Title

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Evaluating a protocol to avoid fish stranding in the Russian River Watershed

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Abstract

The simultaneous withdrawal of water from streams for springtime frost protection of grapevines in the Russian River basin can coincide with the emergence of salmonid fry and the rearing of juveniles. These water diversions have contributed to water level declines, which in some instances, have resulted in the stranding mortality of fish. Endangered coho salmon and threatened steelhead trout can become stranded when water levels decrease abruptly and fish seek refuge in the rapidly dewatering gravel.

In response to this issue, the National Marine Fisheries Service (NMFS) has proposed a site-specific method to determine minimum flows to protect salmonids from these effects. This method seeks to identify "high risk" stranding surfaces and determine the stream stage at which they become exposed. In this study, we evaluated the ability of the NMFS protocol to accurately prescribe protective stages. To do this, we analyzed three components of the protocol: its stranding risk classification system, it's sampling of stranding surfaces and its method of establishing protective stage recommendations.

We evaluated the risk classification system by comparing it to published literature values on salmonid stranding. We assessed the sampling of stranding surfaces by performing the protocol at two sites. NMFS developed the method based on data from a medium-sized drainage (12.6 mi^2), so we selected a small drainage (4.6 mi^2) and a large drainage (50.2 mi^2) to evaluate how effectively the method characterized the variation in potential stranding surfaces in different watershed settings. We evaluated the protocol's protective stage recommendation by comparing the protective stage from our two surveyed sites to stream stage data for the season of regulation.

Our assessment has led us to make several recommendations. First, the risk classification system would benefit from consideration of other factors influencing stranding risk and should adjust stranding risk thresholds to better fit the literature. Also, the protocol is weak in its ability to capture within-site variation. We therefore recommend increased sampling of stream reaches and scaled mapping of each site to better define stranding surfaces. These measures should result in improved protective stage recommendations but further studies may be necessary. With these changes, we believe that the NMFS protocol will be an effective tool for protecting fish from being stranded due to vineyard use of water during frost events in the Russian River Watershed.

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[1] **D. Hines is also a biologist with the National Marine Fisheries Service (NMFS) and a principal developer of the proposed protocol. This evaluation was subject to multiple reviews by UC Berkeley faculty, students and outside reviewers.**

Introduction

In Sonoma County, application of water via overhead sprinklers is widely used in vineyards as the preferred method to protect new growth on vines from damage associated with spring frost events. Because frost events tend to occur at the same time across most of the Russian River Watershed, water is withdrawn from tributaries on the streams at the same time. Research by Deitch *et al.* (2008) showed abrupt reductions in stream flow of up to 97% on cold spring mornings when the air temperature approached freezing. These hydrologic deviations lasted from hours to days and then flow returned to near previous levels as the demand for water subsided. Researchers concluded that natural catchment processes were not sufficient to explain the observed flow changes; rather, they were due to small in-stream diversions associated with frost protection irrigation of vineyards (Deitch *et al.* 2008).

Vineyard frost protection generally occurs between March and May, timing that overlaps with several important life history stages for salmonids, especially steelhead (*Oncorhynchus mykiss*) and coho salmon (*Oncorhynchus kisutch*), which are threatened and endangered respectively in the Russian River Watershed. Water use by vineyards has lead to the death of these species due to stranding when water levels abruptly decline (NMFS 2009, Cluer 2011).

Fish Stranding

Steelhead and coho salmon embryos develop and hatch from redds from December through April, and tiny alevin reside within the interstitial spaces of gravel (Groot and Margolis 1991, Quinn 2005). Whereas embryos can remain viable for weeks in dewatered gravel, alevin will not survive if gravels are dewatered (Hunter 1992).

Once coho salmon emerge from the gravel, the fry occupy shallow water along stream margins, side channels, or other low velocity habitats where they feed and rear (Sandercock 2003, Shapovalov and Taft 1954). Steelhead fry also occupy shallow stream habitats, including riffles and other areas that provide increased foraging opportunities (Barnhart 1986, Olson and Metzgar 1987). These small fry are most susceptible to stranding because they have limited swimming abilities (Hunter 1992). Also coincident with the timing of frost protection in the spring, coho salmon and steelhead smolts, which have spent one to two years rearing in tributaries, migrate from tributaries, into the Russian River, and out to the ocean.

Salmonid fry often occupy shallow stream margins to avoid high velocity flows and predation (Sandercock 2003, Shapovalov and Taft 1954). When water levels drop fry, rather than following water toward the center of the channel, respond by taking refuge in interstitial spaces of substrate (Chapmann and Bjornn 1969, Monk 1989) (Figure 1). Low slope areas also exacerbate the potential for stranding because, for any incremental change in stage, the horizontal retreat of the water is much greater than for lower gradient slopes (Figure 2) (Bauersfield 1978, Monk 1989, Hunter 1992, Bradford 1997, Bell et al. 2008). Areas of small substrate would provide little refuge in interstitial spaces and therefore are areas of low risk to fish.

Regulation

In September 2011, the State Water Resources Control Board (SWRCB) approved a set of rules to govern and monitor water use by vineyard and orchards in the Russian River Watershed (SWRCB 2011). This regulation requires water used for the purposes of frost protection (between March 15 and May 15) be diverted in accordance with a SWRCB approved Water Demand Management Plan. The purpose of these plans is to manage diversions to prevent stranding mortality of salmon. The stream stage monitoring program will be developed in consultation with the National Marine Fisheries Service (NMFS) and the California Department of Fish and Game and will include recommendations of the stream stage necessary to prevent stranding mortality.

Preliminary Protocol Developed

In anticipation of these consultations, NMFS has developed a preliminary site-specific method for determining minimum flows to protect salmonid fry (and juveniles) from stranding on coarse, low gradient stream channel surfaces. This protocol assumes that stream gauges are already placed in locations sufficient to capture hydrologic impacts from frost diversions. This generally includes placing a gauge downstream of vineyard clusters on salmonid streams (Figure 3). Guidance on gauge placement was not included in the protocol and we did not evaluate that aspect of the issue.

Given that a gauge was placed in a stream as a point of compliance for the regulation, the NMFS protocol attempts to define the “protective stage” for salmonids at that site. The State regulation defines protective stage as that stream flow/elevation above which no stranding mortality would occur, beyond background levels, as a result of water withdrawals. NMFS attempts to define this stage by surveying three cross-sections at each site (located in a pool, riffle and run). These surveys yield a sample of all channel surfaces in the reach with their elevation, particle size and lateral slope (i.e. the slope transverse to the longitudinal axis of the stream) defined. A low, medium or high risk of stranding is attributed to each surface based on its slope and mean particle size. High gradient and/or small-grained surfaces are labeled low risk and high risk surfaces are those with low lateral slope and large grain size.

