**Title**

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# Rock Weirs as Tools for Stabilization in Restoration Projects

*An appraisal and comparison of two stream restoration projects in Northern California*

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Rock weirs and root revetments were the main structural components in two San Francisco Bay Area creek restoration projects completed in the 1990's: Uvas Creek in the South Bay and Wildcat Creek in the East Bay. David Rosgen assisted in the design of both restoration projects and the similarities between the two designs are striking considering the differences in size, sediment load, setting and general circumstances of the projects. The two projects have reacted differently in the time that has passed since project completion. In Uvas Creek, which is alluvial in nature and confined in a wide valley, all of the weirs have been buried washed-out, or abandoned by the channel. Topographic surveys of Uvas Creek revealed that the Creek has aggraded across its floodplain, depositing approximately two to three feet in some locations. In Wildcat Creek, which is constrained in a narrow valley, 70 percent of the weirs persist and have created a forced-pool morphology. While rock weirs in Wildcat Creek have added complexity to the channel, and therefore improved the channel from a habitat and aesthetic standpoint, they have not successfully stabilized the creek. Drawing from the study of these two creeks, it seems that rock weirs are not effective in channel stabilization.

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# 1 Introduction

Monetary investment in stream restoration in the U.S. exceeds $2 billion since 1980 (Kondolf et al, 2007). Nonetheless, the success or failure of restoration projects often goes unstudied. In this investigation, two creek restoration projects completed fourteen and twelve years ago, respectively, are appraised and compared. The watersheds and creeks differ substantially in several key aspects including drainage area, mean annual runoff and sediment load (Table 1). The projects have several features in common: vortex rock weirs, rootwad revetments, and earthwork (Table 2). The restoration projects also share the same design rationale: restoration of a more stable creek form. Since completion, the respective creeks have interacted differently to the imposed restoration projects. Uvas Creek abandoned the reconstructed, stabilized, meandering channel, washing out three months following construction (Kondolf et al 2001). Bank failures near the historic walls of Wildcat Creek required additional slope stabilization approximately within four years of project completion (Vandivere, 1997). This investigation is particularly concerned with the effectiveness of vortex rock weirs as tools for stabilization in restoration projects. Side-by-side appraisals of two similar projects involving vortex rock weirs as stabilizing tools allow us to reach more general conclusions as to the reasons for the success or failure of the rock weirs and the projects overall.

## *1.1 Vortex Rock Weirs*

Vortex rock weirs are so-named because they are thought to create vortices and secondary circulation that dissipate energy and steer sediment away from the banks, protecting them from erosion (Rosgen, 1992). A vortex is an element of rotating fluid flow. The rock weirs are also said to “mimic natural boulder steps”, creating habitat (Rosgen, 1992). A typical design includes boulders as well as footer rocks to hold the boulders in place (Figure 1). No concrete or other cementing substance is used.

## *1.2 Project Backgrounds*

### 1.2.1 Wildcat Creek

Wildcat Creek flows from the Wildcat Canyon Regional Park between the Berkeley Hills and San Pablo Ridge through the city of Richmond to San Francisco Bay (Figure 1). Parts of the creek are confined by residential, commercial and recreational development, most notably historic masonry walls in Alvarado Park. Prior to restoration, concrete check dams and sills lined the channel at the Park (Rosgen, 1992). In the summer of 1993, the East Bay Regional Parks District restored a reach of the Creek within Alvarado Park based on a David Rosgen design (Vandivere, 1997). The design made use of the Rosgen classification system (Rosgen, 1997), which divides streams in ninety-four classes based on parameters such as entrenchment ratio and channel material. Rosgen concluded that Wildcat Creek had deviated from its natural class and that this deviation contributed to previous bank failures. The natural classes of Wildcat Creek, per Rosgen (1993) are: moderately entrenched, moderately sinuous, single-threaded channels of moderate width-to-depth ratios (upstream of the stone bridge) and a slightly entrenched, moderately sinuous, single-threaded channels of moderate width-to-depth ratios (downstream of the stone bridge). These classes are otherwise known as “B4” and “C4”, respectively. The primary objectives of the Wildcat Creek restoration related to increasing stability, improving appearance, and removing concrete dams that could impede fish migration (Table 2). Implementation consisted primarily of the installation of rock weirs and native material revetments (Rosgen, 1992).

