Title

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ABSTRACT

Lagunitas Creek and San Geronimo Creek in Marin County, California provide some of the best habitat for endangered coho salmon (*Oncorhynchus kisutch*) in the southern part of their range, making it a priority for local and federal agencies to collect habitat and biological data throughout the watershed. For this paper, we synthesized numerous years of existing data, including flow, sediment conditions, endangered coho salmon densities, and one year (2001) of macroinvertebrate biological assessment data to investigate biotic and abiotic interactions among physical habitat, juvenile coho, and macroinvertebrates. We found that summer juvenile coho densities in Lagunitas Creek were negatively correlated with annual peak mean daily flow, whereas in San Geronimo Creek, variation in peak mean daily flow did not significantly impact juvenile density. Although macroinvertebrate prey were not limiting factors for juvenile coho in 2001, increased coho density was correlated with significant declines in the percentage of vulnerable macroinvertebrates at sampling locations. In addition, San Geronimo Creek had relatively high densities of juvenile coho, despite local evidence of excess nutrients and fecal coliforms from 2001. Analyzing fourteen years of qualitative sediment accumulation observations from Lagunitas tributaries, we found that 1) regular sediment inputs from tributaries could be impacting local habitat quality and may require source investigation, and 2) the highest sediment delivery occurred during wet years, but localized sediment accumulation may also occur in low flow years due to lag time in sediment delivery. Our April 2009 physical habitat survey at the bioassessment site LAG220, above Irving Bridge on Lagunitas Creek, suggested that overall substrate conditions have improved at that location, compared to 2001 conditions. To further evaluate interactions among flow, sediment, coho, and macroinvertebrates in Lagunitas and San Geronimo Creeks, we recommend using a GIS model to evaluate data at multiple reach scales and over time.

INTRODUCTION

Streamflow and sediment composition are two factors shaping the composition of biological communities and interactions in stream ecosystems. High flow events can impact salmonids by scouring developing eggs and embryos within the streambed or washing juveniles out of preferred rearing habitat

(Quinn 2005, Groot and Margolis 1991). Stream macroinvertebrates can also wash out of streams during high flow events, which is followed by re-colonization of the system (Resh et al 1988). Fine sediment accumulation can also reduce diversity, fitness, or survival rates of aquatic organisms. Salmonids require clean gravel and cobble to both provide hiding refuges for juvenile fish and to ensure oxygen availability for developing eggs and young within the streambed. Sediments smaller than 3.4 millimeters (mm) in diameter can inhibit emergence success of coho fry (Quinn 2005, Kondolf 2000). The diversity of benthic macroinvertebrates, which are important prey for juvenile salmonids and good indicators of physical habitat impairment, also declines with increases in stream bed fine sediment (Suttle et al. 2004).

Mediterranean climate streams with predictable wet and dry seasons support biota with life histories adapted to annual disturbance events (Resh 1988, Power 2008). Aquatic organisms within these ecosystems have evolved life history strategies and physiological traits to respond to periodic bed-scouring floods and low flow periods (Resh et al. 1988, Wootton et al. 1996, Power et al. 2008). In fact, studies indicate that biological diversity within streams and rivers increases after bed-scouring floods that open up space for new algal, invertebrate, and fish colonization, as predicted by the Intermediate Disturbance Hypothesis (Wootton et al. 1996, McCabe & Gotelli 2000, Power et al. 2008). However, interannual variation in precipitation can result in periods of intense flooding or extended drought and low winter flows, which can alter or exacerbate these effects on the aquatic community (Lake 2000).

Generally, wet years lead to more sediment delivery to a system while drought years have decreased sediment delivery. In addition, local patches of sediment may accumulate due to localized changes in streamflow (O’Connor and Rosser 2006). Local areas of increased fine sediment deposits may then lead to decreases in diversity of macroinvertebrates (Cover et al. 2008, Suttle et al. 2004). Of particular concern, the percentage of macroinvertebrates that are available as prey to salmonids can decline with fine sediment deposits as low as 10% (Suttle et al. 2004). Potential mechanisms for declines in macroinvertebrate diversity due to fine sediment include decreases in benthic habitat heterogeneity that support diverse assemblages, declines in refuge habitat, respiration blockage, and loss of stable substrate for algal growth providing food for many grazers (Cover et al. 2008, Rabeni et al. 2005, Suttle et al.

2004). The abundance of taxa that burrow into and live within fine sediment may increase, whereas epibenthic drifting insects that need cobble and gravel substrate to feed and find refuge would decrease (Rabeni et al. 2005, Suttle et al. 2004). Local decreases in prey availability could cause reduced growth and higher mortality of juvenile salmonids that consume epibenthic, drifting insects (Suttle et al. 2004).

Lagunitas Creek (Lagunitas) and its tributaries, including San Geronimo Creek (San Geronimo), in West Marin County, California provide habitat for the largest and most stable population of coho salmon south of the Noyo River within the Central California Coast Evolutionarily Significant Unit (ESU), making it one of the most important regions for coho monitoring and conservation efforts (Stillwater Sciences 2008). The existence of long-term fish abundance, streamflow, and sediment data in these streams provides a valuable opportunity for the study of potential ecological interactions both spatially and over time. For example, a recent investigation found that high spring flows and lack of winter habitat availability were the two factors most likely to be limiting coho salmon (*Oncorhynchus kisutch*) populations in Lagunitas during 2006, an unusually wet year (Stillwater Sciences 2008). However, there has been little previous research on the predator-prey interactions between salmonid and macroinvertebrate species in the system.

Previous studies have found that prey availability is not a limiting factor for salmonids in the Lagunitas watershed as a whole (Kelley 1980; Stillwater Sciences 2008). However, increasingly common drought years could create conditions of unusual fine sediment accumulation that cause site-specific declines in habitat availability, macroinvertebrate prey, and juvenile salmonid densities. The San Francisco Bay Regional Water Quality Control Board (RWQCB) collected benthic macroinvertebrates to assess the biological integrity of the watershed in 2001, which was a drought year (RWQCB 2007). In this study, we used these data both as an indication of prey availability and potential water quality impacts for juvenile coho. Combining macroinvertebrate and juvenile coho data may allow us to evaluate whether prey availability and water quality are limiting factors during a low flow year (2001).

For this study, we analyzed the effects of flow and sediment inputs to aquatic communities for Lagunitas Creek and San Geronimo Creek over both time and space. Our objectives for a temporal analysis were to 1) determine the effects of peak mean daily flow on juvenile coho salmon from 1994 to 2008, and 2) assess changes in sediment and physical habitat conditions below the confluence of Lagunitas and San Geronimo Creeks. Our objectives for a spatial analysis of individual stream reaches in 2001 (Figure 1) were to 1) investigate whether macroinvertebrate prey could have limited juvenile coho, and 2) map macroinvertebrate prey, water quality indicators, juvenile coho densities, and sediment conditions for Lagunitas mainstem.

Study area

Lagunitas Creek, with a drainage area of 103 square miles (sq. mi.), flows into Tomales Bay and is protected in both Samuel P. Taylor State Park and Point Reyes National Seashore throughout much of its course. San Geronimo Creek is a smaller tributary to Lagunitas with a drainage area of 9.2 sq. mi. (Smith 1986). In 1954, the Marin Municipal Water District (MMWD) constructed Peters Dam on Lagunitas, approximately one mile upstream of its confluence with San Geronimo. The dam resulted in the formation of the Kent Lake reservoir and blocked off access to upper parts of the watershed for coho salmon and steelhead trout (*O. mykiss*). As mitigation for raising Peters Dam to increase the reservoir capacity of Kent Lake in 1982, MMWD was mandated to augment flow and restore habitat for both coho and steelhead (Hecht et al. 2008). Subsequent restoration efforts have led to extensive research efforts on endangered coho salmon and steelhead.

Peters Dam has also altered the historic flow regime and sediment transport for the Lagunitas mainstem. The dam impounds high winter flows and upstream sediments, thereby decreasing the stream's historical sediment transport capacity. However, storage in the lake is small relative to watershed runoff, so winter high flow spills from the dam augment high flows and fine sediment transport downstream. Researchers are concerned about the impact of such fine sediment inputs on Lagunitas aquatic habitat quality, as well as sediment inputs from adjacent tributaries (Hecht 1983, Hecht and Glasner 2002, Hecht et al 2008.)

Regional and local agencies have identified potential changes to habitat quality in Lagunitas, including excess fine sediment and other pollutants, as a concern for maintaining biological integrity within the system (RWQCB 2007). In 2001, the San Francisco Bay Regional Water Quality Control Board (RWQCB) collected benthic macroinvertebrates, physical habitat, and water quality data from the Lagunitas Creek watershed (2007). Overall, the study found that Lagunitas supports high quality aquatic habitat, compared to other San Francisco Bay Area streams. However, the bioassessment identified several water quality issues including habitat impairment, excess nutrients, herbicides, pesticides, erosion, turbidity, elevated temperature, and presence of fecal coliforms. Specific areas of concern for Lagunitas included the upper reaches of San Geronimo (bioassessment sites LAG290 and LAG300). These sites are located in the most developed areas of the Lagunitas watershed, where there are likely septic tank leaks as well as impacts from cattle grazing. In general, the RWQCB study found that the most important factors affecting biological integrity of streams in the region were land use, altered flow, and flow intermittency.

California coho salmon

Coho salmon in this area typically spend one year in freshwater prior to outmigrating to the ocean in the spring (Groot and Margolis 1991). After 18 months at sea, most California adult coho return to their natal streams to spawn. Their return coincides with high streamflow in the fall, which acts as an environmental cue for adults to make their upstream migration (Brown et al. 1994). Juvenile coho prefer cooler temperatures ranging from 12-14°C and oxygen-rich water. In addition, juveniles are most abundant in slow, deep pools that are well shaded and have a high density of macroinvertebrates as a food source. High turbidity has a negative effect on the emergence and growth of coho juveniles. Additionally, juveniles need habitat refuges from high streamflow to avoid displacement mortality (Moyle et al. 2008).

