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Steelhead Habitat Assessment of Three Small Coastal Central California Streams

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Steelhead habitat assessment of three small coastal central California streams

A Thesis

Presented to the

Faculty of the

Division of Science and Environmental Policy

California State University Monterey Bay

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

in

Coastal and Watershed Science and Policy

by

Colin L. Nicol

Fall 2012

CALIFORNIA STATE UNIVERSITY MONTEREY BAY

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STEELHEAD HABITAT ASSESSMENT OF THREE SMALL COASTAL CENTRAL CALIFORNIA STREAMS

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DEDICATION

Dedicated to Muriel and Oz, who I am grateful to have known.

ABSTRACT

Steelhead Habitat Assessment of Three Small Coastal Central
California Streams
by
Colin L. Nicol
Master of Science in Coastal and Watershed Science and Policy
California State University Monterey Bay, 2012

Anadromous steelhead (*Oncorhynchus* m*ykiss*) populations on the central coast of California have been reduced to critical levels throughout the last century. Six streams run through the Coast Dairies Property near Davenport, CA; three of the streams are known to support steelhead, and three do not support any known populations. This study examined two physical factors that are potentially limiting steelhead success in the three small streams. The first potential limiting factor examined is low density substrate found in the three streams (Santa Cruz mudstone). The presence of low density substrate could lead to increased risk of redd 'washout,' or destruction of the steelhead nest and the associated eggs due to gravel mobility. Alternatively, the presence of low density substrate could shift the size range suitable for spawning. This study used tracer stones of mudstone and granite to populate a logistic regression model that can be used to predict the probability of entrainment for a given particle under defined shear stress conditions. The second potential limiting factor is a migration barrier caused by the presence of a culvert on each stream where it passes under Highway 1. Culverts in the three streams without steelhead and two culverts on streams that have known populations of steelhead were surveyed and modeled using a 1-dimentional hydraulic modeling program. Three separate passage criteria were used to assess if the modeled hydraulic conditions were suitable for steelhead passage.

We found that both factors were potentially limiting steelhead success in the three streams. This study shows substantial evidence that the low density mudstone substrate is more mobile than typical granitic particles. The results indicate a mudstone particle has a probability of motion approximately 30% higher than a similar granite particle under the same flow conditions. This increase in mobility could result in increased redd washout frequency, and might limit steelhead spawning success. The results of the culvert modeling study revealed it is highly likely the tunnels are presenting a barrier at most flows. The two study culverts what are known to pass steelhead had noticeably better depth and velocity conditions than the three culverts with unknown passage suitability. One of the three passage criteria, suggested by the National Marine Fisheries Service and the California Department of Fish and Game, indicated none of the five culverts were passable, suggesting that it may be too conservative to reflect the swimming abilities of steelhead on the central coast of California.

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ACKNOWLEDGEMENTS

I would like to acknowledge the help my friends and family have given me throughout this process. I learned a tremendous amount from my talented classmates and hardworking roommates. I am indebted to Sara Kelly, Casey Lanier and Mark Goin for helping me with the field work and the data processing. I honestly don’t know why you put up with so many long days crawling poison oak with me. The Santa Cruz Resource Conservation District provided a professional setting for me to carry out the technical reporting associated with this work. And of course my advisors, who helped me through this (and so many other projects), and gave me the knowledge and confidence to get this project completed. Finally I owe a big thank you to Michael Westphal and the Bureau of Land Management for providing the funding to support me on this journey.

CHAPTER 1

MANAGEMENT CONTEXT

Streams and riparian corridors are among the most degraded ecosystems in the world, especially in highly developed countries such as the United States (Johnson et al. 1995). Over 90 percent of all riparian habitat has been lost in California (Dahl 1990), resulting in the listing of many species under the Endangered Species Act. Anadromous salmonids (*Oncorhynchus* spp.) are some of the most affected species, which has implications for both aquatic and terrestrial ecosystem health (Wilson and Halupka 1995; Hilderbrand et al. 2004). Historic steelhead (*Oncorhynchus mykiss*) runs in some coastal central California streams numbered in the tens of thousands; today returns from the ocean number in the hundreds at best (Shapovolov and Taft 1954; Titus et al. 2003). Steelhead were federally listed as *threatened* for the coastal central California region in 1996 (CFR 227 1996). Consequently, there is great interest in habitat restoration and improvement to re-establish steelhead populations where they have been reduced or extirpated (NOAA 2008).

The federal recovery outline for coastal central California steelhead (NMFS 2007) lists the main limiting factors for steelhead as habitat loss and flow reduction caused by urban development, mining, agriculture, logging, habitat blockages and water diversion/extraction. Specific agents for habitat loss include reduced summer baseflows, unsuitable water quality in the form of temperature or chemical condition, excess fine sediment, and migration barriers.

In 1998 conservation groups purchased the Coast Dairies Property in Santa Cruz County, California, opening the possibility for steelhead restoration in several small coastal watersheds (Figure 1). Multiple streams on the Coast Dairies Property had historic runs of anadromous steelhead, but three of the six streams today are limited to landlocked populations of rainbow trout (ESA 2001). Genetic studies of *O. mykiss* in small coastal streams in central California indicate there has been little stocking (Boughton pers. comm., 2010), implying the three streams with landlocked *O. mykiss* populations originated through natural means (i.e. anadromous migration). An existing conditions report (ESA 2001) and a watershed assessment (Robins et al 2010) outlined several limiting factors which may be impairing anadromous steelhead viability in the streams without documented runs.

This study focused on further assessment of two potential limiting factors on the Coast Dairies Property: low density sediment in gravel bed streams and highway culverts as migration barriers. In many hydrology and particle transport studies, sediment density is assumed to be that of granite. Mudstone, the predominant bedrock in the three watersheds without modern steelhead runs (Figure 1.1), has a substantially lower particle density than granite. The ecological impactions of this are not well understood. The second area of focus is the hydraulics of the Highway 1 culverts. Each stream in the Coast Dairies property runs through a culvert beneath Highway 1, which may act as a partial or full barrier to steelhead migration. As the highway culverts are near the mouth of each stream, they potentially form a barrier to the entire watershed.

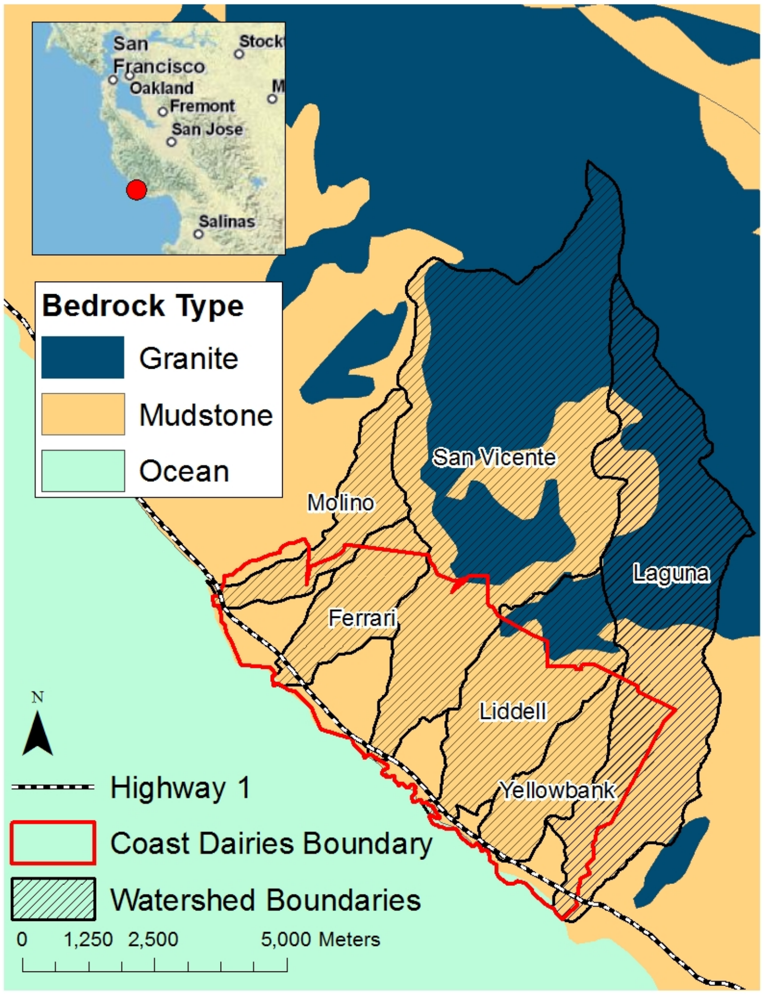

Figure 1.1. Location map of the Coast Dairies Property. The six watersheds that run through the Coast Dairies Propery: Molino, Ferrari, San Vicente, Liddel, Yellowbank and Laguna.

OBJECTIVE

The objective of this project was to assess two potential limiting factors to Steelhead success on the Coast Dairies Property: (1) potential high rates of stream bed mobility due to low density sediment and (2) salmonid passage through borehole culverts under Highway 1. Chapter 2 of this thesis explores the effects of low density gravels, and Chapter 3 explores steelhead passage through the Highway 1 culverts.

CHAPTER 2

EXPLORING PARTICLE DENSITY EFFECTS ON PARTIAL ENTRAINMENT OF STEELHEAD SPAWNING GRAVELS

INTRODUCTION

Gravel entrainment during storm runoff events is a critical part of geomorphic and ecological processes in a stream, but entrainment is difficult to predict. During high flows, there can be variability in both the proportion of the streambed that is entrained and the size distribution of the entrained particles. This variability in physical response in turn leads to variability in geomorphic and ecological impacts. If a stream bed becomes mobilized during a flow event, not only can benthic habitat be highly disturbed, but salmonid redds can be directly destroyed (Carling, 1987; DeVries, 1997). The complex physical behavior of gravel streams makes them difficult to model, and their ecological importance drives the need for further studies.

Work has been done to study salmonid redd loss from particle entrainment (Lapointe *et al.*, 2000; Bigelow, 2005; DeVries, 1997). Much of that work has focused on scour, or the depth of mobilized particles during a flood event (Emmett and Leopold, 1965; Hassan, 1990), as the geomorphic agent for redd loss. Although entrainment and corresponding scour is critical to the renewal of sediment in a streambed (Kondolf and Wilcock, 1996), intense and frequent flood events may scour to the depth of salmonid eggs and wash them away (DeVries, 1997).

Although most of the work linking flow to redd washouts has focused on the use of scour chains (Lapointe *et al.*, 2000; Bigelow, 2005), some studies have used surface tracer stones to find a link between shear stress available in the stream, boundary shear $\tau_{0,}$ and scour (Wilcock *et al.*, 1996; May *et al.*, 2009). Following this work, it is reasonable to assume modeling the entrainment of surface gravels typically used in redd construction will guide understanding of redd loss due to entrainment.

During a flow event where boundary shear τ_0 exceeds the threshold for incipient motion, critical shear τ_{crit}, often only a fraction of the gravel composing the streambed is mobilized. This condition is known as partial entrainment (Wilcock and McArdell., 1993), and can relate to the fractional mobility of substrate as a whole or within a specific size class. Flume studies have found that complete mobilization of a size class is possible when boundary shear is approximately twice the critical shear (Wilcock and McArdell, 1997).

