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Evaluating the Effects of Vortex Rock Weir Stability on Physical Complexity: Penitencia and Wildcat Creeks

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Authors
Corwin, Emily
Jagt, Katie
Neary, Leigh

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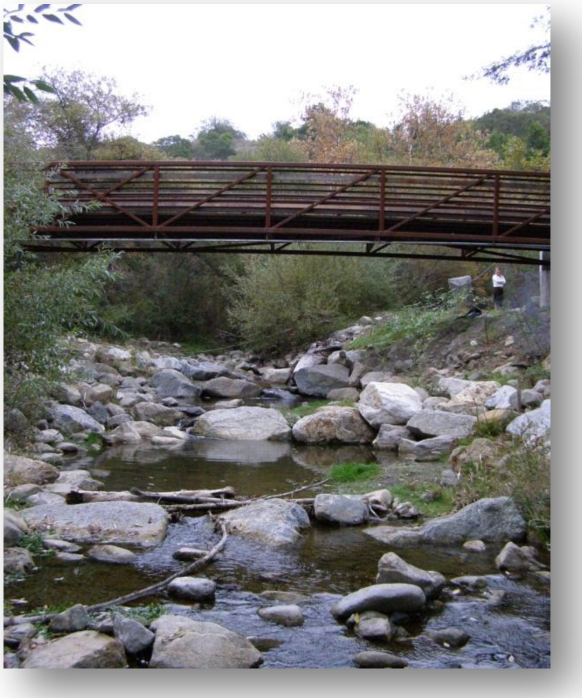

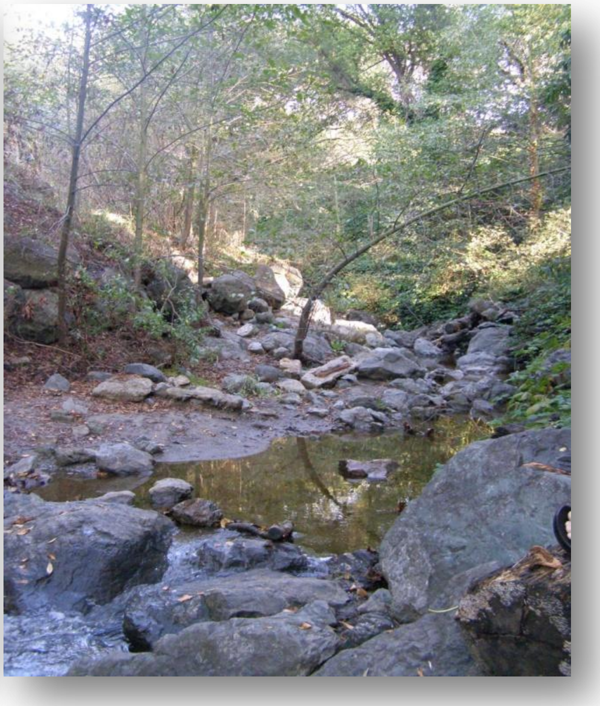

Emily Corwin
Katie Jagt
Leigh Neary

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Evaluating the Effects of Vortex Rock Weir Stability on Physical Complexity
Penitencia and Wildcat Creeks

Emily Corwin
Department of Civil and
Environmental Engineering
ecorwin@berkeley.edu

Katie Jagt
Department of Civil and
Environmental Engineering
katiejagt@berkeley.edu

Leigh Neary
Department of Civil and
Environmental Engineering
leighneary@berkeley.edu

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Abstract

An increasing number of stream restoration projects include structures such as vortex rock weirs to provide grade control. These structures are becoming a preferred option because they pair physical creek stability with the secondary benefit of habitat enhancement. Due to the monetary investment in these restoration strategies, it is essential to evaluate the contributions these structures make both in terms of stability and habitat. This study adopts existing methods for evaluating vortex rock weir stability and develops a new method for examining potential habitat based on the assumption that physical complexity may lead to suitable habitat. These methods for assessing weir stability, physical complexity, and potential habitat were successfully implemented at the Penitencia Creek and Wildcat Creek restoration sites in an attempt to correlate weir stability with physical complexity. Wildcat Creek's structures scored consistently lower than Penitencia Creeks' in the stability assessment. These results mimic results in the literature that find vortex rock weirs fail structurally after ten years in operation. In addition, variance for each of the physical parameters was calculated and compared to a trapezoidal control channel; the results of this analysis indicate that as weirs begin to fail, physical complexity decreases, and the presence of complexity within the system becomes increasingly unpredictable. In evaluating the methods used, we find the criteria for assessing vortex rock weir structural integrity is straightforward and simple, while the complexity measurements are demanding and time intensive. Despite this, coupling the weir stability criteria with the physical complexity analysis provides a powerful tool to assess the physical stream response to vortex rock weirs and other in-stream structures.

Introduction

A common stream restoration practice involves the use of in-stream structures such as vortex rock weirs to control stream bed gradient and provide flow and depth complexity. A common configuration of vortex rock weirs (weirs) is shown in Figure 1 (Maryland Department of the Environment). These weirs are often installed in stream restoration projects in California and numerous other states, to establish grade control, promote bank stabilization, and to improve fish passage. An additional benefit of these structures is their inherent creation of downstream scour pools and upstream riffles which have been shown to enhance in-stream fish habitat by providing channel complexity, refugia, and cover (Marsalek, 2004). Like most restoration elements, data concerning the longevity and effectiveness of vortex rock weirs is limited. Some studies show that vortex rock weirs may only last ten years before failing structurally. In addition, many of these installations have historically failed to meet habitat objectives (Brown, 2000).

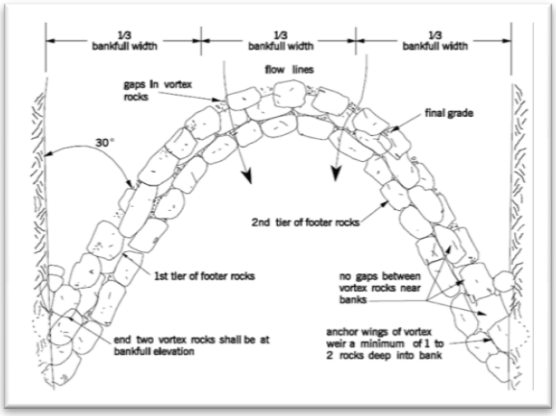


Figure 1. General Configuration of a Vortex Rock Weir (Maryland Department of the Environment)

The functionality of vortex rock weirs is intimately linked to the design and placement of the structure. The shape, height, and stability of the structure all contribute to the hydraulics and fluid movement which drive scour, aggregation, aeration, and ultimately the success or failure of the weir. The placement of weirs in streams is likely to influence local sedimentation, deposition, erosion, and scour processes, therefore post project monitoring is important to ensure the geometry, orientation, and resulting functions are not compromised by geomorphologic processes or that the weirs themselves are not causing channel destabilization, bank erosion, or habitat degradation (Maryland Department of the Environment, 2000). In the comprehensive study *Urban Stream Restoration Practices: An Initial Assessment*, the authors analyzed the effectiveness and success of 24 different stream practices ranging over 450 individual practice installations. Each of the installations was evaluated according to four visual criteria: structural integrity, function, habitat enhancement, and vegetative stability. Of the 24 practices studied only two were shown to exhibit high rates of failure–one of the two was vortex rock weir structures (Brown, 2000). A similar comprehensive study had the same results, with the vortex rock weir structures failing in every instance (Frissell and Nawa, 1992).

Habitat requirements within a specific anadromous salmonid species are known to differ between age classes and seasons. In addition, in a real river environment, habitat demands exerted by multiple species vary through space and time (Shepherd, 1985). Because of these multiple demands, the development of multiple niches for each important species is the reason physical habitat ***complexity*** is a very important parameter in habitat enhancement restoration projects (Flosi, 1998). Complexity can be defined as the range of different habitat areas (differentiated by velocity magnitude, velocity direction, velocity gradients, substrate composition, and depth) present within a certain stream area. The amount of scatter present in the flow or the magnitude of velocity gradients, however, is not the only indicator of physical complexity within a stream. Vorticity, which creates circulation and eddies in the flow, is also an important indicator of habitat suitability alongside spatial habitat heterogeneity. (Harper and Everard 1998).

The concept of ideal habitat is amorphous, and depends on factors such as species, flow and season. Even so, habitat design and desirability are often discussed in terms of a stream or river's physical characteristics. For example, a common method used to determine the habitat function of a stream reach is to (1) classify the stream's "microhabitat" (Moyle 1985) using velocity, substrate, and morphological grid measurements and (2) match the habitat units to habitat physical suitability curves for a target species (Wu 2002). Habitat types are typically defined, using these factors, by terms such as glide, riffle, run, scour pool, etc. (Salmonid Restoration Manual). A habitat suitability curve can be used to estimate the ideal velocities, bed particle size, and stream depth for a target species. In addition, pool tail embeddedness can be a good measure to determine spawning habitat quality. Embeddedness is defined as the degree to which fine sediments surround coarse substrates on the surface of a streambed; this is usually a consequence of an eroding or disrupted watershed. A quantification of the fine sediment located in a stream bed can give an indication of the stream's spawning viability. Literature suggests optimal spawning habitat for rainbow trout is substrate in which no more than 30-40% has a diameter of less than 6.35 mm (Irving and Bjornn 1984, NCASI 1984). However, it is essential not to solely judge a river's habitat quality based on the physical measurements alone. A representation of other habitat parameters—such as food availability and instream cover—must be included to provide a thorough understanding of the target species habitat desires (Kondolf, 2000). Physical measurements of complexity alone do not indicate the presence of a succesful stream ecosystem. To evaluate project success however, physical complexity can indicate the ability of a vortex rock weir to provide *suitable or potential* habitat for a range of species which comprise an ecosystem.

The purpose of this study is to: 1) developed a method to assess vortex rock weir stability and physical channel complexity in the field, 2) assessed the overall stability of vortex rock weir structures on two creeks in the San Francisco Bay area, 3) correlated the vortex rock weir stability with the surveyed physical complexity at the two sites, and 4) assessed the success or failure of these projects in terms of structural integrity and physical channel complexity, while deliberately avoiding an analysis of the presence or absence of specific habitat conditions. Nevertheless, the discussion includes a brief comparison of site-collected physical data and researched habitat suitability criteria.