METHODS

Peak mean daily flow and juvenile coho salmon

We used annual endangered salmonid surveys since 1993, to analyze a temporal relationship between peak mean daily flow and coho populations. We obtained juvenile coho density from Marin Municipal Water District (MMWD) annual surveys, flow data for Lagunitas Creek from the US Geological Survey (USGS), and flow data for San Geronimo Creek from Balance Hydrologics. Because juvenile surveys are conducted in the summer and juvenile coho in our study streams do not emerge from eggs until the spring, we were unable to examine the direct effects of winter peak mean daily flows on juvenile coho. In other words, the juvenile coho sampled were not yet present during periods of peak mean daily flow, although these eggs were developing in stream substrate at this time. Therefore, we were only able to analyze whether peak mean daily flow had indirect effects on juvenile coho densities, such as redd scour or changes in food web dynamics.

We used separate analyses for Lagunitas and San Geronimo to determine the effects of peak mean daily flow and redd abundance on juvenile coho summer density. We included redd abundance as an explanatory variable in our analyses because adult spawning success could be a factor in explaining high juvenile summer densities. To assess variation in summer juvenile coho densities, we used a full-model approach using R version 2.8.1 (The R Foundation for Statistical Computing, 2008). We started with a multiple regression and then switched to a simple linear regression where appropriate. For Lagunitas Creek, we had flow data for 34 years, juvenile density data for 14 of those 34 years, and redd abundance for 9 of those 34 years. Hence, when we ran the multiple regression with all three variables, we only used 9 years of data, whereas we were able to use 14 years of data for the simple regression analyzing a smaller subset of variables: peak mean daily flow and juvenile density.

Sediment conditions

To determine tributary sediment inputs to the Lagunitas mainstem, we reviewed data from Balance Hydrologics' "subjective reconnaissance" reports for 1993-2008, excluding 1994 and 2005, when no reconnaissance was conducted. The subjective reconnaissance was performed by Balance Hydrologics and based on an annual two-day qualitative investigation of sediment condition in the Lagunitas mainstem between Tocaloma Bridge and Shafter Bridge. The reconnaissance team recorded observations of reach scale changes to the system, including evidence of sediment inputs from over nineteen small tributaries that flow into the Lagunitas mainstem within the observation area. We classified subjective reconnaissance narrative observations from the confluence of individual tributaries and the Lagunitas mainstem, using the following scoring system: 3-increased delta size from tributary sediment sources, 2-presence of deltaic bars or fan, 1-presence of other visible trace debris, 0-decreased delta size, visible signs of decreased deposition, or no change, and Null-no observations noted.

To further assess Lagunitas mainstem habitat condition, we conducted a partial physical habitat assessment on April 10, 2009 at site LAG220, located just upstream of Irving Bridge. This is the nearest downstream bioassessment site from the confluence with San Geronimo (Figure 1). We used the same physical habitat assessment method established in the 2001 RWQCB bioassessment – the California Standard Bioassessment Protocol (RWQCB 2007, Harrington & Born 2000). However, we assessed two riffle locations instead of three to avoid disturbing nearby salmonid spawning sites. We then compared our 2009 physical habitat scores to those from 2001 (Table 1) to note any changes.

Macroinvertebrate and juvenile coho interactions

Relatively little is known regarding macroinvertebrate populations in the Lagunitas watershed. For our study, we used RWQCB macroinvertebrate abundance data to calculate the percentage of macroinvertebrates that were vulnerable as prey to fish in 2001; this enabled us to assess potential trophic interactions between fish and macroinvertebrates. We defined the category "vulnerable as prey" after Suttle et al. (2004) as taxa that are neither armored (e.g. caddisflies with stone cases), nor possess a behavioral trait of burrowing into fine sediment (Merritt et al 2008). To define "percent vulnerable as prey," we divided the number of vulnerable individuals by the total number of macroinvertebrate individuals (approximately 500) for each of the 15 samples located in Lagunitas and San Geronimo.

There were ten locations where the 2001 RWQCB bioassessment site locations corresponded with juvenile salmonid survey locations in Lagunitas and San Geronimo Creeks (Table 2, Figure 1). To assess potential relationships between percent vulnerable macroinvertebrates and juvenile coho distribution, we first created a line graph to show percent vulnerable macroinvertebrates and coho densities at each location (Figure 2). We then ran bivariate regressions of macroinvertebrate parameters (percent vulnerable macroinvertebrates, macroinvertebrate taxa diversity, percent EPT, percent sensitive EPT, and average tolerance values) and juvenile coho densities, using STATA statistical software: Release 9 (StataCorp 2005). The sampling dates for macroinvertebrates (April) and juvenile coho

(September to October) occurred during different seasons. Therefore, we assumed that September and October fish density at sampling locations would be relatively similar to earlier fish densities in April, although a proportion of coho probably died over the summer months.

We also ran bivariate and multivariate regression analyses to assess the potential relationship between percent vulnerable macroinvertebrates and physical habitat characteristics related to sediment (RWQCB 2007 data). The sediment parameters included qualitative scores (1-20) of deposited sediment and embeddedness, and average visual estimates of riffle sediment condition (percentages of fines, gravel, cobble, and embeddedness) within the bioassessment stream reaches (Table 1, Figure 1). Embeddedness is the percentage of streambed cobble or boulders surrounded by fine sediment (RWQCB 2007).

Mapping sediment, macroinvertebrates, and juvenile coho distributions

We developed a Geographic Information System (GIS) model for comparing data on sediment, macroinvertebrates, and juvenile coho, collected from various sampling points along the Lagunitas mainstem below Shafter Bridge. First, we created a base map using a Marin Municipal Water District (MMWD) streams layer. We added sampling point locations for the 2001 Bioassessment and MMWD coho data (RWQCB 2007, Stillwater 2008). We then added streambed monitoring locations and approximate tributary sediment monitoring locations, provided by Balance Hydrologics. From 1991 to present, Balance Hydrologics had measured embeddedness eight streambed monitoring sites along the Lagunitas mainstem (Hecht et al. 2008). The map projection was set to California State Plane Coordinate System, Zone 3 (Fipszone 0403), North American Datum of 1983 (HARN). Second, we divided the Lagunitas mainstem into ten subreaches that incorporated the fish sampling, invertebrate bioassessment, and bed monitoring sites closest to one another. We attempted to group sampling sites below the confluence of local tributaries within the Lagunitas mainstem to isolate tributary effects, but this was only possible for a few subreaches. Finally, we chose to analyze 2001 data, because bioassessment sampling for macroinvertebrates was available for this year. We joined 2001 sample data to the appropriate sampling location and compared data for coho, invertebrates, and sediment (both tributary sediment inputs and embeddedness) by subreach on the map.

RESULTS AND DISCUSSION

Peak mean daily flow and juvenile coho salmon

Peak mean daily flows during our study interval appeared to have different impacts in Lagunitas and San Geronimo. From the multiple regression, we found that peak mean daily flow and redd abundance taken together did not explain variation in juvenile coho density in Lagunitas. However, we found a significant negative relationship between juvenile coho density and peak mean daily flow in Lagunitas (Figure 3, $n = 14$ years, $P = 0.010$, $R^2 = 0.441$). Although we used a simple linear regression model, the relationship between juvenile density and peak mean daily flow in Lagunitas could be better described as a negative exponential relationship (Figure 3). Results suggested that a peak mean daily flow of 4,000 cubic feet per second (cfs) might act as a threshold, with juvenile densities remaining relatively low above peak mean daily flows of 4,000 cfs. This may be evidence of redd scour in Lagunitas during high flows, although previous studies in the Lagunitas mainstem suggest that scour is not a primary concern for the system (Hecht et al. 2008, Stillwater Sciences 2008). Additionally, large floods may require more time for invertebrate communities to re-establish, resulting in a lack of food for newly emerged juveniles. For San Geronimo, the multiple regression analysis indicated that redd abundance explained variation in juvenile coho density, while peak mean daily flow did not appear to be associated with juvenile density (Figure 4, $n = 9$ years, redd abundance, $P = 0.007$; peak mean daily flow, $P = 0.176$, $R^2 = 0.780$). In San Geronimo, which had lower peak mean daily flows (maximum peak mean daily flow = 1094 cfs) for our study interval, juvenile coho density is variable throughout the range of peak mean daily flow values. Thus, that redd scour or other indirect effects of flow did not suppress juvenile coho density on San Geronimo.

Sediment conditions (1994-present)

From 1994-2008, regular sediment deliveries to Lagunitas mainstem occurred from six tributaries below the confluence with San Geronimo Creek and above Tocaloma Bridge. These tributaries showed evidence of sediment accumulation for 50% or more of the 14 years of subjective reconnaissance. These were tributary L or the first left bank tributary above Tocaloma (50%), tributary J or the left bank tributary above Kelley's Tocaloma- KF (71%), Cheda Ranch Creek (71%), tributary H or the left bank tributary below the community of Jewell (71%), Devil's Gulch Creek (64%), and Irving Creek (50%), as labeled on map A1. Two of these six tributaries, tributaries L and H, had delta accumulation for more than 50% of annual observations. The two wettest years during the observation period, 1996 and 2006, had more than 50% of tributaries demonstrating evidence of sediment accumulation. Another wet year, 1998, also had higher sediment accumulation (42%). For some tributaries, sediment accumulation continued in dry years that followed extreme wet years, e.g. for 2007 following the floods of 2006.

Overall, we found that 2009 substrate conditions at location LAG220 have improved since the RWQCB 2001 physical habitat assessment (Table 1). For example, epifaunal substrate is now in the "optimal" category (score of 18), defined as greater than 70% of substrate favorable for epifaunal colonization and fish cover with a mix of snags, logs, undercut banks, cobble and other stable substrates. In 2001, epifaunal substrate conditions were "marginal" with 20-40% of stable habitat for benthic organisms. The percent fine sediment deposition in riffles has also improved from approximately 30% in 2001 to 5-10% in 2009. However, significant bar formation within this reach, downstream of a log jam structure, resulted in a lower physical habitat score for deposited sediment in 2009 ("suboptimal" - 11) compared to 2001 ("optimal" - 18). This change may actually enhance the variety of streambed substrate in some areas of the reach. The benthic environment in this reach seems to be sufficiently heterogeneous, and likely is good habitat for diverse stream organisms.

From 2002-2007, Balance Hydrologics reported quantitative bed monitoring results for our bioassessment study site LAG220, corresponding to "KX." In contrast to our findings for the qualitative physical habitat assessment, Balance Hydrologics found a slight increase of mean embeddedness, increasing from 0.299 embeddedness in 2002 to 0.304 in 2007 (Figure 1). Balance Hydrologics also found that mean bed elevation for the site decreased by 0.3% at the site for the same time period (Hecht et al. 2008). In general, Hecht et al. (2008) have observed greater levels of fine sediment in recent years throughout the Lagunitas watershed. Our findings of improved sediment condition at site LAG220 may be the result of having different observers perform the assessment in 2001 and 2009.