These surfaces are then plotted on a hydrograph of the site’s observed stage during the most recent frost season (March 15 through May 15). Protective stage for that site is defined as the stage above all of the high and medium risk surfaces. The method is defined in a way that can be applied to any site, but will describe recommendations unique to each site. NMFS has tested their method at one location in Sausal Creek (Figure 3), a medium sized drainage basin (12.6 mi^2).

Objectives

The objective of our study was to assess the ability of the NMFS protocol to define "protective stage". Our assessment included a comparison of the stranding risk classification scheme to factors found to be important determinants of fish stranding in the published literature. We also examined the methods by which channel surfaces were sampled, surveyed and characterized, by applying it at two additional sites, Lower Mark West Creek and Bidwell Creek. Table 1 describes the differences in watershed settings for each of these sites. This allowed us to comment on how accurately the method captured relevant channel features given the presumed variability between sites and (to a limited extent) within sites. Finally, we comment on the derivation of a stage recommendation based on the interaction of stream stage with medium and high risk stranding surfaces.

Methods

Assessing the NMFS Risk Model

To understand our assessment of the risk model, we begin by describing the NMFS method, which established risk thresholds in three steps. First, d50 values of 2mm, 64mm and 256mm were placed in a matrix showing every combination with the following slope classes: 0, 1, 2, 3, 4, 5, 6, 10 and 20 (Table 2). The authors of this method then subjectively assigned a stranding risk of high, medium or low based on their professional judgment to each combination. Risk classifications followed the trend of increasing risk with increasing particle size and decreasing slope. The product of the ratio of d50 to slope was also included for each combination of variables in the matrix. In the second step, the risk classifications were sorted by ratio value, from lowest to highest. The grouping of low medium and high risks separated cleanly into their respective groups (Table 3). In other words, all of the highest ratio values had high risk associated with them, etc. For the third and final step of the risk model, the authors split the distribution or ratio values along the aforementioned groupings and established risk classes by rounding the ratio values to approximate mid-point values (Table 4).

To assess the performance of the NMFS risk model, we compared its definition of low, medium and high risk stranding surfaces to the published literature. We searched peer-reviewed articles for studies looking at stranding of salmonids. Specifically, we looked for two things: factors influencing stranding of salmonids and combinations of slope and substrate size that resulted in stranding. We were able to extract multiple data points relating slope and substrate size where fish stranding occurred in these studies and plotted them on a scatter graph. We then overlaid the NMFS definition of low, medium and high stranding risk to look at where the literature points landed within the NMFS definitions. Our expectation was that a functioning model would show that all data points where stranding occurred in these studies landed in locations that correspond with NMFS's defined high, medium, and low risk stranding surfaces.

Defining Stranding Surfaces

Our second step in assessing the NMFS protocol was to examine its definition of stranding surfaces. In order to understand how the NMFS protocol defines risks of stranding surfaces, we performed the NMFS protocol at two additional stream sites: Lower Mark West creek and Sausal creek (Figure 3). Per the NMFS protocol, we performed three cross sections, one for each meso-habitat type (one pool, one riffle and one run). While surveying the cross sections we used a stadia rod, auto level, and a measuring tape to survey all major breaks in slope, the thalweg and the water’s edge. Substrate type was noted at each stadia rod location. Pebble counts were performed (100 random stones measured randomly) on gravel and cobble substrates. A map of each meso-habitat type was drawn but the maps were not drawn accurately to scale. Areas of unique substrate type were measured using a measuring tape.

While performing the NMFS protocol in the field we noted areas of concern, areas of ambiguity and methods that were in need of improvement.

Defining Protective Stage

Finally, to look at the NMFS model’s definition of protective stage, we acquired stream stage data from NMFS for our study sites between March 15th and May 15th, 2010. These dates were selected because the water use regulations would only be in effect during this time. We graphed the stream stage data for each stream and added lines depicting the elevation of all surveyed stranding surfaces for the study sites we assessed, and for Sausal Creek as well (Figure 4). In addition, we created a similar graph comparing the NMFS defined protective stage with the same hydrographic data (Figure 5). Creating this graph allowed us to look at the number of days during this two month period when vineyards could have withdrawn water without risking fish stranding. However, the stream stage data is not unimpaired; meaning, water was withdrawn by vineyards during the two months. Realistically, these graphs will tell us how many *more* days the vineyards could have withdrawn water. We will use these graphs to highlight the impact this protocol may have on water users.

Results and Discussion

Assessing the NMFS Risk Model

With the approach proposed by NMFS, the accurate attribution of stranding potential to any given surface in the stream channel is critical to determining the protective stage. This is because the protective stage is defined by the highest elevation high or medium risk stranding surface surveyed at the site. If the risk model inappropriately labels a high elevation surface as a high or medium risk, then the resulting protective stage recommendation may be too restrictive to the water user. Conversely, if it fails to recognize a high-risk surface, it will not be truly protective of the threatened species. To assess the ability of the NMFS risk model to accurately assign stranding risks, we considered two things: First, the appropriateness of limiting the model to just the two variables of particle size and slope, and; Second, whether the method of establishing risk thresholds based on a ratio of substrate size and slope was consistent with published literature on stranding.

With respect to selecting the best possible predictors, the use of slope and substrate size as indicators of stranding risk is well supported in the literature. However, many additional factors are ignored in the NMFS model. These include: The rate of stage change (Hunter 1992, Halleraker et al. 2003, Bradford 1995); Potholes (Eugene Water and Electric Board 2004); Side channels (Eugene Water and Electric Board 2004, Bradford et al. 1997); Time of day (Hunter 1992, Halleraker et al. 2003, Bradford 1995, Bradford et al. 1997), and; Water temperature (Halleraker et al. 2003, Bradford et al. 1997). Incorporation of some or all of these variables may enhance the predictive ability of the risk model and therefore improve the reliability of the protective stage recommendation.

Nearly all of the literature we reviewed examined stranding risk in the context of water releases from hydroelectric dams. The application of their findings to the frost situation should therefore be done with caution as the magnitude, timing, rate and frequency of stage changes due to frost diversions is typically different. In particular, the magnitude of flow and the rate of stage change can be greater below dams. Nevertheless, the NMFS protocol did not explain the exclusion of any of these other factors.

Of particular concern is the omission of ramping rate as a factor in the model. Ramping rate refers to the magnitude of stage decline over time for a given event. Hunter (1992) uses ramping rate as the primary control for reducing stranding risk below dams. However, this may have more to do with the fact that it is the most easily controlled variable affecting stranding in that context. Although Bradford (1995), and many others, implicate ramping rate as factor in stranding, more recent work by Bradford (1997) states: "the rate of flow decrease was not a significant factor in the incidence of stranding." Bell et al. (2008) reached similar conclusions. In any case, the rate of stage change during frost episodes may be an important factor, and its exclusion in the NMFS model has not been adequately addressed.