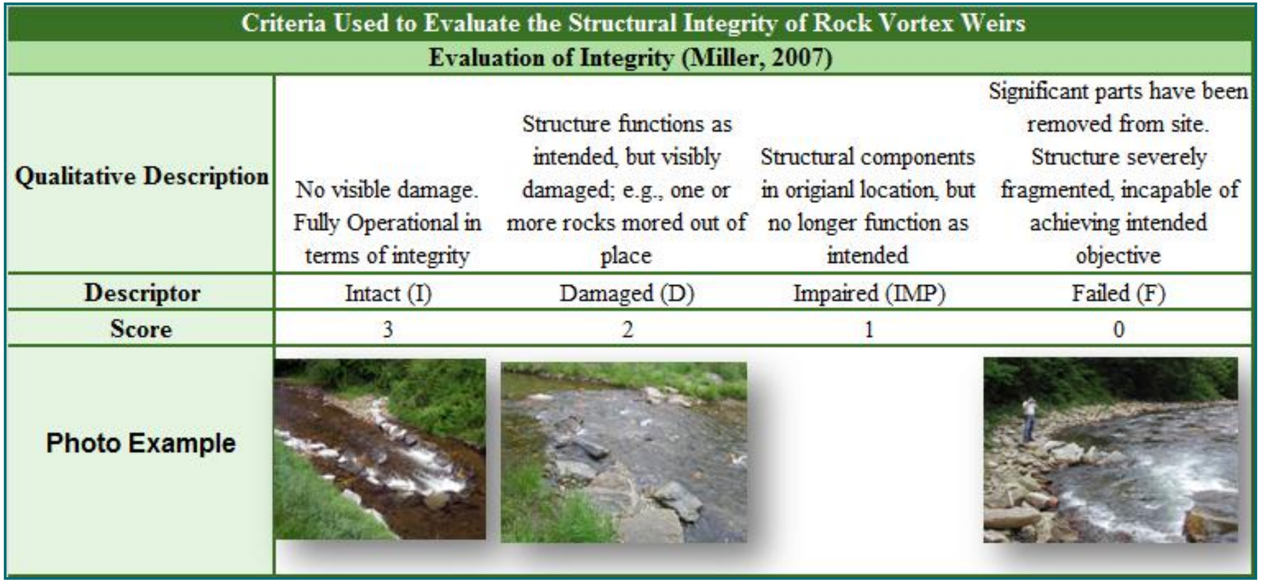
Methods

We collected qualitative and quantitative data at two study sites to evaluate physical complexity around and integrity of seven vortex rock weirs. We borrowed from a previously developed method to evaluate weir integrity (Miller, 2007) and created a unique application of the statistical measure of variance to quantify and compare physical complexity at each site and at each weir. In addition, a habitat suitability analysis of collected sediment size data allowed for an assessment of possible habitat presence.

Vortex Rock Weir Structural Integrity Field Data

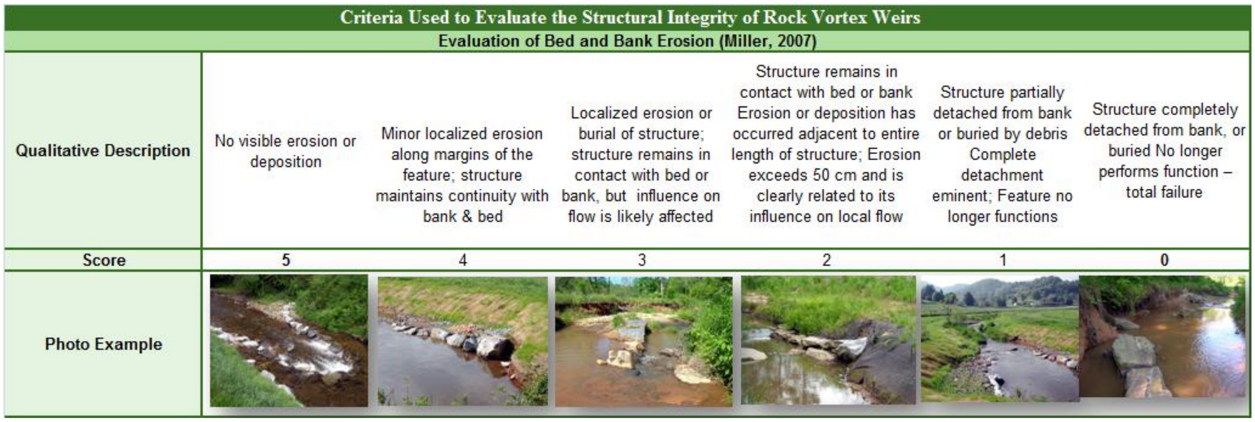
The stability assessment is from a rating system developed by Jerry Miller from Western Carolina University (Miller, 2007). It is qualitative and based on observations of integrity and channel bed and bank erosion. Structural integrity indicators include visible signs of weir damage, such as rocks moved out of place, and how any damage affects weir function. Bed and bank indicators include visible signs of erosion or deposition adjacent to the structure, contact of the structure with the channel bed and bank and how these factors affect weir function.

The degree of structural integrity is divided into four categories with an associated score ranging from zero (failed) to three (intact). Figure 2 summarizes the four degrees of integrity degradation, the associated score and, where available, a picture demonstrating each case. We divided the degree of bed and bank erosion or deposition into six categories with an associated score ranging from zero to five. Figure 3 summarizes the six degrees of bed and bank degradation, the associated score and a picture demonstrating each case. In both cases a higher score indicates a higher degree of structural stability.



Criteria Used to Evaluate the Structural Integrity of Rock Vortex Weirs				
Evaluation of Integrity (Miller, 2007)				
Qualitative Description	No visible damage. Fully Operational in terms of integrity	Structure functions as intended, but visibly damaged; e.g., one or more rocks mored out of place	Structural components in origianl location, but no longer function as intended	Significant parts have been removed from site. Structure severely fragmented, incapable of achieving intended objective
Descriptor	Intact (I)	Damaged (D)	Impaired (IMP)	Failed (F)
Score	3	2	1	0
Photo Example				

Figure 2. The four degrees of structural Integrity; rating criteria for vortex rock weirs.



Criteria Used to Evaluate the Structural Integrity of Rock Vortex Weirs						
Evaluation of Bed and Bank Erosion (Miller, 2007)						
Qualitative Description	No visible erosion or deposition	Minor localized erosion along margins of the feature; structure maintains continuity with bank & bed	Localized erosion or burial of structure; structure remains in contact with bed or bank, but influence on flow is likely affected	Structure remains in contact with bed or bank Erosion or deposition has occurred adjacent to entire length of structure; Erosion exceeds 50 cm and is clearly related to its influence on local flow	Structure partially detached from bank or buried by debris Complete detachment eminent; Feature no longer functions	Structure completely detached from bank, or buried No longer performs function – total failure
Score	5	4	3	2	1	0
Photo Example						

Figure 3. The six degrees of bed and bank degradation; erosion rating criteria for vortex rock weirs.

Physical Complexity Field Data Collection

Using a one-meter grid, we measured depths and velocities upstream and downstream of selected vortex rock weirs. The recorded values are the cell's dominant depth and velocity, which was most often measured in the center of each cell. In instances where the midpoint was obviously misrepresenting the overall depth of the grid, we recorded the representative value. We measured depth using a standard survey rod. By measuring the distance a neutrally buoyant object traveled along the cell's main flow path and the time it took to travel the length of this flow path, we calculated and recorded the surface velocity magnitudes in each cell. We visually observed and recorded velocity direction while generally rounding to the nearest 30 degrees with respect to the overall downstream flow direction. Although studies have shown that vertical velocity profiles are much more complex than surface measurements or models can suggest (Kondolf, 2000), this study measured the surface velocities due to constraints on time and resources.

We also conducted a Wolman Pebble Count at one pool and one bar for each site to determine the general grain size distribution and D_{50} in each stream reach. From this data, we created facies maps for each study area showing notable features in addition to the depth, velocity magnitude, and velocity direction.

Physical Complexity Control Data:

The study also created a control channel to serve as a theoretical creek without any physical complexity. A simple HEC-RAS model was assembled for a standard trapezoidal channel with the same general width, slope, roughness, and flow characteristics as was seen in the field. We developed this model *only* to provide depth and velocity estimates for a channel with no physical complexity and to provide a control point for the complexity analysis. A model schematic and model assumptions are shown in Figure 4.

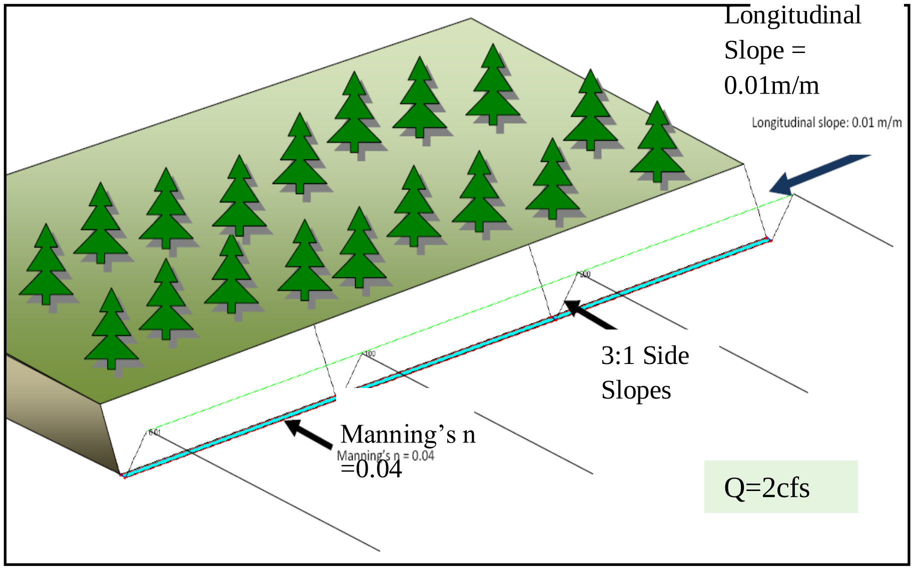


Figure 4. The Control Channel Model Schematic.

Physical Complexity Analysis

We also generated depth histograms and depth profile figures for each site to display the distribution of water depths in the two creeks. These histograms show the breakdown of depths though the study areas. To estimate the percentage of cells with similar depth measurements, the total count of each depth value is divided by the total number of stream grids.

We visualized the velocity data for physical complexity in the vicinity of the rock weirs by developing a velocity scatter plot for each structure. The velocity scatters show the magnitude of the velocity versus the velocity direction. The velocity directions are rounded to the nearest 30 degrees with respect to the downstream flow direction. The value of each cell is the percent of stream grids with that specific velocity magnitude and direction combination. These values indicate the percentage of cells with similar magnitude and direction measurements, or the probability that any random cell in the reach will have that particular combination of velocity magnitude and velocity direction. If the shaded cells are largely scattered, a high amount of physical velocity complexity in both magnitude and direction exists. Conversely, if the points are close together, or few in number, then a low physical velocity complexity is present in the system. We also gathered this data in a table format for each site and each weir with the velocity direction in the columns and the velocity magnitude in the rows. The numerical value in each cell represents the percent occurrence of that specific velocity magnitude and direction.

In addition, a mathematical estimate of complexity was computed though variance calculations. Variance is one measure of statistical dispersion calculated by averaging the squared distance of its possible values from an expected value (Wikipedia 2007). In this application of variance as a measure of complexity, a higher variance indicates more complexity. Variance was calculated for each cell in the 1-meter grid using two methods, the first for each cell in relation to its adjacent cells and the second for each cell as compared to the control channel. The first method is location specific while the second is independent of location. In the first case, the variance was calculated between the central cell and each of its surrounding cells, where the expected value is the value in the central cell. In the second case, the variance was calculated between each cell and the modeled value for the control channel, where the expected value is the value from the control channel. Appendix A presents more detail on variance calculation methodology.

