ASSESSMENT OF A STEP-POOL URBAN STREAM RESTORATION: SAN PEDRO CREEK, PACIFICA, CALIFORNIA

A thesis submitted to the faculty of
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In partial fulfillment of
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The degree

Master of Arts
In
Geography

by

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San Francisco, California

May 2012

CERTIFICATION OF APPROVAL

I certify that I have read *Assessment of a Step-pool Urban Stream Restoration: San Pedro Creek, Pacifica, California* by Marilyn Hope Smulyan, and that in my opinion this work meets the criteria for approving a thesis submitted in partial fulfillment of the requirements for the degree: Master of Arts in Geography at San Francisco State University.

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ASSESSMENT OF A STEP-POOL URBAN STREAM RESTORATION:
SAN PEDRO CREEK, PACIFICA, CALIFORNIA

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San Francisco, California
2012

This research study evaluates the sustainability of the Capistrano Bridge Fish Passage Restoration Project completed in 2005. The conceptual approach was a direct comparison over time of physical characteristics. The study area includes the restoration area, an upstream reach, and a downstream reach. The primary methods were field observation, measurement of physical conditions, and statistical and qualitative analyses. Degradation occurred in all three reaches, but degradation estimates were highest for the Restoration Reach; the longevity of the logs used to create step-pools was a concern; and larger sediment size and increased transport capacity related to the restoration are likely aiding degradation downstream. Recommendations include developing a management and monitoring plan, more study on log longevity, and increasing storage opportunities to reduce flows in the North Fork sub-watershed.

I certify that the Abstract is a correct representation of the content of this thesis.

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Jerry D. Davis Date

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PHOTOS

I. INTRODUCTION

Evaluation of stream restoration projects is essential to their success, as well as for the advancement of restoration-related science. Degradation of urban streams is a problem worldwide, and restoration costs are estimated at more than $1 billion a year in the United States alone (Bernhardt et al. 2005). However, once restoration is completed, few projects can afford to monitor their effects. For those that can, necessary baseline information is not always available, and even when it is, using it can be challenging at best. This study is an attempt to add to the body of literature in watershed restoration science and help fill this gap.

The Capistrano Bridge Fish Passage Restoration Project (CBFPRP) was completed on a 396 m (1,300 ft) reach of San Pedro Creek, Pacifica, California in 2005. The City of Pacifica is a small coastal community located in San Mateo County, approximately 21 km (13 miles) south of downtown San Francisco. The goal of this assessment was to evaluate the current condition of the restoration area, consider its longer term sustainability, and identify downstream effects, if any. Specific research questions asked: 1) has the creek changed since the restoration, and if so how; and 2) are there indications of any threats to the restoration? The term restoration is being used in its broadest sense and is not intended to imply restoration to a former state. The overall goal of the project was to restore system function, and it did so by constructing a system that would not naturally occur in its surroundings. Given that, the CBFPRP may be more precisely described as a stream naturalization (Rhoades et al*.* 1999).

The CBFPRP was implemented to address immediate threats to steelhead trout (*Oncorhynchus mykiss*), a federally listed Threatened Species. Incision in the creek reached 5 m (15 ft) at the Capistrano Bridge from the 1950s to the late 1990s, and fish ladders became ineffective, creating a barrier to fish passage. In addition, significant erosion was occurring along the creek's steeply banked slopes, with some neighboring backyards literally sliding into the creek. The restoration included raising the bed of the deeply incised creek, bank stabilization, re-vegetation, and placement of 26 log and rock weirs. The logs and weirs created a primarily step-pool morphology consisting of 19 steps to slow the flow of water, create habitat niches, and allow fish passage (Temple and Chan 2007). Step-pools, which occur naturally in mountain streams, are increasingly being used to restore system function in degraded urban streams (Chin et al. 2008), especially in areas where development restricts the size of the floodplain. Often described as staircase-like structures, step-pools dissipate energy vertically in a manner analogous to meanders (Abrahams et al*.* 1995; Montgomery and Buffington 1997; Chin et al*.* 2008).

Locally, this research is needed to determine appropriate management options, and to assess whether the project is threatened by upstream conditions. The North Fork tributary joins the main stem of San Pedro Creek approximately 731 m (2,400 ft) upstream from the Capistrano Bridge, and the large, flashy flows coming out of the culvert are part of the cause of incision at the Bridge (Davis et al. 2002). Upcoming public policy decisions related to storm drainage and new development have the potential to further impact the area. More broadly, research on the use of step-pools to restore urban creeks is limited, as is knowledge about longer-term management issues.

Finally, most research on stream restorations is focused solely on the restored area; this assessment is concerned with broader impacts.

The primary conceptual approach was a direct comparison over time of stream-related and riparian physical characteristics. A model intended to capture partial cause, solution, and effect was used to identify two sample reaches in addition to the restoration area. Primary research methods included field observation, measurement of physical conditions, and statistical and qualitative analyses of the data collected.

II. THE STUDY AREA AND BACKGROUND INFORMATION

The City of Pacifica is a coastal community, located in San Mateo County, 21 km (13 miles) south of downtown San Francisco (Figure 1). Defining characteristics include the Pacific Ocean, a backdrop of the northern Santa Cruz mountain range, and a patchwork of urbanized areas. Sixty-six percent of land use is open space. Pacifica's population was 37,234 in 2010 (U.S. Census). The CBFPRP is located on the main stem of San Pedro Creek, in the San Pedro Creek Watershed, the largest and southernmost watershed in the City (Figure 2). San Pedro Creek is a perennial stream that drains into the Pacific Ocean; the main stem is 4.2 linear km (2.6 miles) and drains 21.2 km^2 (8.2 $miles^2$). Human alterations to the creek, which began in the late 1780s, are discussed in the next section.

San Pedro Creek is the only stream with steelhead trout (*Oncorhynchus mykiss*) between the Golden Gate and Half Moon Bay, a 48.2 km (30 mile) coastal reach south of San Francisco (Davis et al*.* 2002). The main stem is joined upstream by two significant tributaries, the Middle Fork and North Fork (Figure 2). The Middle Fork sub-watershed is mostly open space, while the North Fork is highly urbanized and culverted. The restoration area is a 396 m (1,300 ft) reach located south of the Capistrano Bridge. At the Capistrano Bridge, the creek drains approximately 12.7 km^2 (4.9 $miles^2$) of the upper watershed. A Mediterranean climate brings dry summers and heavy winter storms; average yearly rainfall is 0.84-0.96 m (33-38 in) (Amato 2003). The dominant area geology is Montara Mountain granodiorite, marine sandstone, Franciscan Assemblage, and Pleistocene alluvium (Collins et al. 2001). San Pedro Creek is located in an urbanized alluvial valley. Much of the rock is unconsolidated and highly friable, resulting in landslides and sedimentation.

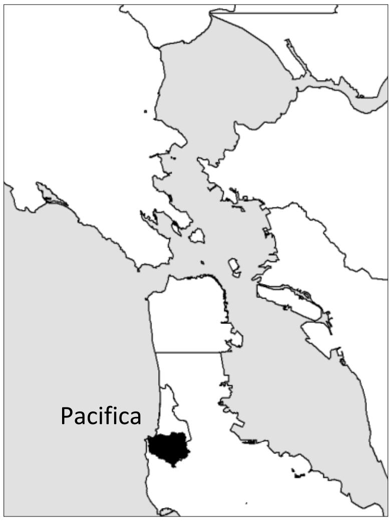

Figure 1: The study area in Pacifica, California. San Pedro Creek Watershed in black.

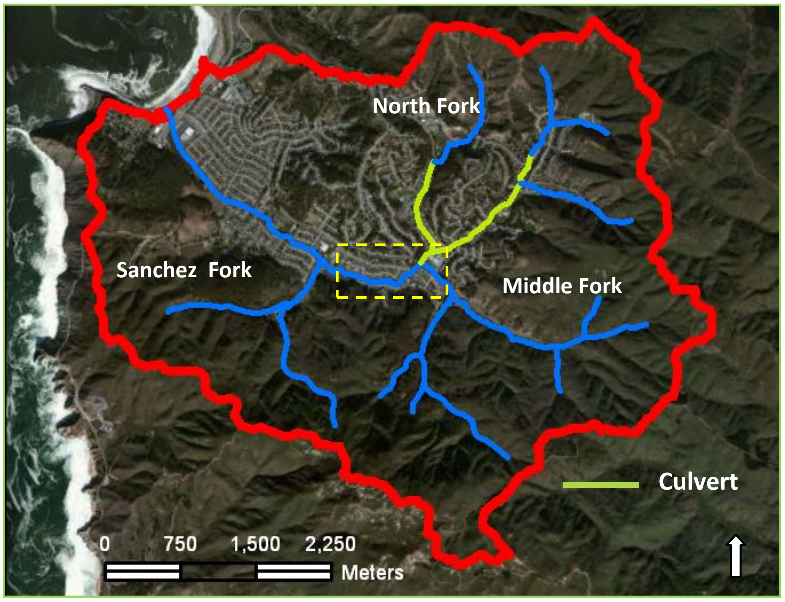

Figure 2: San Pedro Creek Watershed. Study area outlined in dashed box.
Base map Bing Map (c) 2010 Microsoft Corporation and its data suppliers.

Historical Background

Historical and present land uses have contributed to the degradation of San Pedro Creek. Until otherwise noted, the reference for this section is Culp (2002). Alteration of the original coastal scrub landscape to grasslands began with the practice of landscape burning by the Ohlone people. After an outpost for San Francisco's Mission Dolores was established in 1785, grazing was introduced and the added stress initiated the conversion of native perennial grasses to annuals. It was also during this time that the first known ditches were constructed to drain land and make way for agriculture. In 1890, commercial artichokes, which require summer irrigation, were introduced. The earliest known map of the area, drawn in 1835, shows San Pedro Creek flowing through a willow sausal area and draining into the former Lake Mathilda. However, in the 1896 San Mateo County USGS 15 minute map the creek has been straightened and relocated southwesterly into a man-made ditch that emptied into the Pacific Ocean. Later a head-cut progressed upstream. Possible causes of the head-cut include tectonics and the increase in impervious surfaces (Davis, April 3, 2012, pers. comm.) and/or a lowering of the base level of the creek after it was moved (Collins et al. 2001).