We begin our evaluation of the NMFS risk classification system with a graphical comparison of the NMFS threshold values to the relevant literature. We found that the NMFS risk classification system roughly corresponds to the substrate size and slope values associated with fish strandings in the literature, but could use some refinement. We compared the low, medium and high-risk thresholds to published literature values of d50 and slope that resulted in stranding, as well as the associated frequency of fish strandings (Figure 6). With regard to slope, most strandings were documented at or below 2%, although many were reported on slopes of 6% or less. However, no strong trend of increasing stranding frequency with decreasing slope was apparent. With respect to stranding frequency's relationship to substrate particle size, the maximum documented size was an approximate d50 of 100mm. However, strandings occurred with nearly equal frequency down to a d50 of 12mm.

From the small number of data points we were able to find in scientific articles, it appears that the NMFS protocol may be too conservative in its definition of high stranding risk. We found that of nineteen literature points, two points fell within the low risk area delineated by the NMFS protocol, twelve points fell within the medium risk surface and only five fell within the high risk area. Because these are data points that represent actual stranding events, these points would have ideally all fallen within the NMFS-defined medium or high-risk classes, with a greater concentration in the latter. It appears that areas of smaller substrate and steeper slope (around 3% to 5%) may be higher risk areas than indicated by the NMFS system. This is seen in Figure 6, where the two points that indicate a stranding event are lying in the low risk area. In addition, it appears that the NMFS protocol may be better off defining any area with a slope greater than approximately 6% as low risk, no matter what the substrate size is Figure 7. As one can see in this figure, no stranding points lie above a 6% slope.

Defining Stranding Surfaces

The NMFS protocol recommends standard cross-section survey techniques to measure the elevation and lateral slope of each channel surface, which we conclude is sufficient for this purpose. Of greater concern however, is the sampling design and whether it is sufficient to capture reach-level variation in channel surface elevations and whether the area and particle sizes within each cross section are accurately described. We also comment on observed variation of these attributes at multiple sites.

With respect to estimating particle size, the NMFS protocol relies on visual estimates of d50 based on professional judgment. We believed this to be potentially too subjective, so we conducted pebble counts on gravel and cobble surfaces. For surfaces not suitable for pebble counts, such as silt and clay, we noted the approximate grain size at each surveyed point. One advantage to pebble counts is that one can evaluate metrics other than d50 if needed (Figure 7). In addition, the NMFS protocol assumes a homogeneous substrate composition for each surface. However, based on our application of the protocol, this assumption may not be entirely true. Looking at the facies map for the pool in Bidwell Creek (figure 8) for example, we can see that substrate types vary greatly within and between surfaces.

The heterogeneity of channel form also presented problems for estimating channel surface areas. NMFS assumed each cross-section was representative of the habitat unit it was in, and therefore estimated surface area by multiplying the width of the surface (as measured by the cross-section) by an estimated mean length. Our experience was that this did not adequately characterize the complex shapes and sometimes-discontinuous layout of surfaces within a habitat unit (Figure 8). However, although the NMFS method graphed the elevations of stranding surfaces as a function of area (Figure 9), the actual protective stage recommendation defaulted to an elevation, which rendered consideration of surface area inconsequential. Therefore, unless area estimates become more important, perhaps that task could be omitted from the protocol. Figure 10 provides a review of our results showing the surface areas associated with stranding surfaces.

Our final consideration of NMFS methods to quantify stranding surfaces addresses the sampling design and how well it characterizes reach level variation in the elevation of stranding surfaces. The NMFS method requires surveyors to select three habitat units near the gauge site: one pool, one riffle and one run. Single cross-sections are then set up in each unit for a total of three cross-sections. This process yielded a discontinuous distribution of stranding surface elevations that tended to be concentrated at lower elevations near the channel thalweg (Figure 4). We attempted to measure additional variation within the reach by conducting a longitudinal profile survey. However, we failed to adequately relate these findings to any variation related to stranding surfaces. Therefore, the nature of elevational variation of stranding surfaces within the stream reaches surveyed remains unknown. Because elevation is so important to protective stage recommendations, it is important to accurately report the range and distribution of these surfaces. Neither our study nor the NMFS method adequately addressed this issue, which may be a critical flaw.

Defining Protective Stage

Another issue we encountered with the NMFS protocol is its definition of protective stage. Protective stage is defined by the highest elevation medium or high risk stranding surface present in the sampled area of the stream. By setting the threshold at this level, no diversions would be allowed below it. However, the data we collected indicates gaps in the elevations of high/medium risk surfaces. For example, Bidwell Creek has a 1.85 ft. gap, Sausal Creek, a 1.35 ft. gap and lower Mark West Creek has a 0.8 ft. gap (Figure 4). In these cases, if the stream stage prior to a frost event is somewhere within these ranges, data suggest water withdrawals would not be harmful. However, we do not know the elevations of stranding surfaces beyond those surveyed in the three cross-sections. The survey protocol also does not include the range of elevations any single stranding surface may occupy. This consideration, combined with the addition of un-surveyed stranding surfaces, may close the observed gaps to make a continuous spectrum; or maybe it would not. In either case, we cannot know without additional surveys of the reach.

To place the protective stage recommendation into better context, we estimated the percent of time during the frost season that water would be available for withdrawal. We did this by calculating the hours in which the stage for 2011 was above the protective stage threshold.

The following results provide only a coarse estimate, because flow conditions vary widely between years, and the 2011 stage data reflects an already impaired state (i.e. frost diversions were essentially unregulated). The smallest drainage basin, Bidwell Creek, had very few days where the water level was above the protective stage for that stream (1%). However, a closer look at the elevation of stranding surfaces shows that the protective stage (2.4 ft above the critical riffle) is a medium-risk stranding surface. The next stranding surface below this one jumps to 0.55 ft and the only high-risk stranding surface is at 0.17 ft. However, in Lower Mark West Creek, water would be available 28% of the time and the highest stranding surface is a "high risk" at 1.7 ft. The next surface down is also high risk and lies at 1.3 ft. Similarly, Sausal Creek indicated water available for diversion 27% of the time with the highest stranding surface at 1.3 ft. Due the potentially significant ramifications for wine grape growers, additional on-site analysis should provided as an option so a more precise estimation of protective stage may be attempted. The Bidwell Creek results provide an example for such a study because the protective stage is a medium stranding risk and all other stranding surfaces are much lower in the streambed.

Conclusion and Recommendations

Based on our application of the NMFS protocol and our exploration of the literature on this topic, we have come up with some recommendations for further study and improvement of the NMFS protocol

The NMFS Risk Model

We encourage NMFS to explore other risk factors influencing the stranding of salmonids. Rate of stage change may have the most impact on fish stranding and should be examined for its influence on stranding risk due to frost water use. The NMFS protocol should support its use of slope and substrate size as the only factors limiting stranding of fish in the Russian River Watershed.

