding its role in sedimentation processes and fish habitat.

The frequency of LWD measurement should be relatively infrequent, but should average twice per ten year period.

[17] O'Connor Environmental, Inc. 2006. Lagunitas Creek Fine Sediment Investigation. p 49.
[18] O'Connor M. and Ziemer R. 1989. Coarse woody debris ecology in a second-growth *Sequoia sempervirens* forest stream. Gen. Tech. Rep. PSW-GTR-110. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. pp 165-171.

5.1. Field Methods

The number of LWD pieces, characteristics of interest, and an estimate of the volume of LWD will be sampled at each monitoring site using the systematic transects set up for streambed sediment sampling.[19] LWD volume is determined as a function of the diameter of LWD pieces encountered on transect lines.

LWD characteristics of interest are not generally quantitative; hence much of the useful monitoring data will be nominal or categorical. These characteristics include tree species, source (e.g. bank erosion, wind throw, habitat enhancement), decay class (an index of LWD age), position in the channel (e.g. in the wetted channel, in the bankfull channel, spanning above the channel, proportion of channel cross-section affected, orientation to flow), habitat influence (e.g. pool cover, pool formation) sedimentation influence (bar development or sediment deposition associated with LWD), presence or absence of a root wad, and association with other LWD pieces (e.g. single piece, accumulation, debris jam).

5.2. Analysis

Quantitative LWD data will be limited to LWD counts and volume estimates. These data will be compared between pairs of surveys using paired t-tests for comparisons over time. The Wilcoxon signed-rank test is an alternative test for non-parametric data. Comparison of LWD counts or volume among multiple surveys will use 2-way repeated measures ANOVA. For non-parametric data, the Friedman test will be used.

[19] IBID.

6. Study Design for Streambed Elevation and Topography

Patterns of channel change documented by cross-section monitoring pertain primarily to the movement of coarser sediment transported on the streambed as bed load. Cross-sections in pools may record transient deposition of finer sediment transported intermittently in suspension. Monitoring to-date has been quantitative, but trend analysis to-date has not incorporated analysis of sampling error or appropriate statistical tests that differentiate between random variation and true trends.

Prior monitoring provided an annual record of repeated cross-section surveys over the period 1993-2007. This long-term monitoring indicated patterns of channel incision of about 1 ft in Lagunitas Creek at station KB below the confluence of San Geronimo Creek and channel aggradation of about 1 ft in Lagunitas Creek near Tocaloma at station KF. At the six intervening monitoring sites in Lagunitas Creek, patterns of elevation change were variable.[20]

Long-term changes in bed elevation are of interest to the District in relation to overall status of watershed erosion and sedimentation conditions. Given the evidence from monitoring to date and the generally long residence time of bed load sediment in gravel bed streams (decades), it is not necessary to monitor channel bed elevations on an annual basis. The necessary perspective on channel response to variable bed load sediment transport and sediment supply can be maintained with less frequent monitoring, namely, at three year intervals or following a winter with a maximum peak discharge > 3,000 cfs at the Samuel P. Taylor State Park gauge site. Greater confidence in the interpretation of these monitoring data will be achieved through appropriate statistical analysis of topographic survey data.

Topographic surveys will be conducted periodically at two monitoring sites each in the reaches M1, M2 and M3. Monitoring sites will coincide with prior established monitoring reaches KB (reach M3), KC (reach M3), KD (reach M2) and KF (reach M2). Two new monitoring sites will be established in reach M1. It is intended that these monitoring sites will coincide with monitoring sites used for systematic sampling of sediment described above, including q_* sites. This preference for monitoring sites will deviate from random sampling procedure in monitoring site selection in reaches M2 and M3. Acknowledging this compromise

[20] Balance Hydrologics 2008. Lagunitas Creek Sediment and Riparian Management Plan, Marin County, California: Streambed Monitoring Report, 1995-2007. Figure 13a.

on standard sampling procedure has the benefit of maintaining continuity of the prior monitoring record while simultaneously implementing a new monitoring protocol.

Woody debris accumulations and the distribution of sediment deposits and facies in relation to wood and other morphologic features will be mapped. These observations and maps will provide descriptive monitoring data in a three-dimensional context supplementing the numerical two-dimensional data obtained in systematic sampling.