In the 1950s, Pacifica experienced a building boom and large tracts of agricultural land were subdivided for residential development. By 1998, impervious surfaces covered 19% of the North Fork sub-watershed. The original 15 km (9.4 miles) of tributaries became 54.7 km (34 miles) of drainage culverts, gutters, and ditches, increasing the drainage density by 72% (Amato 2003). Increased runoff, combined with direct delivery of precipitation from culverts and gutters to the stream, caused flashier flows, flooding, incision, eroding banks, and the separation of the main channel from the floodplain in parts of the creek (Collins et al. 2001). Incision also initiated at the Capistrano Bridge culvert (Davis et al. 2002). The concrete culvert acted like a knickpoint, an abrupt change in a stream profile formed by a more resistant surface which prevented the stream from eroding back. The first fish ladder was installed in 1965 and the second in the late 1980s (Lee 2003). By the late 1990s, overall incision had reached 5 m (15 ft), creating a 3.6 m (12 ft) jump from the creek to the culvert. The fish could no longer get up the ladder, creating a barrier to fish passage for threatened steelhead trout (Davis et al. 2002). Bridge incision, and related downstream bank failure, are evident in Photos 1 and 2. In 2001, NOAA Marine Fisheries issued a letter warning the City of Pacifica of a potential violation of the 4(d) rule of the US Endangered Species Act of 1973, as amended, and a temporary weir was installed to improve fish passage. The Capistrano Bridge was temporarily closed in 2002, and repairs were made to undercuts that were ~ 3 m (10 feet) deep on each side.

Photo 1: Capistrano Bridge Culvert and fish ladder 1999.
Photo courtesy of San Pedro Creek Watershed Coalition.

Photo 2: Bank erosion below Capistrano Bridge 2004.
Photo courtesy of San Pedro Creek Watershed Coalition.

Capistrano Bridge Fish Passage Restoration Project (CBFPRP)

The CBFPRP was part of a larger effort to restore system function to San Pedro Creek. According to Scott Holmes, then director of public works, the first priority for the City of Pacifica was flood control (Holmes, April 9, 2011 pers. comm.). Major flooding occurred downstream of Capistrano Bridge in the Linda Mar neighborhood in 1962, 1972, and 1982. Property damage was estimated at $5 million for the 1982 flood alone (McDonald 2004). However, it wasn't until 2002 that the problems were addressed. One flood control project created meanders, stabilized banks, and re-vegetated the lowest reach. A second project restored the wetlands at the mouth of the creek.

The San Pedro Creek Watershed Coalition (SPCWC), founded in 1999, initiated several studies that formed the basis of the San Pedro Creek Watershed Assessment and Enhancement Plan (Davis et al. 2002), as well as related research studies that came later (Table 1). They followed a science-based watershed approach, based on the natural channel design method developed by Dave Rosgen in 1994 (Rosgen 1994). This approach is discussed in the literature review.

Restoration of the reach below Capistrano Bridge was one of many projects recommended in the Enhancement Plan. Other projects included improving conditions at culverts upstream of Capistrano Bridge, restoring a creek site near Alma Heights School where a toxic retaining wall was failing, more study of the South Fork tributary, and a feasibility study to consider alternatives for reducing the large, flashy flows coming out of the North Fork culvert. Because of the need to implement a long-term solution to immediate threats to migrating steelhead, the Enhancement Plan assigned the Capistrano Bridge area its highest priority. The Coalition worked closely with the City, conducting studies and outreach and education programs in the community. Conceptual plans for the restoration were developed by Collins (2002), followed by a draft design by L. C. Lee (2003). Lee was a subcontractor to Power Engineering, the firm hired by the City to implement the project. The plans included restoration of the 183 m (600 ft) reach immediately above the Capistrano Bridge restoration (a concrete-walled ditch), but it was later eliminated from the project due to a lack of funds. To date, none of the recommendations to restore the reach above the restoration or to assess and improve conditions on the North Fork have been implemented.

Table 1: San Pedro Creek Watershed Coalition-related studies

Author	Study Purpose
Collins et al. 2001	Geomorphic analysis of the lower 2.6 m of the main stem of San Pedro Creek
Hagar 2002	San Pedro Creek fish habitat assessment
Bioassessment 2002	Benthic invertebrate survey of San Pedro Creek
Culp 2002	A historical study of the watershed
Davis et al. 2002	An assessment of the watershed and enhancement plan
Collins 2002	A conceptual framework for the Capistrano Bridge Fish Passage Restoration
Amato 2003	Case study considering the effects of land use change on storm response by comparing storm-related discharge, turbidity, and bank erosion for two geomorpologically similar sub-watersheds; the undeveloped Middle Fork and the urbanized North Fork.
Pearce et al. 2004	A sediment source analysis for Sanchez, South, and part of Middle Fork tributaries using methods comparable to Collins et al. 2001.
Sims 2004	An analysis of hillslope sediment sources.
McDonald 2004	An integrative analysis of Pacifica's response to flood hazard.
Johnson 2005	A snorkel survey to assess habitat and presence of steelhead trout.

Project Design

Constraints on project design included deep incision, bank erosion, limited easements, homes located on top of the banks, and retaining walls (Collins 2002). The original design called for removing the Denil concrete fish ladder, raising the creek bed to the approximate1950s level, widening the flood plain where possible, bank stabilization, re-vegetation, and placement of 15 rock weirs and three plunge pools (Questa 2005b). However, a few weeks before construction began, Monterey pine logs were made available at no cost, and the City of Pacifica chose to use them instead (Holmes April 9, 2011 pers. comm.; Temple, March 30, 2011, pers. comm.). The revised design included construction of 26 log and rock weirs to form 19 steps (Temple and Chan 2007). The project was designed for a bankfull flow of 9.9 m^3/s (350 f^3/s) and average slope of 1.8%. The logs measured 9.1-10.7 m (30-35 ft) long and 0.9-1.2 m (3-4 ft) in diameter, and they were placed atop boulder filled trenches (Photo 3). Additional boulders, rock weirs, and root wads were placed in the stream to direct the flow away from the banks, and more boulders were added to create surface roughness (Photo 4). New, temporary concrete weirs were also installed on the upstream side of the Capistrano Bridge culvert, the area that had been eliminated from the restoration plans due to cost considerations. Construction occurred in the summer of 2005, and 13,000 native trees and shrubs were planted in the spring of 2006. Low flow notches were cut in most of the fifteen log steps later that year. The following quote from a report prepared for the City of Pacifica, (Questa 2005a p. 1-2) provides a detailed description of the process used in placing the log steps:

The log structures utilized logs 3 to 4 feet in diameter and 30 to 35 feet in length, along with 1.5- to 2-ton boulders for ballast and keyways (placed upstream and downstream of the log). The trench was keyed into the banks approximately 6 to 8 feet on both banks to prevent end-scour. These keyway areas were planted with willow poles to provide additional stability. Smaller rocks, 6- to 12-inch in diameter, were used to fill voids between the larger rocks. The rock/log grade controls were constructed in the following steps.

Step 1: Dig 6- foot deep trench 5 to 6 feet wide. Place 2-ton rock at base. Usually involved two three rocks wide. Place smaller rock pack remainder of trench with smaller rocks and clay soil.

Step 2: Place log; check grade elevation, remove and adjust rock height as necessary. Utilize more 2-ton rock to hold log in place. Cut and place rock in bank keyway.

Step 3: Place willows in excavated trench beside log and rocks. This quickly establishes deep rooting to ensure re-vegetation and as well as aid in soil stabilization.

Step 4: Counter balance log with more 1- to 2-ton rock, utilizing smaller ½- and 3/4-ton rock. A minimum of 2.5 tons (5,000 lbs) is weighted at each end. Place rock keyway 5 feet into solid banks and up to the 25- to 50-year flow elevation.

Step 5: Place 1/2- to 1-ton rock upstream of the log structure. Pack with soil. We also went back and placed a 12- to 18-inch layer of 8-inch to 1/4-ton rock at the surface of each weir.

Logs were also used to form a V-shaped anchored weir (pointing downstream) at the downstream end of the restoration, create in-stream habitat, and stabilization features. The as-built plans (Questa 2005c) show two log cribwalls and logs used for toe slope protection at multiple sites.

The final project cost was recorded at $2,298,000 (Public Works Dept. 2006). According to the maintenance plan that was part of the City's funding contract with the Department of Water Resources, the project was intended to be "…'self-maintaining,' to the extent possible...," once it became stable (DWR 2005, Exhibit C p. 1). Stability was projected to be reached in five years. During the first five years, the City was required to repair any structural defects that arose related to stream flow, keep a maintenance log, and conduct yearly monitoring of plants, wildlife, and geomorphology. A first-year monitoring report was completed in 2008 (TRA and Balance).

Photo 3: Completed log weir prior to backfill. Photo courtesy of Questa E.C.

Photo 4: Intermediate weirs and bed load augmentation. Photo courtesy of Questa E.C.

III. LITERATURE REVIEW

While the body of literature evaluating stream restoration is small, albeit growing, literature focused on fluvial geomorphology is vast. The primary objective of this review is to facilitate an assessment of the CBFPRP. It begins by establishing the larger context in which steam processes exist, and then concentrates on key concepts and methodologies related to this analysis. The review is in five sections: 1) the larger context, 2) urban stream degradation, 3) approaches to stream restoration and evaluation, 4) evaluating restoration success, and 5) step-pool theory and practice. However, first it is important to clarify what is meant by “stream restoration.”

The term restoration implies returning a stream to a previous state. However, not only are previous states at times unknown, human disturbance has been so great in some areas that a return may be impossible (FISRWG 1998; Rhoades et al*.*1999; Montgomery and Wohl 2003). Various definitions of restoration exist and some are more precise than others. The National Research Council adopted a definition of restoration as “returning an ecosystem as closely as possible to pre-disturbance conditions and functions” (FISRWG 1998 p. I-3). However this definition is criticized by Rhoades et al*.* (1999) because of its lack of practicality. Information on past condition is not always available, and even when it is, the return to the past may not be technologically possible or desirable. Rhoades et al*.* propose the term naturalization as an alternative. The goal of naturalization is to establish a sustainable fluvial system that can support diverse ecosystems. In the case of the CBFPRP, it could be argued that the goal is more aligned with that of a naturalization, especially because it is based on the creation of a channel morphology (step-pool) in a reach where it could not naturally occur.

The Larger Context

Streams are dynamic ecosystems that exist within a larger context and respond to changes in the physical, biological, and chemical factors that influence them (Graf 2001). They have long been a major focus of landscape evolution theory, and later, fluvial geomorphology with the introduction of Leopold, Wolman, and Miller's Fluvial Processes in Geomorphology in 1964. Two key concepts that set the foundation for current thinking about fluvial processes are briefly discussed below; time and dynamic equilibrium.