On two non-consecutive years following the implementation of the restoration project, storms that tested the stability of the design. A failure of the bank supporting the historic masonry wall occurred when water flowing around a meander upstream of the wall was constricted in the narrower channel, leading to scour below a rock weir, undermining of bank and ultimately, failure (Vandivere, 1997).

### 1.2.2 Uvas Creek

Uvas Creek is a tributary of the Pajaro River, which drains to Monterey Bay. Though mostly bordered by agricultural land, Uvas Creek intersects the city of Gilroy (Figure 2). The creek was the site of at least four gravel-mining operations from the 1930s through the 1980s (Justine, 1998). Gravel mining typically results in incision and channel widening (Justine, 1998; Kondolf, 1997). In 1995, the City of Gilroy implemented a restoration project of 3000-foot reach within the Uvas Park Preserve (Kondolf et al, 2001). Rosgen's classification system also figured in this design. A primary objective was to return the creek to its pre-disturbance class, which the designers concluded to be the single-threaded, slightly entrenched, sinuous channel class otherwise called “C4” (Zembsch, 1994; Rosgen, 1992). The design called for rock weirs and root wad revetments to reinforce the banks at meander bends as well as significant cut volumes.

### 1.2.3 Previous Restoration Project Appraisals

Both the Wildcat Creek restoration project at Alvarado Park and the Uvas Creek restoration project in Uvas Park Preserve have been appraised previously (Table 4 and Table 5). At Wildcat Creek, Butalao (1996) and Paz (1993) resurveyed cross sections and performed pebble counts. Vandivere (1997) performed a qualitative investigation to assess reasons for the failure of a historic masonry wall five years after completion. In 1998, Vandivere repaired a portion of restoration project extending from a point 140 feet upstream of the stone bridge to a point 320 meters upstream of the bridge (Vandivere, 1998). The repair project involved reconstruction of three rock weirs and reinforcement of a rootwad revetment.

Justine (1998) and Kondolf et al. (2001) surveyed a cross section and resurveyed the long profile. Repeat appraisals are valuable for several reasons. Previous appraisals of these same projects and the stream restoration literature recommend longitudinal monitoring of post-project conditions (Downs and Kondolf, 2002). Monitoring is of particularly interest at times when significant change may have occurred. We learned of significant recent aggradation at Uvas Creek (Personal Communication from Matt Kondolf, October 28, 2007).

# 2 Methods

For each restoration project, we reviewed project design documents, conducted a search of the literature for relevant sources and conducted a field investigation. The following sections describe our methods for each creek separately.

## 2.1 Wildcat Creek

We visited Alvarado Park on October 28, 2007 to investigate the state of the restoration project and follow up previous appraisals. Beginning downstream of the project reach, we walked upstream mapping, observing and taking pictures of relevant features. We numbered individual rock weirs from upstream to downstream and qualitatively evaluated the weirs structure and function according to the method used by Jerry Miller (Personal Communication to Matt Kondolf, October 19, 2007). The method involves categorizing vortex rock weirs as intact, damaged, impaired or failed (Table 6). Signs of erosion, or aggradation were used to assess whether rock weirs were achieving their intended purpose. Undercutting of nearby masonry walls or concrete walls and exposed tree roots indicated erosion and impaired function. Burial of boulders in the vortex rock weirs indicated failure. Neither photographs documenting the as-built condition nor detailed design drawings of the rock weirs were available, making evaluation more difficult. However, because the plan notes that spaces between boulders in the weirs did not exceed 1/2 a boulder diameter (Rosgen, 1992), we assumed boulders were out of place or missing only when the spaces between boulders exceeded this value.