6.1 Field Methods

The length of individual topographic monitoring sites will be comparable to the length of systematic streambed sample sites. Topographic monitoring sites may be extended to incorporate portions of prior monitoring sites KB, KC, KD and KF as necessary.

Systematic sampling of elevation will be conducted in a systematic pattern within the boundaries of the bankfull channel using a Total Station survey instrument. Survey elevation datums from prior surveys will be incorporated to allow comparison with prior survey data. Systematic sampling will conform with transect locations used for systematic streambed sampling to the extent possible to produce a reproducible gridded data set for channel bed elevation. Data collection is sometimes constrained by sight lines required between survey instrument positions and sample locations, and it is not always practical to clear obstructions or reposition the survey instrument. Additional survey points at morphologically significant locations such as edges of stream banks, bar tops and edges, edge of water, thalweg position, and LWD positions will also be collected. Data points from the gridded sample and from other points of interest will all be used for mapping purposes. The primary product of the survey will be a digital elevation model from which topographic maps and cross-sections can be produced using GIS software. Gridded elevation data will also be generated for analyses of changes in mean bed elevation. Appropriate slope data will also be collected in relation to McNeil sample locations for calculation of q_*.

Sample data from prior surveys could be used to determine variance and sample size requirements; however it is recommended that initial survey data collected in the new plan be used for this purpose. Subsequent data sets could be modified to achieve the desired degree of sampling precision and efficiency.

Bed elevation data collected in a systematic pattern will exhibit strong spatial autocorrelation. Variance of the mean cannot be estimated without bias, but the method of local differences can be used to compensate.[21] This permits construction of conservative confidence intervals, and we can estimate sample sizes needed to achieve a given precision. Traditional hypothesis testing is not robust to lack of independence; if applied to grid-sampled, positively autocorrelated data, the error rate will be lower than the nominal alpha. For example, with alpha = 0.05 we will reject a true null hypothesis less than 5% of the time. When we do reject we will be very unlikely to be wrong. That's because the true variance of the mean is less than that given by formulae for simple random sampling.

6.2. Analysis

Data will be summarized and estimates of mean bed elevation will be produced for each monitoring site and each monitoring reach (M1, M2, and M3). Mean bed elevation will be compared between pairs of successive surveys focusing on estimating changes with confidence intervals, using a local difference approximation to estimate variance. Over the long term, plots of means with confidence intervals are expected to reveal trends.

Comparisons between surveys may also be accomplished by a paired t-test for a reproducible sampling grid; a two-sample t-test may be used if the grid is not reproducible. These tests will be conservative and will likely underestimate sampling precision because of spatial autocorrelation in the systematically sampled data. Permutation tests may be used as an alternative approach for comparing surveys that does not require spatially uncorrelated data.[22]

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[21] Heikkinen J. 2006. Assessment of uncertainty in spatially systematic sampling. Chap. 10, pp. 155-176 in: Kangas, A; Maltamo, M (eds.). Forest Inventory – Methodology and Applications. Springer, Netherlands.

[22] Moore, D. S.; G. McCabe, G; Duckworth, W; Sclove, S. 2003: Bootstrap Methods and Permutation Tests. Supplemental Chap. 18 in: The Practice of Business Statistics: Using Data for Decisions. W. H. Freeman, New York.

7. Study Design for Turbidity Threshold Sampling

An effective method of quantifying fine sediment delivery from management activities dispersed over a group of sites or an entire watershed is to measure suspended sediment loads (SSL) at key locations. Turbidity Threshold Sampling (TTS) is an accurate and cost effective SSL monitoring system that estimates loads by sampling suspended sediment (SS) in conjunction with continuous turbidity (an optical property) and streamflow measurements[23] (Lewis and Eads, 2008). The system uses an automatic pumping sampler to collect SS samples for later lab analysis of mass concentration. The timing of the samples is determined in real time based on changes in turbidity; samples are collected when specified turbidity thresholds are crossed. After the concentrations are gravimetrically determined, they can be related to the corresponding discrete turbidity measurements for any period of interest. Then the continuous record of turbidity can be converted to a continuous record of concentration that, combined with the streamflow data, facilitates computation of SSL for any period of record. TTS is an advance over previous methods in that (1) samples are automatically collected based on turbidity conditions during each significant sediment transport event, (2) the resulting samples and recorded data permit reliable estimation of sediment loads for each significant sediment transport event.