Studies have used tagged particles to document partial transport in the field (Konrad *et al*., 2002; Haschenburger and Wilcock, 2003), and have focused on spatial distribution of active particles. Using data from a magnetically tagged particle study in Canada, Haschenburger and Wilcock (2003) found that as flow increases, areas of partial entrainment increase while inactive areas of the bed decrease. The study indicated that conditions of partial entrainment existed until a 7-year flood, at which point there was nearly complete bed mobility. In contrast, Konrad *et al*. (2002) found that partial entrainment does not vary uniformly across rivers with flood recurrence interval, documenting between 10 and 90% entrainment for a 2.5-year flood on different rivers.

Although extensive work has been done on particle entrainment, one aspect of bedload movement that has not been given adequate attention in the literature is the effect of particle density on entrainment, specifically with respect to ecologically damaging entrainment events. The objectives of this study are to observe and model partial mobility in high and low density substrate and apply the model to steelhead spawning gravel and estimate difference in mobility between substrate types at bankfull flow.

METHODS

Study Area

Observations for this study were made on Yellowbank Creek near Davenport, Ca. This watershed was selected because it is underlain by low-denisty "Santa Cruz Mudstone" (McLaughlin *et al*., 2001), supports resident steelhead/trout (*Oncorhynchus mykiss*), and it may have the potential to host anadromous steelhead runs. Santa Cruz mudstone has an average particle density of 2.1 g cm^{-3} (Hecht and Golling, 1982), which is notably lower than the generally assumed substrate density of 2.65 g cm^{-3}. Yellowbank has a drainage area of 1.61 km^2 and empties directly into the Pacific Ocean. The coastal half of the watershed is dominated by a series of marine terraces exposed during Quaternary tectonic uplift (Anderson and Menking, 1994), whereas the inland half is fully dissected by streams. Most of the watershed is grazed shrublands and grasslands. There are small agricultural fields on the first marine terrace in the lower watershed. The vegetation in the upper watershed is dominated by redwoods (*Sequoia sempervirens*), Douglas-fir (*Pseudotsuga menziesii*) and tan oak (*Lithocarpus densiflorus*). Currently the land is lightly grazed but it otherwise unused. The riparian vegetation is dominated by willow (*Salix lasiolepis)*, white alder (*Alnus rhombifolia***)** and other non-woody vegetation.

Annual precipitation in the area is approximately 660 mm (ESA, 2001) and mainly falls between October and April. The small watershed area leads to rapid hydrologic responses in the creek. The stream was gaged between April 2010 and June 2012 approximately 200 m downstream of the study area. The bankfull flow has been estimated to be 0.540 m^3s^{-1} (ESA 2001). In general, the 50th percentile (D_{50}) and 90th percentile (D_{90}) of the stream bed surface material intermediate axis lengths are 14.5 mm and 45 mm, respectively.

The study reach was a 30 m plane gravel bed reach, with no significant features such as pools or riffles. The reach had a slope of 0.7% located approximately 500 m upstream of the basin outlet to the ocean (Figure 1). The reach had a surface D_{50} of 30 mm and D_{90} of 60 mm. The underlying bedrock in the Yellowbank watershed is Santa Cruz Mudstone and the streambed is composed almost completely of mudstone particles. During the time of the study there was a gravel bar formed along the left bank, but otherwise the reach had no riffles, pools or bars.

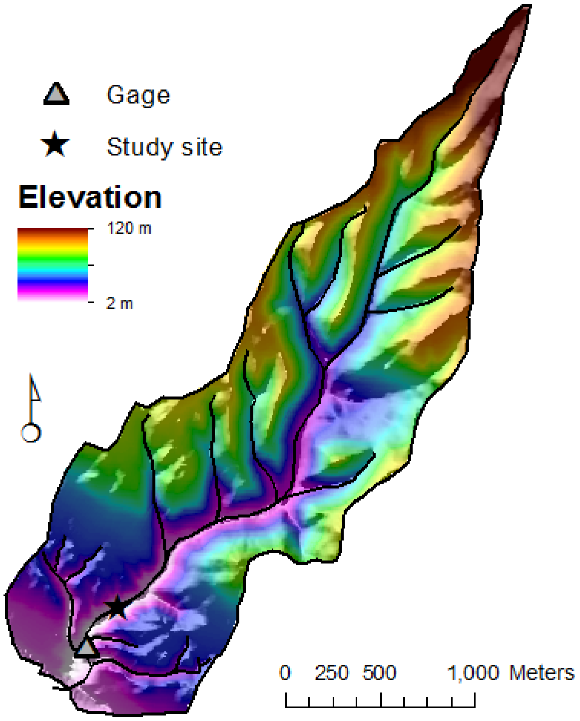

Figure 2.1. Yellowbank watershed showing the location of the stream gage and study site.

Sampling Design

During the winter of 2010-2011, I placed tagged particles in the study reach of Yellowbank Creek. Particles of both granite and mudstone were tagged using orange spray-paint. To make the study more applicable to salmonid spawning, tagged gravels ranged between 22.5 and 128 mm, which cover the range of typical steelhead spawning gravels (Kondolf, 2000). Mudstone particles were gathered from Yellowbank Creek downstream of the study site while the granite particles were gathered from a nearby stream with granitic substrate.

To better understand partial entrainment of a size class, between 5 and 30 particles in each size class were placed in rows across the study site, with the smaller size classes having more particles. Rows were separated by size class and set at approximately 5 m intervals. No attempt was made to imbricate the tagged particles within the substrate matrix.

Particles were placed in the stream for a period of time, or observation period, until a storm runoff event occurred. Particle motion was assessed following the flow event. Particles were counted at the original site by removing all visible tagged particles, and then removing the remaining armor layer to locate any buried particles. Entrained particles were located by walking the stream to a distance of approximately 100 m downstream and removing any visible tagged particles. All recovered particles were replaced in rows to begin a new observation period.

Modeling density effects on partial entrainment

In order to understand how particle density effects partial entrainment I built a logistic regression model which estimated probability of entrainment based on the results of the tagged particle study and existing theory. The model is based on the idea that particle entrainment will occur when hydraulic mobilizing forces meet or exceed resistive forces acting on the particle (Wohl 2000).

A typical index of the hydraulic mobilizing forces present in a stream at any specified flow condition is the boundary shear stress (τ_0):

$$\tau_0 = \rho_w g R S \tag{1}$$

where ρ_w is the density of water (kg m^{-3}), g is gravity (m s^{-2}), S is the energy grade slope, and R is the hydraulic radius (m). Since ρ_w and g are constants, only R and S need to be estimated. One approach for estimating τ_0 is to survey the floodline after a flow event, which will characterize average flow depth and water surface slope which are approximately equal to R and S, respectively. I took the approach of modeling the system to estimate τ_0. Using cross section data from a site survey and gage data from a gage approximately 250 m downstream, I recreated the peak flow at the study site in HEC RAS, a 1-dimentional hydraulic modeling program (USACE 2010). From the model I could estimate both R and S for the peak flow of each observation period.

To estimate the resistive forces of a particle, I used an equation for the shear stress required for incipient motion of a particle, or critical shear stress (τ_{crit}):

$$\tau_{crit} = \tau^* g(\rho_s - \rho_w) D_i \tag{2}$$

where τ^* is Shield's dimensionless critical shear, g is gravity (m s^{-2}), ρ_s is the density of sediment (kg m^{-3}), ρ_w is the density of water (kg m^{-3}), and D_i is the particle size (m). In equation (2), the only parameter that is unknown is τ^*, which can be estimated using a relationship developed by Andrews (1994):

$$\tau^* = 0.0384\left(\frac{D_i}{D_{50}}\right)^{-0.887} \tag{3}$$

where D_{50} is the surface median particle size (m). The range of $\frac{D_i}{D_{50}}$ in our study falls within the range used by Andrews (1994), and although the original study did not vary grain densities, I made the assumption that the equation will hold true for both mudstone and granite particles. Making a proportion of τ_0 and τ_{crit} gives the mobility ratio (M_r):

$$M_r = \frac{\tau_0}{\tau_{crit}} = \frac{\tau_0}{0.0384\left(\frac{D_i}{D_{50}}\right)^{-0.887} g(\rho_s - \rho_w)D_i}$$

which has been used in other studies to describe the intensity of substrate transport and to predict scour (Lapointe et al 2000).

Recent studies have shown incipient motion for a given grain to be a probabilistic process in which only a fraction of the bed is entrained when τ_{crit} has been met (Wilcock and McArdell 1993). I use M_r as the variable to predict partial entrainment (*PE*) in a logistic regression model where

$$\Pr(PE = 1|M_r) = logit^{-1}\,(\beta_0 + \beta_1 M_r)$$

where *PE* is a binary variable indicating whether a particle was entrained (*PE* = 1) or not (*PE* = 0), β_0 is the intercept, and β_1 is a regression coefficient. To test the relative importance of each parameter as a predictor of *PE*, for each model I varied the calculation of M_r as follows

$$\mathrm{M}_0\text{: } M_r = 0$$

$$\mathrm{M}_1\text{: } M_r = \frac{\tau_0}{\tau^* g(\rho_s - \rho_w)D_i}$$

$$\mathrm{M}_2\text{: } M_r = \frac{\tau_0}{\tau^* g(\overline{\rho_s} - \rho_w)D_i}$$

$$\mathrm{M}_3\text{ : } M_r = \frac{\tau_0}{\tau^* g(\rho_s - \rho_w)\overline{D_i}}$$

$$\mathrm{M}_4\text{: } M_r = \frac{\tau_0}{\overline{\tau^*} g(\rho_s - \rho_w)D_i}$$

$$\mathrm{M}_5\text{ : } M_r = \frac{\overline{\tau_0}}{\tau^* g(\rho_s - \rho_w)\overline{D_i}}$$

where M_0 is the null model, M_1 is the full model with all parameters varied, M_2 holds density constant as $\overline{\rho_s}$, M_3 holds particles size constant as $\overline{D_\iota}$, M_4 holds Shield's parameter constant as $\overline{\tau^*}$, and M_5 holds boundary shear constant as $\overline{\tau_0}$. It should be noted that D_i appears both as an independent parameter in M_r, and as part of τ^* (Equation 3). In order to assess the predictive importance of both the particle size and Shield's parameter, I treated D_i as two separate parameters in M_3 and M_4.

For the analysis of the models I used an information-theoretic approach (Burnham and Anderson 2002) to compare the hypotheses that these data were produced by the relevant variation of M_r. The sample unit was an individual particle deployed during an individual observation period, such that the response for each sample unit was either moved *1* or not moved *0*. The six models were evaluated using Akaike's Information Criterion (AIC), which ranks the relative predictive strength of each model. Special interest was paid to the comparison of M_1 and M_2, which revealed the relative importance of density as a predictive parameter.

RESULTS

Tagged particle study results

The results of the tagged particle study cover five observation periods. The first tagged particles were placed on February 24 and the final count occurred on April 14 2011. The study periods experienced a range of peak flows, ranging from 0.063 $\mathrm{m}^3\mathrm{s}^{-1}$ to 1.140 $\mathrm{m}^3\mathrm{s}^{-1}$(Figure 2.2). The smallest peak flow during an observation period occurred on April 5, 2011 and resulted in a τ_0 of 6.9 N m^{-2}, while the largest peak flow occurred on March 28 and resulted in a τ_0 of 42.2 N m^{-2} (Table 2.1).