Based on subjective reconnaissance data for 1991-2008, we considered the impact of increased fine sediment to aquatic organisms and identified six tributaries as potential sources of concern. In addition to these six tributaries, Hecht et al. (2008) have previously described Big Bend tributaries and San Geronimo as main sources of sediment inputs to the Lagunitas system. Four of the six tributaries that we are identified are located downstream of Big Bend on the Lagunitas mainstem and may be contribute to elevated levels of sediment along this reach. Based on sediment threshold levels determined from Oregon streams, O'Connor and Rosser (2006) found that percent fine sediment on the surface of riffles were near the threshold of undesirable levels for coho at several Lagunitas reaches below Big Bend in 2004 and 2005. O'Conner and Rosser have noted, however, that Oregon thresholds may not be applicable to California, and their other sediment measurements found Lagunitas fine sediment to be below levels that impair salmon survival (O'Connor and Rosser 2006).

Macroinvertebrate and juvenile coho distribution

Our analysis of the 2001 RWQCB bioassessment and coho data showed that coho may have negatively impacted the percentage of vulnerable macroinvertebrates, but prey abundance was not limiting for coho in 2001 (Figures 2 & 5). In Lagunitas sample locations, an increase in juvenile coho densities generally corresponded with a decrease in percent vulnerable macroinvertebrates (Figure 2). For example, site LG-7/LAG 190 had a coho density of 18 fish per 30 meters and vulnerable macroinvertebrates of 61%, while the next upstream location (LG-9/LAG 210) had a coho density of 2 fish per 30 meters (decrease of 16 fish per 30 meters) and 72% vulnerable macroinvertebrates (increase of 11 %). The San Geronimo location just upstream of the confluence with Lagunitas (SG-2/LAG240) had the highest observed juvenile coho density in these two streams for 2001 (72 fish per 30 meters). The two most upstream locations in San Geronimo (SG-3/LAG290 and SG-4/LAG300) also had higher juvenile coho densities than those in Lagunitas, but had lower percentages of vulnerable macroinvertebrates than any other locations. Lagunitas sites that are preferred habitat for juvenile coho may initially have higher vulnerable taxa abundance, which decline as the fish consume them. Note that we were only able to perform this analysis for a dry year, when overall juvenile densities were relatively low. Densitydependent effects, related to prey availability, may increase for juvenile populations in years with greater coho populations. Other species of fish are also likely to impact availability of macroinvertebrate prey. None of the macroinvertebrate metrics showed statistically significant relationships with juvenile coho density, except percent vulnerable macroinvertebrates (n = 10 sites, $P = 0.034$, $R^2 = 0.38$) (Figure 5). However, the graph displaying the relationship between average tolerance value and juvenile coho density showed two clear outliers with high tolerance values (relatively poor water quality) and high juvenile coho densities, SG-/LAG290 and SG-4/LAG300, both located in the upper reaches of San Geronimo (Figure 6). This observation may suggest one or more of the following: 1) factors such as flow magnitude or site fidelity are more important for juvenile survival than water quality, perhaps to a certain threshold not reached in this study area; 2) when flow levels are similar, such as those along the mainstem, juvenile coho are more abundant in areas with lower average tolerance values (indicating better water quality); and 3) juveniles in San Geronimo may experience sublethal impacts due to less optimal water quality there.

The percent vulnerable macroinvertebrates and juvenile coho densities did not have statistically significant relationships with any of the sediment-related physical habitat scores. However, comparing a scatter plot graph relating percent fine sediment and percent vulnerable macroinvertebrates (Figure 7) to a graph relating percent fine sediment and juvenile coho (Figure 8) suggests possible interactions among juvenile coho, macroinvertebrates, and sediment. Densities of juvenile coho were very low above a level of 25% fine sediment, which may in turn allow a higher percentage of vulnerable macroinvertebrates to survive. It is possible that for vulnerable macroinvertebrates, decreased predation provides a greater benefit than improved sediment conditions in those locations.

There were several limitations with comparing macroinvertebrates and coho that could be addressed in future work. Working with data obtained from various sources did not allow us to fully examine possible interactions among coho salmon, macroinvertebrates, and abiotic factors because of differences in timing and locations of data collection. Furthermore, we were unable to conduct a temporal analysis examining the effects of flow on macroinvertebrates because bioassessment data was collected only for one year. Future work should attempt to match times and locations for bioassessment and juvenile coho density surveys to better elucidate interactions between juvenile coho and their prey.

Mapping sediment, macroinvertebrates, and juvenile coho distribution (for 2001 only)

We mapped our data solely for 2001, the only year with invertebrate bioassessment data. For 2001 sediment conditions, we found that Balance Hydrologics' embeddedness was highest below the confluence of San Geronimo Creek and Lagunitas at Shafter Bridge, and then decreased downstream toward the large meander, "Big Bend." There was also high embeddedness at the stream segment below Big Bend (Figure 9), while Big Bend itself had an embeddedness of zero. Only three of the nineteen Lagunitas mainstem tributaries showed evidence of sediment delivery for this year: tributary J (the left bank tributary above Kelley's Tocaloma - KF), tributary H (the left bank tributary below Jewell), and Devil's Gulch Creek (Figure A1). Delta accumulation was observed for all three tributaries.

In order to compare macroinvertebrate and juvenile coho densities with sediment conditions, we combined reach data for Zanardi Creek and McIsaac Creek reaches, as well as for Cheda Ranch and Big Bend reaches (Figure 9). No consistent relationship was found between variability of 2001 juvenile coho density and availability of invertebrate prey, habitat quality, or embeddedness among Lagunitas mainstem reaches. High coho density was found in the reaches below Shafter Bridge and near Irving Creek, despite higher embeddedness at these locations (Figure 9). It is likely that embeddedness values for 2001 did not reach a threshold that impacted coho.

Although we did not observe localized sediment deposit impacts on coho or invertebrate populations on the Lagunitas mainstem for 2001, further analysis is needed for high flow years. Hecht et al. have referred to 1999-2001 as a "clean bed period" for the reach between Shafter Bridge and Big Bend. Since 2001 was a dry year with no high flow spills from Peters Dam, we expected less sediment inputs to Lagunitas for 2001. High flow spills effectively double the size of flow in Lagunitas (often to bankfull levels) and are estimated to contribute over 1,000 tons of sediment per year to Lagunitas bedload (O'Connor and Rossi 2006). Thus, interactions among sediment deposits, coho, and invertebrates may still occur during high flow years for two reasons. First, percent fine sediment would be more likely to exceed thresholds that impact coho survival. Second, we observed a lag time for sediment delivery from some local tributaries following high flow years, so fine sediment mobilized during high flow events could still accumulate to harmful levels in years following high flow for some tributaries. O'Connor has suggested moderate spills from Peters Dam as a solution to localized sediment buildup (O'Connor and Rosser 2006).

Scale is an important factor for observing and evaluating sediment impacts. In their 2008 report, Hecht et al. suggested that sediment inputs from the San Geronimo confluence and Big Bend areas have led to lower habitat quality for reaches below these points. Additionally, Hecht (1991) has hypothesized that local tributary sediment inputs accumulate within microreaches along the Lagunitas mainstem (i.e., the series of two to five riffle sequences immediately below the confluence of local tributaries and the mainstem). Our study attempted to explore reach scale habitat variation to achieve finer spatial comparison of existing sample data. However, additional data on invertebrates and finer scale fish counts are needed for such comparisons of habitat impacts to be successful. Our GIS model for reach scale spatial comparison could provide a useful tool for comparing complex biotic and abiotic data over variable reach sizes and over time.

CONCLUSIONS

Our findings suggest that streamflow and sediment inputs could have indirect effects on aquatic organisms. For example, higher Lagunitas peak mean daily flows in the winter appeared to be associated with declines of Lagunitas juvenile coho populations in the fall, while we found no effect of lower peak flows on coho for San Geronimo. Thus, the magnitude of peak mean daily flows may affect stream habitat conditions, thereby influencing the presence or absence of specific biological assemblages and interactions. The 2001 bioassessment data did not indicate a relationship between fine sediment and the percentage of vulnerable macroinvertebrates. On the other hand, two sites with fine sediment deposition at over 25% were associated with very low juvenile coho densities. Lower juvenile densities at sites with a high percentage of fine sediment may enable more vulnerable macroinvertebrates to survive.

Our study did not show that prey availability was a limiting factor for juvenile coho in 2001, nor did we observe significant spatial patterns of sediment impacts on coho or juveniles for 2001. However, the 2001 data was collected in a so-called "clean bed year," in which sediment impacts were less likely. Also, data comparison was limited to ten macroinvertebrate and juvenile coho sampling locations, because these were the only locations that approximately corresponded with one another. We suggest that future research involve simultaneous physical habitat, macroinvertebrate, and juvenile coho surveys throughout the Lagunitas watershed for additional years.

Habitat quality varied throughout the study sites, but we found no clear association between habitat impairment and declines in aquatic organisms based on currently available data. In general, San Geronimo seems to provide preferred habitat for juvenile coho rearing compared to the Lagunitas mainstem, perhaps because San Geronimo peak flows are lower than in Lagunitas. However, in 2001, the upper reaches of San Geronimo had the worst water quality among our study sites, yet relatively high juvenile coho densities. Although San Geronimo water quality did not impact juvenile coho densities in 2001, we recommend improving water quality to avoid potential future impacts.

Regular sediment inputs to Lagunitas occurred at six local tributaries, based on visual observations. Sediment inputs were particularly high during wet years, but low flow years can also contribute to localized sediment accumulation due to lag time in sediment delivery. Considering the results of O'Connor's 2006 fine sediment studies, tributary sediment input to Lagunitas could be approaching levels that impair local habitat and require source investigation, especially for downstream areas. Finally, understanding the complex dynamics of sedimentation and aquatic communities in the Lagunitas system requires more fine scale monitoring data, which is not yet available for macroinvertebrates or coho. A Geographic Information System (GIS) could provide a valuable tool for comparing coho, macroinvertebrate, and sediment data across multiple scales for Lagunitas. Future GIS analysis should also include local impacts of large woody debris and monitoring data on endangered California freshwater shrimp, *Syncaris pacifica*.