## 2.2 Uvas Creek

The US Army Corps of Engineers Section 404 (1995) permit for the restoration projected included seven transect surveys showing pre-project and project design elevations as well as a map with cross section locations (Figure 3a-b). No as-built drawings were available for this project, making it difficult to precisely monitor changes since implementation. Also, we were unable to find any cross section endpoint markers.

Consequently, cross section surveying was an imprecise process. To determine the scale of the map we measured the length of the side of a lot in the field and compared it to the same lot length on the map. We located the previously surveyed cross sections in the field by measuring their distances from distinct points on the map corresponding to identifiable objects in the field. On November 12, 2007, we reproduced three transects of the project (heretofore referred to as cross sections 1, 2, and 3) with a horizontal precision estimate of ±10ft, which is sufficient to compare the main features of the river bank and bed. We used an auto level and a 300-foot tape to measure the differences in elevation and the distance between the points surveyed. We hammered nails hammered into trees or in one case asphault (Cross section 3) to mark the approximate location of cross section endpoints.

With the data collected we drew the surveyed cross sections and superimposed them on the pre-project cross sections using AutoCAD 2006 (Figures 3, 4 & 5). Assuming that erosion and deposition on the levee to the north and the high bank to the south are small relative to elevation changes within the channel and floodplain, we superimposed our surveyed cross sections with the historical cross sections by matching the tops of banks on each side.

To create the superposition map of the bed, we used an aerial photograph from Google Earth, 2006, as base map. We scanned and traced the work of Justine (1998), which superposed channel positions of 1939, 1956 and 1997. We also added the design channel to the base map (Figure 6).

On November 23, 2007, we surveyed a long profile of the main channel extending from the downstream face of the bridge to a point 700 meters downstream, taking elevations measurements at twenty-five meter increments (measured using a 100-meter tape). We used a constant increment rather than increment based on detected changes in slope because of the high frequency of deep pools and elevated areas and the limited time. The channel surveyed intersects that northern edge of the bridge then crosses the floodplain and continues along the floodplains southern edge. It is visible in Figure 6 as a dark green, thin line. We used a benchmark established by the Santa Clara Valley Water District benchmark on the southwestern part of the Santa Teresa Boulevard Bridge to determine the absolute elevation of our long profile survey point.

# 3 Results

## *3.1 Wildcat Creek*

The original design called for 19 rock weirs downstream of the stone bridge and 23 rock weirs upstream. During the field investigation we located only 9 downstream of the bridge and only 20 upstream of the bridge. We classify the 13 missing weirs as failed. The structural integrity of the remaining rock weirs varied throughout the reach. Two weirs were highly aggraded or buried completely (Figure 14 and Figure 18). We deviated slightly from method outlined by Miller in that we classified some weirs as damaged and impaired. These weirs have not failed because at least one function, such as habitat restoration, remains unimpaired. Signs of erosion such as exposed tree roots and undercut banks were visible at four weirs (for example Figure 11 and Figure 17). We also noted evidence of stream bank erosion where a tarp had been placed to protect the bank from rainfall above the stone bridge (Figure 22). Missing rocks were noted at four weirs (for example Figure 19). On a percentage basis, 50% of the original weirs failed or were damaged or impaired (not including those reconstructed in 1998) (Table 7). Intact and minimally damaged weirs on Wildcat Creek created a build up of sediment (corresponding step in elevation on the upstream side) and a pool on the downstream side (Figure 10, Figure 13, Figure 15 and Figure 16).

Root wad revetments were visible in almost all of the locations shown in the design drawings. In most cases they seemed to be in good condition, continuing to function as channel stabilizing entities. Some of the revetments were being undercut and showed signs of instability (Figure 20).