Geologist Grove Karl Gilbert was the first to propose an interaction between form and process in his chapter on Land Sculpture in the Geology of the Henry Mountains (1877). He built upon the concept of base level, the lowest level to which a stream can flow, first proposed by John Wesley Powell (Pazzaglia 2003). Gilbert's use of a systems approach led him to the concept of "equality of action" of driving and resisting forces. He proposed that landforms respond to their underlying geologic structure and endogenic and exogenic processes, recognized the role of climatic influences on the influence of slope morphology, and identified the positive relationship between the rate of erosion and declivity. His law of declivity, based on the inverse relationship between slope and quantity of water, offered an explanation for the concave profile of rivers. Gilbert considered time the independent factor and equilibrium a steady state reached through the law of declivity. However, once geographer William Morris Davis' theory of the geographic cycle was proposed (Davis 1899), it dominated landscape theory for half a century. In his time dependent idealized model, after uplift, the landscape evolves through three major stages; from youth, to maturity to old age, and flattens over time. While Gilbert had focused on the present Davis's more simple explanations of mean elevation and mean relief change over time provided a compelling explanation (Pazzaglia 2003).

With the rise of the quantitative revolution in mid-century, interest in descriptive solutions such as Davis' began to diminish. J. T. Hack (1960), like Gilbert, thought in terms of systems and revived interest in Gilbert's equilibrium concept. He viewed landforms as time independent and recognized geological differences as the primary reason for differences in form. Hack assumed that "within a single erosional system, all elements of the topography are mutually adjusted so that they are down wasting at the same rate," and he proposed the theory of dynamic equilibrium (Hack 1960 p. 85).

Schumm and Lichty (1965) tried to reconcile the time independent models of Hack and Gilbert with the time dependent model of Davis. They asserted that processes are more complex, with cause and effect dependent on both temporal and areal scale. After identifying three timeframes (cyclic, graded, and steady), they proposed a causal relationship between drainage basin variables and periods of time. The ten drainage basin variables were time, initial relief, geology and structure, climate, vegetation, relief, runoff and sediment, drainage network morphology, hillslope morphology, and discharge. In the steady state, short-term present time, they found discharge to be the only dependent variable. As systems theory developed, multiple types of equilibrium were proposed. In their 1971 textbook, Chorley and Kennedy described seven more equilibrium conditions. But along with the understanding that different processes work at different scales of time and place, dynamic equilibrium continues to provide the foundation for fluvial geomorphology.

Urban Stream Degradation

The effects of urbanization on stream morphology have long been known. More than 40 years ago, Wolman (1967) recognized a three-stage cycle of urbanization: 1) an initial stable agricultural or forested condition; 2) an erosional period following construction; and 3) an entirely new landscape dominated by impervious surfaces and gutters, and a new hydrological regime and channel morphology. A few years later, Leopold's (1972) 1953-1972 resurveys of monumented cross sections on the Watt's Branch near Rockville, MD provided long-term quantification of channel change due to urbanization. His data revealed that after 12 years of increasing sediment production, a threshold was reached, the channel form took on a more trapezoidal shape, and the number of floods increased dramatically; a sequence of events that is now well-documented (Booth 1991; Walsh et al. 2005). Hard impervious surfaces limit absorption of precipitation and create more overland low. When combined with extensive channelization, culverting, and gutters, the result is larger and more frequent peak flows, incision, and flooding. Christopher Walsh et al. (2005) have coined the term "urban creek syndrome" to describe what has become a common condition of creeks in urban areas.

For San Pedro Creek, Paul Amato (2003) measured discharge and compared the storm response of the urbanized North Fork with that of Middle Fork. The Middle Fork is a nearby tributary in the same watershed comparable to the North Fork in general location, size, and structure; the major difference is that it is not developed. His study found that while the Middle Fork received an average 31% more rainfall than the North Fork, the discharge from the North Fork was 2 to 7.5 times that of the Middle Fork when measurements were taken during or shortly after rainfall.

Approaches to Stream Restoration

Until the mid-1990s, stream-related problems were primarily addressed by targeting singular symptoms based on a reductionist, engineering-based process (Hillman and Brierley 2005). For example, flood protection was mainly achieved via armoring. However, over time, these short-term solutions were found to exacerbate the very problems they were designed to fix, and there was growing recognition that more complex interactions had to be addressed. In addition to changes in sediment and stream equilibrium, urbanization and agriculture are major causes of degraded water quality and habitat and species loss as well. In response, a more probabilistic, multi-disciplinary watershed and ecosystem approach was developed, and in 1996, the Environmental Protection Agency (EPA) formally adopted its Watershed Protection Framework (Rhoades et al. 1999). Rather than focusing on short-term, immediate solutions, this science-based approach is based on situating problems into a larger watershed context, identifying the source(s) of problems and creating solutions that target underlying causes (FISRWG 1998; Riley 1998; Hillman and Brierley 2005).

Stream Classification Systems

Stream classification systems have been used as a means for studying the relationship between streams and the larger watershed ever since Davis first classified streams by age (Niezgoda and Johnson 2005). However, Arthur Strahler is usually credited with creating the first stream classification system with his method for designating stream order (FISRWG 1998). Classification systems are an important tool in evaluating stream condition and designing restoration projects. Schumm (1977) focused on form and process when he classified alluvial channels by channel pattern (braided, meandering, and straight), and related pattern to sediment load and stability. So did Montgomery and Buffington (1997) when they classified seven channel types found in Pacific Northwest mountain drainage basins. Their system is based on channel response to sediment input and transport capacity. Montgomery and Buffington’s seven channel types include one each based on colluvium and bedrock foundations and five types based on alluvium; cascade, step-pool, plane bed, pool-riffle, and dune ripple. Colluvial channels are found in small headwater streams and have limited transport capacity. Bedrock reaches are found on the upper steep, confined slopes that have high transport capacity. The alluvial channel types represent a continuum that begins with the steeper, cascade channel, with high transport and low storage capacity, and ends with the dune ripple type, with high storage capacity and low transport. Montgomery and Buffington (1997) recognize one additional channel type that is different from the others. Forced morphologies are a type controlled by obstructions, most often step-pool or pool-riffle channels that are forced by log jams. Any changes in sediment supply, transport capacity, and vegetation can alter channel morphology. Montgomery and Buffington

(1998) also identified four hierarchical scales of influence; geomorphic provinces, watersheds, valley segments, and channel reaches. While restoration projects occur at the scale of the reach, an understanding of the larger context is essential because a reach may be influenced by factors from multiple scales.

The San Pedro Creek Watershed Approach

A science-based watershed approach was used by the San Pedro Creek Watershed Coalition when it began assessing San Pedro Creek in the late 1990s and creating the conceptual plans for the Capistrano Bridge restoration (Davis et al*.* 2002). It is based on the natural channel design method developed by Dave Rosgen (1994). Natural channel design is the most commonly used classification system, and has been adopted by the by the Environmental Protection Agency (FISRWG 1988) and the United States Department of Agriculture National Resource Conservation Service (2007). However, it is not without controversy, from concerns about its lack of focus on process to questions about Rosgen's lack of publication in peer-reviewed journals (Lave 2009; Lave 2012).

Rosgen's method is based on identifying a comparable, stable reference reach and using it as the basis of comparison and prediction of what is needed in the reach to be restored (Rosgen 1994). He provides a detailed four-level systematic methodology for making field observations, taking measurements, and classifying condition. Eight major form types are defined, each with three to eighteen variations. Number of channels, entrenchment and width to depth ratios, sinuosity, water surface slope, and bed material size, are some of the characteristics used to describe form. In their review of stream classification systems, Niezgoda and Johnson (2005) question whether it is possible to know if the reference reach is actually stable.

Evaluating Stream Restoration Success

The most common comment in the literature about the science of stream restoration evaluation is the lack of it, and the most often cited reasons are inherent difficulties in measuring success and/or a lack of funding (Kondolf and Micheli 1995; Bernhardt et al*.* 2007). Evaluation is based on the monitoring of physical conditions, and provides a snapshot in time. It must be repeated over several years, and according to Kondolf (1998), along the California coast the high seasonal and inter-annual variability can result in longer time periods of adjustment.

In 2001, the National River Restoration Scientific Synthesis (NRRSS) working group was formed to evaluate river restoration from a scientific perspective (Bernhardt et al*.* 2005). After creating a 37,000-record database of river restoration projects, they estimated that more than $1 billion a year is spent on stream restoration in the United States, but could only find documentation of monitoring in 10% of the projects (Bernhardt et al*.* 2007). Interviews with 317 project managers yielded more positive results, with 40% of the managers reporting that some monitoring of their projects had occurred. However, Bernhardt et al*.* speculate that the managers they were able to reach for their survey are most likely associated with longer-running projects and not typical of the projects as a whole. Additionally, only 10% of those interviewed met the evaluation criteria established by NRRSS for assuring evaluation success: 1) a clearly defined project goal, 2) a series of objective testable success criteria, and 3) an evaluation of success based on measurements related to the success criteria made before and after restoration at the restoration and a reference site. An assessment of California projects yielded similar results (Kondolf et al. 2007). Of the monitoring that is done, few projects are published in the scientific literature, translating into a significant loss of information on lessons learned that could be used to improve restoration science and outcomes. To remedy this situation the NRRSS is recommending a national program of rigorous monitoring on a smaller number of future projects.

Methods

The basic geomorphic methods used in restoration evaluations are described in the 1994 Stream Channel Reference Sites: An Illustrated Guide to Field Technique published by the U.S. Forest Service (Harrelson et al.). Step-by-step instructions for measuring the variables that control channel size, first described by Leopold et al. in 1964, are included: width, depth, velocity, discharge, slope, roughness of bed and bank materials, sediment load, and sediment size. If change occurs in any of these variables, the others adjust accordingly. The guide begins with a chapter on reference site selection and has chapters covering drawing a site map, surveying basics, longitudinal and cross-section measurement, staff gauge installation, discharge measurements and characterization of bed and bank material. For those using the Rosgen method, these measurements are entered into forms related to his classification system. While the guide to field techniques is well documented, field-based methods are not without challenges. Field measurement is labor-intensive, subject to individual variability, can be difficult to replicate, and is discharge dependent (Madej 1999). Some current research is focused on developing alternative methods to fieldwork, usually GIS and remote sensing, but it is not reviewed here. Neither are methods for assessing biological indicators, because they were not a focus of this assessment.

Evaluation of the CBFPRP

One official evaluation of the CBFPRP occurred in 2008. The City of Pacifica hired TRA Environmental Sciences, Inc and Balance Hydrologics to monitor the project and determine if it had met the target goals listed below (TRA and Balance 2008 p. 6):

1. As conditions allow, restore the longitudinal slope and hydrologic complexity to the project reach that will allow for the passage of juvenile and adult steelhead.
2. Improve water quality by increasing the residence time of water within the restoration site.
3. Restore native forest, scrub-shrub, and emergent plant communities within the restoration site.
4. Establish a compositionally and structurally complex ecosystem with attributes important to wildlife, specifically focused on increasing habitat functioning for the Central California Coast ESU Steelhead (*Oncorhynchus* mykiss) and the California red-legged frog (*Rana aurora draytonii*).