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Table 1. Comparison of selected physical habitat parameters at location LAG220 on April 17, 2001 and April 10, 2009.

Physical Habitat Measure	**LAG 220**	
	4/17/2001	4/10/2009
Epifaunal Substrate (1)	7	18
Embeddedness (1)	11	16
Velocity/ Depth Regimes (1)	12	15
Sediment deposition (1)	18	11
Channel Flow (1)	19	13
Channel Alteration (1)	20	15
Riffle Frequency (1)	15	20
Substrate Complexity T1 (2)	8	9
Substrate Complexity T2 (2)	8	9
Riffle Embeddedness T2 (3)	10	5
Substrate Consolidation T1	Med	Low
Substrate Consolidation T2	Med	Low
Fines T1 (3)	30	10
Fines T2 (3)	30	5
Gradient T1	1	0.009
Gradient T2	1	0.0135
WaterTemp, degrees Celcius	12	10
Average Depth T1 (inches)	13	9
Average Depth T2 (inches)	10	8

Notes:

1.) Measurement based on qualitative scores of least to most optimal condition (1-20).

2.) Measurement based on qualitative scores of least to most optimal condition (1-10).

3.) Visual estimate of percent of total.

T1= most downstream riffle

T2= must upstream riffle

Table 2. Corresponding Juvenile coho and bioassessment locations

Juvenile Coho Site ID	Macroinvertebrate Site ID	Combined Site ID for Comparison
LG-1	LAG130	LG-1_LAG130
LG-3u	LAG165	LG-3u_LAG165
LG-5	LAG180	LG-5_LAG180
LG-7	LAG190	LG-7_LAG190
LG-9	LAG210	LG-9_LAG210
LG-15.86	LAG220	LG-15.86_LAG220
LG-12	LAG320	LG-12_LAG320
SG-2	LAG240	SG-2_LAG240
SG-4	LAG290	SG-4_LAG290
SG-3	LAG300	SG-3_LAG300

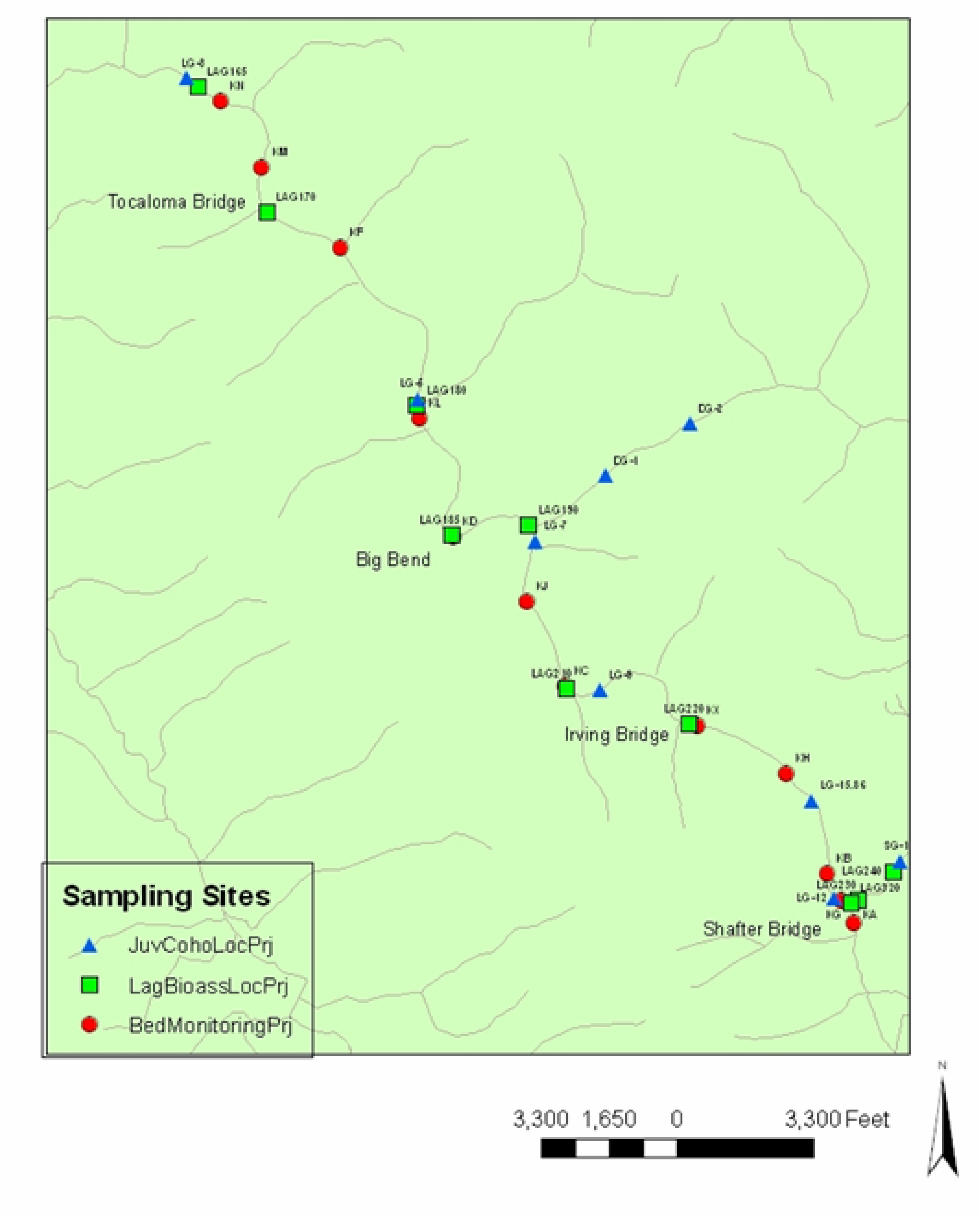

Figure 1. Lagunitas Creek Below Shafter Bridge: sampling sites for juvenile coho, macroinvertebrates, and bed monitoring.

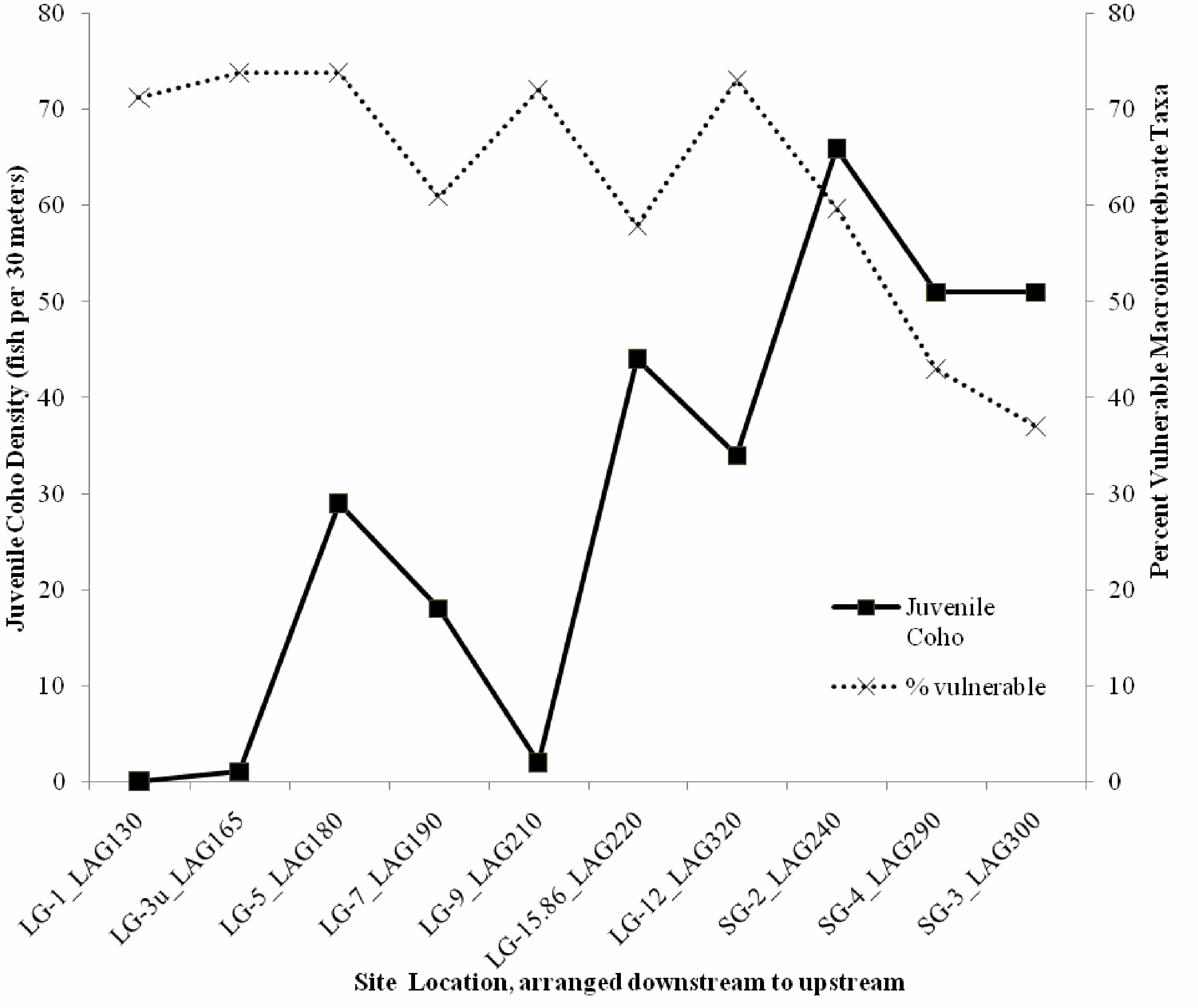

Figure 2. Distribution of Juvenile Coho and % Vulnerable Macroinvertebrate Taxa in 2001

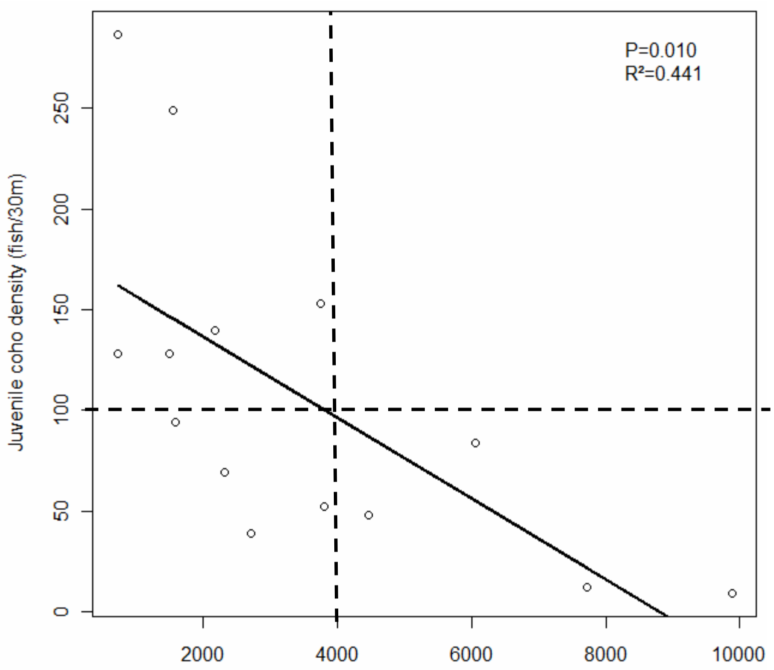

Figure 3. Juvenile coho density vs. peak mean daily discharge for Lagunitas Creek at the SPTSP gage (1994, 1996-2008) indicating a threshold effect at 4000 cfs.