## *3.2 Uvas Creek*

Crisscrossing the floodplain while surveying we noticed piles of gravel (Figure 24) indicative aggradation as well as steep unvegetated banks indicative of erosion. Quantitatively, aggradation of the *lit majeur* relative to the design elevation was two to three feet at each cross section (Figures 3, 4 and 5). Transect 1 experienced the most aggradation. The single-threaded channel of the restoration design has been completely filled and a large mound has built up in the center-left portion of the *lit majeur*. The main channel is located across the *lit majeur* from the design channel, confirming that the creek bypassed the stabilized channel of the design. Identifying the main channel proved to be non-trivial because of the lack of flow and large bars in the center of the *lit majeur* suggestive of braided bar morphology. Ultimately, we considered what appeared to be the most continuous channel to be the main channel. An example of channel movement over the *lit majeur* is found also in transects 2 and 3 where channels not shown in the project design drawings cut into the bed (Figures 3 & 4). At both transects the main channel has cut 2 to 3 feet below the *lit majeur* elevation depicted in the design drawings.

At transect 2, the main channel is on the opposite side of the *lit majeur* from design channel. At transect 3, a secondary channel has cut into the *lit majeur* at the location of the pre-project main channel.

While erosion of narrow channels up to three feet deeper than the restoration design *lit majeur* elevation appears to have occurred at transects 2 and 3, everywhere else aggradation outpaced erosion. We found no vortex rock weirs while walking up the main channel. According to our evaluation method, these lost weirs are all failed.

The long profile resurvey shows a decrease in thalweg slope from the project design slope of 0.21% in 1995 to 0.28% feet per feet in 1998 to 0.15% feet per feet at the time of our survey. A general rise and flattening in the thalweg elevation downstream of the Santa Teresa Bridge is visible (Figure 6).

# 4 Discussion

## *4.1 Wildcat Creek*

The rock weirs and root revetments did not fully achieve the objective of stability, given the wall failure that occurred in 1996, the large number of missing weirs, the exposed tree roots, and unstable right bank slope above the stone bridge now covered by a tarp. All these observations suggest that the stabilizing function of many rock weirs in the project is impaired or never existed.

The project appears to have better met its goals of habitat restoration, improvement of aesthetics, and removal of concrete sills, the projects has fared better. Prior to restoration, concrete check dams and sills created elevation drops as much as seven vertical feet over two feet horizontal (Rosgen, 1992). The rock weirs have created many smaller drops with scour pools below each weir. A step-pool morphology was a secondary intended outcome of the restoration project. While the weirs yielded pools, the bed morphology more closely resembles the forced bar pattern, where curves and other obstructions (e.g. rock weirs) enforce the formation of bars and pools. The higher frequency of weirs upstream of the stone bridge in rare locations suggested a step-pool morphology. Other studies confirm the finding of pool formation and improved habitat due to the rock weirs. Pool frequency in the restored reach is high (63 m) relative to other reaches of Wildcat Creek (SFEI, 2007).

Evaluating progress toward the “natural” stability objective is difficult since the natural state of Wildcat Creek is not necessarily a stable one. Due to high tectonic activity, it is prone to frequent landslides that in turn generate a high sediment load (SFEI, 2007). The need for stabilization is understandable due to the geologic context and effects of surrounding development. Instability is a concern along all the urban reaches of Wildcat Creek. An extensive study of the Creek by the San Francisco Estuary Institute identified many different stabilization methods in place in addition to rock weirs throughout Wildcat Creek. However, stabilization may not always be consistent with habitat restoration objectives.

## 4.2 Uvas Creek

At the three cross transects surveyed, the design involved substantial quantities of cut relative to pre-project conditions. Comparing the pre-project and design transect surveys with our results suggests that the transects are trending towards pre-project conditions. The sediment that was removed as part of restoration is being replaced by new sediment. Note that while aggradation is occurring along all three transects, their elevations remain below pre-project elevations (Figures 3, 4 and 5). The main and secondary channels have reoccupied pre-project channel locations in some instances.