Habitat Suitability Analysis:

The countless number of unique factors associated with each stream including watershed land use, connectivity, flow rates, and surrounding riparian ecosystem make it difficult for the authors to state the full habitat suitability at these sites. However, an analysis compared the Wolman Pebble Count and D_{50} data from each pool and riffle to the preferred substrate data in an attempt to qualify the presence of suitable or potential habitat for rainbow trout. This analysis can only provide a rough indicator for habitat presence, as this study did not make detailed observations of riparian productivity, refugia or cover, temperature, water quality, and actual fish presence. Studies have quantified the maximum percent of "fines", or embeddedness, suitable for spawning habitat within a stream as less than 30-40%. (Irving and Bjornn 1984, NCASI 1984). Data obtained from the Wolman Pebble Count led to the derivation of percent fines for each stream's pool and deposition bar matrices.

Site Descriptions

We chose two sites in the San Francisco Bay area to test the assessment criteria and evaluate the structural stability and physical stream complexity of vortex rock weirs. The sites have similar geomorphic, land use and climate characteristics. The sites also have analogous primary and secondary objectives as well as proximity to critical infrastructure. Differences between the sites include the installation dates, design methods, drainage areas and geology.

The first of the two sites evaluated was Penitencia Creek located in Alum Rock Park, approximately 6 miles northeast of downtown San Jose, California, as shown in Figure 5. Alum Rock Park was founded in 1872, and became known nationally as a health spa with 26 mineral springs, which are no longer in operation. Alum Rock Park encompasses approximately 700 acres in the foothills of the Diablo Mountain Range in eastern Santa Clara County. The headwaters of Penitencia Creek are in the Diablo Mountain Range. At the project location, the Penitenica watershed is approximately 24 square miles of undeveloped park and private land primarily consisting of upland shrubs and grasses typical in California's Mediterranean climate (SH&G 2001). Steelhead trout, *Oncorhynchus mykiss*, were spawning in the upper reaches of the creek alongside a resident rainbow trout population (Leidy 2005).

Figure 5. Penitencia Creek Vicinity Map.

The Penetencia Creek restoration project is located near the transition of the creek out of the Diablo Mountain Range foothills onto its (prior to development) alluvial fan, as shown in Figure 6. The 2-year event and 100-year event are estimated to be 360 cfs and 4,050 cfs, respectively with lower summer base flows of approximately 0.5 cfs. The approximate slope in this restoration reach is 3.5%. The goals of the project were to replace an in-stream low water crossing, restore 150-feet of stream channel and install a new pedestrian bridge across the stream. The restoration project was completed in 2005 and included the placement of four vortex rock weir structures with the primary objective of providing grade control and a secondary objective of habitat improvement. At the time of

Figure 6. Penitencia Creek site location map.

this assessment, the structures had been in the creek for two years.

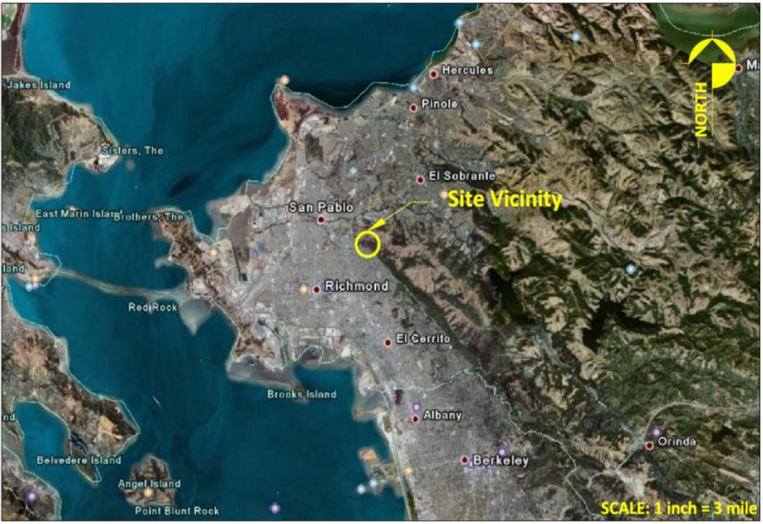


Figure 7. Wildcat Creek site vicinity map.

Wildcat Creek is located in Richmond, California's Alvarado Park, one of the many parks in the East Bay Regional Park system, as shown in Figure 7. Similar to Penitencia Creek, upstream of the project site the 7.3 acre Wildcat Creek watershed is primarily undeveloped forested park and private land Depending on location within the watershed it is not uncommon for portions of the stream to be dry during summer and fall months, as is the case at the restoration site in Alvarado Park. The approximate slope in this reach of Wildcat Creek is 2%. The goals of the Wildcat Creek restoration project were to first protect historical masonry walls, enhance stream bank stability, reduce erosion along the bank, and secondarily to improve fish migration and fish habitat for rainbow trout. In 1992, a series of vortex rock weirs were installed along a 1,600 foot stretch of Wildcat Creek. Severe floods and minor project failures in 1997 necessitated re-installation and further stream bank stabilization. At the time of this study, the current weirs had been in place for 10 years.

Results

Field work for Penitencia Creek and Wildcat Creek was conducted on November 10, 2007, and November 12, 2007, respectively. The Penitencia Creek survey included the entire project area reach upstream and downstream of all four vortex rock weirs. This represents a longitudinal distance of approximately 27 meters (89 feet). The Wildcat Creek Survey was conducted at the three installed vortex rock weirs immediately upstream of the protected bridge, representing a longitudinal distance of 24 meters (79 feet). The estimated flows at the time of the surveys were 1 to 2 cfs for both Penitencia and Wildcat Creeks.

Structural Integrity Results

Table 1 presents a summary of the stability criteria scores. The scores for both structural integrity and bed and bank erosion were higher for Penitencia than for Wildcat Creek.

Table 1: Stability Results

	Penitencia Creek		Wildcat Creek	
Structure	Integrity	Bed and Bank Erosion	Integrity	Bed and Bank Erosion
Weir 1	2	5	2	4
Weir 2	3	4	1	4
Weir 3	3	4	2	4
Weir 4	3	5	-	-
Average Score	2.75	4.5	1.67	4

The results of the vortex rock weir structural assessment at Penitencia Creek indicate all four weirs remain intact and retain their overall function. The two middle weirs (weirs 2 and 3) had signs of minor localized erosion around the margin of the features on the left bank, primarily originating from runoff from the pedestrian bridge. Weir 1 and 4 had no signs of erosion. The downstream weir (1) was the only weir that is categorized as slightly damaged—the weir's rocks appeared displaced. All four weirs are functioning as intended with respect to the stability goals. The results of the structural assessment at Wildcat Creek indicate the structural stability of all three weirs has been compromised. We observed signs of weir damage and localized erosion at weirs 1 and 3. Weir 2 also showed signs of localized erosion, and due to the displacement of the rock originally placed in the weir structure, it was classified as impaired. Figure 1 compares the average scores for each site in terms of both structural integrity and bed and bank erosion.

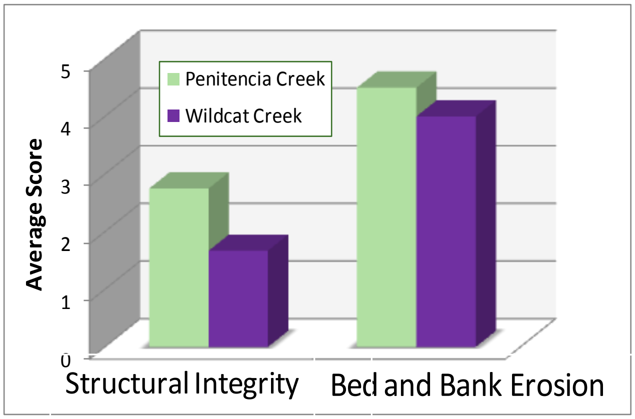


Figure 8. Average structural stability scores for Penitencia Creek and Wildcat Creek.

Physical Complexity Results

We generated a combination depth and velocity facies map for each site to summarize collected data and visually depict the observed conditions at each site. Depth and velocity facies maps for Penitencia Creek are presented in Figures 9 and 10 and for Wildcat Creek in Figures 11 and 12. Darker shades represent grids with higher depths and faster velocities, while the lighter shades represent slower velocities, and shallower depths. The arrows show the general direction of flow within each meter grid cell. These maps also show important physical stream characteristics such as boulders, walls, bedrock outcrops, and woody debris.