We recommend refining the risk classification model to better fit the data points from the literature. As a component of this refinement, we recommend that NMFS limit the medium risk category to lateral slopes equal to or less than 6%, since the published literature only supports slopes up to this gradient. In addition, further analysis should be conducted to incorporate all documentation of stranding conditions.

Defining Stranding Surfaces

In order to better understand reach level variation in stranding surfaces, we recommend that NMFS determine the number of cross sections needed to accurately capture such variation. This would involve saturating the entire reach with cross sections and then scaling back in order to see when significant resolution is lost and when the variation within the reach variation ceases to be captured. This will help guarantee that the NMFS definition of protective stage is applicable within the reach, despite variation present.

However, if we accurately understand the range and distribution of elevations of stranding surfaces and if the medium and high-risk surfaces are continuously distributed at all elevations of the stream, then the protective stage may be difficult and/or impossible to define.

To better capture within-habitat variation, it would be beneficial to include a map of features to scale within each habitat unit. This will provide a more accurate calculation of stranding surface areas.

Defining Protective Stage

We also encourage NMFS to change the use of protective stages in limiting water withdrawals. When a frost event occurs, it is more important to know the stage at the time of the event and be able to predict which stranding surfaces are below the current stage. These are the surfaces that may have a high risk of stranding fish if the water level drops. Therefore, we recommend a dynamic approach where stranding surfaces below the current stage are taken into account during a frost event. This may help eliminate unnecessary restrictions of water withdrawals as compared to the NMFS protocol as it stands now.

Our final recommendation is, in light of the potentially restrictive nature on water diversions, that an option for more intensive site-specific study be included in the protocol. This could involve inspection and documentation of individual surfaces when stream flows recede over them, to verify whether stranding of fish actually occurs.

With the incorporation of recommendations contained in this paper and the use of adaptive management, we believe that the NMFS protocol will be a powerful and effective tool for protecting threatened and endangered fish from being stranded due to vineyard use of water during frost events in the Russian River Watershed.

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Tables

Table 1: Watershed characteristics for the two study sites (Mark West and Bidwell Creeks), plus the NMFS site previously surveyed (Sausal Creek).

Stream	Drainage Area (mi^2)	Mean annual precipitation (inches)	Geomorphic Setting	Mean basin slope (%)	Percentage of basin covered by forest	Mean Stream Gradient at gauge
Mark West	50.2	42.3	Alluvial Floodplain	22.6	37.7	0.001
Sausal	12.6	46.4	Alluvial Floodplain	Unkn	Unkn	0.0035
Bidwell	4.6	39.7	Unconfined Valley	22.2	28.7	0.0056

Table 2. NMFS matrix of all combinations of d50 and slope classes with ratio values and subjective assignments of stranding risk.

d50	slope %	slope	d50 /Slope	Risk	d50	slope %	slope	d50 /Slope	Risk
2	0.0	0.0	2000	Low	2	5.0	0.05	40	Low
64	0.0	0.0	64000	High	64	5.0	0.05	1280	Medium
256	0.0	0.0	256000	High	256	5.0	0.05	5120	High
2	1.0	0.01	200	Low	2	6.0	0.06	33	Low
64	1.0	0.01	6400	High	64	6.0	0.06	1067	Medium
256	1.0	0.01	25600	High	256	6.0	0.06	4267	High
2	2.0	0.02	100	Low	2	10.0	0.10	20	Low
64	2.0	0.02	3200	High	64	10.0	0.10	640	Medium
256	2.0	0.02	12800	High	256	10.0	0.10	2560	Medium
2	3.0	0.03	67	Low	2	20.0	0.20	10	Low
64	3.0	0.03	2133	Medium	64	20.0	0.20	320	Low
256	3.0	0.03	8533	High	256	20.0	0.20	1280	Low
2	4.0	0.04	50	Low					
64	4.0	0.04	1600	Medium					
256	4.0	0.04	6400	High					

Table 3. NMFS risk assignments sorted by d50/slope ratios. Note the nearly complete separation of risk categories into their respective groups.

d50/Slope	Risk	d50/Slope	Risk	d50/Slope	Risk
10.0	Low	640.0	Medium	3200.0	High
20.0	Low	1066.7	Medium	4266.7	High
33.3	Low	1280.0	Medium	5120.0	High
40.0	Low	1280.0	Low	6400.0	High
50.0	Low	1600.0	Medium	6400.0	High
66.7	Low	2000.0	Low	8533.3	High
100.0	Low	2133.3	Medium	12800.0	High
200.0	Low	2560.0	Medium	25600.0	High
320.0	Low			64000.0	High
				256000.0	High

Table 4. NMFS risk model classification thresholds.

Range	Risk
0 to 500	Low
500 to 3,000	Medium
3,000 - greater	High

Figures

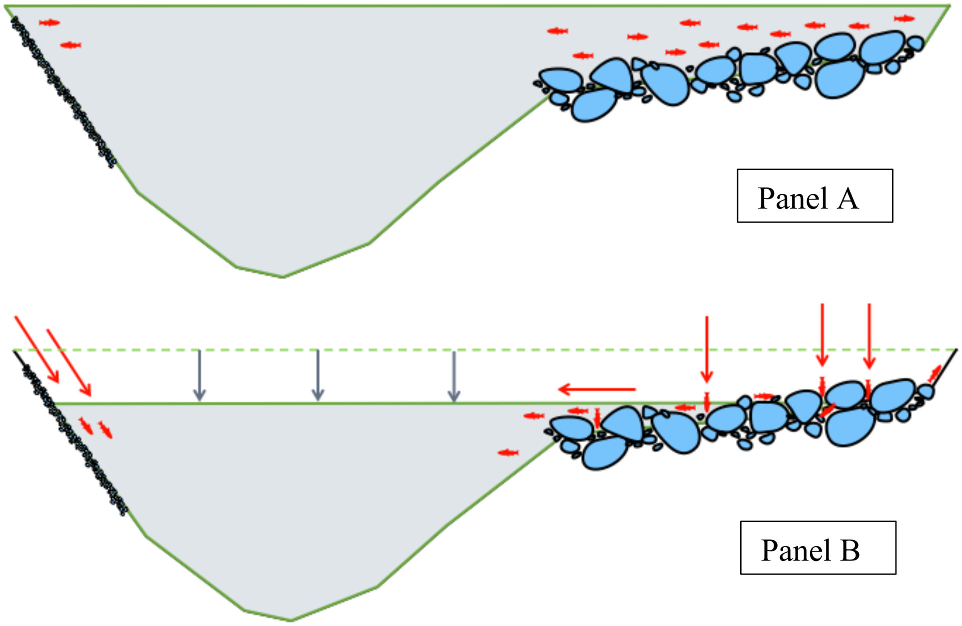


Figure 1. Diagramatic depiction of the stranding process. Salmonid fry preferentially occupy shallow stream margins (Panel A). When water levels recede, they often retreat into the interstitial spaces of large cobbles (Panel B).