Benefits of a TTS monitoring program are several:

1. Provides the most direct available measure of fine sediment inputs from dispersed areas in the watershed.
2. Provides a means for comparing trends in fine sediment transport at different locations (see the following two paragraphs).
3. Advances our understanding of fine sediment routing by providing quantitative transport data for use in a fine sediment budget
4. Fine sediment transport can be computed for different size fractions
5. Could accurately establish the quantity of fine sediments entering the system from Peters Dam.

Event-wise load estimates provide much better statistical power than annual loads for comparing the long-term sediment transport response at two or more monitoring locations. An unpublished statistical power analysis for the South Fork of Caspar Creek showed that, having collected 11 years (60-70 events) of pretreatment data, a 40% increase in sediment load would be detectable with at least 80% probability within 2 years after harvest in most subwatersheds. Failure

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[23] Lewis J and Eads R (2009). Implementation guide for turbidity threshold sampling: principles, procedures, and analysis. Gen. Tech. Rep. PSW-GTR-212. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 87 p.

to detect such an increase in sediment loads could be interpreted as evidence that fine sediment inputs have been no greater than 40%. In an environment such as Lagunitas there might be ongoing disturbances in watersheds being compared. Rather than testing for a discrete shift, the analysis would focus on identifying trends in the residuals from an average relationship (see example in next subsection). If disturbances can be limited or excluded from one watershed, then it can serve as a control and any detected changes can be more reliably attributed to the other watersheds being compared.

7.1. TTS Monitoring Designs

Four configurations are typical of studies designed to detect management-related sediment inputs:

1. above and below a confluence of the tributary of concern (e.g. Lagunitas Creek above and below Devil's Gulch)
2. above the confluence on both the tributary and the stream that it flows into (e.g. Devil's Gulch and Lagunitas Creek, above their confluence)
3. on streams draining a watershed of concern and a similar nearby watershed (e.g. San Geronimo Creek and Devil's Gulch).
4. on a single stream channel above and below the terrain draining activities of concern

The first two are essentially equivalent designs and the choice between the two depends mainly on whether the tributary or the receiving stream is more suitable and convenient for installing the equipment. Although the relationship between the two responses in the second design will have lower variance than the first, the expected change is smaller because the tributary output is diluted by that of the upper station. The third design is preferable to the second when there is another stream available that is very similar to the tributary of concern. The fourth design is appropriate where activities of concern occur on "face" watersheds drained primarily by subsurface flow or low-order channels into a larger stream. The fourth design is used for studying localized sites of activity, while the others are used for assessing entire watersheds. All four designs are best when one of the streams is relatively stable in terms of management and sediment delivery, and all four designs are most effective when monitoring is begun before the activities of concern are implemented.

Even without before and after monitoring these designs can be effective for assessing relative performance of two watersheds over time. The analysis focuses on shifts in the relationship between responses over time, either by analysis of covariance (in the case of temporally discrete disturbances) or by plotting regression residuals through time. For example, the left frame of Figure 8 shows the logarithms of the suspended sediment storm loads at 2 stream gaging stations. The right frame shows the residuals plotted as a function of storm sequence. (The data are real but the trend was added artificially for illustration.) The non-linear trend in the residuals depicts a declining trend with time in the response of gauge 2 relative to gauge 1. Trends of arbitrary shape can be tested statistically for significance using generalized additive models[24] (Hastie and Tibshirani, 1990).