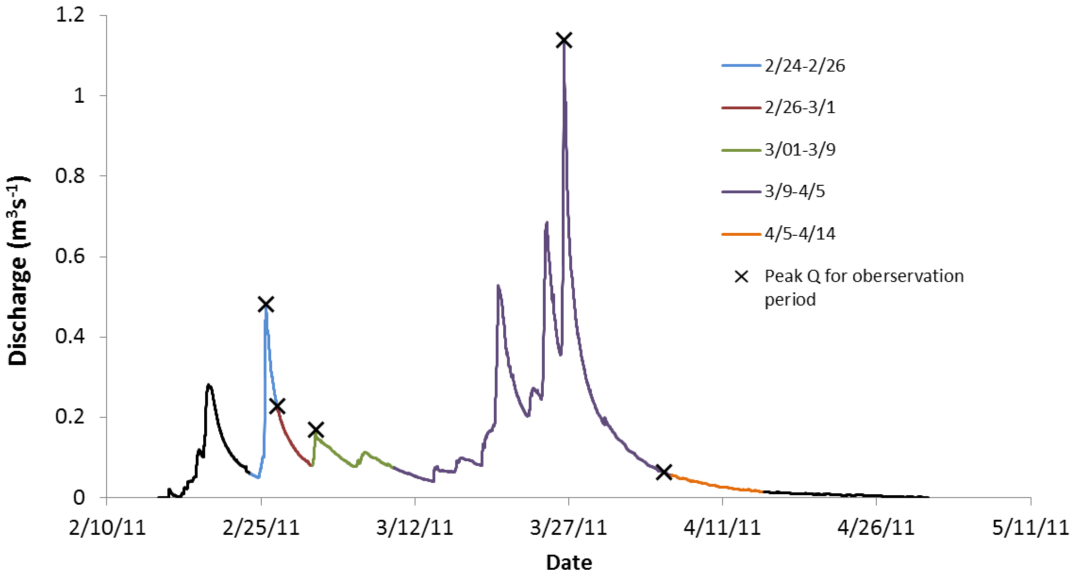

Figure 2.2. Hydrograph of study periods showing the range of peak flows experienced during the five observation periods.

Throughout the five observation periods 376 granite and 331 mudstone particles were observed (N = 707), of which 18 granite and 146 mudstone particles were entrained. Partial entrainment occurred across all size classes of mudstone, while two granite size classes (45-64 and 64-90 mm) remained immobile throughout the study. Two of the smallest peak flows (with a τ_0 of 6.9 and 12.5 N m^{-2} on April 5 and March 2, respectively) failed to move any granite particles, while the same two flows were the only floods without enough shear to mobilize the largest size class (90-128 mm) of mudstone particles. For the event on 26 March, 2011 only two size classes were properly placed in the stream and could yield useful entrainment data.

Table 2.1 Results of tagged particle study showing the relative partial entrainment of granite and mudstone particles across a range of peak flows. Note the small amount of granite particles entrained compared to mudstone particles throughout the study.

		Modeled Parameters				Granite			Mudstone		
Date Range	Peak Q (cms)	*R* (m)	*S* (%)	τ_0 (N m^{-2})	Size Class (mm)	N	Moved	Proportion Entrained	N	Moved	Proportion Entrained
2/24-2/26	0.482	0.202	0.011	21.4	90-128	5	0	0.00	5	4	0.80
					64-90	10	0	0.00	10	7	0.70
					45-64	24	0	0.00	25	16	0.64
					32-45	30	8	0.27	28	21	0.75
					22.6-32	25	6	0.24	25	21	0.84
2/26-3/1	0.229	0.134	0.011	14.5	90-128	5	0	0.00	5	4	0.80
					64-90	10	0	0.00	10	7	0.70
					45-64	24	0	0.00	20	11	0.55
					32-45	25	2	0.08	21	14	0.67
					22.6-32	23	0	0.00	20	11	0.55
3/1-3/9	0.170	0.114	0.011	12.5	90-128	5	0	0.00	5	0	0.00
					64-90	10	0	0.00	10	2	0.20
					45-64	24	0	0.00	24	3	0.13
					32-45	27	0	0.00	21	2	0.10
					22.6-32	25	0	0.00	19	4	0.21
3/9-4/5	1.140	0.290	0.015	42.2	90-128	5	2	0.40	5	5	1.00
					64-90	10	0	0.00	10	9	0.90
4/5-4/14	0.063	0.070	0.010	6.9	90-128	5	0	0.00	5	0	0.00
					64-90	10	0	0.00	6	2	0.33
					45-64	24	0	0.00	22	0	0.00
					32-45	27	0	0.00	21	1	0.05
					22.6-32	23	0	0.00	14	2	0.14
					Total	376	18		331	146	

Modeling Results

The modeling results for the tagged particle experiments reveal the importance each of the parameters used in the calculation of the full *Mr*, including density (Table 2.2).The results of the AIC analysis support the full model, M_1, as the strongest model to predict entrainment of particles. The other models had virtually no support, indicating that none of the parameters are superfluous. Holding ρ_s and D_i constant in M_2 and M_3, respectively, results in the two lowest ranking models. This indicates sediment density ρ_s is second only to grain size D_i in predictive importance.

Table 2.2. AIC table showing model intercept (β_0), M_r coefficient (β_1), degrees of freedom in the model (df), AIC value, number of parameters in model (K), AIC corrected for sample size (AIC_c), AIC_c difference from the best model (ΔAIC), and AIC weights (AIC_w). The models are sorted by AIC rank.

Model Name	β_0	β_1	df	K	AIC	AIC_c	ΔAIC	AIC_w
M_1	-4.63	3.11	2	6	229.70	231.97	0.00	1.00
M_5	-7.80	5.84	2	5	295.18	296.76	64.79	0.00
M_4	-3.22	2.28	2	5	329.73	331.30	99.33	0.00
M_2	-3.17	3.37	2	5	358.36	395.94	127.97	0.00
M_3	-2.23	1.19	2	5	364.90	366.47	134.50	0.00
M_0	1.00	0.00	1	2	448.38	448.68	216.70	0.00

Examining each parameter graphically again reveals the importance of density on particle entrainment (Figure 2.3). Under certain conditions (h = 1.5, p = 0.05 m, $\tau_0 = 26$ N m^{-2}) a granite particle has a 36% chance of moving while a mudstone particle has an 81% chance, approximately a factor of two difference (Figure 2.3.B). For each varied parameter, mudstone was consistently predicted to be more mobile than granite.

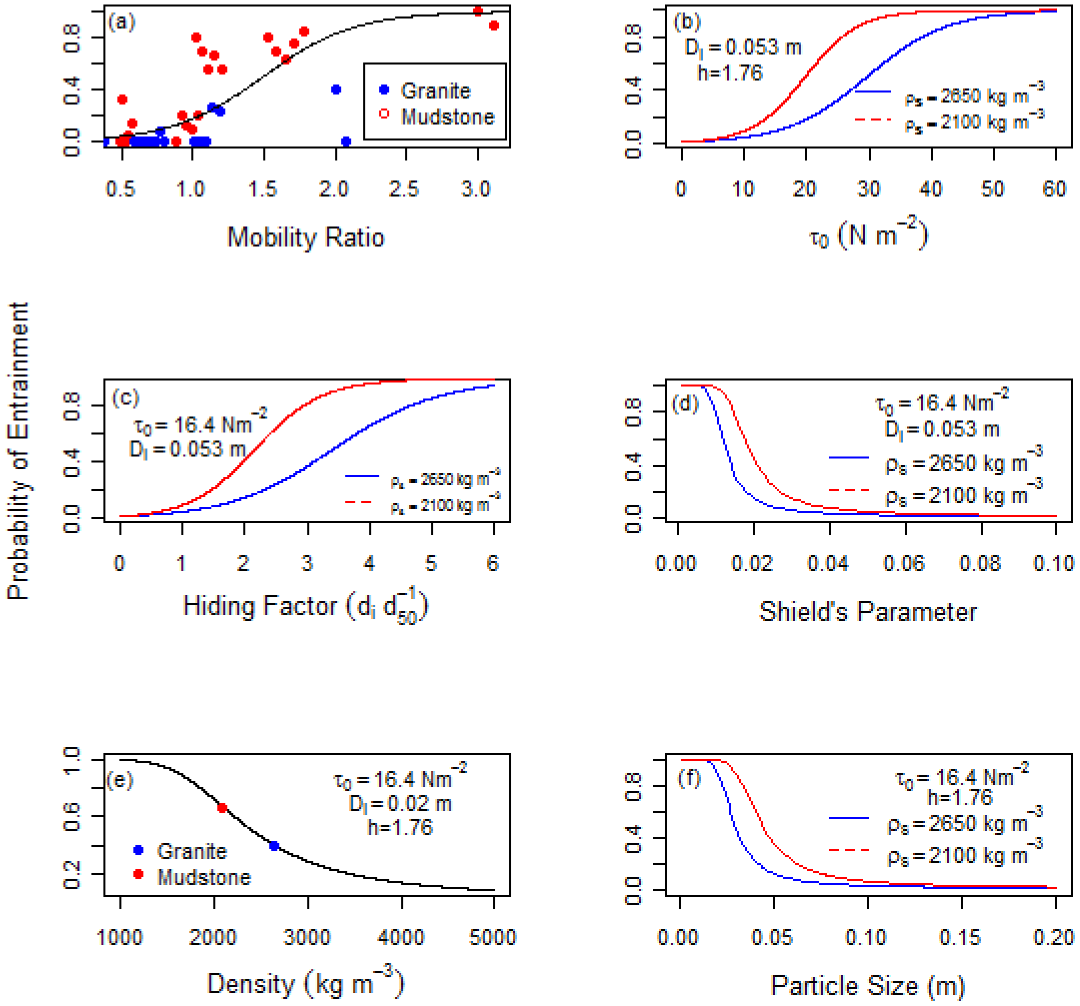

Figure 2.3. Figure showing (a) field data such that each dot represents the proportion of active particles at different values of M_r, and the line represents the fit of model M_1. Figures also show predicted model results from M_1 when varying (b) boundary shear (τ_0), (c) hiding factor (h), (d) Shield's parameter (τ^*), (e) sediment density (ρ_s), and (f) particle size (Di). Note in each of the figures particles with the density of mudstone have a higher probability of entrainment than granite particles.

When the results are related to spawning gravels in a typical winter flow at the study site, particles with a density of mudstone had approximately a 35% increase in the probability of entrainment over granitic particles. The model was run with reach-specific substrate distribution characteristics (D_{50} = 0.03 m) under approximate bankfull conditions. The observed peak discharge of 0.482 m^3s^{-1} is slightly less than the bankfull discharge for Yellowbank, 0.540 m^3s^{-1}, which corresponded to a τ_0 of 21.4 N m^{-2}. Bounding D_i between 0.01 m and 0.15 m, using a D_{50}

of 0.03 m and a τ_0 of 21.4 N m^{-2}, calculation of M_r, shows that density affects probability of entrainment more in the smaller size classes (Figure 2.4). The hiding factor *h* was calculated for each model input to mimic the surveyed stream bed, as opposed to the previous model graphs (Figure 2.4) which hold *h* constant. When D_i is 0.15 m, probability of entrainment of mudstone and granite is 46% and 16%, respectively. When D_i is 0.01 m the probability of entrainment of mudstone and granite is 81% and 36%, respectively. The mean probability of entrainment for mudstone under the specified conditions is 56%, while the mean probability of entrainment for granite is 21%, a difference is 35%.