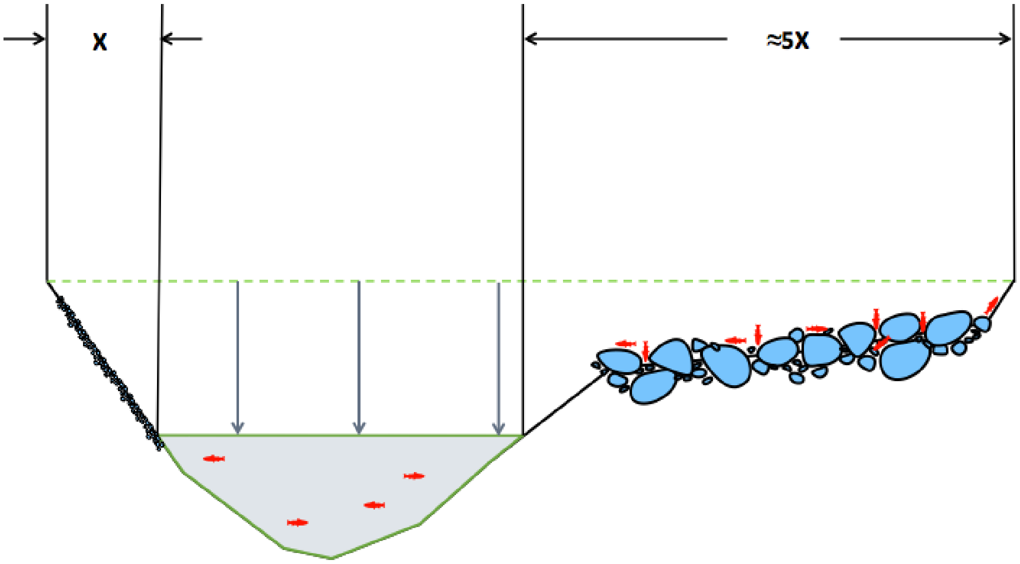
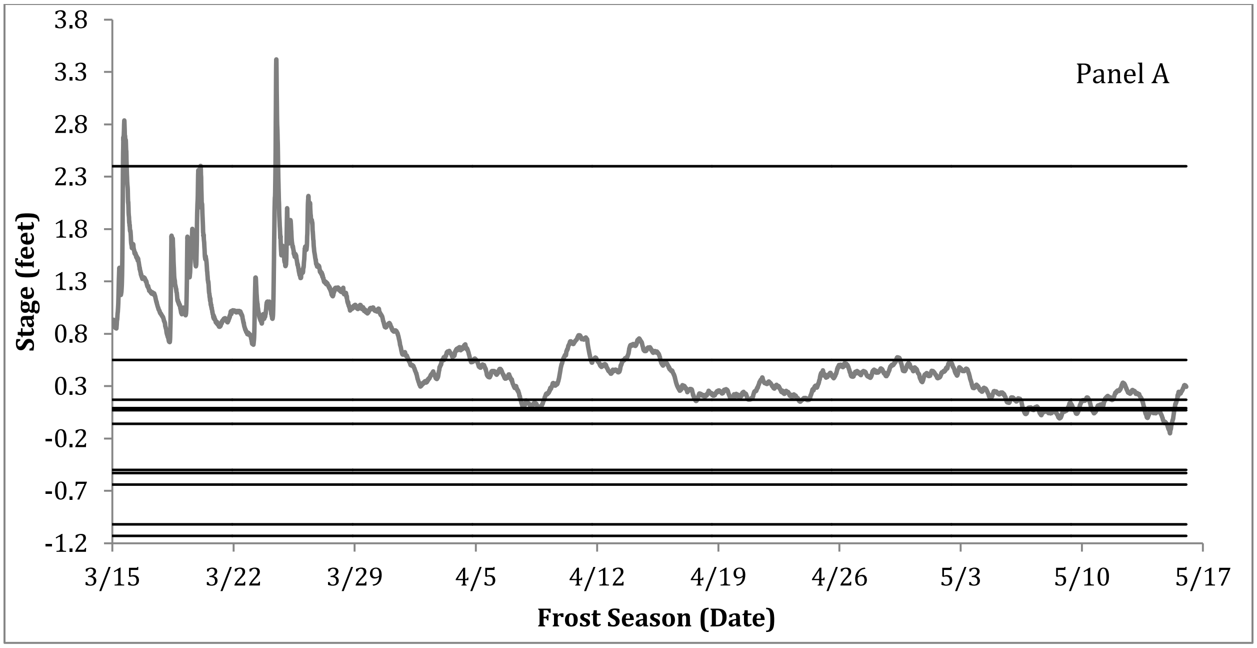
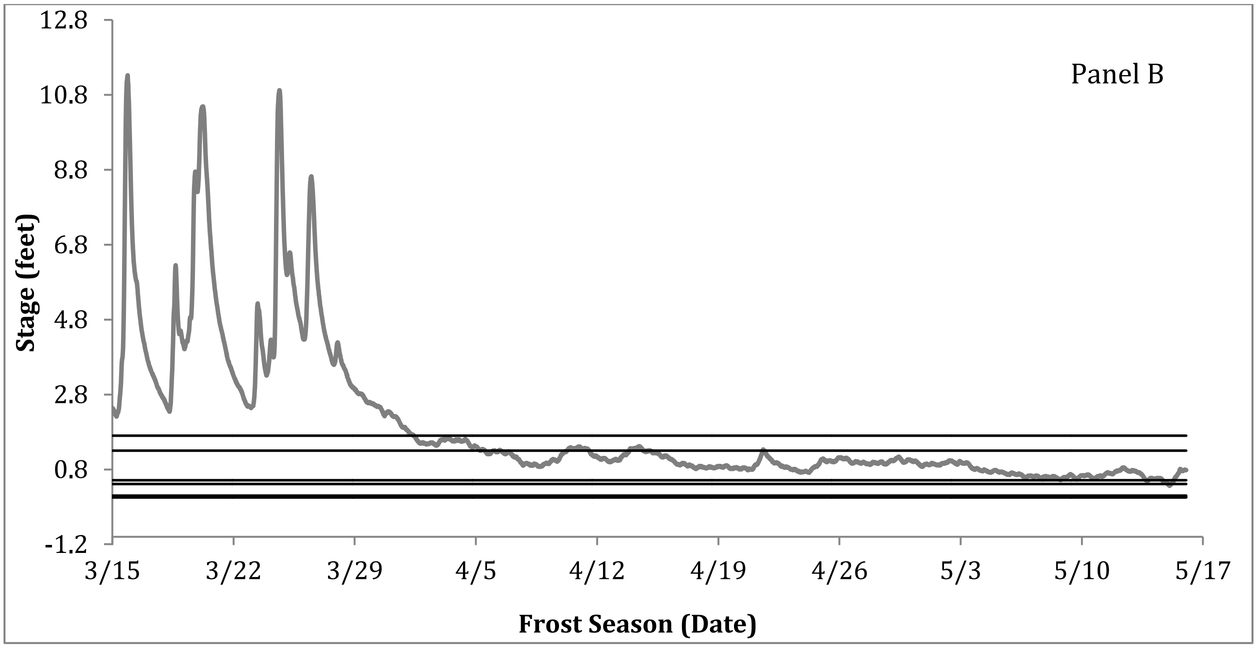