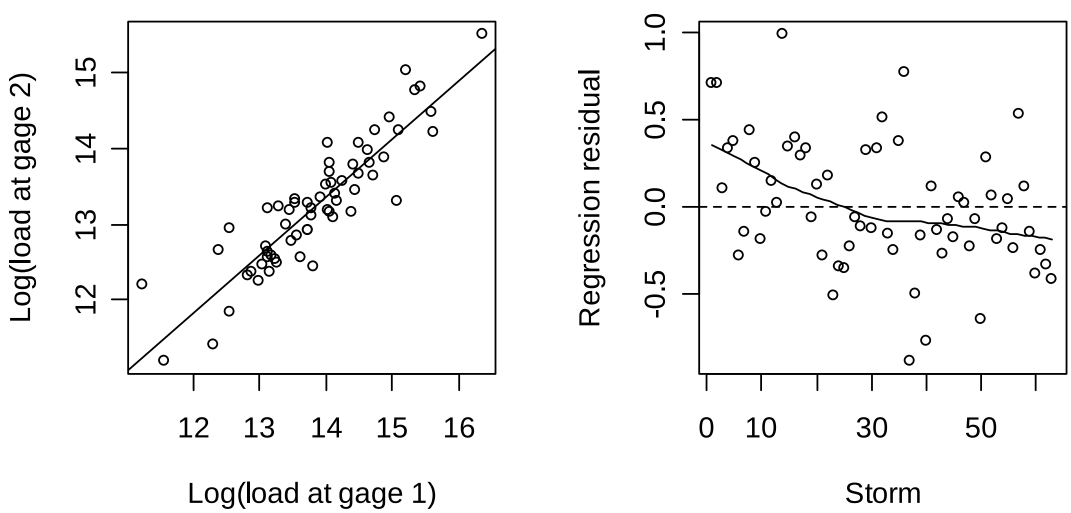

Figure 8. Representative TTS data.

7.2 Site Selection

A complicating factor when assessing a TTS program in the Lagunitas Creek watershed is the effect of dam releases. Key to the designs discussed is a strong relationship between responses at the two monitored locations. Geographic proximity usually ensures that streamflow is well-related between watersheds draining similar terrain. But if streamflow is decoupled by artificial flow controls, turbidity, concentrations and loads also may not be well-related. A comparison of San Geronimo Creek and Devil's Gulch would not be subject to that difficulty, but above and below measurements of Devil's Gulch would be affected by releases from Peters Dam that would likely reduce the sensivity of the design.

Some advantages can be gained by implementing TTS at existing stream gaging stations. Existing stations already have established discharge rating equations and, in some cases, existing infrastructure may be utilizable for TTS. Finally, adding suspended sediment measurements to sites with longer discharge records may permit certain analyses, such as estimation of historical loads, that would be

[24] Hastie, T. J. and Tibshirani, R. J. 1990. Generalized Additive Models. Chapman & Hall/CRC.

more difficult at previously ungauged sites.

Considering the above discussion, we recommend implementation of TTS at the following locations.

1. San Geronimo Creek at Lagunitas Road bridge. This is an existing stream gauge operated since 1980 by Balance Hydrologics. This gauge is approximately one mile above the confluence of San Geronimo Creek with Lagunitas Creek, capturing runoff from about 90% of the 9.3 mi^2 San Geronimo watershed. The San Geronimo Creek watershed is considered to be a major source of sediment in Lagunitas Creek.
2. USGS gauge 11460400 on Lagunitas Creek at Samuel P. Taylor State Park. This gauge has been operated by the USGS since 1982. The watershed area of 35.9 mi^2 includes 21.5 mi^2 from Peters Dam, and 5.1 mi^2 draining to Lagunitas Creek below the dam, plus all of San Geronimo Creek. This gauge is ideal for integrating all sediment inputs from the basin. Sediment transport at sites further downstream would be more difficult to interpret as management-related because of the large amounts of stored alluvial sediment that are episodically transported in the lower reaches of Lagunitas Creek.
3. Devil's Gulch near the confluence with Lagunitas Creek. This would be a new gaging location. Sediment from Devil's Gulch is not measured at USGS gauge 11460400, which is just upstream of the Devil's Gulch confluence. Since Devil's Gulch flows are unregulated, this site provides one of the best comparisons with San Geronimo Creek within the Lagunitas watershed below Peter's dam. Because the watershed is largely contained in the State Park, management activities are limited and it might serve well as a control for evaluating trends in San Geronimo Creek. In addition this gauge will provide a reading on the effectiveness of several erosion control projects located within Devil's Gulch.

If a fourth station were to be included, it could be at Lagunitas Creek above Shafter Bridge. This would be another new gauging site. Located about 0.6 mi downstream from Peters Dam, the drainage area includes 2 small tributaries below the dam. Because of the regulated flows, it would not be informative in relation to San Geronimo Creek, but would provide a nearly direct measure of the sediment being released from Peters Dam. Such sediment, however, is expected to consist only of very fine sediments and will be minimal except during spills over the dam, which are of concern primarily for their scouring effect rather than their sediment content.