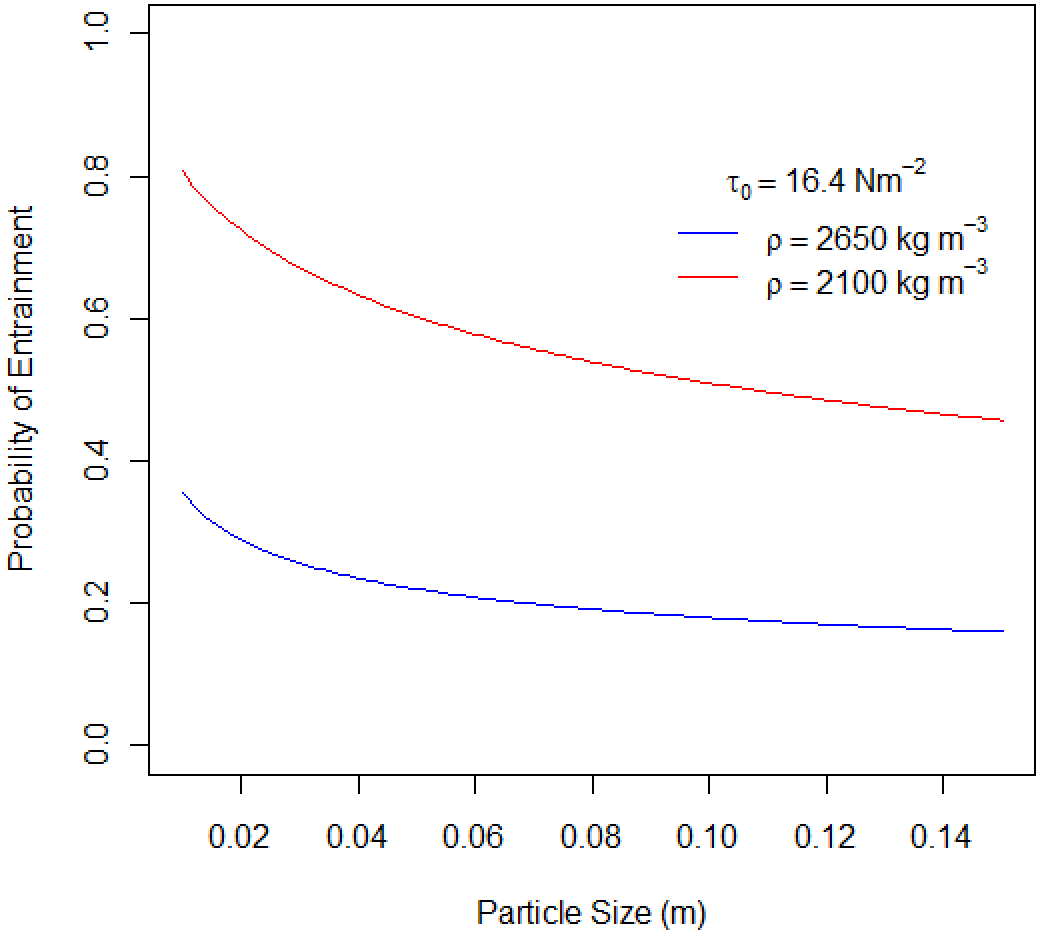

Figure 2.4. Model run results showing approximately a 35% difference in mobility between mudstone (ρ = 2100 kg m^{-3}) and granitic (ρ = 2650 kg m^{-3}) particles using reach specific gravel size and bankfull flow conditions. The two curves were calculated for gravels between 10 mm and 150 mm using the substrate conditions from the study reach.

DISCUSSION

Partial entrainment of both granite and mudstone particles was observed in Yellowbank Creek. During five observation periods tagged particles in size classes between 22.5 and 128 mm were placed in rows across the channel. In every size class of mudstone particles partial entrainment was observed, while three of five size classes of granite particles experienced partial entrainment. Two size classes of granite (45-64 and 64-90 mm) were not entrained by the range of flows that occurred during the study.

Using the results of the tagged particle study, logistic regression models were created to estimate the probability of entrainment for a given particle. The independent model variable was the mobility ratio M_r, which ratios mobilizing stresses over resistive stresses. The ratio was populated by four estimated input parameters: sediment density ρ_s, particle size D_i, Shield's parameter $\tau^*$and boundary shear τ_0. An AIC analysis of model results showed decisively that all input parameters are important for predicting the probability of entrainment for a given particle. The model rankings also indicate sediment size is the only parameter more important in predicting entrainment than sediment density.

The results of this study align well with previous studies. Flume studies by Wilcock and McArdell (1993) revealed full mobility of a size class exists when $M_r > 2$. The results of this work show that at $M_r = 2$, the probability of entrainment is approximately 80%. The full model, M_1, shows the start of a sharp increase in the probability of entrainment when τ^* is approximately between 0.02 and 0.04. These values are within the range of values reported in the literature which state values of τ^* at incipient motion in a gravel bed stream are be between 0.02-0.065 (Buffington and Montgomery 1997).

In my AIC model comparison results boundary shear stress was not a highly predictive parameter, which is likely a result of using a reach average approach. AIC model comparison indicates the loss of τ_0 as a predictive parameter does not affect the predictive strength of the model as much the loss of other parameters. Lack of predictive importance for boundary shear τ_0 is likely an indication that geometrically determined reach average τ_0 has a high degree of scatter when compared to the actual local stresses. In another study modeling entrainment, Konrad et al (2002) found wide variability in predicted τ_{crit} and observed τ_0 at incipient motion of a tagged particle. The stochastic nature of local turbulence and transient high shear stress, in contrast to estimated average channel conditions, may lead to incipient motion occurring at lower values of τ_0 than would be expected from calculation of τ_{crit}.

I documented partial entrainment in a range of both granite and mudstone particle sizes, and modeling results indicate that sediment density ρ_s is an important factor in particle entrainment in natural settings. When the model was run using approximate bankfull flow conditions and substrate characteristics from the study reach, the probability of entrainment was on average approximately three times higher for mudstone than granite, with density affecting mobility more strongly in the smaller sized particles. Although the results of this study clearly relate lower particle density to higher mobility, further work should be done to refine the magnitude of the difference caused by variations in density. The connection between particle density, partial entrainment, scour and redd washout should be examined more specifically as well. Ecological implications of less dense and more mobile substrate are unclear, but potential impacts include: altering the size range of suitable spawning gravels, increased probability of redd washout or burial, spatially shifting redd location in a stream and altering suitable spawning flows and timing of spawning.

CHAPTER 3

STEELHEAD MIGRATION THROUGH HIGHWAY CULVERTS: A HYDRAULIC MODELING APPROACH

INTRODUCTION

Upstream spawning migration is a critical stage in the life of an anadromous steelhead (*Oncorhynchus mykiss*). One of the potential limiting factors to steelhead success in central California is man-made barriers to upstream migration which restrict access to suitable spawning habitat (NMFS 2007). Natural migration barriers have always existed in the form of sandbars, woody debris, boulders and waterfalls. However, man-made barriers have further fragmented steelhead riparian habitat. Man-made barriers can take many forms including dams, water diversions and culverts (Collins et al. 1962; Pejchar and Warner 2001). This study specifically addressed culverts, which can create hydraulic conditions that restrict upstream migration (CDFG 2002).

Large steelhead runs have been documented in the north coast of Santa Cruz County since the mid-1800s (ESA 2001). In 1906 a coastal railroad grade was completed that crossed the lagoon or mouth of every stream in the region (Figure 3.1). In each case where a stream valley had been filled and occluded for the railroad grade, the stream was diverted into a bedrock bore that was dug into the hillsides north of the fill. Immediate reports of the detriment to fish stocks led to Scotts Creek (a stream farther north which was not crossed) becoming recognized as an important fisheries resource (ESA 2001). Furthering the impact, by the 1950s, Highway 1 had been straightened to allow for faster automobile travel, and its new straighter alignment followed the old railroad grade (ESA 2001). At stream crossings, the new Highway 1 engineering included extending the existing railroad fill inland, and burying box culverts in the fill to lengthen the existing boreholes. The culverts will be referred to as the Highway 1 culverts, as the railroad is no longer operational.

Some of the creeks which have been diverted through the box culvert and borehole are known to support limited anadromous steelhead runs today (ESA 2001; HES 2009). For other streams, there are no modern steelhead runs and it is unclear if impaired upstream migration through the culverts and boreholes is the limiting factor for the steelhead.

Figure 3.1. Construction of the railroad trestle crossing the mouth of San Vicente Creek at the Davenport beach. (Copied from ESA 2001)

I assessed fish passage through five Highway 1 culverts in a region of northern Santa Cruz County known as the Coast Dairies Property. I focused on five streams which are confined by the highway culverts. The objectives of this study were to model the hydraulics of the five culverts to evaluate flows which meet the conditions of commonly used passage criteria, and to estimate the frequency of those flows which meet the conditions of the passage criteria.

METHODS

Study Sites

I examined the hydraulics of five culverts on five separate streams: Molino, Ferrari, San Vicente, Yellowbank, and Laguna (Figure 3.2). With the exception of Ferrari, each culvert is the final culvert before the stream drains into the ocean. On Ferrari, there is an abalone farm downstream of the Highway 1 culvert that directs the stream through its facilities before discharging the water (Robins et al 2010). Passage conditions through the abalone farm are unknown, and will not be considered for this study.

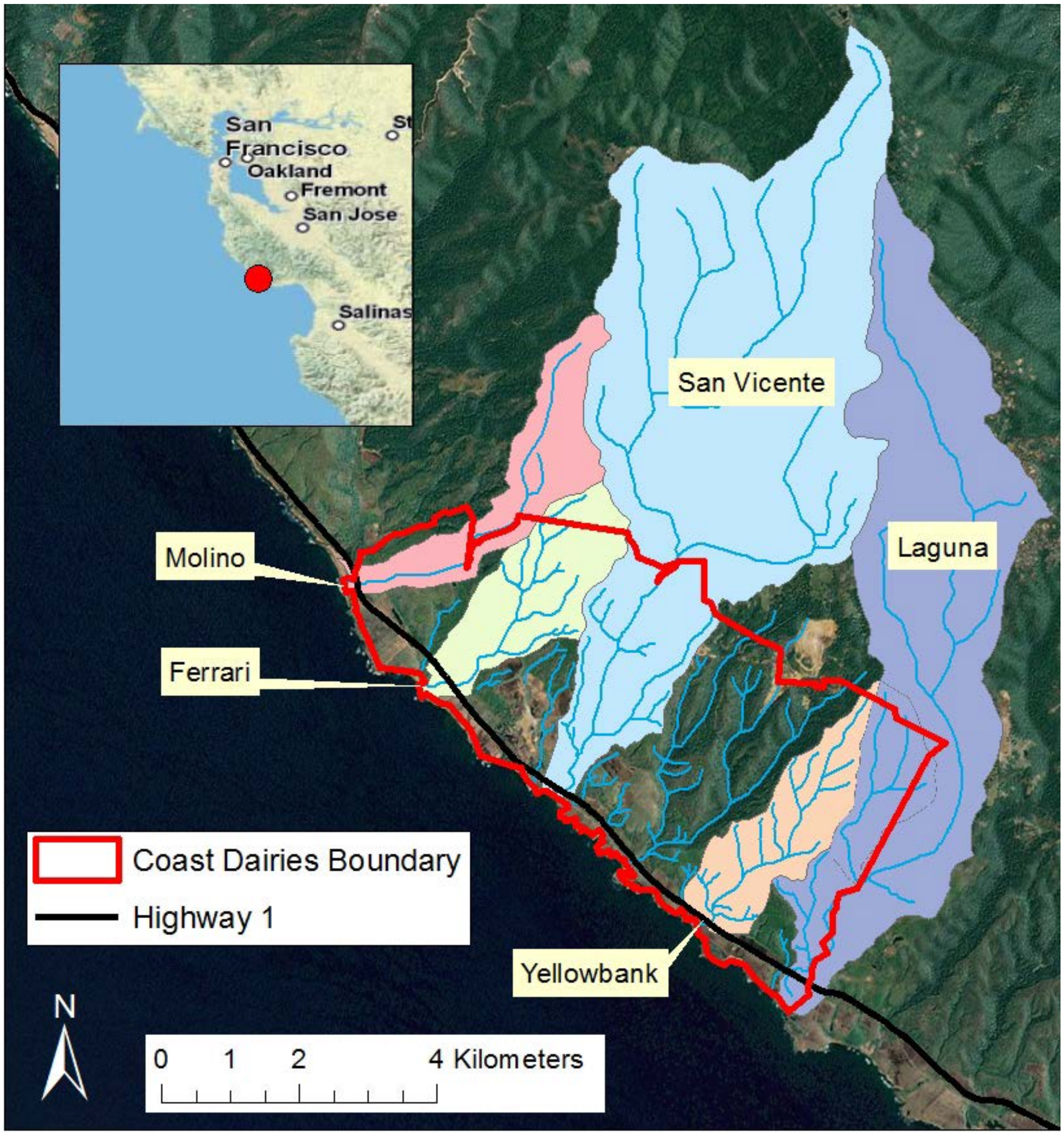

Figure 3.2. Study streams and associated drainages. Note Highway 1 crossing each stream near its mouth.