Figure 2. Diagramatic depiction of the stranding process. Shallow sloped surfaces have a greater tendency to entrap fish because the rate of surface water retreat is greatest per increment of stage change (Panel C).

Figure 3: Site Map showing our two survey sites (Bidwell Creek and lower Mark West Creek) and the original NMFS survey site (Sausal Creek, Panel A) in the Russian River, California (Panel B).


Panel A
Stage (feet)
3.8
3.3
2.8
2.3
1.8
1.3
0.8
0.3
-0.2
-0.7
-1.2
3/15
3/22
3/29
4/5
4/12
4/19
4/26
5/3
5/10
5/17
Frost Season (Date)


Panel B
Stage (feet)
12.8
10.8
8.8
6.8
4.8
2.8
0.8
-1.2
3/15
3/22
3/29
4/5
4/12
4/19
4/26
5/3
5/10
5/17
Frost Season (Date)

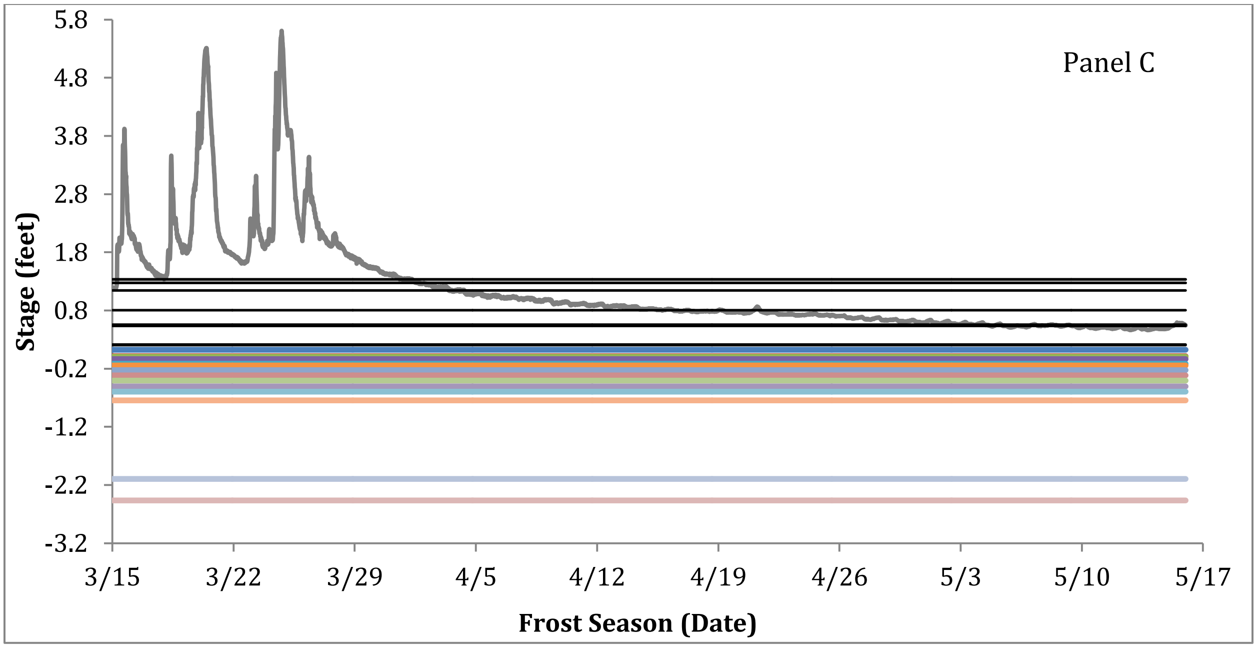


Figure 4: Stream stage changes for the 2011 frost season in Bidwell Creek (Panel A), Lower Mark West (Panel B) and Sausal Creeks (Panel C). Horizontal lines indicate elevations of all high and medium risk stranding surfaces surveyed.

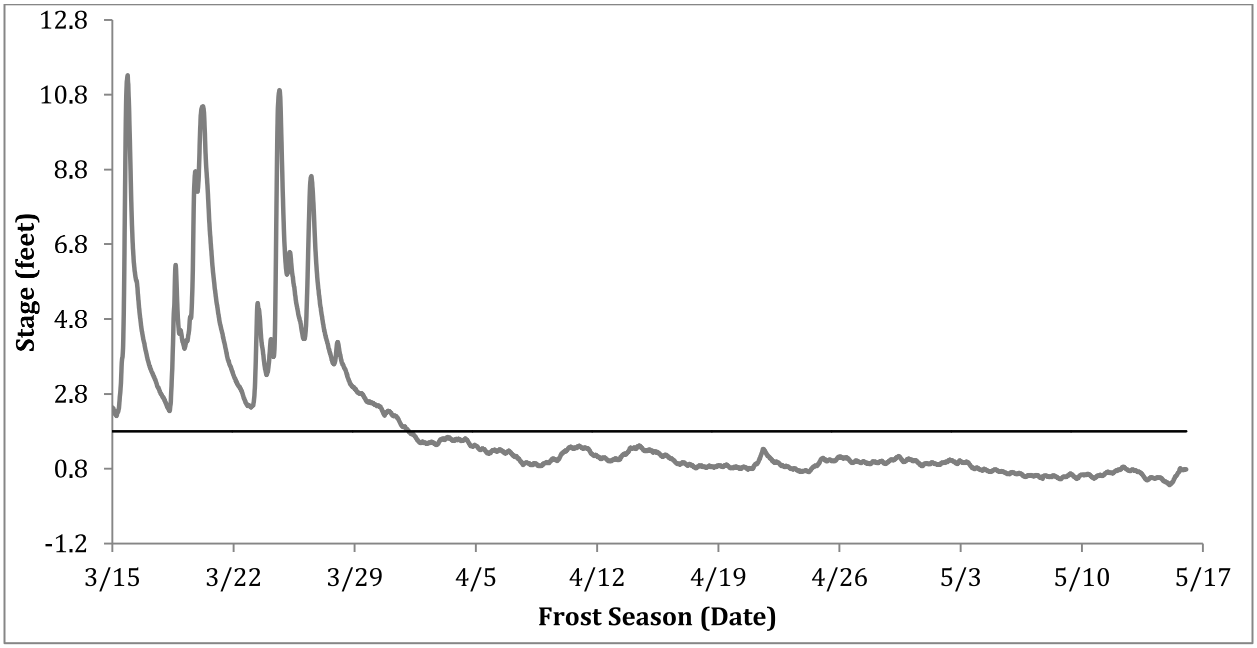


Figure 5. Stage changes in lower Mark West Creek during the 2011 frost protection season with the protective stage shown. Water level was above the 1.8 foot protective stage 28% of the time.