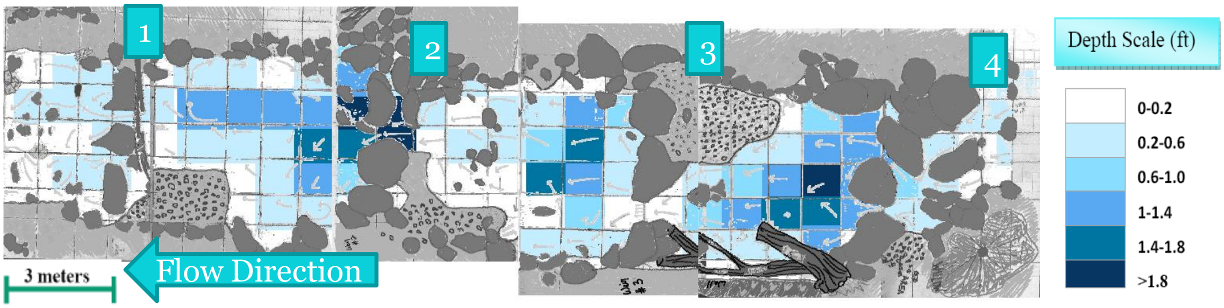


Figure 9. Penitencia Creek Depth Facies Map

Figure 10. Penitencia Creek Velocity Facies Map

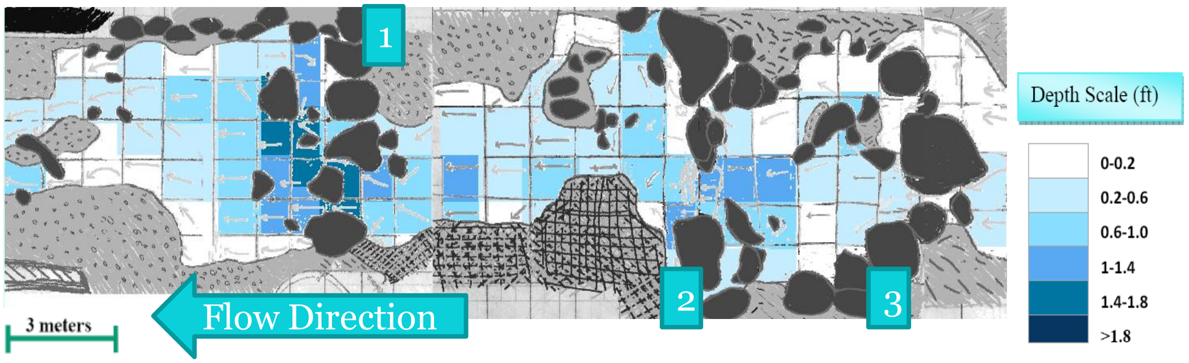


Figure 11. Wildcat Creek Depth Facies Map

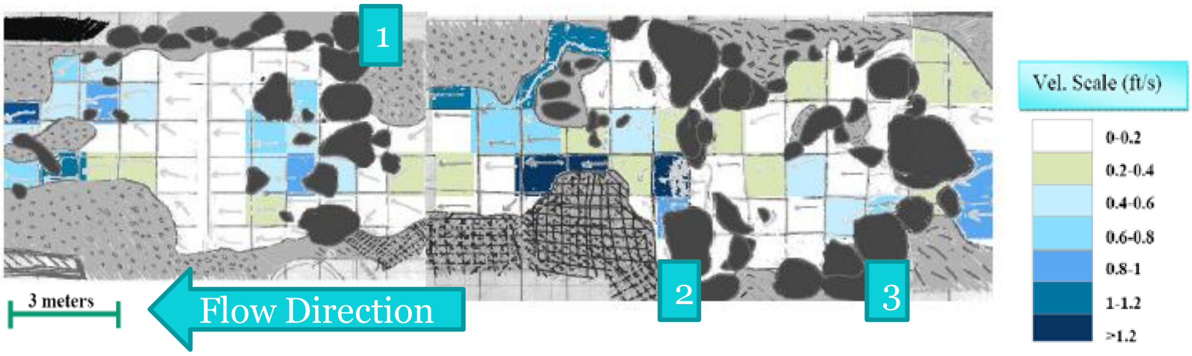


Figure 12. Wildcat Creek Velocity Facies Map

A three-dimensional longitudinal plot of depth along the entire restoration stream reach at Penitencia Creek (Figure 13) shows the clean delineation of pools downstream of the vortex rock weir structure with tail out areas at the downstream ends of the pools.

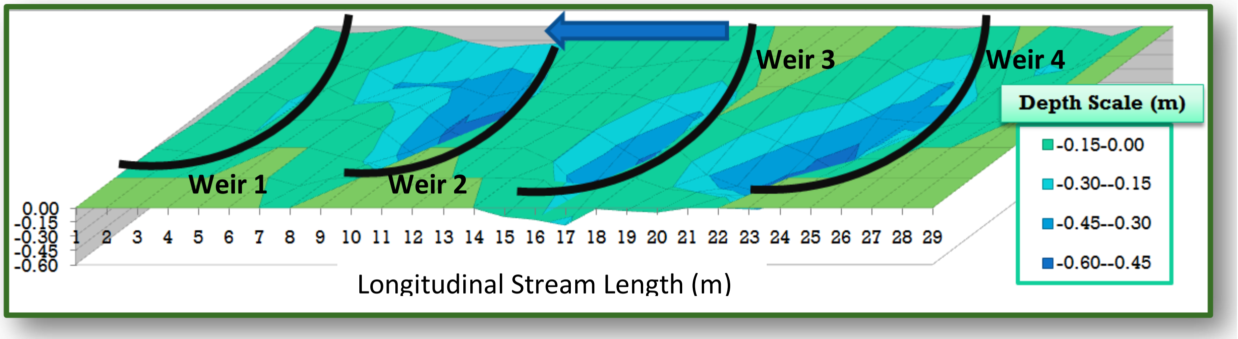


Figure 13. Penitencia Creek Depth Distribution.

The three-dimensional plot of depth measurements along Wildcat Creek (Figure 14) illustrates the presence of pools both upstream and downstream of the vortex rock weirs.

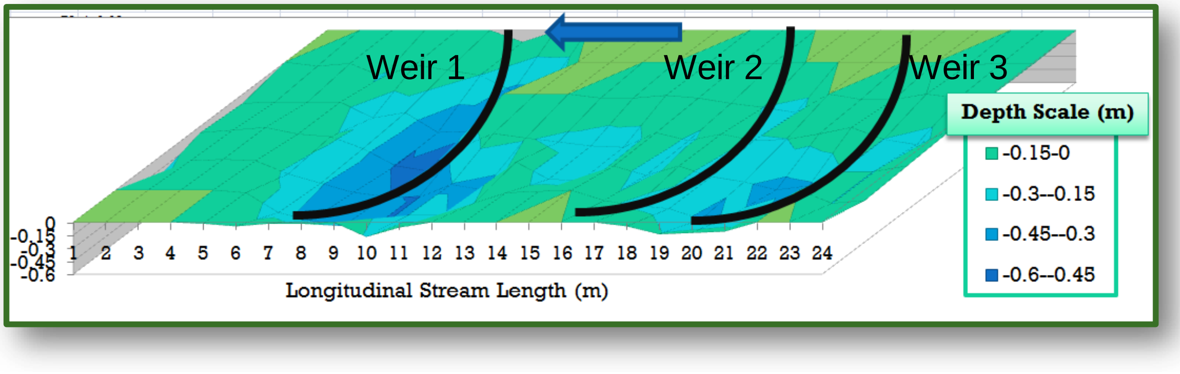


Figure 14. Wildcat Creek Depth Distribution

The maximum measured depth in Penitencia Creek was 1.95 feet and the maximum recorded depth in Wildcat Creek was 1.70 feet. Velocity magnitudes ranged from 0 ft/s to 2.17 ft/s in Penitencia Creek and 0 ft/s to 3.64 ft/s in Wildcat Creek. Both creeks exhibited eddies and vortices as well as flow paths that did not always align with the creeks longitudinal axis.

To best serve as a control model, we assumed no longitudinal variability in either depth or velocity along the length of the modeled trapezoidal channel. As such, no plan view figures are provided. The control reach has a standard depth and velocity distribution. The control channel velocity estimated from the model is 1.17 ft/s. The control channel depth estimated from the model is 0.16 feet. Velocity scatter plots for the individual weirs and the entire reaches of both Penitencia and Wildcat Creek are included in Appendix B. Similarly, depth histograms and the grain size data for Penitencia and Wildcat Creek are also included in Appendix B.

Physical Complexity Analysis

The primary mechanism for determining physical complexity used two methods of variance calculation, one by calculating the variance as a measure of depth and velocity gradients across adjacent cells and the second by calculating variance compared to the control. In other words, the first method compares each cell's values to the values around it and the second method compares the cell to the expected values if the reach contained no complexity at all. Figure 15 presents the results for these calculations on a weir and reach basis. For the entire Penitencia Creek reach, the velocity and depth cell variance

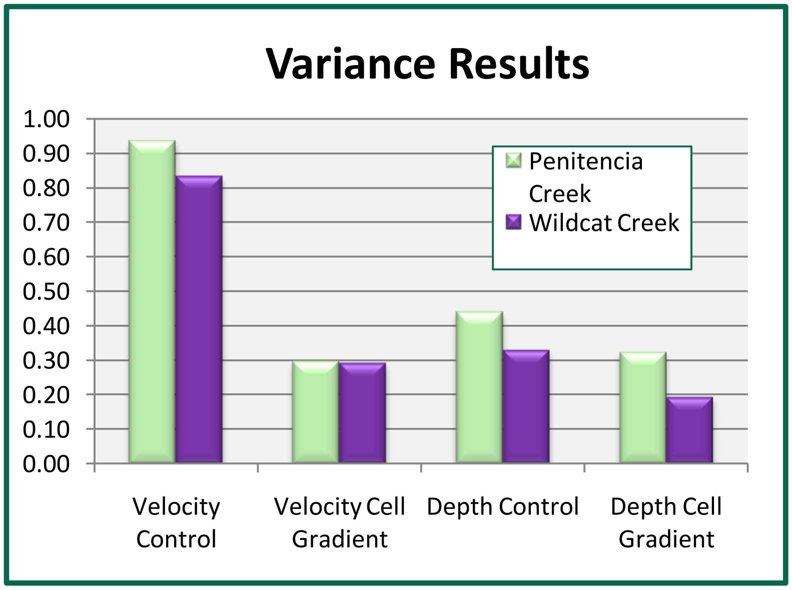


Figure 15. Physical Complexity Variance Results

between cells are 0.3 ft^2/s^2 and 0.32 ft^2, respectively. For the entire Wildcat Creek reach the velocity and depth cell variance between cells are are 0.46 ft^2/s^2 and 0.2 ft^2, respectively. For the entire Penitencia Creek reach the velocity and depth variance, as compared to the control, are 0.89 ft^2/s^2 and 0.45 ft^2, respectively, and for the entire Wildcat Creek reach, the velocity and depth cell variance, as compared to the control, are 0.8 ft^2/s^2 and 0.30 ft^2, respectively. The variance results in a tabular format are shown below in Table 2.

Table 2: Summary of variance estimates

Penitencia Creek					
	Total Structural	**Control**		**Cell Gradient**	
Weir Number	Stability Score	Velocity Variance	Depth Variance	Velocity Variance	Depth Variance
1	7	0.84	0.09	0.15	0.08
2	7	1.01	0.65	0.51	0.59
3	7	0.96	0.35	0.29	0.30
4	8	0.90	0.58	0.19	0.24
Reach	7.25	0.94	0.44	0.30	0.32

Wildcat Creek					
	Total Structural	**Control**		**Cell Gradient**	
Weir Number	Stability Score	Velocity Variance	Depth Variance	Velocity Variance	Depth Variance
1	6	0.83	0.48	0.17	0.26
2	5	0.81	0.16	0.44	0.14
3	6	0.86	0.26	0.36	0.13
4	--	--	--	--	--
Reach	5.67	0.83	0.33	0.29	0.19

* Control Velocity of Trapezoidal Channel = 1.17 ft/s and Control Depth of Trapezoidal Channel = 0.16 ft

<u>Habitat Suitability Analysis</u>:

The pebble count results for Penitencia Creek's pools and riffles gave D$_{50}$ values of 1.00 inches and 0.35 inches, respectively, with 34-39 percent of the sample and 45-50 percent of the deposition bar sample smaller than 6.35 mm. Wildcat Creek's pool and riffles had D$_{50}$ values of 0.50 inches and 0.40 inches, respectively, with 39-46 percent of the pool sample and 50-60 percent of the deposition bar sample size below the threshold of 6.35 mm. Grain size distributions for Penitencia and Wildcat Creek, are also included in Appendix B.

Discussion

Physical indicators alone cannot determine the presence or absence of suitable habitat for a specific species. However, the intent of this project's developed criteria is not to assess if a specific microhabitat exists for a specific species; instead the goal of the criteria is to determine if the addition of vortex rock weirs provides ancillary benefits of creating velocity, depth and sediment size complexity and how the presence of complexity correlates to visual evidence of structural stability. The measurements collected in the field represent a snapshot in time, and depict the velocity and depth distributions in the channel for one particular flow rate. The results for this analysis apply only to flows within the range observed at the time of the survey. However, it is likely that the channel complexity, indicated by the depth and velocity distributions observed, persists through a wide range of flow magnitudes.