Final site selection will require a field reconnaissance to determine the precise location of instrumentation and site specific equipment needs. Primary considerations will be the type and location of the equipment shelter and configuration of the boom from which the turbidity sensor and pumping sampler intake are deployed.

7.3. Implementation, Data Processing, and Analysis

Details of general TTS implementation can be found in the "Implementation Guide for Turbidity Threshold Sampling: Principles, Procedures, and Analysis" (Lewis and Eads 2009). Once a station is established, the basic components of implementation at MMWD stations would be

1. Field data collection
    a. Visual inspection and maintenance of gauge site
    b. Reading staff plates and taking field notes
    c. Interacting with the data logger and software
    d. Downloading and plotting TTS data
    e. Retrieving pumped samples and replacing bottles
    f. Collecting simultaneous depth-integrated and pump sample pairs
    g. Current-meter discharge measurements
    h. Equipment troubleshooting
2. Laboratory processing of pumped and depth-integrated samples
    a. Filtration and weighing of samples
    b. Separation of sand fractions on a subset of pumped samples and all simultaneous pumped and depth-integrated samples
    c. Determination of sand fractions and concentrations
3. Data processing and analysis
    a. Calculate discharge from current meter measurements
    b. Establish and/or update stage:discharge ratings
    c. Collate staff plate readings for comparison with stage data
    d. Correct and finalize electronic stage and turbidity data
    e. Apply discharge rating equation to finalized stage data
    f. Establish relationship between simultaneous pumped and depth-integrated sample concentration
    g. Define storm events and calculate loads
    h. Calculate annual loads of fine sediment and sand
    i. Re-evaluate TTS sampling parameters

Current meter measurements will be required at Devil's Gulch and possibly at San Geronimo Creek, depending on Balance Hydrologics' stream gauging program. We assume that the USGS gauging station has an ongoing program of discharge measurements and rating curve maintenance.

Paired depth-integrated and pump samples are needed to determine whether the pump samples adequately represent the cross-sectional mean concentrations of suspended sediment and sand. If a bias is detected, a correction can be developed from the paired sample concentrations.

The collection of discharge measurements and paired depth-integrated and pump samples should be most intense the first year of monitoring (15 or more samples well-distributed with respect to flow). These programs can be continued at a lesser intensity during subsequent monitoring years (5-10 measurements per year).

TTS sampling parameters will initially be estimated from existing data records at the San Geronimo and Lagunitas Creek gaging stations. Ideal sampling parameters will yield at least 4-12 samples per storm event (depending on the maximum level and smoothness of turbidity), with scattered samples between events, resulting in about 100-150 pumped samples per station per year. In order to quantify annual sand transport, sand fractions will be analyzed on about one-third of all pumped samples, including all those associated with simultaneous depth-integrated samples.

Electronic stage and turbidity data will be corrected in conjunction with field notes using the TTS Adjuster program, which facilitates corrections by displaying staff plate readings and scatterplots of turbidity and SSC. The program will also calculate discharge if a rating equation is supplied. If necessary USGS discharge data will be merged with the TTS data using customized scripts.

7.4. Resource Requirements

Installation of three gauging sites is assumed. Instrumentation costs will vary somewhat depending on unknown factors such as required cable lengths. Optimally, 4 x 6 ft walk-in shelters will be constructed at each gauge site. Such shelters are highly desirable for servicing and protecting instrumentation during inclement weather, especially at long-term gauging sites. However, if existing structures can be utilized, or if new structures of that size are impractical alternative instrument shelters can be used.

Laboratory resources to analyze 150 pumped samples and 15 depth-integrated samples during the first year for each station, with sand fractions on 50 pumped samples and all depth-integrated samples. In subsequent years the number of pumped samples and depth-integrated samples would likely be reduced by 5 each and the number of sand fractions is correspondingly reduced by 10, at each station.

Trained field staff would be required to conduct 15 site visits during storm events the first year and 10 site visits during storm events the second year, as well as 10 non-storm maintenance visits each year.