Although the first target captures measures related to channel stability, it does not provide adequate information for a full geomorphic or a longer term assessment, nor does it consider a reference site. Specific project standards for the first target include the following (TRA and Balance 2008 p. 7):

- Approximately 1,200 ft downstream of the bridge: bankfull width = 22-28 ft; bankfull depth = 2-4 ft at thalweg; bankfull width : depth ratio = 8-13 ft at thalweg
- Mean water surface slope: first 500 ft downstream of bridge = 1.25-1.50%; downstream of 550 ft = 1.75-2.00%
- Related to the constructed weirs: depth of flow notch = minimum of 24 inches; width of flow notch = minimum of 8 inches; constructed weirs remain stable and the low flow notch is not obstructed by debris and/or sediment.

The study concluded that the geomorphic targets were being met. However, it identified one undercut log step and recommended that it be repaired. Recommendations were also made to remove or control invasive species, specifically French broom shrubs (*Genista monspessulana*), Cape ivy (*Delairea odorata*) and poison hemlock (*Conium maculatum*).

Step-pool Theory and Practice

Step-pools, which occur naturally in confined channels in steep mountain streams, are increasingly used to restore more natural processes in degraded urban streams (Chin et al. 2008). Most often described as regularly-spaced, staircase-like structures that alternate steps and pools, step-pools are one in a continuum of channel forms (Abrahams et al. 1995; Montgomery and Buffington 1997; Chin et al. 2008). In Montgomery and Buffington's (1997) classification of seven reach types, they fall between cascade and plane-bed channels, and they are found in many environments, including humid, desert, semi-arid, forest, and even ice-covered settings (Chin and Phillips 2009). Geomorphologically, step-pools are significant because they dissipate energy, in a manner analogous to meanders, but oscillating vertically rather than laterally (Abrahams et al. 1995; Montgomery and Buffington 1997; Chin et al. 2008). In severely impacted urban streams where encroaching land uses don't allow for the re-creation of past meanders and/or wider floodplains, constructed step-pools can reduce water velocity and the frequency of peak discharge, eliminate barriers to fish passage, and create habitat niches (Chin et al. 2008). In the natural world, Montgomery and Buffington (1997) find them more resilient to changes in sediment and discharge than plane-bed and pool-riffle channels.

Flume and field studies confirm that step-pools form in high discharge events and self-organize until they reach maximum energy resistance during lower flow events through bed scour and armoring (Abrahams et al. 1995; Chin and Phillips 2007; Chin et al. 2008). The process is thought to be initiated by exponential growth of minor perturbations (Chin and Phillips 2007). Once formed, large floods can cause step-pools to break down, and then they begin the process of reformation (Chin and Phillips 2007). They dissipate the most energy during low flows when water tumbles over the steps into pools; when the steps are fully submerged there is little effect. Steps are usually formed from larger cobbles and boulders (Chin et al. 2008); however, they can also be formed by large woody debris (LWD).

Figure 3 indicates the measurement of step-pool geometry as described in Abrahams et al. (1995) using data from this study. Length is measured from the top of one log to the next, height is measured from pool bottom to the height of the top of the upstream log, and the slope measurement is the gradient between logs.

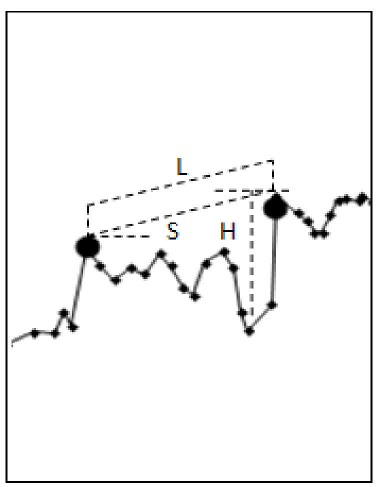

Figure 3: Diagram of step-pool geometry measurements.

Step-pools with maximum flow resistance exhibit the following geometric relationships (Abrahams et al. 1995; Chin et al. 2008):

- Within a reach, spacing between steps is regular, and it is equal to 1 to 4 channel widths.
- The relationship between resistance to flow and step length, calculated as $(\overline{\mathrm{H/L}})/S$, typically ranges between 1 and 2.
- Step height and frequency increase with increasing slope.
- The average ratio of height to mean diameter step-forming particle size is 1 to 1.5.

Modeling and predicting steps is still difficult, but an excellent discussion of models is provided by Curran (2007). She evaluates five existing models (particle cluster, migrating hydraulic jump, cascade, antidune, and scouring formation) and proposes three new models (rough bed, exhumation, and dune).

Step-pool Practice

Anne Chin has studied step-pools for over ten years and led efforts to evaluate their use in stream restorations (Chin et al. 2008; Chin et al. 2009; Chin et al. 2010). Table 2 summarizes strategic information about the five restoration projects for which the most detailed geomorphic analysis is available. The primary method of assessment is analyzing step geometry and observing step conditions. Chin has also studied the ecological response of three streams with step-pool structures in Austin, Texas

(Chin et al. 2010), but they are not included because the information on step-pool geometry is not provided. Four restorations involved smaller reaches, 36-80 m (118-262 ft), with slopes ranging from 3% to 10%, and construction of 5-10 steps (Table 2). Baxter Creek, with five original steps, began to readjust to 14 steps in 1997. Karnowsky Creek is a larger restoration, approximately 350 m (1,148 ft) in length. Rock material was used in three of the Bay Area restorations and two projects (Karnowsky and Codornices) also included log weirs. The (H/L)/S is within or slightly under the range considered ideal (1-2) at Baxter, Dry Canyon, and Karnowsky creeks; but, it is higher at East Alamo (2.2 to 4.3) and Codornices (2.2) creeks. All of the restorations are reported as being stable, although most are still relatively new and likely adjusting. Some reorganization has occurred at the two projects that have experienced the largest floods (Baxter Creek, 14 year flood and Codornices Creek, 25 year flood). Baxter Creek has experienced the most reorganization, but it is also the oldest project and was constructed when less information was available. Water flowing through steps has been identified as a problem at East Alamo and Codornices creeks.

Table 2: Characteristics of constructed step-pool restorations.

Location and Year	Reference	Original Problem/ Problem Type	Project Description	Step Material	Evaluation
Baxter Creek El Cerrito, CA 1996	Chin et al. 2008 and 2009; Purcell et al. 2002	Urbanization, aging culvert. Daylighting, bed reconstruction, bank stabilization	10% slope, 70 m reach, originally 5 steps, and now 14. (H/L)/S 1.1.	Salvaged rock, self-adjusting	Latest survey 2006. 14 year flood. Originally spaced too far apart. Natural re-organization began 1997. Now stable. Ecologically improved.
East Alamo Creek Contra Costa County, CA 2001	Chin et al. 2008	Grazing, incision, channel widening, bank collapse. Floodplain grading and bank and floodplain stabilization. Part of larger restoration.	Reach 1: 3% slope, 80 m reach, 8 steps, (H/L)/S 3 & 4.3. Reach 2: 5% slope, 100 m reach, 10 steps, (H/L)/S 2.2 & 3.0.	Boulders, deeper foundations every 3-4 steps.	Latest survey 2006. 9 year flood. Piping not effective in low flows, water flowing through some steps. Erosion at side of rock steps during floods. Maintenance program recommended.
Codornices Creek Berkeley, CA 2003	Chin et al. 2009	Deep incision below culvert, slumping, fish passage barrier. Bed and bank stabilization, improve fish passage, establish riparian corridor	7.5% slope, 36 m reach, 10 steps. (H/L)/S 2.2	Boulders and log weirs. Some boulders anchored.	Latest survey 2007. 25-year flood. One step-pool series lost, localized erosion and bank slumping. Water running through some steps; pools have deepened, but sediment deposition has occurred too. Ecologically improved.
Dry Canyon Creek Calabasas, CA 2006	Chin et al. 2008	Channel narrowing; invasive plants, debris accumulation.	8.3% slope, 40 m reach, 10 steps, (H/L)/S 0.7 to 1.2	Rock material from channel. Designed to self-scour	Latest survey 2007. 2-3 year flood. Scouring and pool deepening has occurred.
Karnowsky Creek, Tributary 3 Siuslaw National Forest, OR 2003-2004	Chin et al. 2008	Agriculture and Channelization, incision, ground water loss. Habitat restoration, bank stabilization, human needs	2.7% slope, ~350 m reach, (H/L)/S 1	Nearby sandstone boulders and logs. Designed to self-scour.	Latest survey 2007. 5 year flood. Scouring and deepening of pools, some aggradation upstream of steps. Initial bank erosion before scouring occurred

IV. CONCEPTUAL APPROACH AND METHODS

The primary conceptual approach of this research was a direct comparison over time of stream-related physical characteristics. A model intended to capture longer term sustainability was used to identify two sample reaches in addition to the restoration area. The primary research methods were field observation, measurement of physical conditions, and statistical and qualitative analyses. Interviews were also conducted with six of the eight people most involved in the project to better understand the final project design and implementation.

Figure 4 presents the conceptual model and the sample reach locations are identified in Figure 5. The first reach is an upstream sample that represents a partial cause of the incision at Capistrano Bridge. It begins at the outflow of the main culvert that drains the developed North Fork tributary, and it ends approximately 67 m (220 ft) downstream at the confluence with the Middle Fork. The reach immediately upstream from the restoration was not chosen, because it is above a major grade control (the concrete fish ladder) and therefore not influenced by the project. As previously discussed, the unnaturally large, flashy flows coming out of the culvert are thought to be a major source of the incision that occurred at the Capistrano Bridge. Because this problem remains, this sample is important to understanding aspects of the restoration's longer term sustainability. In addition, the City of Pacifica is developing a new storm drain master plan. If that plan recommends increasing storm drain capacity, it may result in increased outflow at the culvert which could impact the restoration. The second, solution reach, is the 396 m (1,300 ft) restoration area. The third reach was selected to help assess what, if any, effects the restoration is having downstream. The 92 m (302 ft) reach immediately below the restoration area was chosen to ensure that any influences from the Sanchez Fork, which joins the main stem further downstream, were not included.

Figure 4: Study conceptual model.

Figure 5: Aerial view of the three study reaches. Dashed boxes indicate study areas. Base map Bing Map (c) 2010 Microsoft Corporation and its data suppliers.