That we were unable to find any vortex weirs indicates that all weirs were buried, washed out or abandoned by the channel and overgrown. Given the predominance of aggradation along all three surveyed transects, we infer that the rock weirs were buried.

The local changes in slope seen in the long profile plot correspond with Justine's data (1998). The local changes in slope represent pools and bars, elements of the channel complexity. The slope for the 700-meter reach of 0.15% is slightly below the minimum slope reported by Kondolf et al (2001): 0.17% slope. The reduction in slope may be explained by an increase in sinuosity or a recovery from incision.

Uvas Creek was unsuccessful in reaching at least one of its two primary objectives, "restoring stability". The dramatic deviation of the main channel from the course intended by the design, the aggradation across the floodplain, the cutting of new channels through the alluvium and the rise in slope all indicate that the channel has been anything but stable in the 12 years since implementation. The tools used for stabilization, rock weirs of 2-3 feet diameter, and root wad revetments performed poorly.

## 5 Conclusion

Both the Uvas Creek and Wildcat Creek restoration projects have failed to some degree in achieving stabilization, Uvas Creek because of the abandonment of the stabilized design channel, and Wildcat Creek because of the masonry wall failure. Data collected in this study indicates increasing channel change with time in Uvas Creek and a decline in the functionality of rock weirs at Wildcat Creek. The difference in rock weir failure rate between Uvas Creek (100%) versus Wildcat Creek (50%) may be due to the size of the weirs relative to the sediment load and stream power. In spite of the much larger stream power of Uvas Creek and higher absolute sediment yield (due to greater drainage area), both project designs used rock weirs of approximately the same size. The reason for the failure maybe due to: 1) limitations of the Rosgen classification system, which is more descriptive than mechanistic, and 2) the incorrect assumption of historical, natural stability. Neither project rationale provided evidence of a channel historically different or more stable than the pre-project channel. In Wildcat Creek the project successively restored channel complexity and so improving habitat. The failure of the stabilization measures at Uvas Creek may be regarded as an improvement for habitat over the design because of the Creek's historical condition of multiple, dynamic channels rather than a single channel.

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# 7 Tables

### Table 1. Basic Creek Characteristics

| Characteristic | Uvas Creek | Wildcat Creek |
|---|---|---|
| Drainage area (sq. miles) | 71 | 7.0 |
| Annual sediment yield (tons/ sq. mile) | 1,337 | 2,500 |
| Mean annual runoff at nearest gage (AF) | 28,031[1] | 3,727[2] |

[1] 1960-1992

[2] 1965-1995

Sources: USGS, 2007; Rosgen, 1992; Knott, 1973; Zembecsh, 1995.

### Table 2. Restoration Project Features

| Design Feature | Uvas Creek | Wildcat Creek |
|---|---|---|
| Reach length (feet) | 3000 | 1700 |
| Vortex rock weirs | unknown | 42 |
| Vortex rock weir diameter (ft) | 2-3 | 2-3 |
| Vortex rock weir boulder volume (cubic yards) | 111 | 600 |
| Post-project Rosgen classification | C4 | B4, C4 |
| Cut (cubic yards) | 8,313* | 2,370 |
| Fill (cubic yards) | 4,316* | 1,700 |

*Below ordinary high water

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Sources: Zembecsch, 1995; Rosgen, 1992.

### Table 3. Restoration project objectives

| Wildcat Creek | Uvas Creek |
|---|---|
| -Improve Aesthetics | -Restore stability |

| | |
|---|---|
| -Protect historic masonry walls<br>-Restore "natural" stability<br>-Remove concrete dams<br>-Reduce bank erosion | -Restore habitat |