<u>Structural Integrity</u>

The structural rating at Penitencia Creek is higher than that at Wildcat Creek, possibly due to construction and design methods or the "operating time" of the structures. The project completion dates are nearly a decade apart, with Penitencia Creek completed in 2005 and Wildcat Creek most recently completed in 1997, and as discussed in the introduction, vortex rock weirs have been shown to fail within ten years. A ten year lifespan fits well with our visual observations of structural stability at the site. Issues of appropriate construction and design could also contribute to decreased stability at Wildcat Creek, where there is sufficient literature suggesting that the site contains major design flaws (Vandivere, 1997).

Weir spacing in Wildcat Creek appears to have affected pool development. Weirs two and three are only five meters apart, and as a result it appears the pool length insufficiently dissipates velocities between structures. The proximity of the two structures also contributes to the instability observed at weir two. Another factor affecting weir integrity at Wildcat Creek is the transport of rock from failed riprap and weir structures upstream. These larger rocks, held up by downstream weirs, change flow paths and cause instability in the downstream structures. This result is most obvious at Wildcat weirs two and three.

Physical Complexity and Analysis

Penitencia Creek has easily observed scour pools directly downstream of each weir, while Wildcat Creek has pools beginning to develop directly upstream of each weir (refer to Figures 13 and 14). The depth histograms show that shallow depths at both sites dominate the creek landscape and that there were very few depths large enough to represent the presence of a substantial pool. The histograms are weighted heavily toward shallow and intermediate depths, and have a well graded, even distribution.

The velocity scatter plots show that, for the first two weirs at Penitencia Creek, there is a large distribution of flow velocities and magnitudes throughout the restoration stream reach.

In terms of complexity, and as expected, the results for the two project sites differ from the modeled control channel. The depth histogram for Penitencia Creek shows a high degree of variation, specifically when compared to the control channel.

The variance measurements, used here as a complexity indicator, were higher overall at Penitencia Creek than at Wildcat Creek, indicating the vortex rock weirs at Penitencia Creek create more velocity and depth complexity, as well as a larger amount of vorticity in the flow. Vorticity is proportional to the gradient, or the square root of variance in the flow. The one outlier is the velocity variance, as compared to the cells around it, at weir number three on Wildcat Creek. A single velocity measurement of 3.64 ft/s dramatically influences the variance calculation at this weir. In reflection on our field methods at this location, we have confidence in this measurement, though in future applications we would more carefully standardize our velocity measurements through locations where water quickly accelerates through the weir.

At Penitencia Creek, weirs two and three reported the highest cell gradient velocity and depth variance, compared to weirs one and four. In this sense, the four variance measurements were "predictable" and returned similar results at each weir. By contrast, at Wildcat Creek the four variance methods were more variable, or "unpredictable". For example, on Wildcat Creek weir one has the highest cell gradient depth variance, the lowest cell gradient velocity variance, the highest control depth variance and the intermediate control velocity variance. This dissimilarity between measurement methods continues for weirs two and three, indicating that between all calculation methods variance becomes less predictable across the measurement methods on Wildcat Creek as compared to Penitencia Creek.

Vortex Rock Weirs and Physical Complexity

The reach level stability scores are higher at Penitencia Creek (7.25) than at Wildcat Creek (5.67), which is a possible cause for the higher complexity at Penitencia Creek and the dissimilarity between variance calculations at each weir on Wildcat Creek. This indicates a potential correlation between vortex rock weir stability and physical complexity. Further investigations which would increase the data set used for comparison may increase confidence in this correlation. The dissimilarity between the weirs on Wildcat Creek, in terms of variance "predictability" captures the effect of weir degradation. Complexity differences between each of the weirs is predicted as the rocks in the weir are displaced, erode, or are moved downstream at varying rates depending on specific site factors. The degradation of the weirs unpredictably influences water movement around the structure and decreases development of the downstream pool. The dissimilarity of variance measurements at Wildcat Creek captures this phenomenon.

Habitat Suitability:

Rainbow trout, which are target species at both of the study area sites, have greatly varied velocity preferences due to the microhabitat needs of the fish at different lifecycle stages. Table 3 emphasizes this intra-species difference with data originating from a study in Deer Creek in Tehama County, California (Moyle 1985). Areas of Penitencia and Wildcat Creeks at the flows measured contain velocities and depths of this magnitude, which may mean that these areas could provide potentially suitable habitat for rainbow trout. Penitencia Creek's pool D_{50} value fell into the classification of coarse gravel or coarse pebbles. Wildcat creek's pool D_{50} value classified as medium gravel or medium pebbles. The literature suggests rainbow trout prefer to spawn in areas with gravel and cobble, indicating the sediment size at each site is slightly smaller than the target species' preferred conditions. (Harris, 2005)

Table 3: Rainbow Trout Habitat Suitability

Habitat Suitability (Moyle 1985)		
	Total Depth (inches)	**Surface Velocity (in/s)**
Fry	14 ± 6.5	8 ± 10
Juvenille	25 ± 12	16 ± 13
Adult	32 ± 12	19 ± 10

We cannot, however, directly related these observed ranges of velocity and substrate in Penitencia and Wildcat Creeks to the presence of rainbow trout habitat because of the singular flow observed at the sites during data collection, and the intentional neglect in this analysis of additional factors such as the pool to riffle ratio, food availability, and seasonal hydrograph variations (Waite 1992).

Conclusions

With more reference sites and a further inventory of vortex rock weir complexity, the development of a criteria rating method for complexity assessment might be possible. At this time, there is no basis for correlating certain values of depth and velocity variance with either a positive or negative determination of habitat complexity. In the future, if habitat monitoring plans were developed with this assessment method in mind, species specific depth and velocity requirements could be evaluated. For example, if we had known target depth and velocity distributions at 1 cfs for specific species, we could evaluate how the vortex rock weir structures perform in their intended function of providing secondary habitat benefits. Regardless, the depth and velocity variance values are useful for relating stability and complexity and comparing complexity between two sites. In terms of time and effort required to complete the analysis, very little is required to perform visual observations of structural stability. The complexity analysis, requiring one meter grid depth and velocity measurements, is more time intensive, but provides a potential correlation between system function and potential suitable habitat. More data is needed to determine if a 1-meter grid is fine enough to capture specific species habitat requirements. The sediment distribution analysis also does not require a large time commitment and provides useful information about potential suitable habitat. In summary, all assessments completed at this site provide beneficial data to evaluate project success. Further development and data accumulation would improve the usefulness of the complexity indicator data, specifically for incorporating into a post project assessment checklist for vortex rock weirs.

Researchers have written many papers emphasizing the need for scientific evaluation of habitat "enhancement" projects (Frissell and Nawa, 1992). However numerous costly projects have occurred and continue to occur in many areas of the United States without proper evaluation. The method developed in this paper presents a potential opportunity to evaluate habitat success in terms of physical complexity at future restoration sites. Our analysis at two sites indicate that vortex rock weirs can create physical complexity related to flow velocity magnitude, velocity direction, velocity gradients, and depth distributions, and this physical complexity decreases as weir integrity deteriorates.

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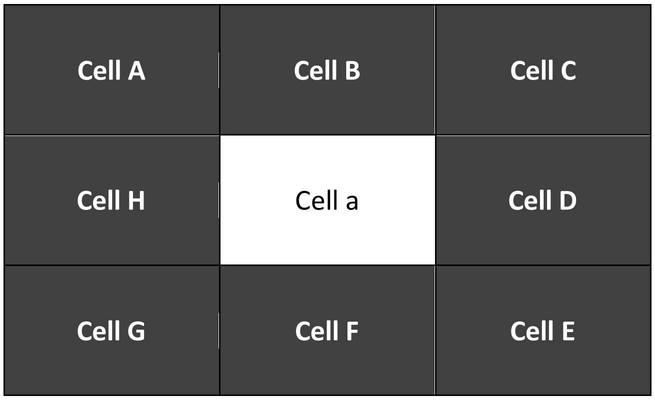
Appendix A: Variance Calculation Methods

Variance Calculations compared to adjacent Cells

Given a single physical measurement for each grid as shown in Figure A1, the equation for the total variance of the measurement for cell a is shown below:

$$\sigma^2 = \sum_{1=1}^{n} \left(\frac{1}{\mathrm{n}}\right)(x - a)^2$$

Where the variance (σ^2) is a function of the value in Cell a (a), the value of the adjacent cells Cell A, Cell B, Cell C, Cell D, Cell E, Cell F, Cell G, and Cell H (x), and the total number of adjacent cells (n).



Cell A	**Cell B**	**Cell C**
Cell H	Cell a	**Cell D**
Cell G	**Cell F**	**Cell E**

Figure A1: Grid schematic for variance calculations.

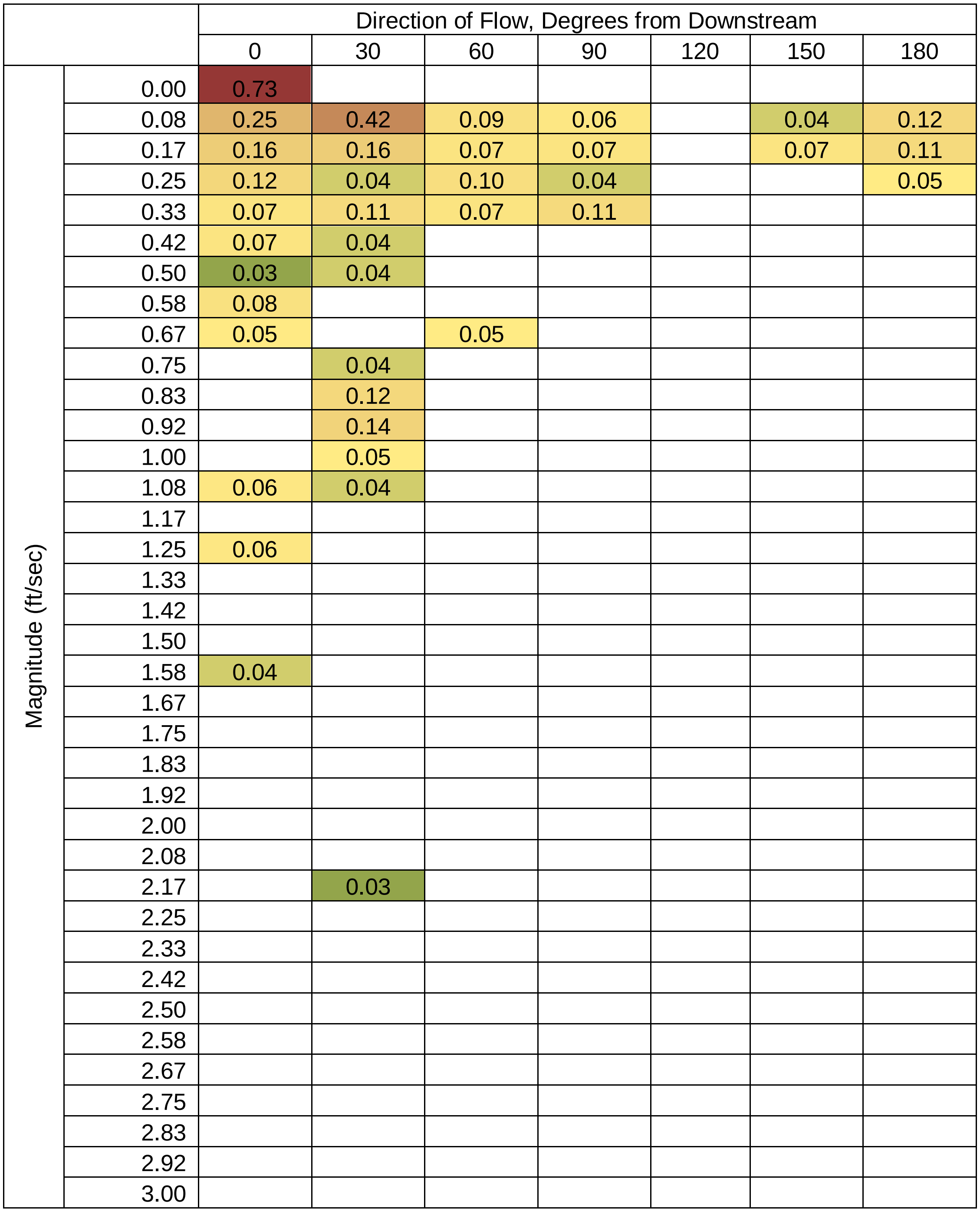
Variance Calculations Compared to Control