Comparison Data

Table 3 summarizes potential sources of comparison data. Comprehensive geomorphic data, including longitudinal profiles, cross-sections, bed substrate, and bank material and condition, were collected before the restoration for San Pedro Creek (Collins et al*.* 2001; Davis et al*.* 2002) and the Middle Fork (Amato 2003). For the North Fork, only longitudinal profiles and cross-sections exist (Amato 2003). Since the restoration, two San Francisco State University student groups surveyed cross-sections and partial longitudinal thalweg profiles in the restoration area (Crowley and Edgell 2006; Tatu and Krizan 2008). The restoration area was also surveyed by Balance Hydrologics, the firm hired by the City of Pacifica to do the hydrologic analysis for a monitoring study (TRA and Balance 2008).

Table 3: Available comparison data.

	Study Area	Long Profile	Cross-sections	Additional Data
Collins et al. 2001 (1999)	Lower 4 km (2.5 miles)	Yes	22	Comprehensive geomorphic data
Amato 2003 (1999, 2000)	North and Middle Forks	Yes	At the confluence	Rain gage, discharge, turbidity, impervious surfaces
Davis et al. 2002 (2001)	Lower 4 km (2.5 miles)	Yes	No	
Crowley and Edgell 2006	Restoration area	Yes (partial)	Steps 1, 8, 10.5, 12	
Tatu and Krizan 2008	Restoration area	Yes (partial)	Steps 1, 8, ~10.5	Pebble counts
TRA and Balance Hydrologics 2008	Restoration area	Yes	Six as indicated in their study (p. 35)	WQ, vegetation, amphibians, casual steelhead count

For the North Fork the available dataset was used, and for the Downstream Reach the 2001 data was known to be a more precise survey and was used for that reason. For the Restoration Reach, all three datasets were analyzed after the 2011 survey was completed, and none were found to be perfect. Both student sources were partial profiles, with missing data for approximately the last 50 m (164 ft) on the steeper, downstream end of the restoration. Additionally, one dataset had an unlikely 51.8 cm (1.7 ft) drop in elevation approximately 61 m (200 ft) downstream from the Capistrano Bridge culvert that continued up to the culvert. Variation in the vertical measurement of the logs occurred in all datasets, but this was expected because of variations in where the logs were measured. Some measurements were taken in the low flow notches that are not flat, and others were taken on top. The dataset provided by Balance Hydrologics (Hastings 2011) covered the entire reach. However, the locations of three of the log steps were not documented and they had surveyed fewer points, averaging a point every 3.9 m (12.8 ft). The student data was similar to that of the 2011 survey for which average point distance was every 1.4 m (4.6 ft).

After analyzing all three datasets, the Balance data was chosen because it covered the entire reach and it was a good horizontal match. The three missing log weirs were easy to locate based on peaks in elevation at the expected location of each. Given that three large, consecutive logs were missed, it seemed likely that the surveyors forgot to document them in their notes. After the three missing log locations were estimated, only small horizontal adjustments had to be made to most of the data.

The culvert, log weirs, and end of restoration were used as match points for the two datasets, and Equation 1 was applied to every surveyed point of the 2008 data to adjust the horizontal distance between each set of match points:

$$D_{a(i)} = D_{a(i-1)} + \frac{(u_2 - u_1)}{(v_2 - v_1)} \times (D_i - D_{a(i-1)}) \quad [1]$$

$D_{a(i)}$ = adjusted distance, $D_{a(i-1)}$ = adjusted distance of the 2008 upstream point, u_2-u_1 = the distance between two log weirs in the 2011 data, v_2-v_1 = the distance between the same two log weirs in the 2008 data, D_i = the unadjusted distance of the 2008 point being adjusted.

The average adjustment was 70 cm (2.2 ft) over areas that averaged 23.8 m (78 ft). However, the 2008 survey was 4.7 m (15.4 ft) shorter between log weirs 11 and 12, a span of 51 m (167 ft), where the creek flows around a significant bend. This is thought to be due to differences in how the tape was laid around the bend.

Fieldwork

Field work was completed during the summer of 2011 and involved ten days of surveying and four days examining banks and logs and taking photos. Two faculty members, Davis and Oliphant, assisted with surveying, as did six graduate students, all of whom had experience doing stream surveys. The survey was performed with a Leica Sprinter 250M digital level, and a Suunto compass was used to set the horizontal circle. Table 5 lists all field equipment used for the study. Measurements were taken in decimal feet to enable matching with prior surveys. However, all results have been converted to meters. The study variables are given in Table 5.

Table 4: Equipment used in fieldwork

EQUIPMENT LIST	
Leica Sprinter 250M digital level	Pruning shears
Tripod	Plastic tape (pink)
Digital stadia rod	Marking pen
Telescoping rod	Stakes
Camera	Hammer
Field notebooks and pencils	ID keys
Trekking pole	Pacifica vests
Suunto compass	First aid kit
Cell phone	Insect repellant
100 m tape	Collins' streamline graph
Hip waders/rubber boots	Questa as built drawings

Table 5: Study variables by reach.

Variable	Reach 1: North Fork	Reach 2: Restoration Area	Reach 3: Downstream
Longitudinal Profile			
Thalweg	Yes	Yes	Yes
Channel-bed slope	Yes	Yes	Yes
Water surface	Yes	Yes	Yes
Water surface slope	Yes	Yes	Yes
Pools	Yes	Yes	Yes
Riffles	Yes	Yes	Yes
Step Location	NA	Yes	NA
Substrate	Yes	Yes	Partial
Channel Cross-section			
Bank profile	Partial	Partial	NA
Water's edge	Yes	Yes	NA
Water depth	Yes	Yes	NA
Substrate	Yes	Yes	No
Observed Conditions			
Eroding banks	Yes	Yes	Yes
Revetments	Yes	NA	Yes
Log weir steps	NA	Yes	NA

Longitudinal Thalweg Profiles

For the longitudinal thalweg profiles, a 300 ft decimal tape (91.4 m) was secured at one end and then pulled and laid out in the center of the creek. Distance stations were marked with pink tape tied to tree limbs every 25-50 ft (7.6-15.2 m). Standard level survey procedures were followed as described in Harrelson et al. (1994). Surveying began in the Downstream Reach, because there was a known benchmark to set the height of the survey instrument and match the survey to the longitudinal profile completed in 2001 (Davis et al. 2002).

The longitudinal survey followed the thalweg (the flow of the deepest water in the channel). On a few occasions, when water was too deep to safely measure, the reading was taken as close to the thalweg as was possible. The person with the stadia rod walked upstream, stopping at all points indicating a change in measurement. To minimize error, the principal investigator set the horizontal circle at most turning points, was the official note taker, and directed the assistant with the stadia rod to points of interest for most of the surveying. The digital level automatically recorded height and horizontal distance. These data, along with the direction of the horizontal circle, water depth as read from the stadia rod, and a description of the substrate, were also recorded manually. The substrate surrounding each point was estimated visually and categorized as Quaternary clay, silt, sand, gravels, cobbles, boulders, logs, and/or vegetation. Multiple categories were allowed.

Elevation readings on the log weirs were taken in the low flow notch if one was present. When distance or vegetation obstructed views, a control point was identified, a reading taken, and it was either marked with yellow paint or the person with the stadia rod stayed in place until the level was set up in a new site and a foresight could be taken to set the height of the instrument. Every evening, data from the digital level was downloaded into an Excel spread sheet and all additional notes were entered. The level was recalibrated for vertical accuracy using the peg-to-peg method twice during the course of the study. For the Restoration Reach, the total taped distance recorded in the survey was 381 m (1250 ft).

Cross-sections

For the North Fork and Restoration Area reaches, the students' who originally surveyed the cross-sections volunteered to assist with surveying. They were both successful in locating the rebar monuments they had placed years before. For each, a tape was pulled across the channel from one rebar stake to the other with the zero point on the left bank (all banks are identified facing downstream). At the North Fork, the digital level was set up over the zero point on the cross-section so that all readings were at the same angle in degrees. By surveying from a point in the vertical plane, the distances recorded by the digital level can be used directly. This was not possible in the Restoration Reach because of dense vegetation, so taped distances were used instead.

An attempt was made to survey at least one cross-section in each reach. For the North Fork, the only comparison cross-section available was used. It was located at the confluence of the North Fork and Middle Fork. In the Restoration Reach, the cross-section was located in a riffle area between Logs 10 and 11 at approximately 2595 m (8514 ft). Due to large trees and shrubs, it was not possible to survey the upper banks. A second cross-section was planned at a well-monumented site between two telephone poles. However, the vegetation so obstructed the view that it was not attempted. In the Downstream Reach, a cross-section was attempted at 2408 m (7903 ft), but the monuments from the 2001 survey could not be located.

Observed Conditions

The method of assessing bank conditions varied by reach, because of differences in the availability and quality of comparison data. No comparison data is available for the North Fork Reach, so all revetments and unusual conditions were recorded. In the Restoration Reach, the extensive bank and bed data collected by Collins et al*.* (2001) is no longer applicable with two exceptions; the gabions that were left in place during the restoration, and the location of culverts. For this area, the researchers walked up the channel and recorded any problems noticed. However, it was difficult to visually identify erosion of most banks because of root wads and other vegetation that effectively hid lower bank problems. This situation became apparent while surveying the cross-section. An undercut in the bank that was clearly revealed while surveying, had not been noticed during the earlier visual inspection. In the Restoration Reach, the log weir steps were also observed and problems noted.

For the Downstream Reach, the extensive data collected by Collins et al*.* (2001) was used. The researchers walked up the channel with the data sheets in hand, compared bank conditions with previously noted conditions, and noted those that had changed. A summary of key data collection information for each reach follows (Table 6):

Table 6: Data collection information by study reach. Dates in parenthesis indicate year study conducted if different from date of publication.

	North Fork Reach	Restoration Reach	Downstream Reach
Reach Length	87 m	381 m	92 m
Drainage Area	6.13 km^2	12.7 km^2	13 km^2
2011 Survey Dates			
Long Profile	6/20	6/27, 7/6, 7/19, 7/23	6/13, 6/22
Cross-section	7/10	7/25	8/10 (attempted)
Visual Surveys	6/20	7/13, 7/15, 8/22	6/13, 6/22
Comparison Data			
Long Profile	Amato 2003 (1999, 2000)	Balance 2008	Davis et al. 2002 (2001)
Cross-sections	Amato 2003 (1999, 2000, 2001)	Crowley 2006	NA
Bank Surveys	NA	NA	Collin et al. 2001(1999)
Longitudinal Profile Benchmarks	GPS reading taken by Davis 1/2012	Continuation of survey from downstream sample	Matched to Davis et al. 2002 profile at TP 35 Station 7862

Estimating Elevation Change

To estimate elevation change in each reach, the following interpolation formula (Equation 2) was used to create matched points, every 5 m (15 ft), between the 2011 survey and the comparison data.

$$z_{int} = z_1 + \frac{(x_{int} - x_1)}{(x_2 - x_1)} + (z_2 - z_1) \quad [2]$$

z_{int} = the elevation of the interpolated point, x is horizontal distance, z is vertical distance, and $_{int}$ is the interpolated point between them.