San Vicente and Laguna have documented anadromous steelhead populations, while the other three streams do not (ESA 2001). This observation indicates that the culverts on those two streams are passable under some range of reasonably frequent flow conditions. Both San Vicente and Laguna are substantially larger in drainage area than the other three streams, which are more similarly sized (Table 3.1). The larger drainage areas of San Vicente and Laguna produce much larger winter flows than are present in Molino, Ferrari and Yellowbank.

Table 3.1. Characteristics of study streams and associated culverts

	Drainage Area km^2	Bankfull Discharge[1] m^{3}s^{-1}	Median February Flow[2] m^{3}s^{-1}	Length of Bedrock Bore m	Length of Box Culvert m	Total Length of Culvert m
Molino	4.1	1.274	0.049	NA	58.0	58.0
Ferrari	4.2	1.039	0.028	NA	52.7	52.7
San Vicente	29.2	7.136	0.514	122.8	26.6	149.4
Yellowbank	3.7	0.541	0.021	99.3	47.2	146.5
Laguna	20.2	6.765	0.380	43.5	78.9	122.4

[1] Source: ESA 2001

[2] Source: Jackson 2004

Hydraulic Modeling

A 1-dimentional model, HEC-RAS (USACE 2010), was used to model the hydraulic conditions of the study culverts under various flows. This model uses site specific channel cross section geometry and roughness estimates to calculate water surface elevation and hydraulic conditions for a given discharge. Models for each of the five culverts were created to estimate depth and velocity conditions at each cross section of all the culverts at a range of flows. Although turbulence is another hydraulic factor that can create a barrier, it was not considered in this study.

The model geometric parameters were defined from site surveys of each culvert. The surveys were completed between 2010 and 2011 using a laser level and standard survey techniques. Cross sections were surveyed on each creek to capture the geometry in the reaches of natural channel, box culvert and bedrock bore. A longitudinal profile was surveyed through each culvert to place all the cross sections surveys in the same vertical framework. The only input to HEC-RAS that was not based on the surveyed geometry data was Manning's roughness coefficient, Manning's n. Values of Manning's n were chosen from a table of common channel types and associated values (FishXing 2010) (Table 3.2).

Table 3.2. Manning's n values used in models

Channel Type	Manning's n
Natural channel	0.045
Floodplain	0.060
Culvert	0.017
Bedrock bore	0.030

Manning’s n is commonly an unconstrained variable in hydraulic modeling. To compensate for a lack of field data, a reasonable range for Manning’s n values was used, based on published values (FishXing 2010). I performed a parameter sensitivity analysis within the defined range of roughness values to explore how strongly roughness affects flow conditions in San Vicente Creek.

Steelhead Passage Criteria

Steelhead kinematics have been previously studied, with the literature often reporting three swimming modes: prolonged, burst and leap swim speeds, as well as time to exhaustion for those speeds (FishXing 2010; Powers 1985). Conversely, others have published passage requirements, which focus on the hydraulics of a given reach of stream needed for steelhead passage (Thompson 1972; Bates 2002; CDFG 2002).

For this study I used three widely cited threshold hydraulic requirements for upstream migration (Table 3.3). Criterion 1, the most conservative set of requirements (Bates 2002), has been published by several regulatory agencies including the California Department of Fish and Game (CDFG 2002) and the National Marine Fisheries Service (NMFS 2001). Criterion 2 is recommended by the Department of Transportation (DOT 2011), and combines a velocity threshold from Bell (1986) and a depth threshold from Everest et al (1985). Criterion 3 uses recommendations Thompson (1972), has been cited by consulting reports on steelhead passage in California (SYRTAC 1999; Chartrand et al 2005; HES 2009).

Table 3.3. Adult steelhead upstream passage criteria used in this study.

		Culvert Length m	Maximum Average Water Velocity m/s		Minimum Flow Depth m
Criterion 1	*CDFG (2002)*	18.3	1.829		0.3048
		18.3-30.5	1.524		
		30.5-61.0	1.219		
		61.0-91.5	0.914		
		>91.5	0.610		
Criterion 2	*Bell (1986)*		1.402	*Everest et al (1985)*	0.248
Criterion 3	*Thompson (1972)*		2.438		0.183

A range of flows were modeled and evaluated using these criteria. The minimum and maximum flows that allowed passage for a given criterion were modeled to the nearest 0.05 m^3s^{-1}, and "passable" was defined as a flow which met both depth and velocity criteria at every cross section in the culvert.

Recurrence of passable flows

To estimate the frequency of passable flows I used the available flow data for each of the study streams (Table 3.4) and estimated the recurrence of the minimum flow to allow passage using a partial duration series analysis (PDS) (Dunne and Leopold 1978). Yellowbank and Molino did not have a long enough gaged period to warrant a PDS analysis, so minimum flow thresholds were visually compared to the existing hydrographs for those streams.

To calculate a recurrence interval using a PDS, all of the storm peaks above a given threshold are ranked. In contrast to an Annual Maxima Series (AMS), which uses only the peak flow for a given year, a PDS uses all storm peaks and can therefore more accurately calculate the frequency of frequent flows, and can assess recurrence intervals that are a fraction of a year (Dunne and Leopold 1978). Therefore PDS is more suitable to estimate fish passage events, which typically happen at least once per year on steelhead-bearing streams. The minimum flow necessary for passage in individual streams was used as the threshold above which all storm peaks were counted in the respective PDS analysis.

Table 3.4 Source of flow data for streams

Stream	Source	Date Range *Start - End (mm/yyyy)*
Molino	Jackson 2003	7/2002- 6/2003
Yellowbank	Nicol 2012	7/2010 - 5/2012
San Vicente	USGS	10/1969 - 8/1985
Laguna	USGS	10/1969 - 10/1976

RESULTS

Modeling Results

The five culverts were modeled under a range of flows. The three sets of passage criteria were compared to modeled depth and velocity conditions in each culvert under a range of flows. This section is broken up into two parts. The first will show the results from the culverts that are known to allow upstream fish migration (San Vicente and Laguna) and the second section will discuss the culverts where the ability of a fish to pass is unknown (Molino, Ferrari, Yellowbank). Minimum and maximum passage flows are summarized at the end of the section (Table 3.5).

Passable culverts (San Vicente and Laguna)

Model results from the two culverts that are known to pass steelhead, San Vicente and Laguna, show that they have the two most favorable hydraulic conditions for passage of the five modeled culverts (Figure 3). The culverts were modeled under flows ranging from 0.05 to 7.0 m^3s^{-1} which approximately covers the range from baseflow to bankfull flow.

The model outputs for the two known steelhead-bearing streams were evaluated based on the same three published passage criteria. Criterion 1, the most conservative of the three evaluated passage criteria, indicate that there are no modeled flows in which San Vicente or Laguna culverts meet the required conditions for both depth and velocity. Using Criterion 2, there is a small range of flows that would allow steelhead to pass all cross sections on both San Vicente and Laguna. On San Vicente the culvert is passable between 0.30 and 0.45 m^3s^{-1}, and the Laguna culvert is passable between 0.90 and 1.05 m^3s^{-1}. When examining the culverts using Criterion 3, both San Vicente and Laguna have a wider range of flows in which steelhead can pass. San Vicente can pass steelhead between 0.20 and 5.05 m^3s^{-1}, while Laguna can pass steelhead between 0.55 and 5.85 m^3s^{-1}.

The downstream section of San Vicente was the least favorable for passage. The bore at the mouth of the tunnel has a steep drop off onto the sand, which creates very high velocities and shallow water approximately 5 m upstream from the end of the culvert (Figure 3.2). The least favorable cross section on Laguna was approximately 60 m upstream of the mouth of the culvert. There is a 0.3 m drop in the bedrock bore at that point, which creates high velocities and shallow water.