For the control variance calculation a similar equation was used:

$\sigma^2 = (x\text{-}a)^2$

Where variance (σ^2) is a function of the control depth (0.16 feet) or velocity (1.17 ft/s) value (x) and the value in cell a (a). The values of variance were averaged for all the cells in each weir, to return an average weir variance compared to control. Similarly, the values for variance were averaged across the entire survey reach to return an average reach variance compared to control.

Appendix B: Additional Figures and Tables



	Direction of Flow, Degrees from Downstream						
Magnitude (ft/sec)	0	30	60	90	120	150	180
0.00	0.73						
0.08	0.25	0.42	0.09	0.06		0.04	0.12
0.17	0.16	0.16	0.07	0.07		0.07	0.11
0.25	0.12	0.04	0.10	0.04			0.05
0.33	0.07	0.11	0.07	0.11			
0.42	0.07	0.04					
0.50	0.03	0.04					
0.58	0.08						
0.67	0.05		0.05				
0.75		0.04					
0.83		0.12					
0.92		0.14					
1.00		0.05					
1.08	0.06	0.04					
1.17							
1.25	0.06						
1.33							
1.42							
1.50							
1.58	0.04						
1.67							
1.75							
1.83							
1.92							
2.00							
2.08							
2.17		0.03					
2.25							
2.33							
2.42							
2.50							
2.58							
2.67							
2.75							
2.83							
2.92							
3.00							

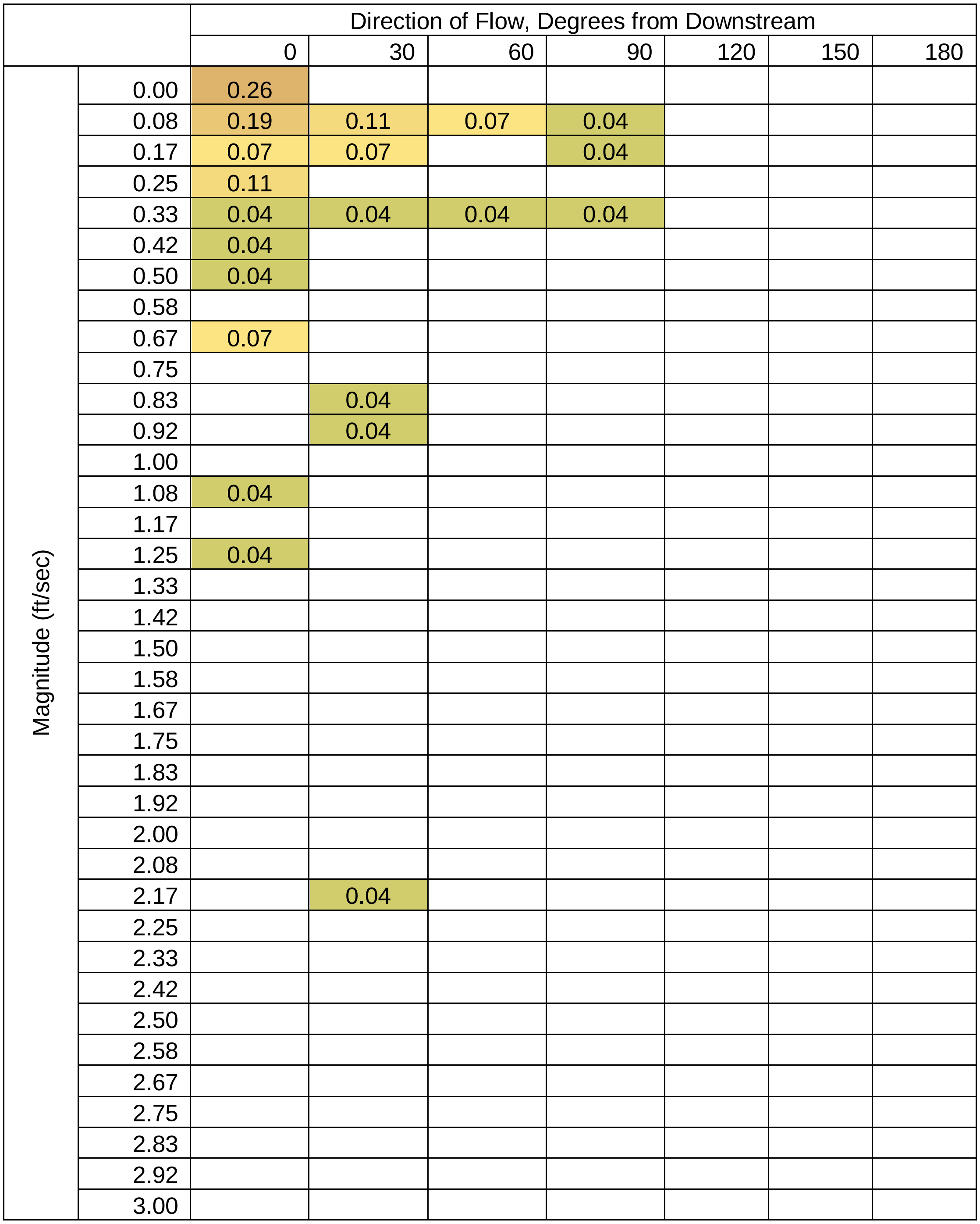
Figure B1: Velocity scatter diagram for the entire Penetencia Creek study area.

		Direction of Flow, Degrees from Downstream						
		0	30	60	90	120	150	180
Magnitude (ft/sec)	0.00	0.14						
	0.08	0.05	0.05					0.05
	0.17				0.05			
	0.25	0.05		0.10				0.05
	0.33	0.05	0.05	0.05	0.05			
	0.42	0.05						
	0.50							
	0.58	0.05						
	0.67			0.05				
	0.75							
	0.83		0.10					
	0.92							
	1.00		0.05					
	1.08							
	1.17							
	1.25							
	1.33							
	1.42							
	1.50							
	1.58							
	1.67							
	1.75							
	1.83							
	1.92							
	2.00							
	2.08							
	2.17							
	2.25							
	2.33							
	2.42							
	2.50							
	2.58							
	2.67							
	2.75							
	2.83							
	2.92							
	3.00							

Figure B2: Velocity scatter diagram for weir one in the Penetencia Creek study area.

		Direction of Flow, Degrees from Downstream						
		0	30	60	90	120	150	180
Magnitude (ft/sec)	0.00	0.22						
	0.08	0.07	0.07	0.04	0.04			0.07
	0.17	0.04	0.04	0.07			0.07	0.07
	0.25				0.04			
	0.33		0.04		0.04			
	0.42							
	0.50		0.04					
	0.58							
	0.67							
	0.75							
	0.83							
	0.92							
	1.00							
	1.08							
	1.17							
	1.25							
	1.33							
	1.42							
	1.50							
	1.58	0.04						
	1.67							
	1.75							
	1.83							
	1.92							
	2.00							
	2.08							
	2.17							
	2.25							
	2.33							
	2.42							
	2.50							
	2.58							
	2.67							
	2.75							
	2.83							
	2.92							
	3.00							

Figure B3: Velocity scatter diagram for weir two in the Penetencia Creek study area.



		Direction of Flow, Degrees from Downstream						
		0	30	60	90	120	150	180
Magnitude (ft/sec)	0.00	0.26						
	0.08	0.19	0.11	0.07	0.04			
	0.17	0.07	0.07		0.04			
	0.25	0.11						
	0.33	0.04	0.04	0.04	0.04			
	0.42	0.04						
	0.50	0.04						
	0.58							
	0.67	0.07						
	0.75							
	0.83		0.04					
	0.92		0.04					
	1.00							
	1.08	0.04						
	1.17							
	1.25	0.04						
	1.33							
	1.42							
	1.50							
	1.58							
	1.67							
	1.75							
	1.83							
	1.92							
	2.00							
	2.08							
	2.17		0.04					
	2.25							
	2.33							
	2.42							
	2.50							
	2.58							
	2.67							
	2.75							
	2.83							
	2.92							
	3.00							