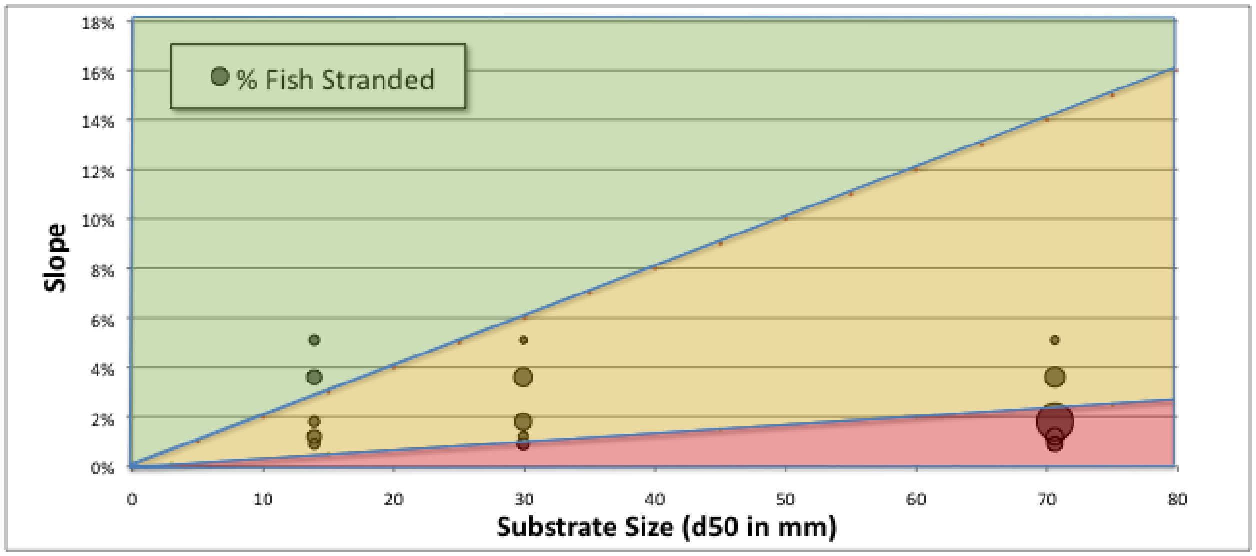


Figure 6. Comparison of NMFS risk classification thresholds to stranding proportions of fish in the published literature as a function of lateral slope and substrate particle size.

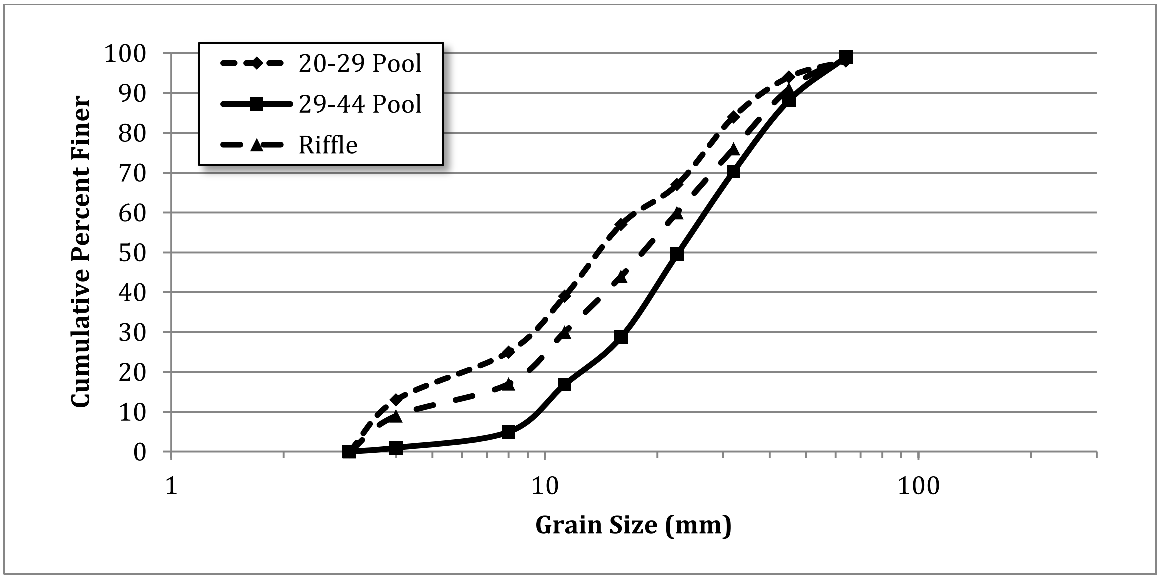


Figure 7. Grain size distribution for multiple surfaces in Lower Mark West Creek.