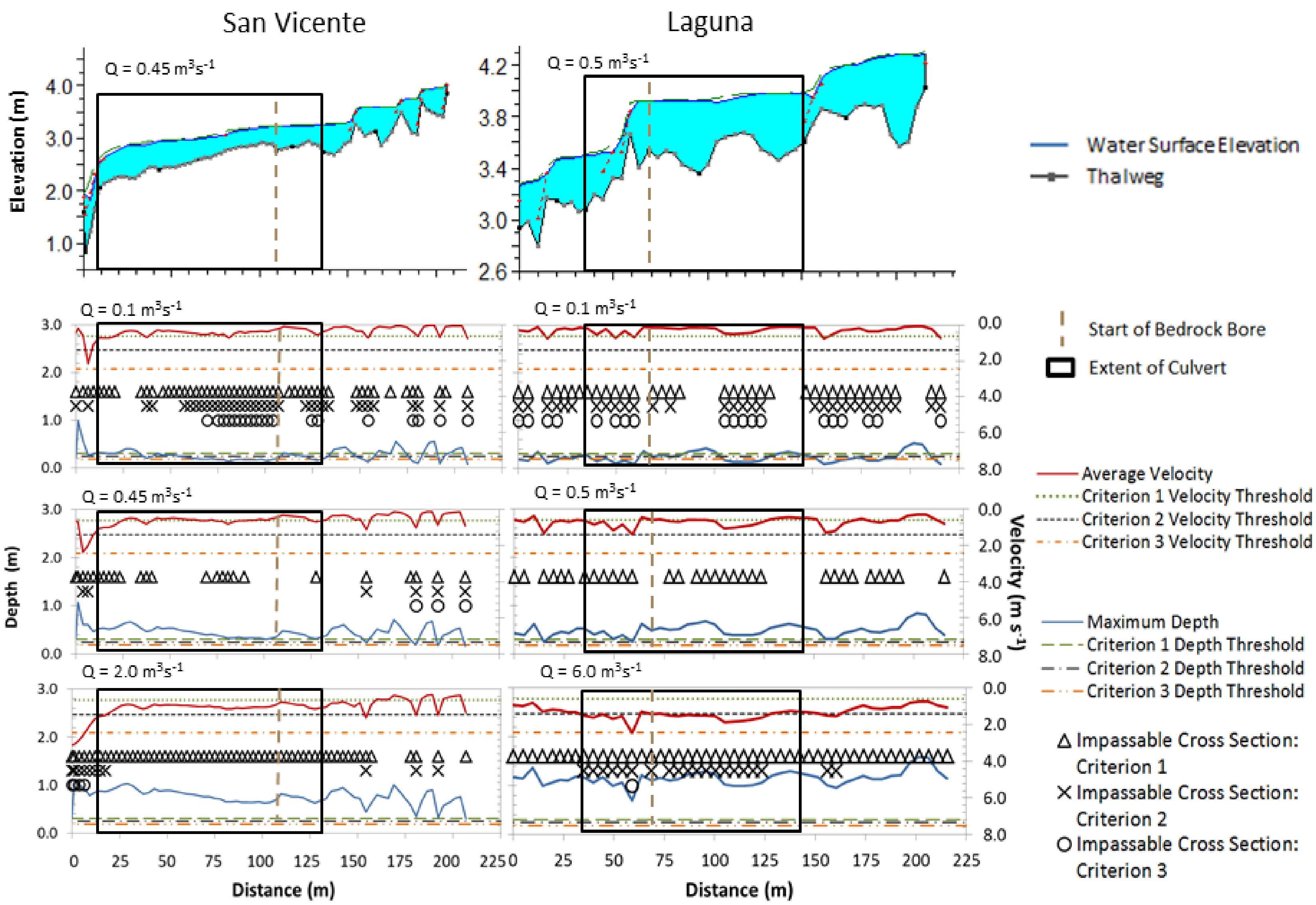

Figure 3.3. Model results from San Vicente and Laguna, two culverts which are known to pass steelhead

Culverts with unknown fish passage potential (Molino, Ferrari, Yellowbank)

Molino, Ferrari and Yellowbank Creeks are small watersheds without documented steelhead runs. The range of flows modeled for Molino and Ferrari was 0.01 to 2.0 m^3s^{-1}, and 0.01 to 3.0 m^3s^{-1} for Yellowbank. These flow ranges approximately covered baseflow to bankfull flow, although in the case of Yellowbank this range exceeded bankfull flow.

The three culverts uniformily had worse fish passage conditions than San Vicente or Laguna. Model results from Molino, Ferrari and Yellowbank indicate that none of the culverts meet Criterion 1 or Criterion 2 under any flows. Ferrari is not passable under any flow conditions using any of the three criteria (Figure 3.3), even when disregarding a 2 m waterfall at the end of the culvert. Molino and Yellowbank, however, meet Criterion 3 for a range of flows (Table 3.5).

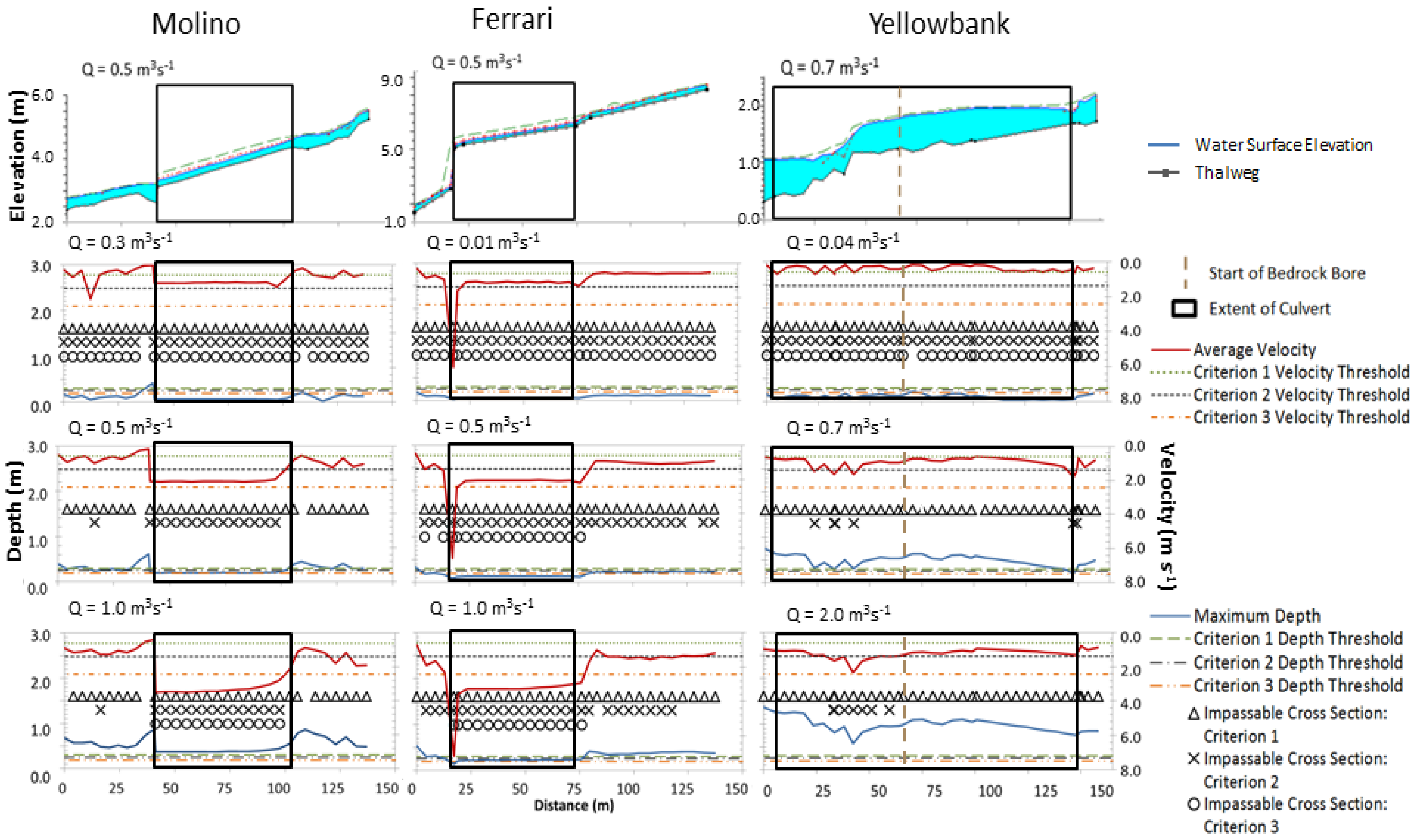

Figure 3.4. Model results from culverts in which steelhead passage is unknown.

The results of modeling steelhead passage through the tunnels show none of the culverts are passable using Criterion 1 (Table 3.5). Using the guidelines Criterion 2, San Vicente and Laguna have a passable range of flows. Criterion 3 allows for a passable range of flows in all of the culverts except for Ferrari.

Table 3.5. Results of hydraulic modeling. Values indicate minimum and maximum Q (m^3s^{-1}) which allow for steelhead passage.

	Criterion 1		Criterion 2		Criterion 3	
	min	max	min	max	min	max
Molino	Not Passable		Not Passable		0.50	0.75
Ferrari	Not Passable		Not Passable		Not Passable	
San Vicente	Not Passable		0.45	0.45	0.25	5.05
Yellowbank	Not Passable		Not Passable		0.70	2.25
Laguna	Not Passable		0.90	1.05	0.55	5.85

Manning's n sensitivity

As Mannings's n was the only input parameter without field calibration, I performed a sensitivity analysis to explore the amount of uncertainty Manning's n could introduce to the San Vicente model. To obtain each range of passable flows I varied Manning's n only in the channel type of interest, and held it constant for the other section of channel. The results show variation in the box culvert and natural gravel bed sections have little impact on the range of passable flows (Table 3.5). Variation of Manning's n in the bedrock bore, however, dramatically changed the upper end of the passage window. There are two specific cross sections at the end of the bedrock bore that are constraining the upper limit of passable flows (Figure 3.3). These two cross sections are highly influenced by Manning's n in the bedrock bore section of the model. The sensitivity analysis indicates the limiting low flow condition is fairly robust with respect to a range of roughness coefficients, but the limiting high flows are highly influenced by changes in model roughness, and could be improved with field calibration.

Table 3.6. Results of sensitivity analysis on the San Vicente culvert, showing how variation of Manning's n in the different channel types affects the range of passable flows. Flow values given in m^3s^{-1}.

		Range of Passable Flows on the San Vicente culvert (m^3s^{-1})					
		Criterion 1		Criterion 2		Criterion 3	
Channel Type	Mannings n	min	max	min	max	min	max
Box Culvert							
Low	0.010	Not Passable		Not Passable		0.3	5.0
High	0.025	Not Passable		0.45	0.45	0.25	5.05
Bedrock Bore							
Low	0.020	Not Passable		Not Passable		0.35	1.85
High	0.040	Not Passable		0.3	0.45	0.2	5.05
Natural Gravel Bed							
Low	0.025	Not Passable		0.45	0.45	0.25	5.05
High	0.050	Not Passable		0.45	0.45	0.25	5.05

Recurrence of optimal flows

Results of the modeling analysis were compared to existing hydrographs from the study streams to estimate recurrence of passable flow ranges. The longest record available for one of the study streams is a United States Geological Survey (USGS) gage record on San Vicente from October of 1969 to August of 1985 (Gage 11161800). Visual inspection of the gaging record with the minimum threshold values for fish passage show the flows are frequently within the passable range (Figure 3.5). In the years of record the winter baseflow was often above both the Criterion 2 and Criterion 3 minimum passage flow threshold. There were two years in the record (the 1975-76 and 1976-77 water years) in which the flows were never high enough to be passable by either criteria, but that was during a rare regional dry event (CDEC 2012). Using 0.25 m^3s^{-1} as a threshold, a PDS indicates flows with magnitudes of 0.45 and 0.25 m^3s^{-1} have approximate recurrence intervals of 0.19 years (five times per year) and 0.16 years (seven times per year), respectively.