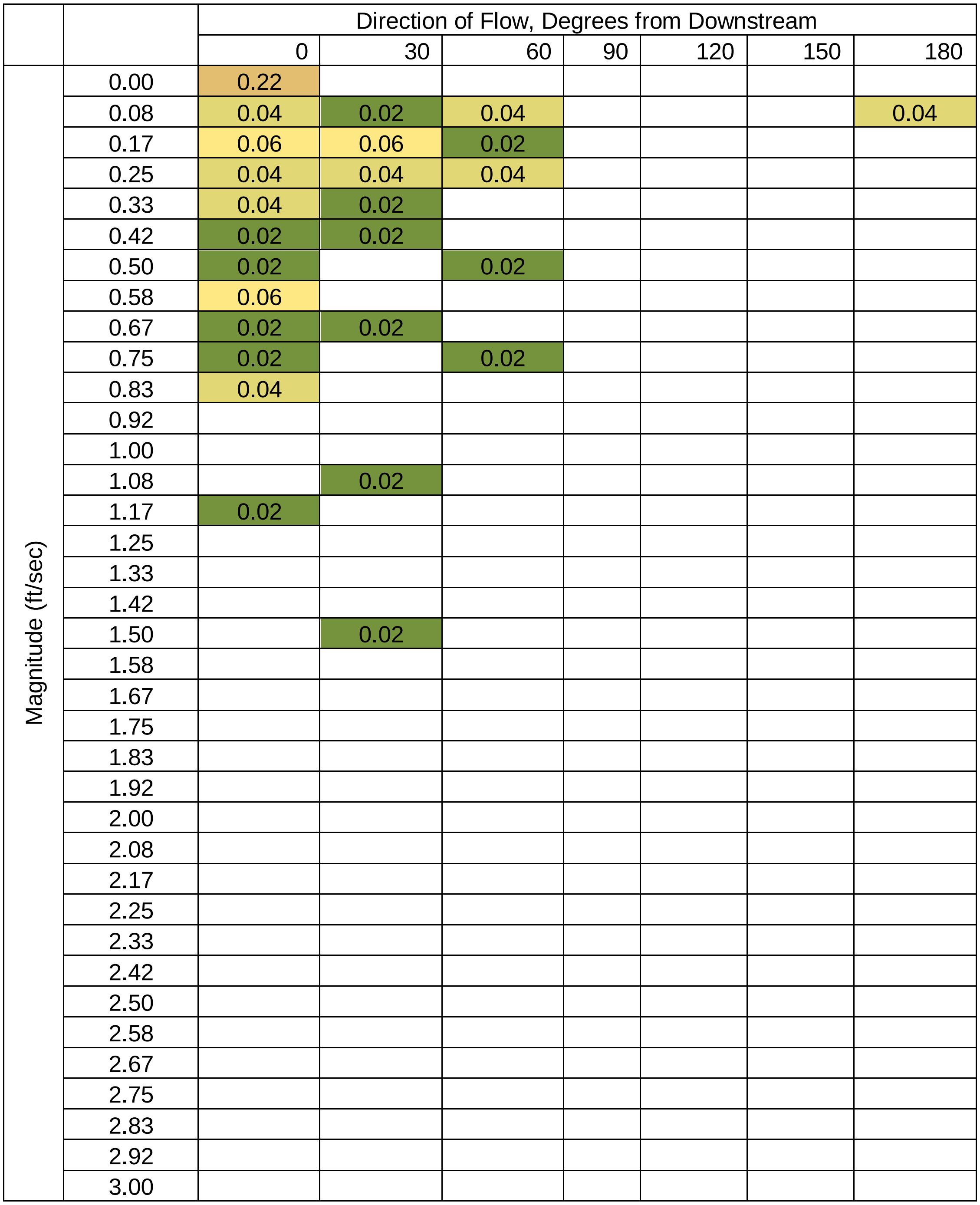
Figure B4: Velocity scatter diagram for weir three in the Penetencia Creek study area.

		Direction of Flow, Degrees from Downstream						
		0	30	60	90	120	150	180
Magnitude (ft/sec)	0.00	0.19						
	0.08		0.22				0.04	
	0.17	0.07	0.07					0.04
	0.25		0.04					
	0.33							
	0.42		0.04					
	0.50							
	0.58	0.04						
	0.67							
	0.75		0.04					
	0.83							
	0.92		0.11					
	1.00							
	1.08	0.04	0.04					
	1.17							
	1.25	0.04						
	1.33							
	1.42							
	1.50							
	1.58							
	1.67							
	1.75							
	1.83							
	1.92							
	2.00							
	2.08							
	2.17							
	2.25							
	2.33							
	2.42							
	2.50							
	2.58							
	2.67							
	2.75							
	2.83							
	2.92							
	3.00							

Figure B5: Velocity scatter diagram for weir four in the Penetencia Creek study area.

		Direction of Flow, Degrees from Downstream						
		0	30	60	90	120	150	180
Magnitude (ft/sec)	0.00	0.45	0.03					
	0.08	0.18	0.17	0.07				0.09
	0.17	0.18	0.18	0.02	0.03		0.05	
	0.25	0.18	0.04	0.09	0.03			
	0.33	0.07	0.10	0.05				
	0.42	0.02	0.07		0.08			
	0.50	0.05	0.08	0.02				
	0.58	0.14						
	0.67	0.02	0.02					
	0.75	0.05		0.02			0.05	
	0.83	0.04						
	0.92	0.05	0.05					
	1.00	0.03						
	1.08		0.02					
	1.17	0.02	0.06					
	1.25							
	1.33	0.03						
	1.42							
	1.50	0.03	0.02					
	1.58							
	1.67							
	1.75							
	1.83							
	1.92							
	2.00	0.03						
	2.08							
	2.17							
	2.25							
	2.33							
	2.42							
	2.50							
	2.58							
	2.67							
	2.75							
	2.83							
	2.92							
	3.00							
	3.64	0.05						

Figure B6: Velocity scatter diagram for the entire Wildcat Creek study area.



		Direction of Flow, Degrees from Downstream						
		0	30	60	90	120	150	180
Magnitude (ft/sec)	0.00	0.22						
	0.08	0.04	0.02	0.04				0.04
	0.17	0.06	0.06	0.02				
	0.25	0.04	0.04	0.04				
	0.33	0.04	0.02					
	0.42	0.02	0.02					
	0.50	0.02		0.02				
	0.58	0.06						
	0.67	0.02	0.02					
	0.75	0.02		0.02				
	0.83	0.04						
	0.92							
	1.00							
	1.08		0.02					
	1.17	0.02						
	1.25							
	1.33							
	1.42							
	1.50		0.02					
	1.58							
	1.67							
	1.75							
	1.83							
	1.92							
	2.00							
	2.08							
	2.17							
	2.25							
	2.33							
	2.42							
	2.50							
	2.58							
	2.67							
	2.75							
	2.83							
	2.92							
	3.00							

Figure B7: Velocity scatter diagram for weir one in the Wildcat Creek study area.

		Direction of Flow, Degrees from Downstream						
		0	30	60	90	120	150	180
Magnitude (ft/sec)	0.00	0.09	0.03					
	0.08	0.09	0.06	0.03				
	0.17	0.03	0.12		0.03			
	0.25	0.09			0.03			
	0.33	0.03	0.03					
	0.42				0.03			
	0.50	0.03	0.03					
	0.58	0.03						
	0.67							
	0.75	0.03						
	0.83							
	0.92							
	1.00	0.03						
	1.08							
	1.17		0.06					
	1.25							
	1.33	0.03						
	1.42							
	1.50	0.03						
	1.58							
	1.67							
	1.75							
	1.83							
	1.92							
	2.00	0.03						
	2.08							
	2.17							
	2.25							
	2.33							
	2.42							
	2.50							
	2.58							
	2.67							
	2.75							
	2.83							
	2.92							
	3.00							

Figure B8: Velocity scatter diagram for weir two in the Wildcat Creek study area.

		Direction of Flow, Degrees from Downstream						
		0	30	60	90	120	150	180
Magnitude (ft/sec)	0.00	0.14						
	0.08	0.05	0.09					0.05
	0.17	0.09					0.05	
	0.25	0.05		0.05				
	0.33		0.05	0.05				
	0.42		0.05		0.05			
	0.50		0.05					
	0.58	0.05						
	0.67							
	0.75						0.05	
	0.83							
	0.92	0.05	0.05					
	1.00							
	1.08							
	1.17							
	1.25							
	1.33							
	1.42							
	1.50							
	1.58							
	1.67							
	1.75							
	1.83							
	1.92							
	2.00							
	2.08							
	2.17							
	2.25							
	2.33							
	2.42							
	2.50							
	2.58							
	2.67							
	2.75							
	2.83							
	2.92							
	3.00							
	3.64	0.05						

Figure B9: Velocity scatter diagram for weir three in the Wildcat Creek study area.

		Direction of Flow, Degrees from Downstream						
		0	30	60	90	120	150	180
Magnitude (ft/sec)	0.00							
	0.08							
	0.17							
	0.25							
	0.33							
	0.42							
	0.50							
	0.58							
	0.67							
	0.75	0.40						
	0.83							
	0.92							
	1.00							
	1.08							
	1.17	0.60						
	1.25							
	1.33							
	1.42							
	1.50							
	1.58							
	1.67							
	1.75							
	1.83							
	1.92							
	2.00							
	2.08							
	2.17							
	2.25							
	2.33							
	2.42							
	2.50							
	2.58							
	2.67							
	2.75							
	2.83							
	2.92							
	3.00							

Figure B10: Velocity scatter diagram for the modeled control channel.

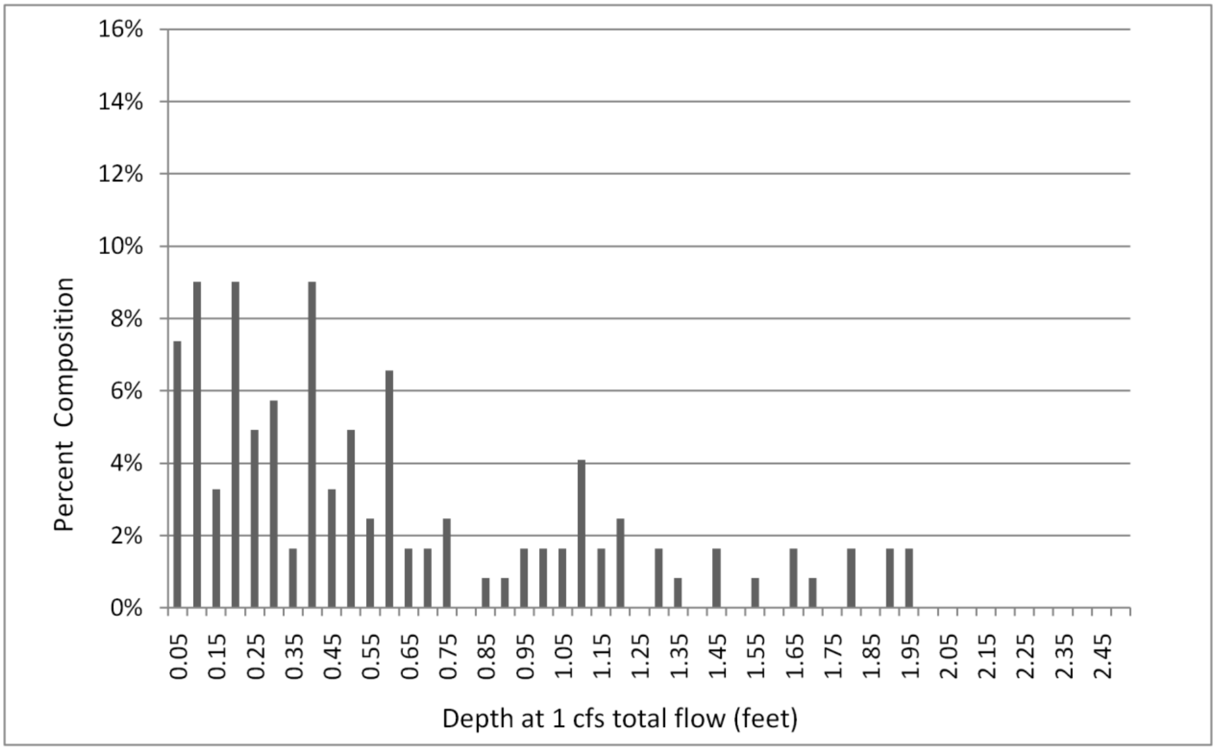


Figure B11: Depth Histrogram for Penetencia Creek.