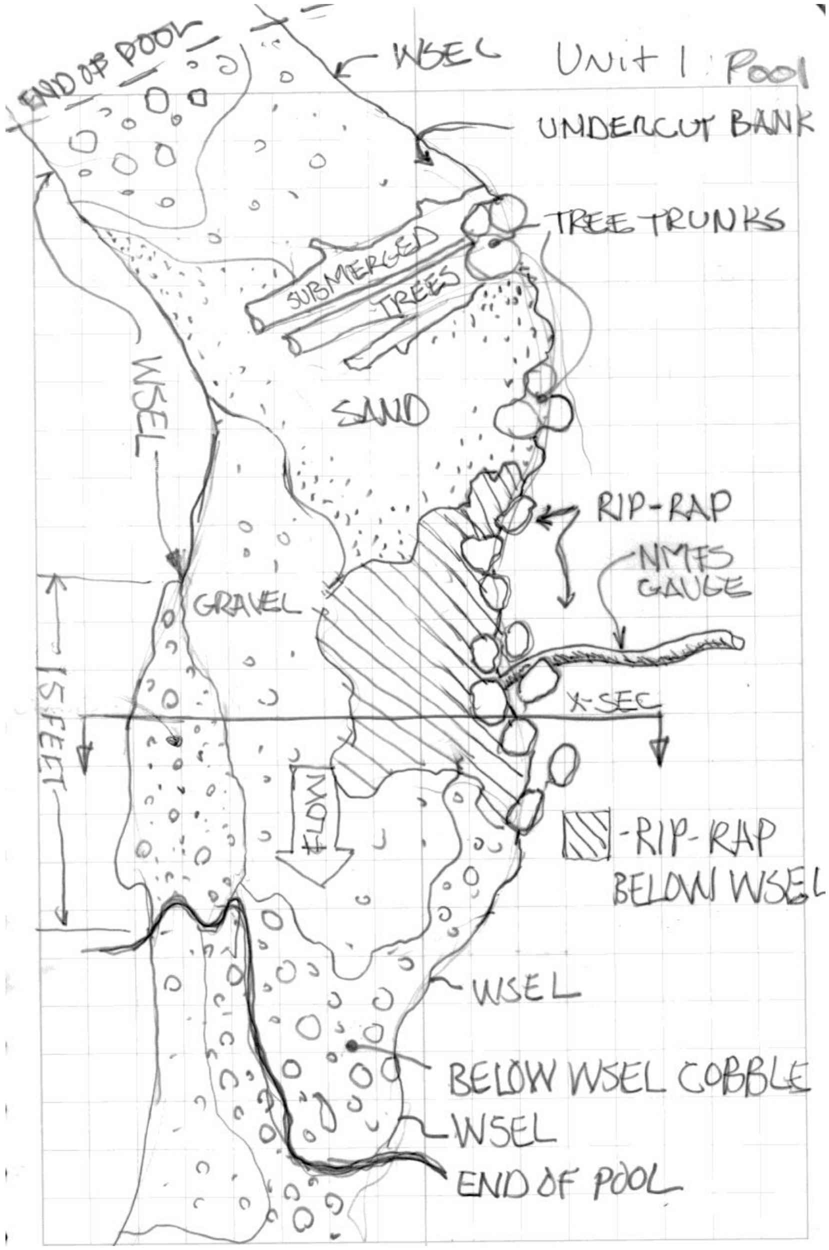


Figure 8: Bidwell Creek pool facies map indicating complexity of surfaces and particle size distributions.

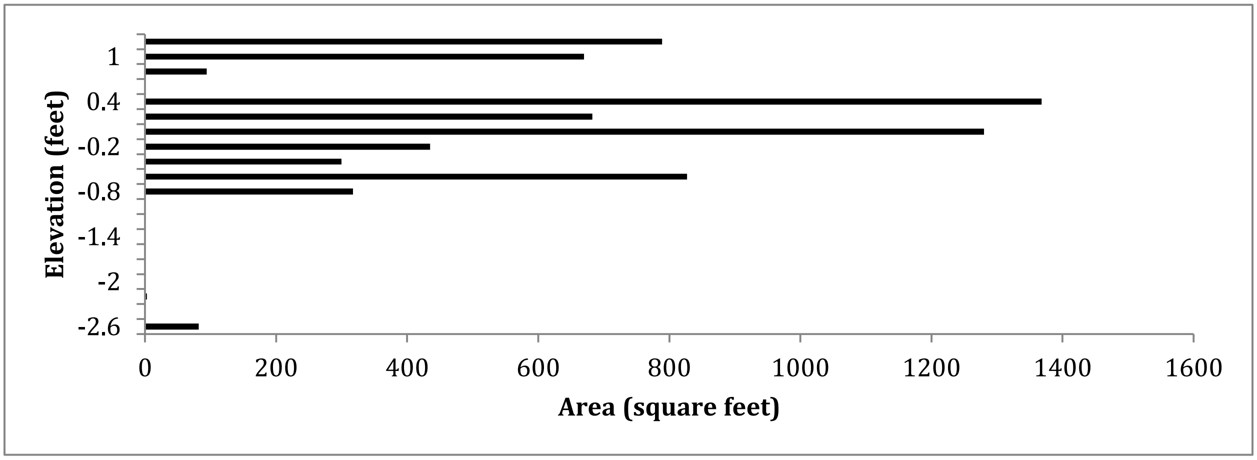
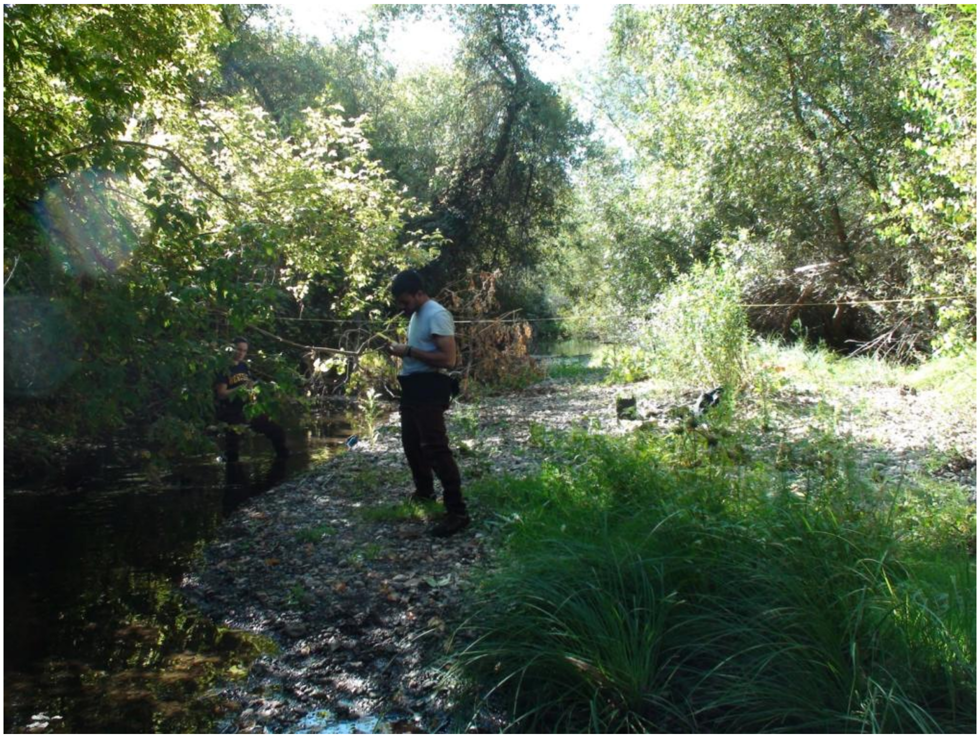


Figure 9. Elevation of all surveyed high and medium stranding risk surfaces in Sausal Creek, 2011. The length of horizontal bars is proportional to the surface area in square feet.

Appendix: Survey site photographs for Fall 2011 LDARCH 227. Hines, Kohlsmith, Kayed



Lower Mark West Creek survey site.

Bidwell Creek survey site.