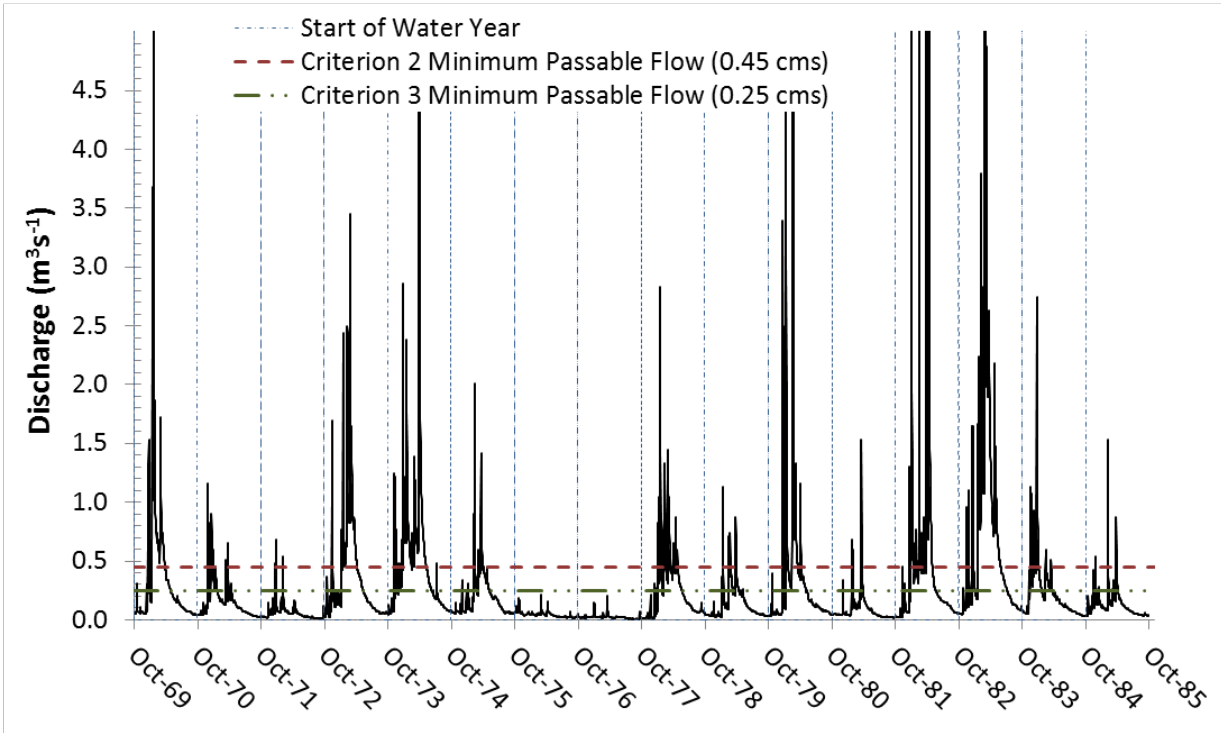

Figure 3.5. Flow record for San Vicente (USGS Gage 11161800*)*. Both minimum flow requirements were passed several times in all but two of the gaged water years. Note the figure is focused on the lower flows and does not show the peak flows.

The USGS also gaged Laguna creek from October of 1969 to October of 1976. The minimum passable flows appear to happen less frequently on Laguna, with only storm peaks reaching higher than both of the minimum passable flows thresholds (Figure 6). Using 0.55 m^3s^{-1} as a threshold, a partial duration series reveals flows with magnitudes of 0.90 and 0.55 m^3s^{-1} have approximately recurrence intervals of 0.5 years (two times per year) and 0.3 years (three times per year), respectively.

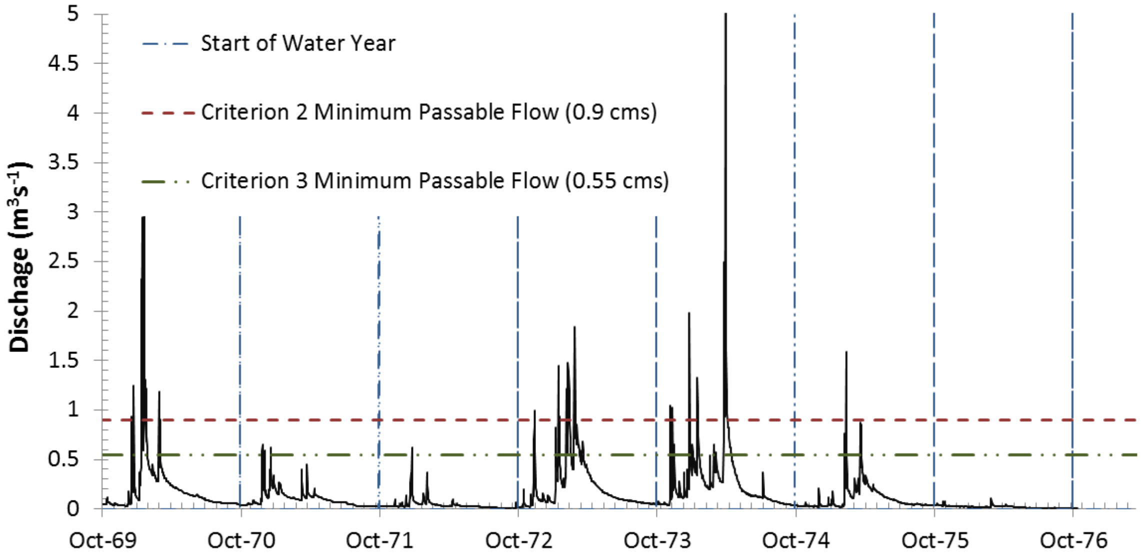

Figure 3.6. Flow record for Laguna (USGS Gage 11161590). The flow thresholds are crossed by peak flows with approximately a 0.3 recurrence interval.

Yellowbank and Molino both have slightly over one year of available gage data, which is not enough to calculate a PDS. Visual examination of the minimum passable flows using Criterion 3 show the flows are relatively high for both streams. Yellowbank had one storm peak in 2011 which was over the requisite minimum flow for 12.5 hours (Figure 6), while the highest storm peak on Molino (0.41 m^3s^{-1}) was approximately 0.1 m^3s^{-1} below the required minimum flow (Figure 8).

The 2010-2011 water year when Yellowbank was gaged had an above average rainfall year, with 1,016 mm at the Santa Cruz rain gage, which usually averages 758 mm (CDEC 2012). The 2002-2003 water year in which Molino was gaged, had an approximately average rainfall of 738 mm with 386 mm falling in December.

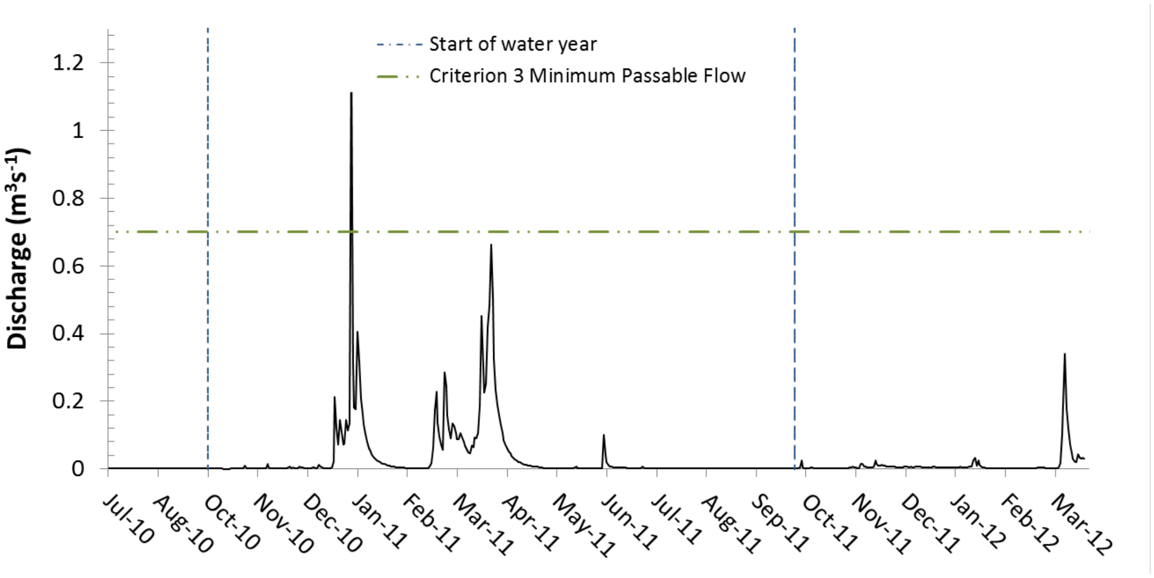

Figure 3.7. Gaged period of flow at Yellowbank. The flow increased to the requisite minimum flow for passage one time during the gaged period, and was over for 12.5 hours.

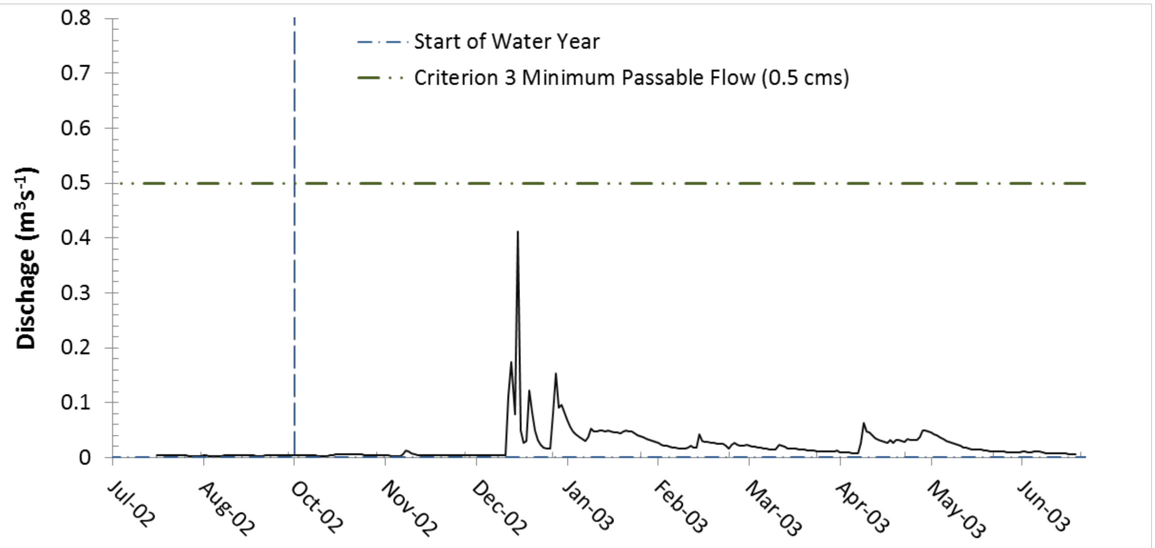

Figure 3.8. Hydrograph of the single gaged season on Molino. The flow remained well below the required minimum flow for passage throughout the gaged period.

DISCUSSION

I modeled upstream steelhead passage through five culverts that run under Highway 1. The objectives were to model the hydraulics of the culverts to evaluate flows which meet the conditions of three commonly used steelhead passage criteria, and to estimate how often these flows occur. Two of the study streams are known to pass steelhead (San Vicente, Laguna), while the three have unknown fish passage conditions (Molino, Ferrari, Yellowbank). Three different passage criteria were used; each consisted of a maximum average velocity threshold and minimum depth threshold. Estimation of the recurrence of passable flows was done by comparing modeled flows with existing flow data for each stream.

Agreement between recurrence of estimated passage flows and actual knowledge of steelhead usage varied according to which criterion was used to define passage flow. Criterion 1 appeared to be too conservative, as modeling results indicated there are no passable flows for any of the study streams. Modeling results using Criterion 2 indicated passage flows do occur on the two streams known to support anadromy, but the flows occur infrequently. Specifically San Vicente had suitable hydraulic conditions at a flow which occurs approximately five times per year (RI = 0.19 years), while minimum passable flow conditions at Laguna occur two times per year (RI = 0.5 years). Using Criterion 3, there was a range of passable flows which were estimated to occur on all streams except Ferrari. Recurrence of the passage flows does not appear to be a limiting factor on San Vicente or Laguna; however, examining the short hydrographs for Yellowbank and Molino, it appears that the estimated passage flows may happen infrequently. Yellowbank was gaged during an above average rainfall year and had one stormflow which rose above the minimum threshold for passage, while Molino was gaged in an average rainfall year and never had enough flow to meet the estimated minimum flow for passage; this evidence suggests passage flows are infrequent on these two streams.