The resulting data was used to calculate estimates of the annual rate of elevation change and change as a portion of bankfull depth for each reach.

Interviews

Information from key informant interviews was used to fill gaps in the written materials, especially to aid in understanding the decision making process that led up to the final plans (Table 7). Jerry Davis, past president of the SPCWC, the nonprofit watershed group formed in 1999 in support of San Pedro Creek, provided the names of those most involved in the CBFPRP. Everyone was interviewed with the exception of the former coordinator of the SPCWC, Christine Chan, and L. C. Lee, the engineer originally hired to design the project. However, his replacement, Sydney Temple, who both designed and supervised implementation of the final project, was interviewed. Davis and Bill Bassett were interviewed in person; the others by phone.

Table 7: Key informant interviews.

Interviewee and Date	Project Role	Relevant Affiliation(s)
Jerry Davis Feb. 23, 2011 April 20, 2011	President	San Pedro Creek Watershed Coalition Pacifica property owner (not in project area) Geomorphologist, San Francisco State University, Geography Professor
Scott Holmes April 9, 2011	Project Director, Engineer	City of Pacifica Department of Public Works (retired)
Laurel Collins April 4, 2011	Consultant, Geomorphologist	San Pedro Creek Watershed Coalition
Roger Leventhal April 1, 2011	Consultant, Engineer	San Pedro Creek Watershed Coalition
Bill Bassett April 8, 2011	Board Member	San Pedro Creek Watershed Coalition Pacifica property owner in project area.
Sydney Temple March 30, 2011	Design Engineer, Hydrologist	Questa Engineering, sub-contractor to Power Engineering hired by City of Pacifica

V. DATA ANALYSIS AND RESULTS

The geomorphic analysis includes elevation change, slopes, pools and riffles, substrate, and identification of observed problems for all three reaches. In addition, step-pool geometry is analyzed in the Restoration Reach. Data analysis and results are discussed in five sections: 1) Restoration Reach results, 2) Downstream Reach results, 3) North Fork Reach results, 4) comparison of the three study reaches, and 5) Restoration Reach step-pool comparisons.

Restoration Reach Results

In 2005, the 396 m (1,300 ft) Restoration Reach that drains 12.7 km^2 of the San Pedro Creek Watershed was restored. It was transformed from a deeply incised, unstable reach that created a barrier for fish passage, to a primarily step-pool morphology that now has the appearance of a stable reach. Prior to the restoration, the reach had the greatest length of eroding banks (53%) of all reaches and lowest percentage of stable banks (30%) in the entire 3.86 km (2.4 miles) of San Pedro Creek (Collins et al. 2001). As already discussed, the distance recorded in the 2011 survey was shorter; for this analysis it was measured at 381 m (1250 ft).

While the primary comparison data is from 2008 (Balance 2008), the as-built plans (Questa 2005c) and 2001 survey by Collins et al. are also referenced (Figure 6). The 2001 survey is relevant to the study question of potential impacts downstream and the as-built plans provide a frame of reference for understanding the restoration. However, not all of the features were as they appeared in the as-built plans. Most notably, there was an extra log weir step, fewer rock weirs, and the V-shaped log weir shown at the downstream end of the restoration was not there. The anchors for the V-shaped weir failed during a storm on December 31, 2005, and the two logs were cabled to the right bank approximately 25 m (82 ft) downstream (Temple, January 30, 2012, pers. comm.). The storm, estimated at 950 f^3/s (26.9 m^3/s) (TRA and Balance 2008), is the largest to have occurred since the restoration. Some of the missing rock weirs may have also repositioned and spread out during the storm. Regarding the extra log step, the researcher was informed that it must have been unintentionally left out of the plans, because no logs have been added since the restoration (Temple, January 30, 2012, pers. comm.). A summary of key findings related to specific variables follows, after which the results are listed by location, referencing log weir numbers and distance stations.

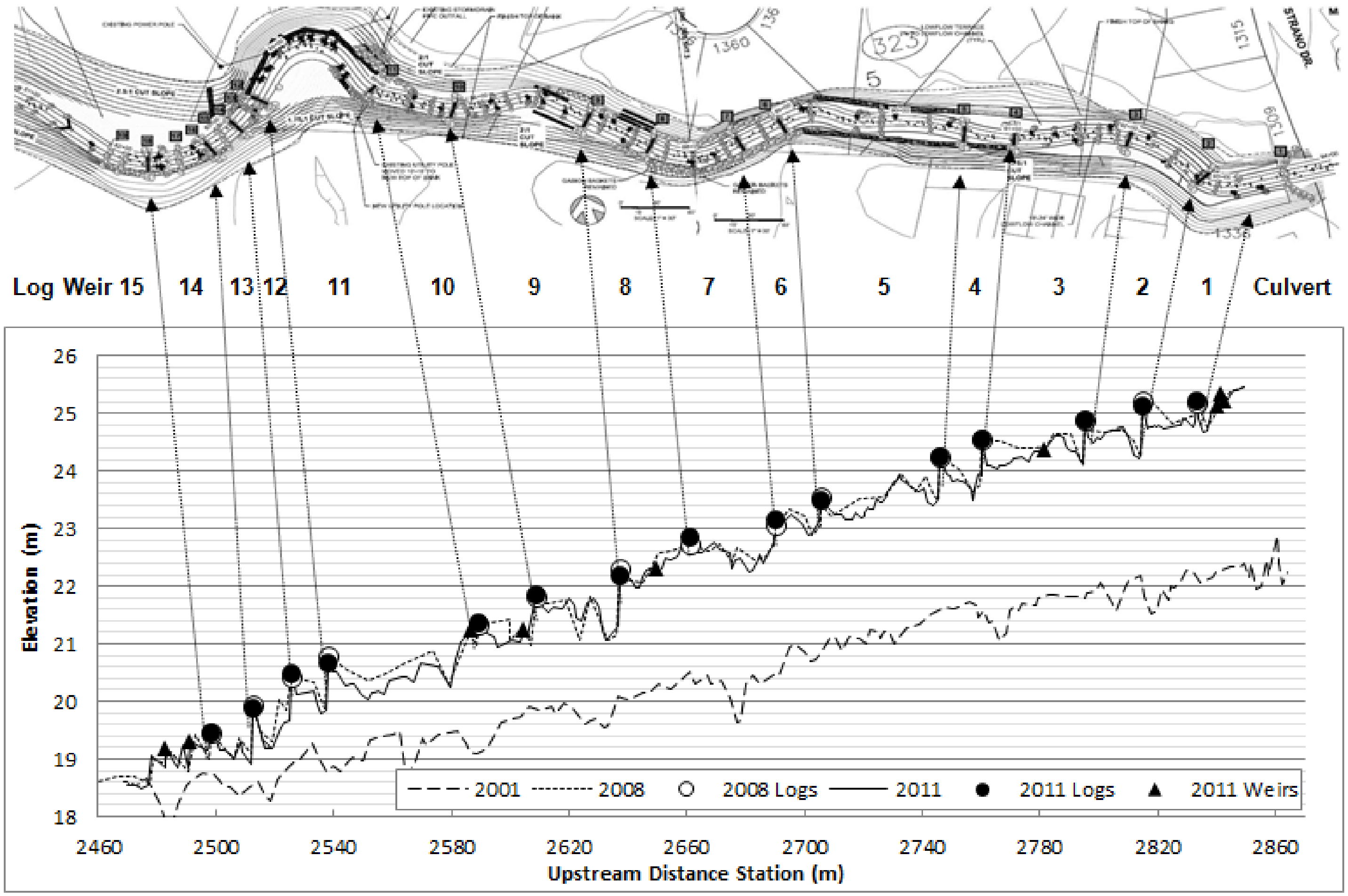

Figure 6: Restoration Reach longitudinal profiles 2001, 2008, and 2011 in relation to as-built plans. 2001 data source Davis et al. (2002). 2008 data source Balance Hydrologics. Diagram created using partial as-built drawing courtesy of Questa E.C.

Slopes

A significant change in slope occurred throughout the reach when the channel bed was raised for the restoration (Table 8). Depending on how slope was calculated (linear regression or average measured gradient), the 2011 end-to-end channel bed slope was 0.65-0.95% higher than it was in 2001, and the water surface slope was 0.79% higher using linear regression. An even larger increase has occurred at the lower end of the reach below Log Weir 13. There, the channel bed slope was 0.74-2.41% greater in 2011, depending on the method of calculation. Slope changes from 2008-2011 were not as significant.

Table 8: Restoration Reach slopes 2001-2011. 2001 data source Davis et al. (2002). 2008 data source Balance Hydrologics (2008).

	Channel Bed Slope (gradient)	Channel Bed Slope (linear regression)	Water Surface Slope (linear regression)
2011 Reach	1.80%	1.75%	1.88
• Culvert- Log Weir 13	1.54%	1.65%	1.73
• Log Weir 13-End	3.31%	1.84%	2.32%
2008 Reach	1.77%	1.77%	1.78%
• Culvert-Log Weir 13	1.56%	1.66%	1.64%
• Log Weir 13-End	2.74%	2.04%	2.11%
2005 As-built plans	1.8%		
2001	0.90%	1.10%	1.09%

Elevation Change

The longitudinal profile suggests (Figure 6), and interpolated data from the two matched datasets (Figure 7) confirms that, while aggradation occurred in some places within the reach, degradation has occurred throughout most of it. When the data was interpolated, 21 of the 79 matched points required crossing steps to calculate the interpolation so they were rejected. Therefore, the results are slightly more reflective of areas further away from the steps than close to them. The mean elevation change between 2008 and 2011 was -8.5 cm (-0.28 ft) with an average annual rate of change of -2.8 cm (-0.9 ft). According to the survey data, the most degradation occurred in two pools, both located immediately above log steps; -40 cm (-1.3 ft) above Log Weir 4 and -30 cm (-1.0 ft) above Log Weir 2. Correlation between elevation change and distance station was tested and rejected using Spearman's test. The correlation coefficient was 0.008 and the single-tailed p-value of 0.478 was greater than 0.05; therefore, it is not significant at a 95% confidence level.