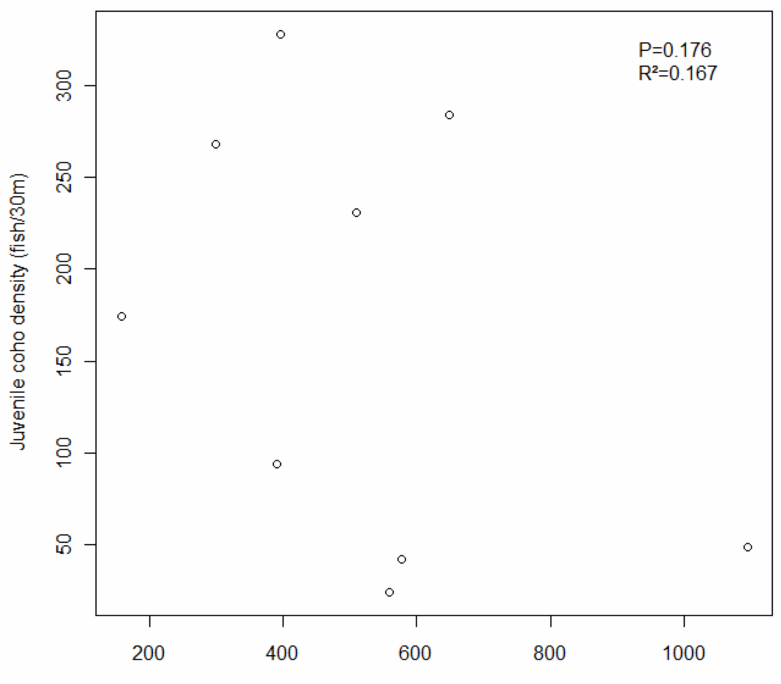

Figure 4. Juvenile coho density vs. peak mean daily discharge for San Geronimo Creek at Lagunitas Road (2000-2008).

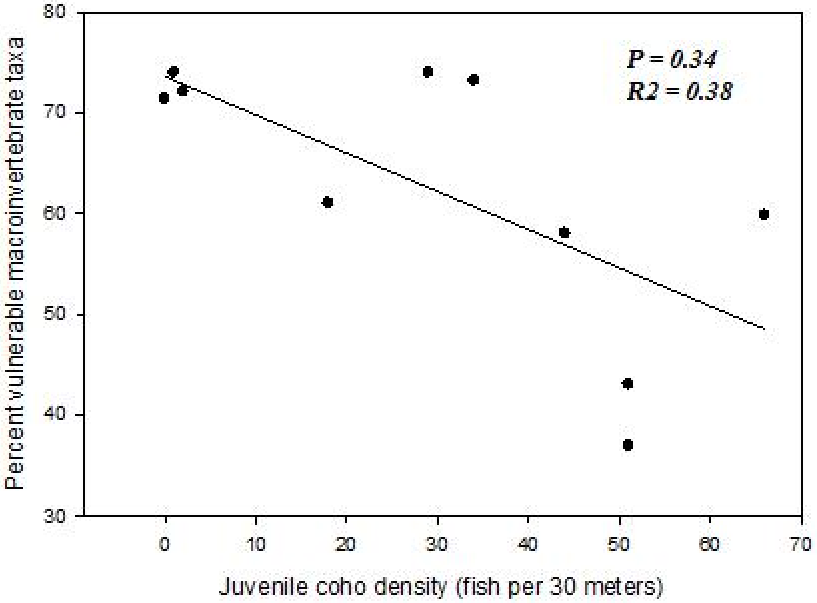

Figure 5. Relationship between %vulnerable macroinvertebrate taxa and juvenile coho density.

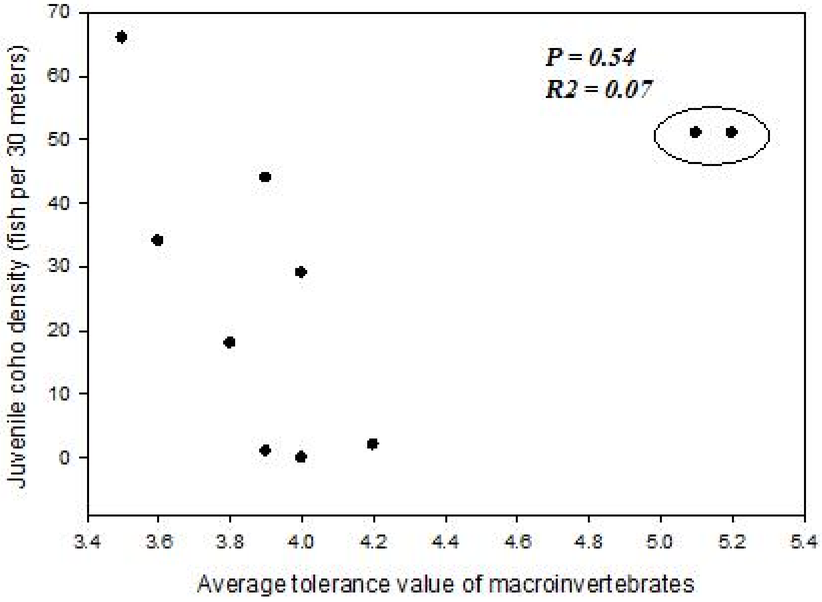

Figure 6. Relationship between average tolerance value of macroinvertebrates and juvenile coho density.

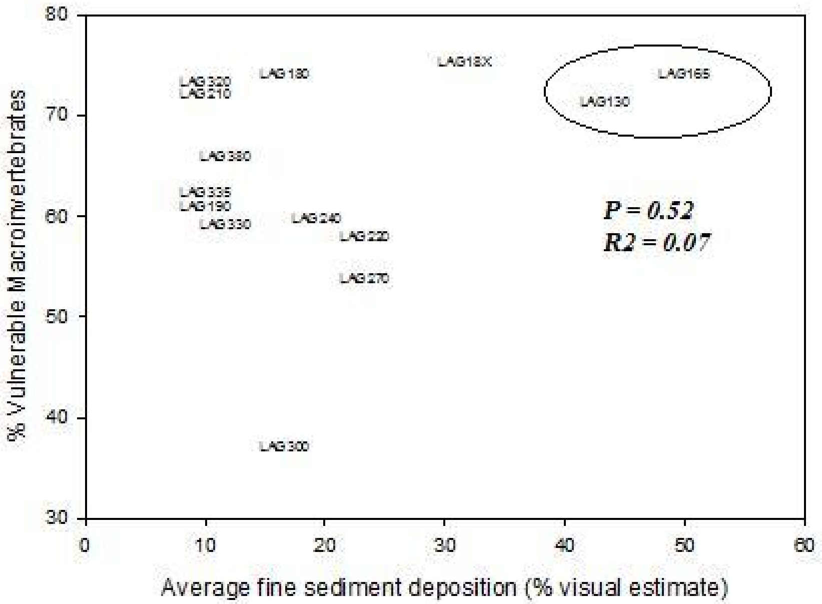

Figure 7. Relationship between average % fine sediment in riffles and % vulnerable macroinvertebrate taxa.

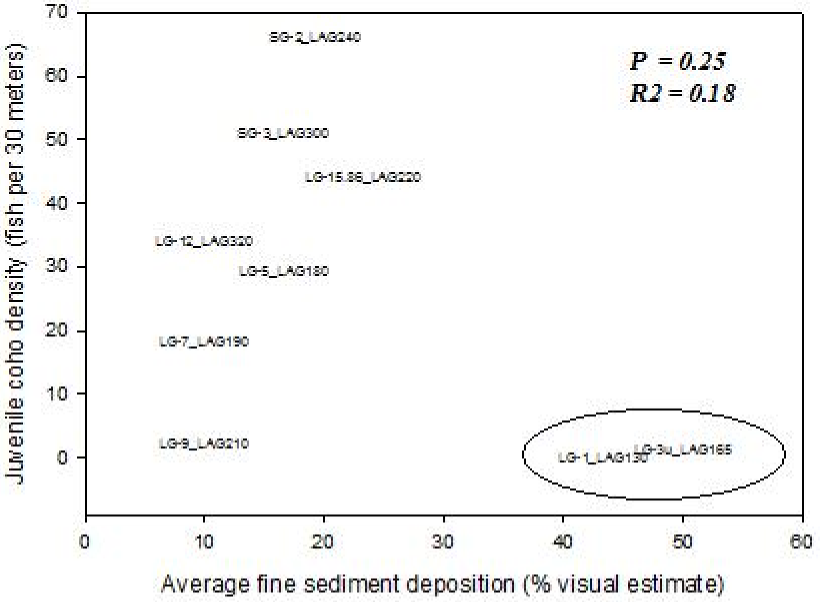

Figure 8. Relationship between average % fine sediment in riffles and juvenile coho density.