**Table 4. Previous Appraisals of the Uvas Creek Restoration Project**

| Data Collection/Analysis | Key Findings | Reference |
|---|---|---|
| • Surveys of transect 900 m downstream of Santa Teresa Bridge<br>• Longitudinal profile starting x feet above the Bridge.<br>• Estimate of maximum volume of gravel extracted.<br>• Comparison of aerial photographs from 1939 through 1998. | • Upstream of Santa Teresa Boulevard, channel “active” between 1939 and 1956 with the channel migrating 500 feet towards the left bank. By 1997, channel had returned to 1939 location.<br>• At the Santa Teresa Bridge, the channel narrowed from 500 in 1939 to 185 feet in 1997.<br>• At transect, reduction in active channel width by 260 feet between 1939 and 1997, and 7 feet of incision.<br>• Along profile, increased channel complexity (i.e. pools and riffles) in 1997 relative to 1980 and restoration design. Aggradation relative to restoration design.<br>• Maximum gravel extraction rate estimated at 1,500,000 tons per year. | Justine, 1998 |
| • Review of restoration project documents.<br>• Reoccupation of historical photographs.<br>• Flood frequency analysis.<br>• Inspection of restoration project reach documenting scour, deposition, vegetation and channel change.<br>• Analysis of historical maps.<br>• Analysis of data collected with Justine (1998). | • The root wad revetments were observed in place in 1997 with only slight scour. However, the channel abandoned the channel at the rootwad revetments and cut a course through constructed floodplain.<br>• Little difference in bed elevation along the profile was noted between 1984 to 1998.<br>• The long profiled survey showed channel gradients between 0.17% and 0.3%<br>• The active channel was narrower and incised 2 feet in 1998 relative to 1939.<br>• Channel at the threshold between the braided and meandering classes based on the slope and a bankfull discharge estimate. | Kondolf et al, 2001 |

|  |  |  |
|---|---|---|

**Table 5. Previous Appraisals of the Wildcat Creek Restoration Project**

| Data Collection/Analysis | Key Findings | Reference |
|---|---|---|
| • Visual inspection | • Stable vortex rock weirs (no movement of boulders).<br>• Diverse and stable step/pool morphology with high quality pool habitat.<br>• Stable revetments and only minor slope erosion<br>• Stable point bars<br>• Significant damage to first revetment downstream of the stone bridge.<br>• Bank failures<br>• Masonry wall collapse | Vandivere, 1997 |
| • Ten channel cross sections<br>• Four Wolman pebble counts | • Too soon to appraise project success because no high flows since construction<br>• Stream bed dominated by fine material<br>• Channel more entrenched and of lower width to depth ratio than undisturbed reach upstream | Paz, 1993 |
| • Resurvey of 10 cross sections previously surveyed in January and October, 1994<br>• Four Wolman pebble counts | • Aggradation at two of ten cross sections (one foot on average).<br>• Erosion at seven cross section (1.125 foot on average).<br>• No net change at one cross section | Butalao, 1995 |
| NA | • In 1996 flood, scouring occurred below vortex rock weir resulting in erosion at toe of wall requiring repair<br>• Otherwise, streambanks and archealogical site protected<br>• Cold water fish habitat provided | Rosgen, 1997 |
| • Longitudinal profile<br>• Detailed mapping of rock weirs | Not available | Minick and Stark, 2002 |

**Table 6. Vortex Rock Weir Evaluation Rubric**

| **Rating** | **Condition** |
|---|---|
| Intact | No visible damage<br>Fully operational in terms of integrity |
| Damaged | Structure functions as intended, but visibly damaged; e.g., one or more rocks moved out of place |
| Impaired | Structural components in original location, but no longer functions as intended |
| Failed | Significant parts have been removed from site. Structure severely fragmented, incapable of achieving intended objective |

**Table 7. Wildcat Creek Weir Evaluation**

| Classification | Number | Percentage of Original Weirs |
|---|---|---|
| Intact | 13 | 31% |
| Damaged | 2 | 7% |
| Impaired | 3 | 5% |
| Damaged, Impaired | 3 | 7% |
| Failed | 21 | 50% |
| Total | 42 | 100% |

# Figures

## Figure 1. Vortex Rock Weir Typical Design