Considering the evidence presented through knowledge of existing anadromous steelhead populations, modeling of passage flows and estimation of recurrence intervals, I interpret Criterion 1 to be overly conservative. Although it is possible that this criterion was intentionally written to be conservative for culvert design and construction (Bates et al 2003), future studies need to take care not to use this criterion when determining if a culvert is a barrier. This study presents a case where two streams support well documented populations of anadromous steelhead which pass through culverts that do not meet the hydraulic requirements for upstream salmonid passage set in Criterion 1.

There was no clear evidence whether Criterion 2 or Criterion 3 better represents the swimming abilities of the steelhead populations in the study streams. Further work to link the known data on spawning timing in San Vicente and Laguna with the estimated recurrence of passage flows found in this study, may elucidate which criterion is a better choice for this area. In general Ferrari has the worst hydraulics for upstream passage, and San Vicente and Laguna have the most favorable hydraulics. The hydraulics of Molino and Yellowbank lie somewhere in between, and may have small windows of suitable conditions of upstream migration, but it is likely those flows do not occur often.

CHAPTER 4

CONCLUSIONS AND MANAGEMENT RECCOMENDATIONS

The aim of this work was to examine two potential factors limiting anadromous steelhead success on the Coast Dairies Property. The two limiting factors examined are the effects of low density substrate on spawning habitat (Chapter 2) and highway culverts as migration barriers (Chapter 3). As there are six streams on the Coast Dairies, three of which have anadromous steelhead and three of which do not, this study focused on the three streams without populations of anadromous steelhead, and used the other streams as comparison.

The particle density study provided substantial evidence that particle mobility is strongly inversely related to particle density. This result suggests that streams with low density substrate (i.e. Santa Cruz Mudstone) have a more mobile stream bed than streams with a granitic substrate. This increased mobility may reduce the energy required to construct a red, but there is also a greater risk of redd washout that would ultimately limit the success of a steelhead population. Although future work needs to be done to clarify the tradeoff between ease of redd construction and risk of redd destruction, it is strongly apparent that generalizations about particle size need to be adjusted upwards when working in systems with low density substrate such as mudstone. On the Coast Dairies Property, the three streams with mixed granitic and mudstone bedrock (Liddell, San Vicente and Laguna) all have anadromous steelhead runs, while the three streams with strictly mudstone (Molino, Ferrari and Yellowbank) do not have steelhead runs. Further work is needed to establish the connection between increased particle mobility and salmonid spawning habitat suitability, but the results in this paper should be considered when prioritizing stream restoration efforts, especially on the fully mudstone dominated streams Molino, Ferrari and Yellowbank.

The study on steelhead passage through the highway culverts revealed that different commonly used passage criteria result in a range of suitable passage flows.

Additionally, it was found that one of the three passage criteria may be too conservative to represent the swimming abilities of steelhead in the study streams. In general, modeling results agreed well with known anadromy conditions; streams with known steelhead populations had better hydraulic conditions than streams with unknown anadromous populations. Ferrari had no passable conditions under any flows, but Molino and Yellowbank both had a small range of passable flows. Molino and Yellowbank are likely not passable every year, which may limit the long term success of anadromous steelhead in those streams.

This thesis focused on two limiting factors for anadromous steelhead success on the Coast Dairies Property. The results are focused on the three streams which do not have known runs of anadromous steelhead. Results suggest on Molino, Ferrari and Yellowbank that low density mudstone substrate is approximately three times more mobile than more common granitic substrate, and Highway 1 culverts act as barriers to migration under most flows. Further studies are needed to conclusively illustrate or challenge the idea these factors are limiting steelhead success, but these preliminary results indicate low density substrate may change conventional generalizations about steelhead spawning requirements and the culverts under Highway 1 act as a barrier under many flows. Stakeholders interested in steelhead success in Molino, Ferrari and Yellowbank should consider these potential limiting factors before making future restoration plans.

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APPENDIX

R CODE

```
data =
read.table("F:/01_School/Current_School/Coast_Dairies/Streams/Yellow_Bank/Tagge
d_particle/Analysis_R/LogisticRocks_Basic_120209.csv",sep=",", header = TRUE)
#p = particle size (low end of range), P = particle size (high end of range), n
= number of particles placed in stream,
#Moved = number of particles moved in a given storm, Rtype = G(granite) &
M(mudstone), t  = boundary shear, d = density of particle
attach(data)

prop = Moved/n #proportion of moved stones

Y = prop
N = n

D50 = 0.03 #Surface d50 (m) of site
data$h = p/D50 #hiding factor with LOW end of size range
data$H = P/D50 #hiding factor with HIGH end of size range

attach(data)

k1 = 0.0384 #Constant from Andrews and Ermine 1984
k2 = -0.887 #Constant from Andrews and Ermine 1984
g = 9.81 #m/s2 Gravity
dw = 1000 #kg/m3 density of water

t.const= mean(t)
h.const= mean(h)
d.const= 2650
d.mud.const= 2100
p.const= .02

#Model with use of averge values as constants
Xthdp = t/(k1*((h)^k2)*g*(d-dw)*p)
Xhdp = t.const/(k1*((h)^k2)*g*(d-dw)*p)
Xtdp = t/(k1*((h.const)^k2)*g*d*p)
Xthp = t/(k1*((h)^k2)*g*d.const*p)
Xthd = t/(k1*((h)^k2)*g*(d-dw)*p.const)

data2 = data.frame( Y, N, Xthdp, Xhdp, Xtdp, Xthp, Xthd,Rtype)

#Number of parameters (K) included in calculation of Y variable
K0 = 2
Kthdp = 6
Khdp = 5
Ktdp = 5
Kthp = 5
Kthd = 5

Xdf=c(K0, Kthdp, Khdp, Ktdp, Kthp, Kthd)

#list of models. Model list was made by including all (M1)
#and then removing one parameter from M1
#t = shear, h = hiding factor, d = density, p = particle size
M0 = glm(Y~1,data=data2,family=binomial(link = "logit"), weights =N)
Mthdp = glm(Y~Xthdp,data=data2,family=binomial(link = "logit"),weights=N)
Mhdp = glm(Y~Xhdp,data=data2,family=binomial(link = "logit"),weights=N)
```

```
Mtdp = glm(Y~Xtdp,data=data2,family=binomial(link = "logit"),weights=N)
Mthp = glm(Y~Xthp,data=data2,family=binomial(link = "logit"),weights=N)
Mthd = glm(Y~Xthd,data=data2,family=binomial(link = "logit"),weights=N)


#AIC analysis of models
AICtable <- function( aic, n) {
  XK <- Xdf
  AICc <- aic$AIC + 2 * XK * (XK+1) / ( n - XK - 1 )
  delAIC<- AICc - min( AICc )
  AICw <- exp(-0.5*delAIC) / sum( exp(-0.5*delAIC))
  #This is the AIC table to be published:
  data.frame( aic, XK, AICc, delAIC , AICw)
}

#AIC analysis for the glms:
aic.glm=AIC(M0,Mthdp,Mhdp,Mtdp,Mthp,Mthd)
aic.glm=AICtable( aic.glm, length(data2[,1]))
aic.glm=aic.glm[order(-aic.glm$AICw),]
aic.glm

#Plot predicted probability of particle motion vs. input paramater
#create sequences for each of the paramaters
t.seq=seq(0.01,60,.01)#boundary shear
h.seq=seq(0.01,6,.001)#hiding factor
d.seq=seq(1000,5000,2)#density
p.seq=seq(0.001,.2,.001)#particle size
s.seq=seq(0.001,.1,.001)#shields parameter

X.t.seq.thdp.gran= t.seq/(k1*((h.const)^k2)*g*(d.const-dw)*p.const)#vary tau
while holding granite density constant
X.t.seq.thdp.mud= t.seq/(k1*((h.const)^k2)*g*(d.mud.const-dw)*p.const)#vary tau
while holding mudstone density constant

X.h.seq.thdp.gran= t.const/(k1*((h.seq)^k2)*g*(d.const-dw)*p.const)#vary hiding
factor while holding granite density constant
X.h.seq.thdp.mud= t.const/(k1*((h.seq)^k2)*g*(d.mud.const-dw)*p.const)#vary
hiding factor while holding mudstone density constant

X.s.seq.thdp.gran= t.const/(s.seq*g*(d.const-dw)*p.const)#vary shields while
holding granite density constant
X.s.seq.thdp.mud= t.const/(s.seq*g*(d.mud.const-dw)*p.const)#vary shields while
holding mudstone density constant

X.d.seq.thdp= t.const/(k1*((h.const)^k2)*g*d.seq*p.const)
X.d.const.thdp= t.const/(k1*((h.const)^k2)*g*d.const*p.const)
X.d.mud.const.thdp= t.const/(k1*((h.const)^k2)*g*d.mud.const*p.const)

X.p.seq.thdp.gran= t.const/(k1*((h.const)^k2)*g*(d.const-dw)*p.seq)#vary
particle size while holding granite density constant
X.p.seq.thdp.mud= t.const/(k1*((h.const)^k2)*g*(d.mud.const-dw)*p.seq)#vary
particle size while holding mudstone density constant


PrMthdp.tseq.gran=predict(Mthdp,type="response",newdata=data.frame(Xthdp=X.t.se
q.thdp.gran))
PrMthdp.tseq.mud=predict(Mthdp,type="response",newdata=data.frame(Xthdp=X.t.seq
.thdp.mud))

PrMthdp.hseq.gran=predict(Mthdp,type="response",newdata=data.frame(Xthdp=X.h.se
q.thdp.gran))
```

```
PrMthdp.hseq.mud=predict(Mthdp,type="response",newdata=data.frame(Xthdp=X.h.seq
.thdp.mud))

PrMthdp.sseq.gran=predict(Mthdp,type="response",newdata=data.frame(Xthdp=X.s.se
q.thdp.gran))
PrMthdp.sseq.mud=predict(Mthdp,type="response",newdata=data.frame(Xthdp=X.s.seq
.thdp.mud))

PrMthdp.dseq=predict(Mthdp,type="response",newdata=data.frame(Xthdp=X.d.seq.thd
p))
PrMthdp.gran=predict(Mthdp,type="response",newdata=data.frame(Xthdp=X.d.const.t
hdp))
PrMthdp.mud=predict(Mthdp,type="response",newdata=data.frame(Xthdp=X.d.mud.cons
t.thdp))

PrMthdp.pseq.gran=predict(Mthdp,type="response",newdata=data.frame(Xthdp=X.p.se
q.thdp.gran))
PrMthdp.pseq.mud=predict(Mthdp,type="response",newdata=data.frame(Xthdp=X.p.seq
.thdp.mud))

#Find max difference in Y between gran and mud

diff.t.seq = PrMthdp.tseq.mud-PrMthdp.tseq.gran
data.diff.t.seq =
data.frame(PrMthdp.tseq.mud,PrMthdp.tseq.gran,diff.t.seq,t.seq)
data.diff.t.seq = data.diff.t.seq[order(-data.diff.t.seq$diff.t.seq),]
data.diff.t.seq[1:10,]

#Find max difference in Y between gran and mud for redd sized gravel
#Run code in "Plot of REDD particle size vs probability" first
diff.p.redd.seq = PrMthdp.p.redd.seq.mud-PrMthdp.p.redd.seq.gran
data.diff.p.redd.seq =
data.frame(PrMthdp.p.redd.seq.mud,PrMthdp.p.redd.seq.gran,diff.p.redd.seq,
p.redd.seq)
data.diff.p.redd.seq = data.diff.p.redd.seq[order(-
data.diff.p.redd.seq$diff.p.redd.seq),]
data.diff.p.redd.seq[1:10,]
```