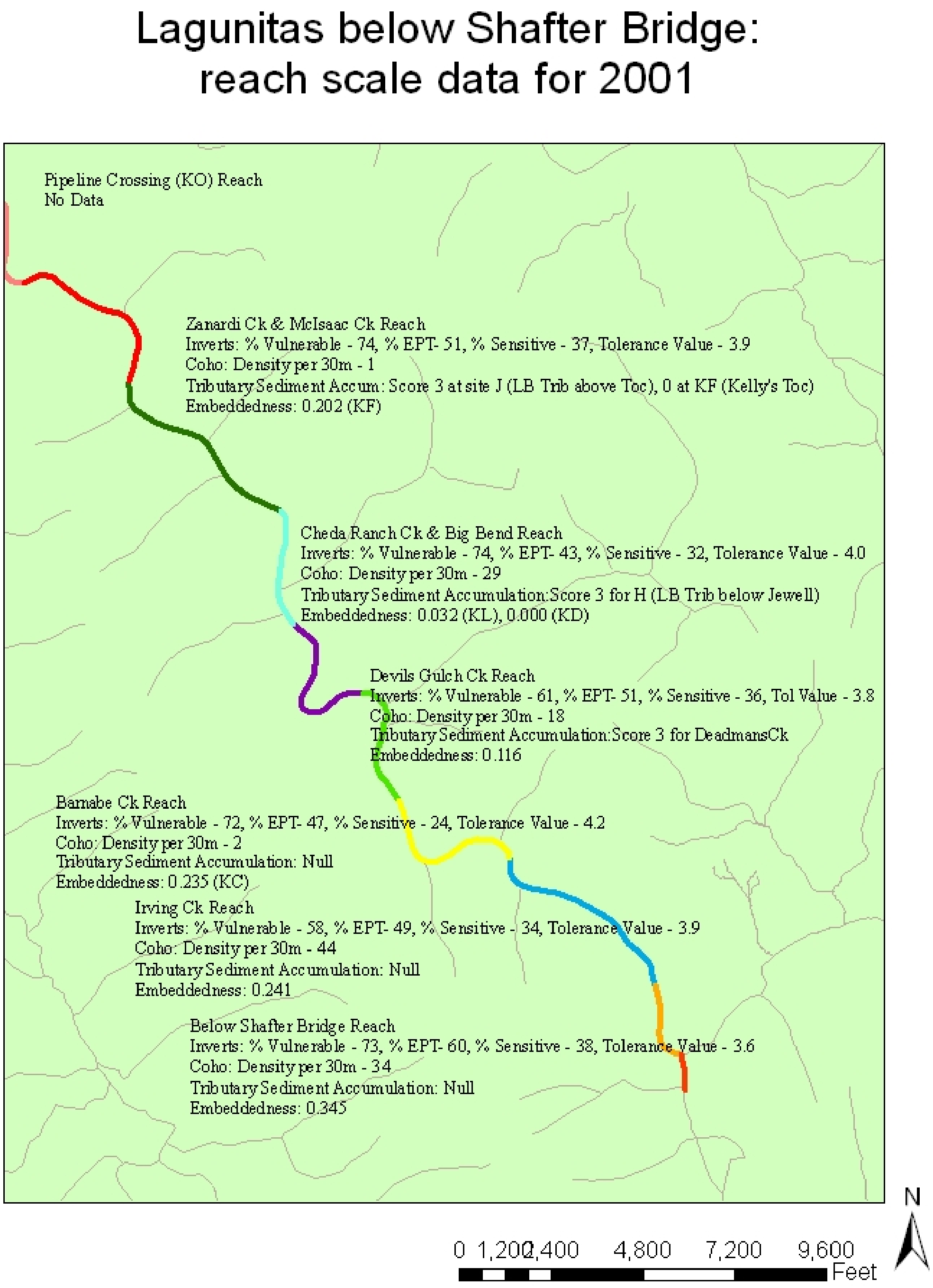

Figure 9. Reach-scale data for juvenile coho density, macroinvertebrates, tributary sediment accumulation, and embeddedness on the Lagunitas mainstem below Shafter Bridge.

Appendix

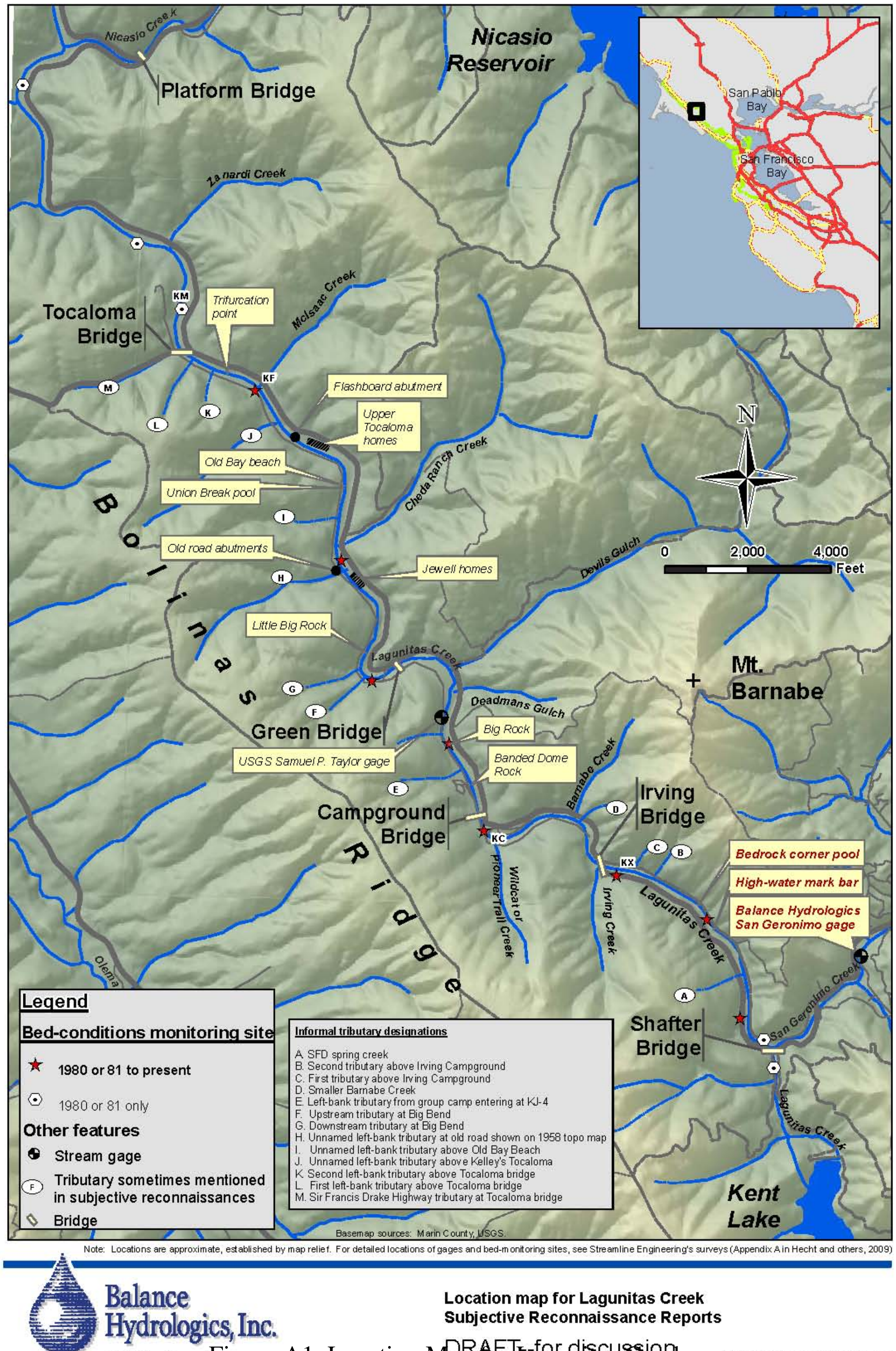

Figure A1. Location Map for Lagunitas Creek

Slope Calculation for Site LAG220

$$s = \frac{98.68 - 97.22}{270 - 1} = 0.00542$$

Hydraulic Radius Calculations for Cross Section 2 at Site LAG 220 (2009).

$$R = \frac{546\ ft.^2}{53.3\ ft.} = 10.2\ ft.$$

Table A1. Roughness elements for Site LAG220 (2009).

Cross Section	Material Involved (n_0)	Degree of Irregularity (n_1)	Channel Variation (n_2)	Effect of Obstructions (n_3)	Vegetation (n_4)	Degree of Meandering (m_5)	Roughness (n)
2	0.028	0.003	0.001	0.010	0.015	1.00	0.0570

Velocity and Discharge Calculations for Cross Section 2 at Site LAG220 (2009).

$$v = \frac{1.49(.00542^{0.5}\ x\ 10.2^{0.67})}{0.057} = 9.12\ \frac{ft}{sec}$$

$$Q = \left(9.12\frac{ft}{sec}\right)(546\ ft^2) = 4{,}980\ cfs$$

Table A2. Cross-sectional measurements for Site LAG220 (2009).

Cross Section	Slope	Area (ft.^{2})	Wetted Perimeter (ft.)	R (ft.)	n	v (ft/s)	Q (cfs)
2	0.00571	47.41	23.75	1.996	0.325	2.45	116.20