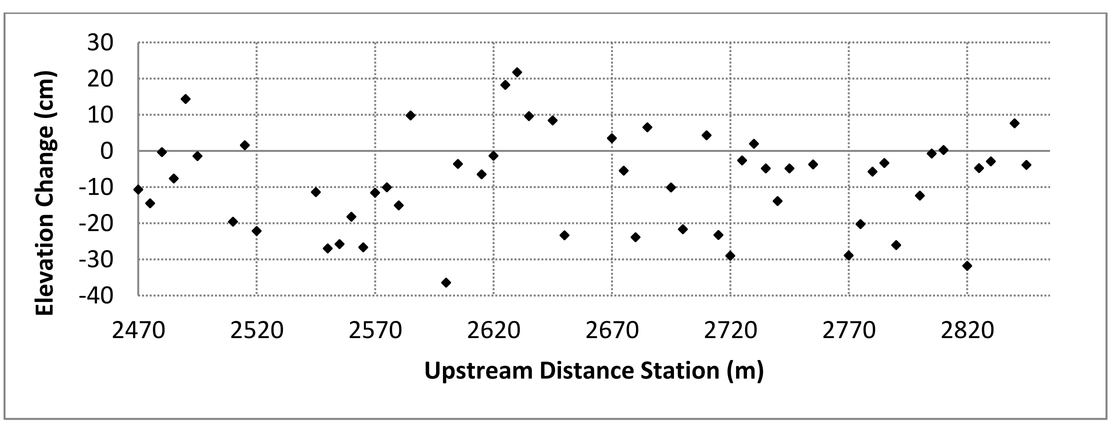

Figure 7: Restoration Reach interpolated elevation change 2008-2011.
Datasets matched and interpolated every 5 m.

Cross-section

The cross-section (Figure 8) was surveyed in a straight, riffle reach at approximately 2595 m (8514 ft) between Log Weirs 10 and 11, where the channel bed consists of sand and gravels. It indicated aggradation averaging 20 cm (0.7 ft) on the right bank, degradation in most of the channel, and an undercut in the left bank of 45.7cm (1.5ft). These changes could be due to a minor perturbation, or the undercut could be a sign of lateral widening caused by the increase in stream power from the steeper slope and relatively steep bank. The comparison data for the cross-section is from 2006, two years earlier than that used in the longitudinal profile.

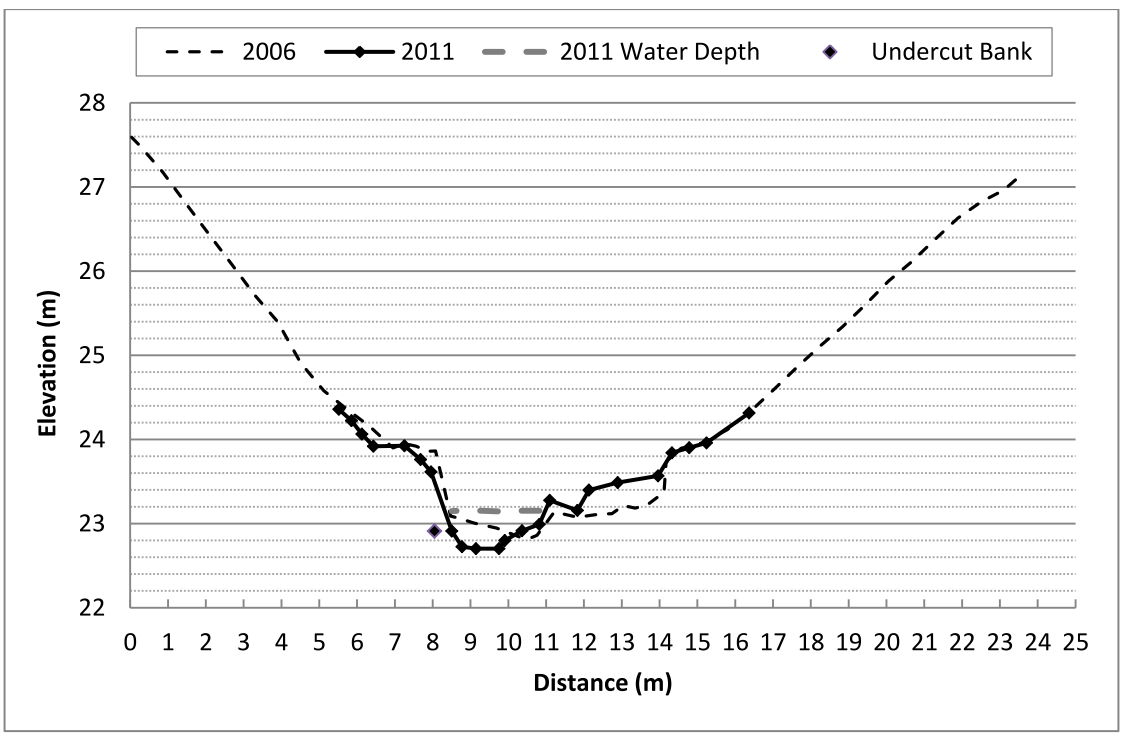

Figure 8: Restoration Reach cross-section 2006-2011. 2006 data source Crowley (2006).

Steps, Pools, and Riffles

Fifteen large log weir steps were identified, and smaller steps formed by boulders and rock weirs created riffle-like areas between Log Weirs 5-6, 8-9, and Log Weir 15 to the end of the restoration. An analysis of the step-pool geometry, comparing it to that found in nature and in other restoration projects, is at the end of this chapter. Twenty pools were identified, equal to the number found in the 2008 survey (TRA Balance 2008). Areas with two pools were located where step length was longer, between Log Weirs 1-2, 2-3, 3-4, 5-6, and 7-8. However, the longest step, where the creek flows around the bend between Log weirs 11-12 had only one pool. This was also the narrowest section of the low-flow channel in the Restoration Reach, 2.44 m (8 ft), and it had the second deepest pool, 85 cm (2.8 ft).

Undercut steps were identified as a problem in two of the reviewed step-pool projects (Table 2 p. 31), and they were also observed in the Restoration Reach. Two logs were undercut, at Log Weirs 12 and 14, and a vortex was developing above Log Weir 13 that may indicate an undercut forming. Log Weir 14 was also recorded as being undercut in the 2008 survey although its location, as identified in the 2008 survey data, was misrepresented in the report (TRA and Balance 2008). Photo 5 shows the undercut Log Weir 14, and in contrast, Photo 6 is a view of a well-performing log. In addition, property owners at the upstream end of the reach reported having filled in undercuts at the logs abutting their properties (Basset 2011).

Photo 5: Undercut at Log Weir 14 at 2513 m.

Photo 6: A well-performing log step, Log Weir 9 at 2437 m.

Substrate

Figure 9 shows the distribution of substrate for the Restoration and Downstream reaches. There was no comparison data from 2008. In 2011, the distribution of boulders increased downstream. This is in contrast to the substrate found before the restoration. Prior to the restoration, the Restoration Reach was considered a pool-riffle reach, which is typically made up of gravels. Gravels were the dominant substrate (39%) found in the 1999 survey (Collins et al. 2001), and no boulders were identified at that time. The presence of boulders in 2011 is likely due to the large amount of rock that was added to the channel bed to create surface roughness (Photo 4, p. 15). Additionally, the December 31, 2005 storm likely moved some of the rock, as well as some of the rock weir material, downstream. Cobbles, which were also absent in the 1999 survey, occurred in clusters, with more in the upper third of the reach. Gravels were generally distributed throughout, but they decreased downstream. Although not shown on the substrate survey, a large gravel bar has developed inside the Capistrano Bridge Culvert indicating greater sediment supply than transport capacity at this location. Sand was found in most of the reach except at the lower end, beginning near Log 14. Most silt and Quaternary clay was found in the upper third of the reach.

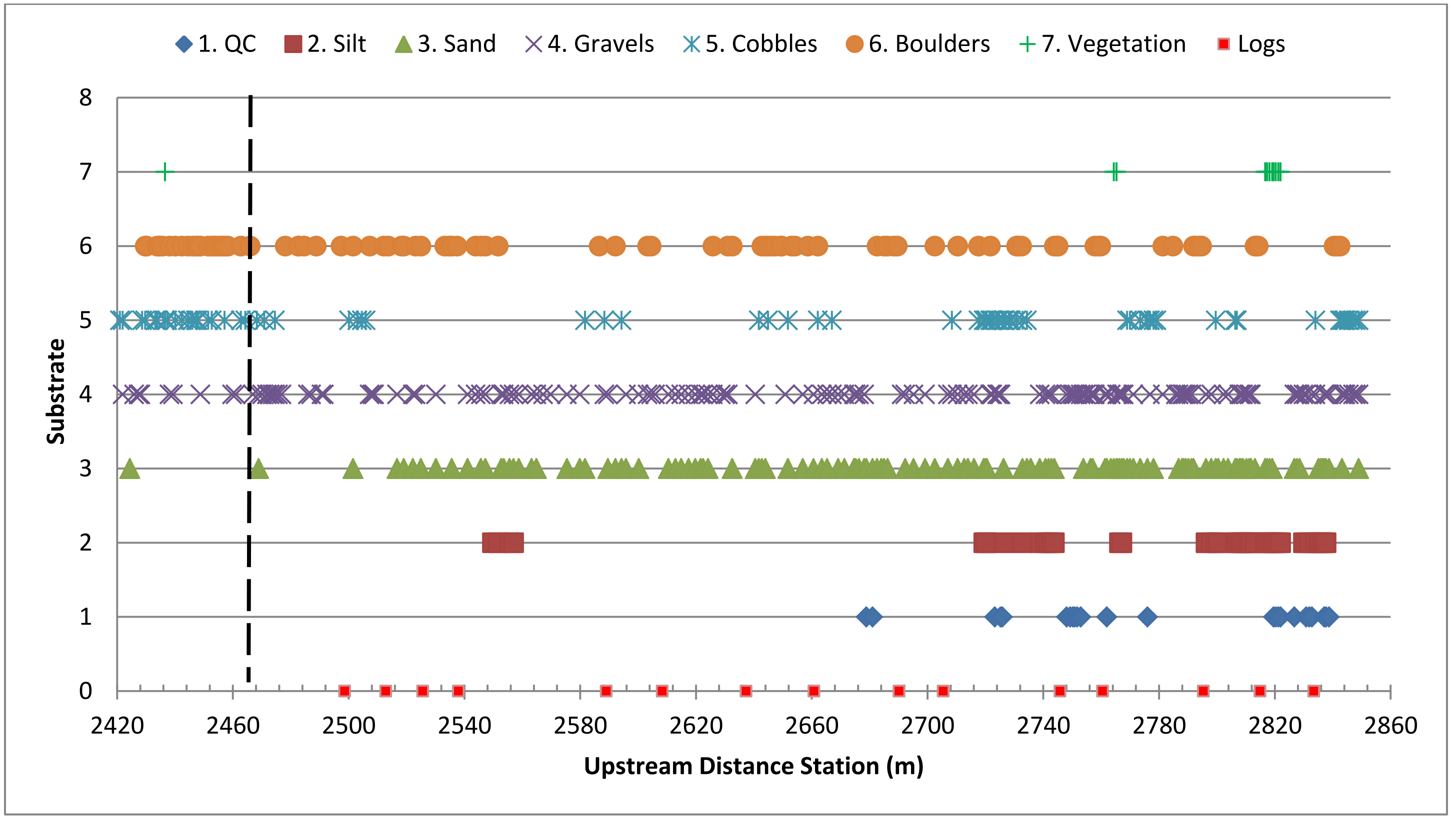

Figure 9: Distribution of substrate in the Downstream and Restoration reaches. The dashed line separates the two reaches; red markers on the bottom indicate log weir locations.