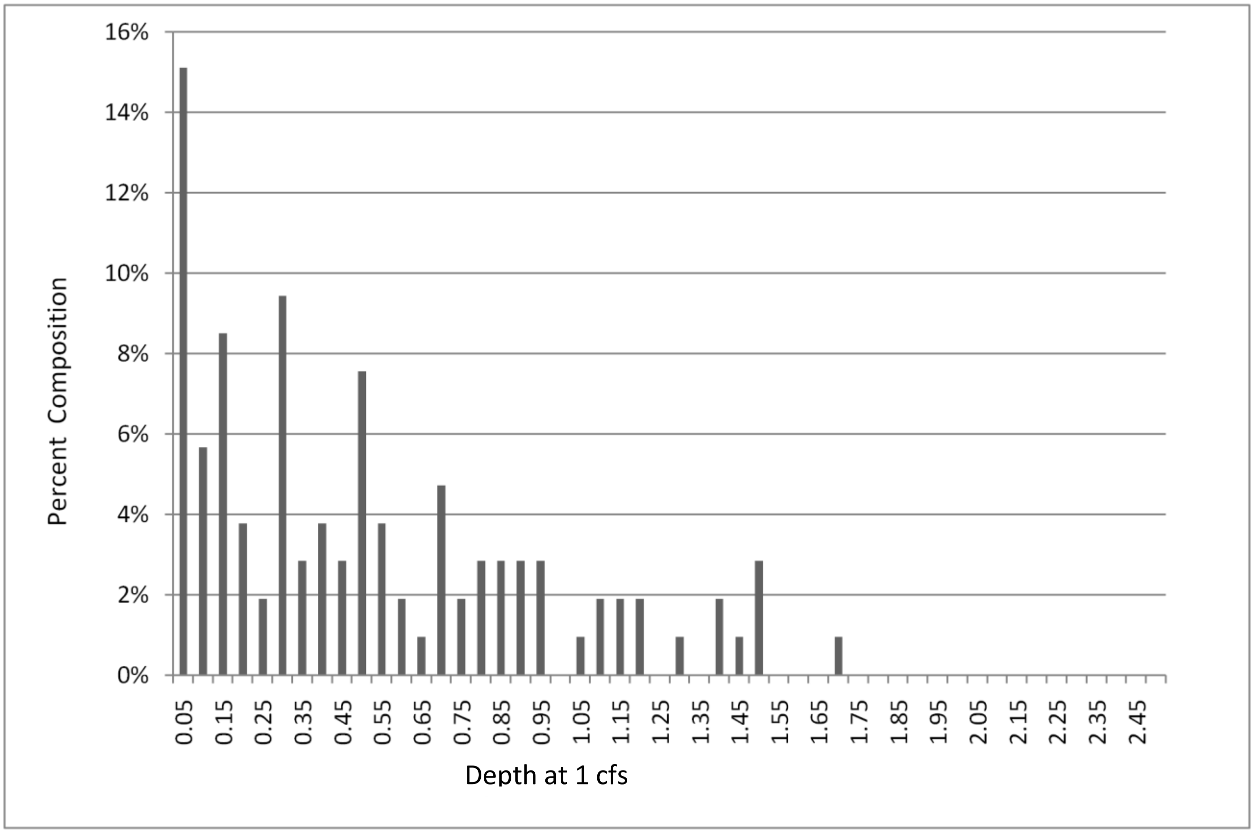


Figure B12: Depth Histogram for Wildcat Creek.

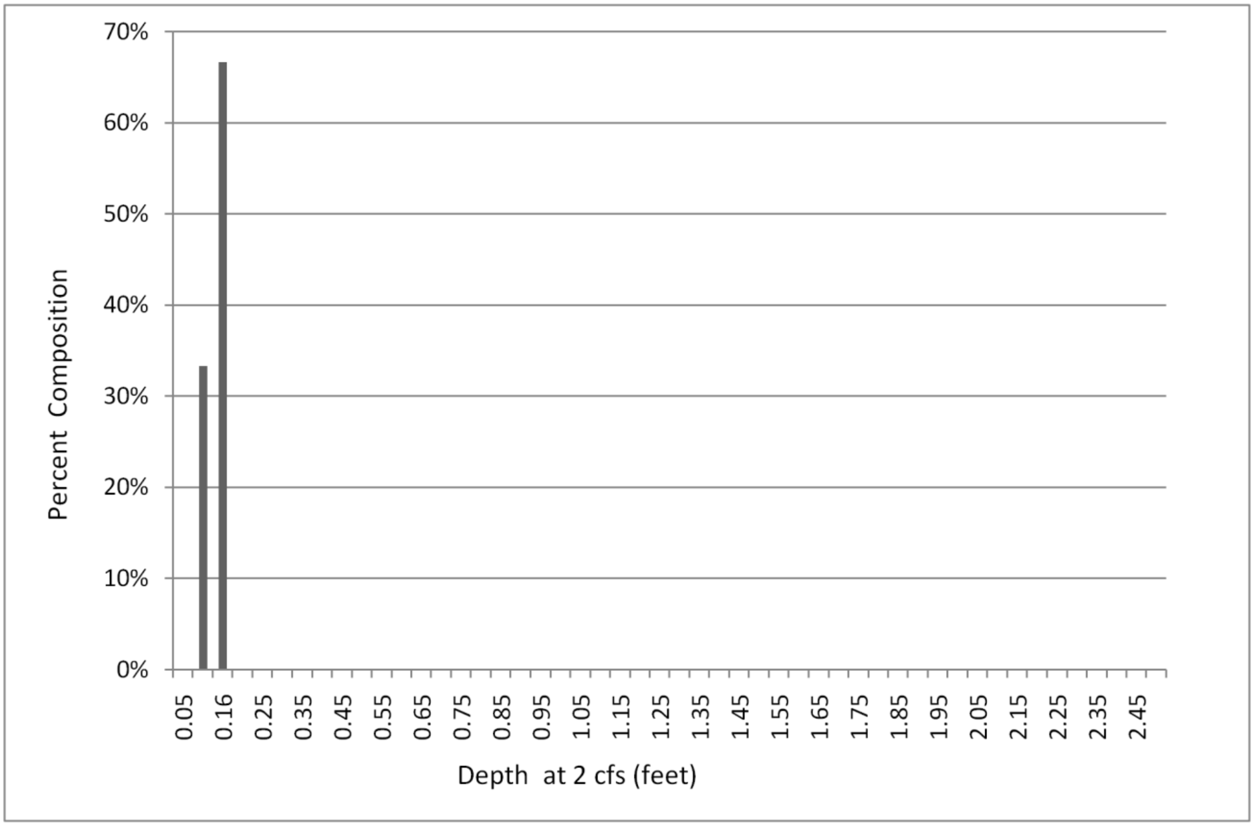


Figure B13: Depth Histogram for the modeled control channel.

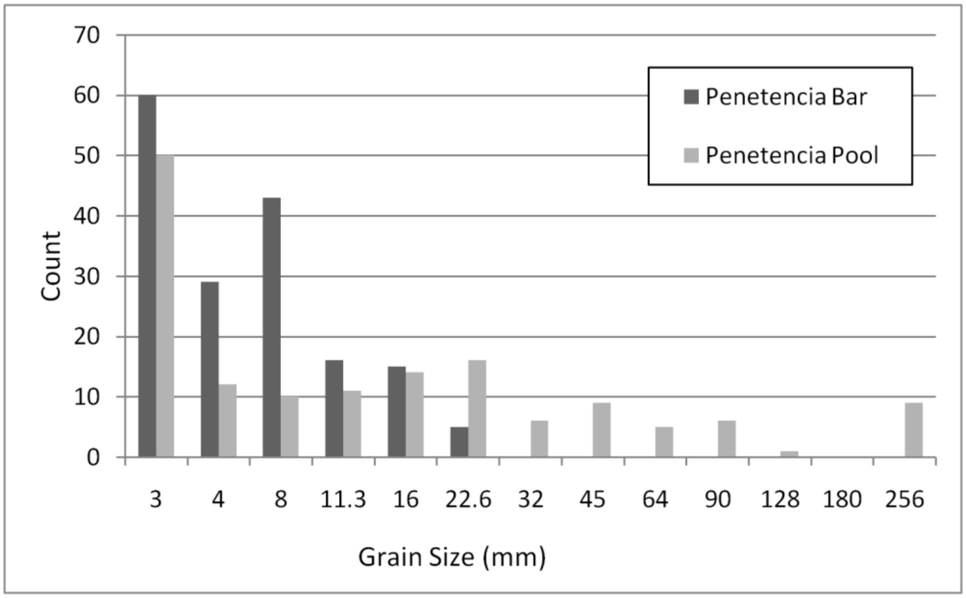


Figure B14: Surface grain size distribution for Penetencia Creek.

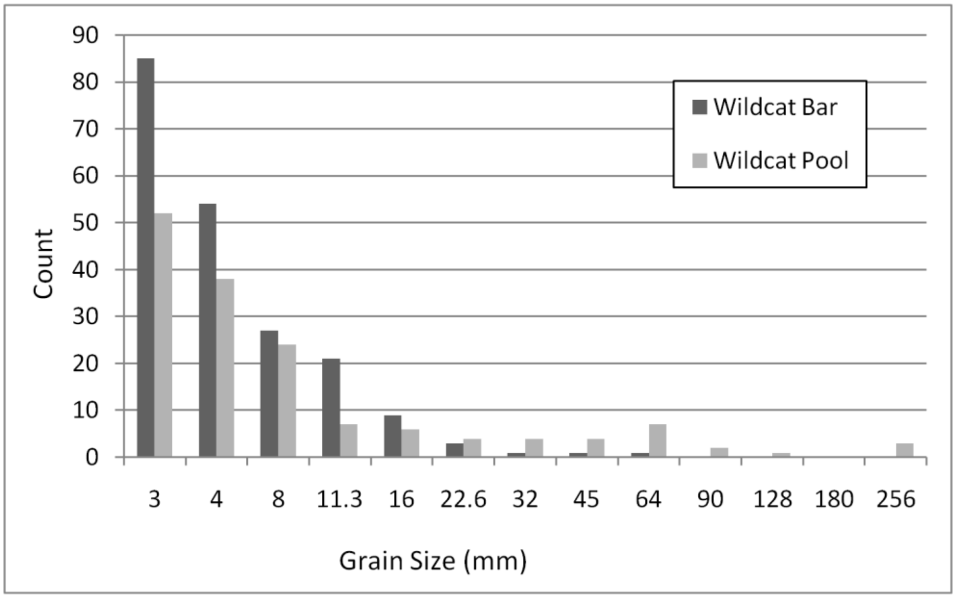


Figure B15: Surface grain size distribution curves for Wildcat Creek.