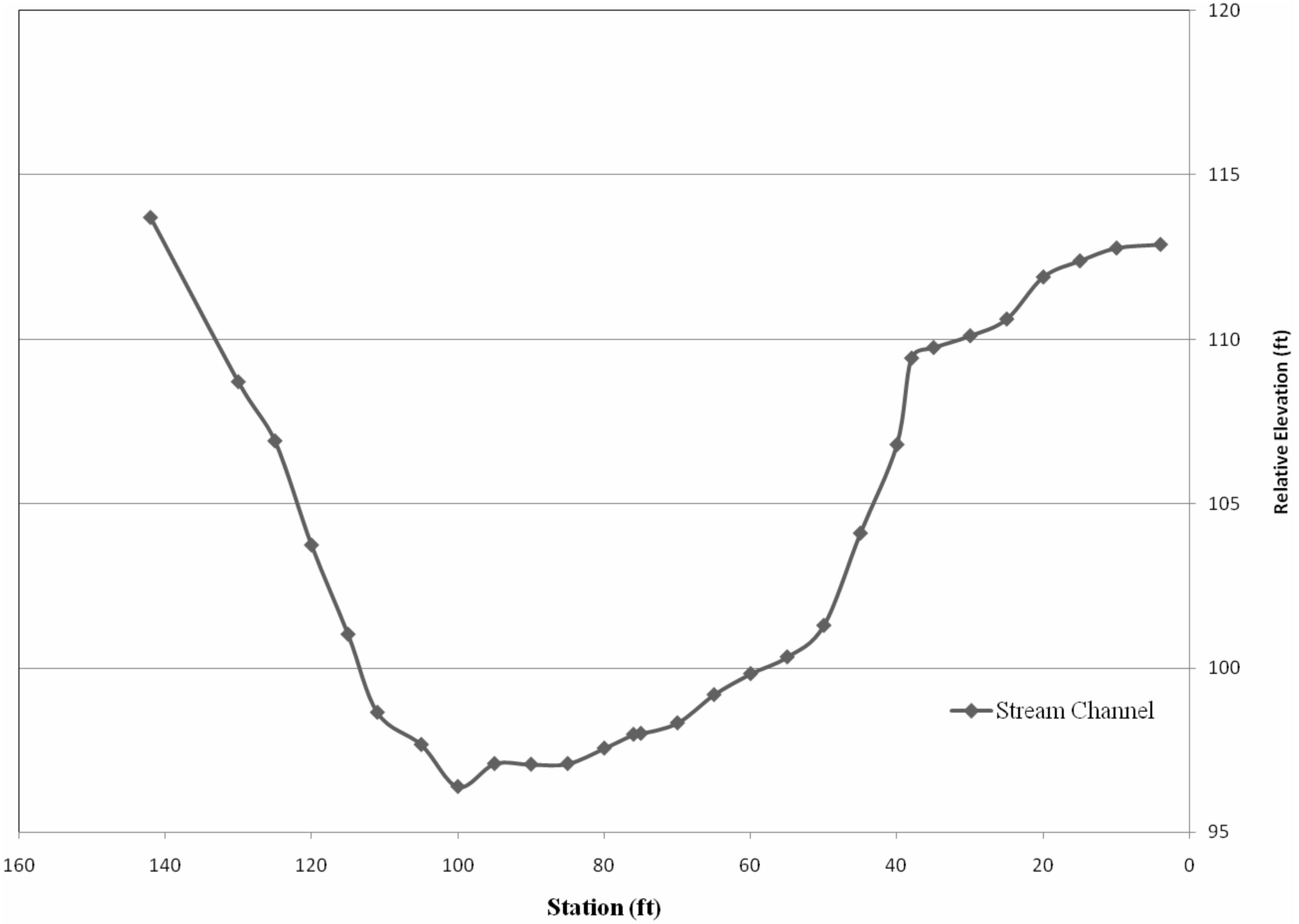

Figure A2. Cross section survey #1 at Lagunitas Creek upstream of Irving Bridge

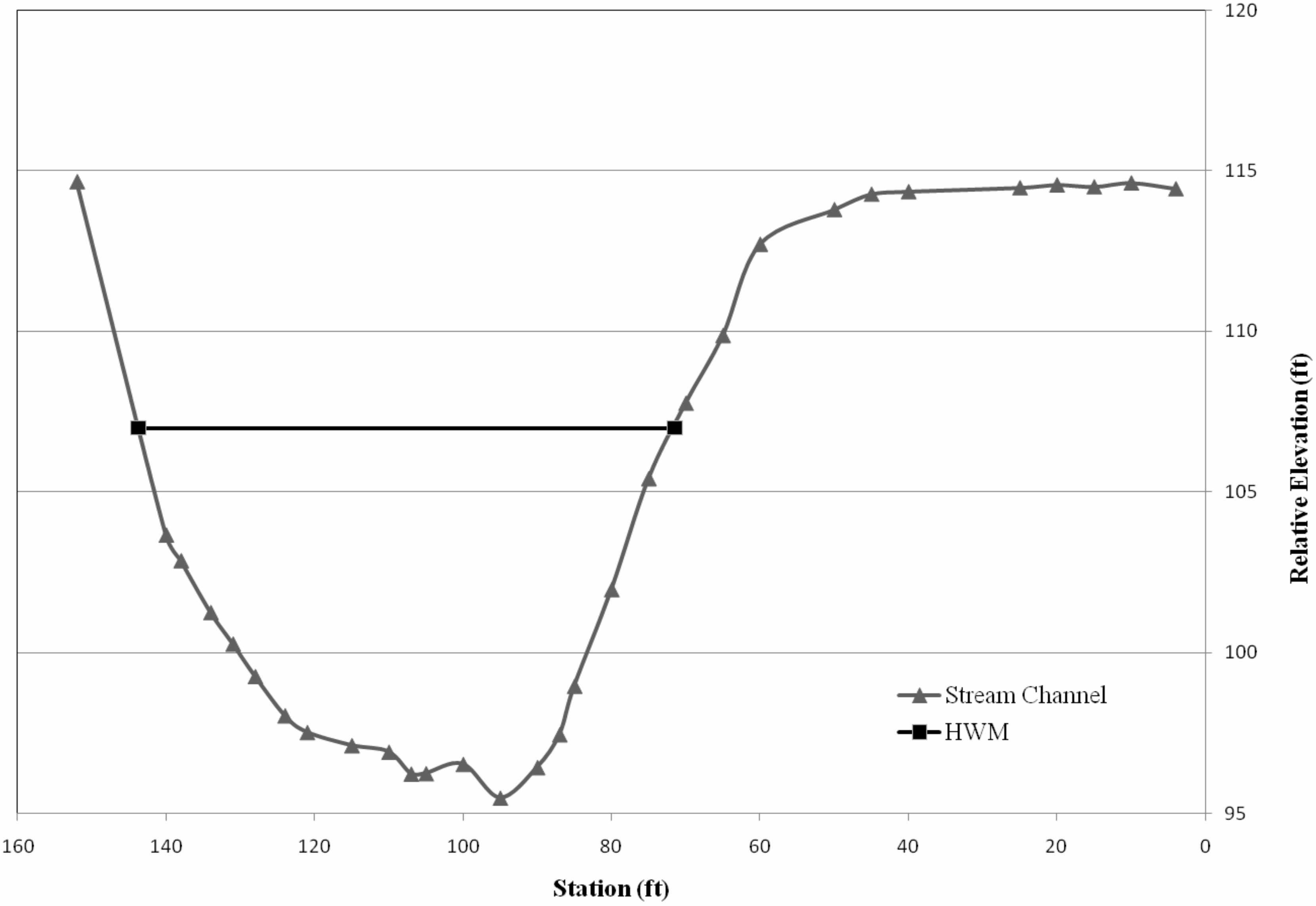

Figure A3. Cross section survey #2 at Lagunitas Creek upstream of Irving Bridge.

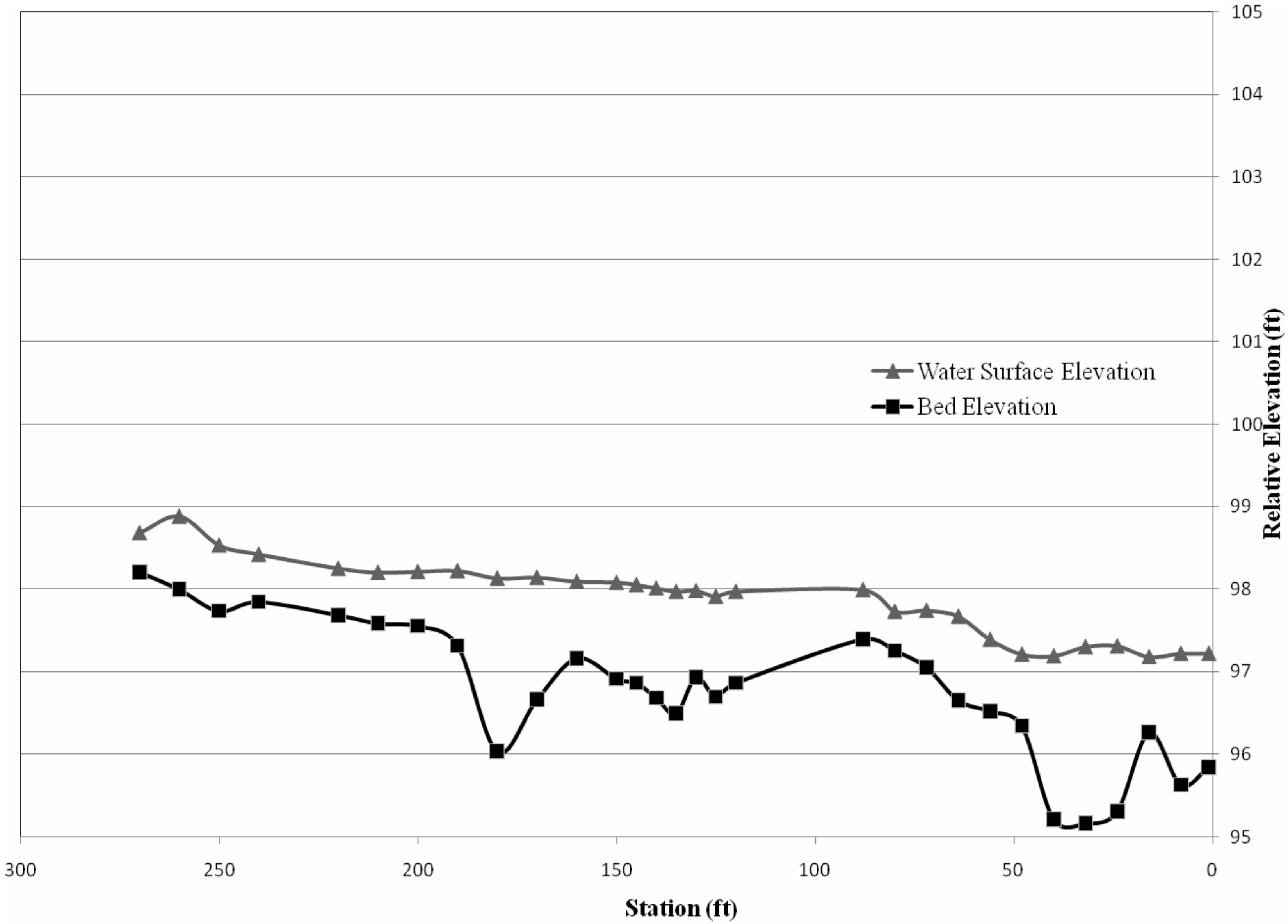

Figure A4. Long profile survey of Lagunitas Creek upstream of Irving Bridge.

Tributary Name	1993	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2006	2007	2008	Tot yr with sed accum	Tot yr with delta accum	% yr with accum	% yr with delta accum
SFD Hwy Trib at Tocaloma Bridge (M)	Null	Null	Null	Null	Null	Null	Null	Null	Null	Null	Null	Null	1	0	1	0	0.07	0.00
1st Left Bank Trip Above Tocaloma (L)	Null	3	3	1	0	0	0	Null	1	1	1	3	0	0	7	3	0.50	0.21
2nd Left Bank Trib Above Tocaloma (K)	Null	0	0	1	0	0	0	Null	0	0	0	3	0	0	2	1	0.14	0.07
Kelly's Tocaloma/McIsaac Bridge, MM 20.3 (KF)	3	Null	0	2	0	0	Null	0	3	3	0	1	3	0	6	4	0.43	0.29
Left Bank Trib Above Kelly's Toc - KF (J)	3	Null	3	3	2	3	3	3	1	0	0	3	2	0	10	7	0.71	0.50
Cheda Ranch Ck	3	3	3	1	3	Null	1	Null	3	0	2	0	2	2	10	5	0.71	0.36
Left Bank Trib at Old Road (below Jewell)(H)	3	3	2	Null	3	0	1	3	3	3	0	1	0	3	10	7	0.71	0.50
Downstream Trib at Big Bend (G)	Null	1	1	Null	Null	0	1	Null	Null	Null	Null	1	0	1	5	0	0.36	0.00
Upstream Trib at Big Bend (F)	Null	Null	1	Null	Null	0	1	Null	Null	Null	Null	1	Null	Null	3	0	0.21	0.00
Devil's Gulch Creek		1	3	Null	3	3	2	3	0	3	0	3	0	3	9	7	0.64	0.50
Deadman's Creek	Null	Null	0	Null	Null	2	1	Null	0	0	2	2	0	1	5	0	0.36	0.00
Big Rock (KJ)	Null	Null	Null	Null	Null	Null	3	Null	Null	Null	Null	2	Null	Null	2	1	0.14	0.07
Left Bank Trib from Group Camp KJ-4 (E)	Null	Null	3	Null	3	0	Null	Null	3	0	0	2	3	0	5	4	0.36	0.29
Campground Bridge (KC)	Null	Null	Null	Null	3	Null	Null	Null	Null	Null	Null	Null	Null	Null	1	1	0.07	0.07
Wildcat & Pioneer Trail Creek	Null	Null	Null	Null	1	Null	Null	Null	Null	Null	Null	Null	Null	Null	1	0	0.07	0.00
Irving Creek	Null	Null	3	1	3	0	1	Null	Null	1	0	3	0	2	7	3	0.50	0.21
Irving Bridge (KX)	Null	Null	Null	Null	Null	Null	Null	Null	Null	3	Null	Null	Null	Null	1	1	0.07	0.07
1st Trib Above Irving Campground (C)	Null	Null	Null	Null	Null	Null	Null	Null	Null	Null	Null	Null	Null	Null	1	0	0.07	0.00
2nd Trib Above Irving Campground (B)	Null	Null	2	Null	Null	Null	Null	Null	Null	Null	3	Null	Null	Null	2	1	0.14	0.07
Tot. tribs with accumulation	4	5	10	6	8	3	9	3	6	6	4	12	5	6				
Tot. tribs with delta accumulation	4	3	6	1	6	2	2	3	4	4	1	5	2	2				
% tribs with accum.	0.21	0.26	0.53	0.32	0.42	0.16	0.47	0.16	0.32	0.32	0.21	0.63	0.26	0.32				
% tribs with delta	0.21	0.16	0.32	0.05	0.32	0.11	0.11	0.16	0.21	0.21	0.05	0.26	0.11	0.11				

Table A3. Evidence of tributary sediment deposits at Lagunitas tributaries from Balance Hydrologics subjective reconnaissance reports, 1993-2008. Observations taken at the confluence of individual tributaries and the Lagunitas mainstem into five categories: (3) increased delta size from tributary sediment sources, (2) presence of deltaic bars or fan, (1) presence of other visible trace debris, (0) decreased delta size, visible signs of decreased deposition, or no change, and (Null) no observation noted. See map A1 for site locations.

Figure A5. Geographic coordinates of bed monitoring, Juvenile coho sampling, bioassessment , and tributary sediment monitoring sites.

Data_Type	Site_ID	Latitude	Longitude	Site_Desc
BedMonitor	KB	38.00670960600	-122.71098799300	
BedMonitor	KH	38.01326665510	-122.71457952000	
BedMonitor	KX	38.01631047710	-122.72220563100	
BedMonitor	KC	38.01875567100	-122.73342969300	
BedMonitor	KJ	38.02430992020	-122.73684364300	
BedMonitor	KD	38.02857077910	-122.74314633000	
BedMonitor	KL	38.03634815330	-122.74622565800	
BedMonitor	KF	38.04755781670	-122.75320285800	
BedMonitor	KG	38.00495240050	-122.70978589600	
BedMonitor	KA	38.00342630250	-122.70863302400	
BedMonitor	KM	38.05277894400	-122.75996003900	
BedMonitor	KO	38.06735137950	-122.77379644000	
BedMonitor	KN	38.05718299970	-122.76354921700	
Bioassess	LAG130	38.080640	-122.784500	Gallagher's Ranch Lagunitas Creek
Bioassess	LAG165	38.058390	-122.765220	Below Tocaloma Lagunitas Creek
Bioassess	LAG170	38.049700	-122.759450	Tocaloma Lagunitas Creek
Bioassess	LAG180	38.037220	-122.746110	Cheda Lagunitas Creek
Bioassess	LAG185	38.028720	-122.743260	Swimming Hole @ SPTaylor Lagunitas Creek
Bioassess	LAG190	38.029640	-122.736360	Devils Gulch Devils Gulch
Bioassess	LAG210	38.018610	-122.733060	Taylor Park Lagunitas Creek
Bioassess	LAG220	38.016110	-122.722970	Irving Bridge Lagunitas Creek
Bioassess	LAG230	38.005000	-122.708330	Inkwells San Geronimo Creek
Bioassess	LAG240	38.007030	-122.705690	White Horse Bridge San Geronimo Creek
Bioassess	LAG270	38.013560	-122.666640	Creamery Gulch San Geronimo Creek
Bioassess	LAG290	38.013050	-122.650550	Lag Water Treatment Plant San Geronimo Creek
Bioassess	LAG300	38.012750	-122.646890	Woodacre Creek San Geronimo Creek
Bioassess	LAG320	38.004530	-122.708780	Shafter Bridge Lagunitas Creek
Bioassess	LAG330	37.991940	-122.669720	Big Carson 1 Big Carson Creek
Bioassess	LAG335	37.992220	-122.660000	Big Carson 2 Big Carson Creek
Bioassess	LAG380	37.967220	-122.649440	Little Carson Big Carson Creek
Bioassess	LAG390	37.932500	-122.635560	Cataract Cataract Creek
Coho	LG-2	38.065900	-122.773500	
Coho	LG-3	38.058700	-122.766300	

Coho	LG-5	38.037700	-122.746400	
Coho	LG-7	38.028400	-122.736500	
Coho	LG-9	38.018700	-122.730500	
Coho	LG-15.86	38.011400	-122.712600	
Coho	LG-12	38.005200	-122.710200	
Coho	SG-1	38.007700	-122.704900	
Coho	SG-2	38.013600	-122.698000	
Coho	SG-3	38.012700	-122.652100	
Coho	SG-4	38.013300	-122.651100	
Coho	DG-1	38.033200	-122.730800	
Coho	DG-2	38.036700	-122.723500	
TribSed	KB	38.006710	-122.710988	Below Shafter, MM 15.49 (KB)
TribSed	KH	38.013267	-122.714580	Kelly's Upper State Park (KH)
TribSed	KX	38.016310	-122.722206	Irving Bridge (KX)
TribSed	KC	38.018756	-122.733430	Campground Bridge (KC)
TribSed	KJ	38.024310	-122.736844	Big Rock (KJ)
TribSed	KD	38.028571	-122.743146	Big Bend/Green Bridge (KD)
TribSed	KL	38.036348	-122.746226	Above Cheda Ranch Ck (KL)
TribSed	KF	38.047558	-122.753203	Kelly's Tocaloma/McIsaac Bridge, MM 20.03 (KF)
TribSed	KG	38.004952	-122.709786	At Shafter Bridge (KG)
TribSed	KA	38.003426	-122.708633	Above Shafter (KA)
TribSed	KM	38.052779	-122.759960	Tocaloma Pump (KM)
TribSed	KO	38.067351	-122.773796	Pipeline Crossing (KO)
TribSed	KN	38.057183	-122.763549	Zanardi (KN)
TribSed	M	38.051509	-122.760334	SFD Hwy Trib at Tocaloma Bridge
TribSed	L	38.050856	-122.760194	1st Left Bank Trib Above Tocaloma
TribSed	K	38.050026	-122.759780	2nd Left Bank Trib Above Tocaloma
TribSed	J	38.045375	-122.751409	Left Bank Trib Above Kelly's Toc (KF)
TribSed	I	38.038986	-122.746195	Left Bank Trib Above Old Bay Bridge
TribSed	ChedaRanchCk	38.037314	-122.746431	Cheda Ranch Ck
TribSed	H	38.035626	-122.745679	Left Bank Trib at Old Road
TribSed	G	38.029211	-122.744110	Downstream Trib at Big Bend
TribSed	F	38.028730	-122.743733	Upstream Trib at Big Bend
TribSed	DevilsGulchCk	38.029200	-122.736617	Devil's Gulch Creek
TribSed	DeadmansCk	38.027711	-122.736572	Deadman's Creek
TribSed	E	38.023929	-122.736441	Left Bank Trib from Group Camp KJ-4
TribSed	WildcatPioneerTrailCk	38.018233	-122.732713	Wildcat & Pioneer Trail Creek
TribSed	BarnabeCk	38.019526	-122.725976	Barnabe Creek
TribSed	D	38.019054	-122.725118	Smaller Barnabe Creek
TribSed	C	38.012422	-122.713777	1st Trib Above Irving Campground
TribSed	B	38.011685	-122.712529	2nd Trib Above Irving Campground
TribSed	A	38.008537	-122.711129	SFD Spring Creek
TribSed	IrvingCk	38.016559	-122.723699	Irving Creek