Other Observed Conditions

During the restoration, all but the largest trees were removed from the banks, and 13,000 native trees and shrubs species were planted throughout. The 2008 monitoring report found a vigorous three-storied canopy which remains today. One plant not mentioned in 2008, which appeared to be having a deleterious effect, was pampas grass. Pampas grass covered an island located immediately outside of the Capistrano Bridge culvert, and it was forcing the flow of water to the right bank (Photos 7 and 8). While it is not likely to threaten the restoration, it may present local erosion problems on the right bank property, a concern mentioned by the property owner.

Photo 7: Downstream view of pampas grass island at Capistrano Bridge culvert at ~2850

Photo 8: Upstream view of pampas grass island at Capistrano Bridge Culvert at ~ 2850

Another pampas grass covered island occurred near the downstream end of the reach, on the left bank side between the two lowest weirs. This was the widest section of the channel, 8.84 m (29 ft), and it appeared as though the island had forced the flow of water to the left bank, causing erosion in this area. Pampas grass was also present, and likely responsible, for the narrowing of the low-flow channel around the bend on the left bank. The lower right bank around the bend may be eroding (Photo 9), but it was unclear because root wads that lined the bank made visual interpretation difficult. In addition, the upper right bank below the Sanchez Art Center was almost entirely covered with invasive species, as was the small flood plain located above the bend below Log Weir 11. Human impacts were visible in the form of garbage in the creek, including a bicycle trapped in the vegetation below Log Weir 11. Finally, some of the gabions, which were installed before the restoration and left in place, were showing signs of rust.

Photo 9: Possible erosion at alder roots around bend at ~2550 m

Summary of results by location

Table 9 is referenced to the distance station and log locations as described on the longitudinal profile (Figure 6).

Table 9: Restoration Reach results by location.

Log # and Distance Station	Description
Capistrano Bridge Culvert to Log Weir 1 2849-2833.4	• A large gravel bar has formed inside the culvert, and a pampas grass-covered island has developed immediately outside . Inside the culvert, the low-flow channel was narrow, approximately 1 m (3.3 ft) wide. • The combined effect of the gravel bar and the island is that, with the exception of high flow conditions, the entire flow is forced to the right bank side of the channel and the left bank side is left dry. While this is not likely to threaten the restoration, it may present local erosion problems on the right bank property. • There were two pools (the upstream pool was shallow), separated by a large, curved rock weir that begins ~ 6 m (19.7 ft) below the culvert.
Log Weirs 1-2 2833.4-2814.8	• Log Weir 1was set on an angle, rather than level across the creek as are the others. The right bank side was higher and the left side completely submerged. This is the log that is missing from the as-built plans. • A large patch of watercress was growing on the right bank between Log Weirs 1 and 2, narrowing the channel until it bends to the right and re-opens. • One of two areas with the highest recorded elevation loss since 2008 was a pool above Log Weir 2, at ~2822, where it degraded 30 cm (1 ft). • The property owner adjacent to Log Weir 2 reported filling in an undercut that formed above this log on more than one occasion.
Log Weirs 2-3 2814.8-2795.3	• Two pools were separated by a run.
Log Weirs 3-4 2795.3-2760.5	• A small rock step and weir separated two pools. • The property owner adjacent to these logs reported filling in undercuts that developed above the logs (Bassett April 8, 2011 pers. comm.). • The pool above Log Weir 4, at 2765, had the highest recorded elevation loss since 2008. It degraded ~40 cm (1.3 ft).
Log Weirs 4-5 2760.5-2745.7	• The third deepest pool in the reach, 85 cm (2.78ft), was located at 2757.1
Log Weirs 5-6 2745.7-2705.4	• Small boulder steps separated two pools.

Log Weirs 6-8 2705.4 2690.2 2660.8	• Log Weirs 6-8 were not documented in the 2008 survey, and their location was estimated as discussed earlier.
Log Weirs 7-8 2690.2-2660.8	• This area had a small pool upstream, and larger pool downstream • Log Weir 8 was completely underwater.
Log Weirs 8-9 2660.8-2637.3	• This area had small boulder steps and a weir in the middle.
Log Weirs 9-10 2637.3 2608.5	• The deepest pool was below Log Weir 9 at 2632.6 and measured 97 cm (3.2ft).
Log Weirs 10-11 2608.5-2589.0	• The cross-section is located at ~ 2595. It indicated aggradation on the right bank, erosion in the channel, and an undercut of approximately 45.7 cm (1.5 ft) on the left bank.
Log Weirs 11-12 2589.0-2537.9	• Log Weir 11 was underwater. • An abandoned bicycle was found, trapped in vegetation on the right bank below Log Weir 11. • The area around the bend was the narrowest low-flow area of the reach, measured at 2.44 m (8 ft). • A floodplain on the left bank was covered with invasive plants. Most notably, a thick mass of pampas grass was lining the left bank edge of the channel. • The second deepest pool in the reach, 85 cm (2.8 ft), was located on the downstream end of the bend at 2551.6. • The right bank around the bend appeared to be eroding, but a visual inspection alone cannot ascertain whether the exposed roots are due to erosion or part of the root wads and vegetation planted to keep water away from the bank.
Log Weirs 12-13 2537.9-2525.6	• Log Weir 12 was being undercut from above and had no water flowing over it. • A small vortex was developing above Log Weir 13, suggesting that an undercut may be developing.

Log Weir 13-15 2525.6-2498.6	• Much of the upper right bank slope, located beneath the Sanchez Arts Center (approximately between Log Weir 13-and the end of the restoration) was covered with invasive plants. • Although fenced, this was the one area with easy public access down into the creek through a break in the chain-link fence.
Log Weirs 14-15 2512.8-2498.6	• Log Weir 14 was being undercut from above and had no water flowing over it. • A small rock step was located between the two logs.
Log Weir 15-End 2498.6-2468.9	• Log Weir 15 was originally misidentified as a rock weir. • Two rock weirs were located downstream, followed by small boulder steps. • A pampas grass covered island has developed between the two lowest weirs on the left bank side. • This was the widest section of the channel, 8.84 m (29 ft). The island may have directed the flow of water to the left bank, causing erosion in this area. • The gabions on the left bank appeared to be rusting. • The anchors to the V-shaped log weir shown on the as-built plans (Questa 2005c), failed during a storm on December 31, 2005. It has been cabled to bank trees, approximately 25 m (82 ft) downstream for fisheries habitat (Temple, January 30, 2012, pers. comm.).

Summary

Raising the creek bed has resulted in a significant increase in channel bed and water surface slope, especially in the lower end of the reach below Log 13. Since 2008, degradation has occurred throughout most of the reach, averaging -2.8 cm (-0.89 ft) per year. The undercut bank identified in the cross-section could be a minor perturbation, or a sign of lateral widening. The number of pools has remained the same since 2008, 20. At least one pool has formed between each log step and two between five of the six upper steps. Sand and gravels were distributed throughout the reach, and a large gravel bar has developed under the Capistrano Bridge Culvert. Cobbles occurred in clusters with more in the upper reach. The distribution of boulders increased downstream. This is likely due to the large amount of rock and boulders added to the creek bed during restoration. The large storm that occurred December 31, 2005 may be, in part, responsible for the movement of so much of the larger material downstream. Two of the log steps were being undercut (Log Weir 12 and 14), and an undercut may be developing at Log Weir 13. Log Weir 14 was also reported as being undercut in 2008 (TRA and Balance 2008). Two upstream property owners also reported filling-in undercuts in logs abutting their properties. Human impacts were visible in the form of trash on some of the banks, including an abandoned bicycle. Invasive species covered the small floodplain on the left bank of the bend and the upper bank below the Sanchez Art Center. Pampas grass was growing on two islands, one at the Capistrano Bridge Culvert and the other and the downstream end of the reach. Both of these islands were forcing the flow of water to one bank; the upstream island to the right bank, and the downstream island to the left. Some of the gabions, which were placed before the restoration, were showing signs of rust.

Downstream Reach Results

The Downstream Reach is a 92 m (301.8 ft) primarily pool-riffle reach that drains an area of 13 km^2 (5.2 $miles^2$), and it is steeply banked on both sides of the channel. Residential homes sit on top of the left bank, while the top of the right bank is primarily vegetation. Collins et al. (2001) classified the reach as 50% Rosgen Class B, 29% Class F and 21% Class G. Class B is considered stable, while the others are unstable and entrenched.

Since 2001, the channel bed and water surface slope have both increased indicating an increase in stream power (Table 10).

Table 10: Downstream Reach change in slope 2001-2011.
2001 data source Davis et al. (2002).

	Channel Bed Slope (m/m)	Channel Bed Slope (linear regression)	Water Surface Slope (linear regression)
2011	1.18%	1.45%	1.29%
2001	1.13%	1.28%	1.26%

The longitudinal profile (Figure 10) suggests, and interpolated data from the two matched datasets (Figure 11) confirm, degradation throughout most of the reach. The mean elevation change over the ten year period was -15.6cm (-0.51 ft) or -1.55 cm (-.05 ft) per year. The highest amount of degradation occurred in a downstream pool located approximately 6 m (19.6 ft) downstream from a 30.48 cm (1 ft) culvert that comes in on the left bank. Correlation between elevation change and distance station was tested and rejected using Spearman’s test. The correlation coefficient was 0.437 and the single-tailed p-value of 0.062 was greater than 0.05; therefore, it is not significant at a 95% confidence level. Four distinct pools were identified, separated by three riffle areas and a riffle/step area upstream. The areas with the most aggradation were two riffle areas; one above and the other below the area of deepest degradation. An approximate 7 m (23 ft) long area of recent erosion was identified on the right bank, immediately below the area where the two logs from the restoration area were cabled to right bank trees in 2006. Collins' geomorphic analysis (2001) did not indicate any erosion at this site. Table 11 summarizes results by location.

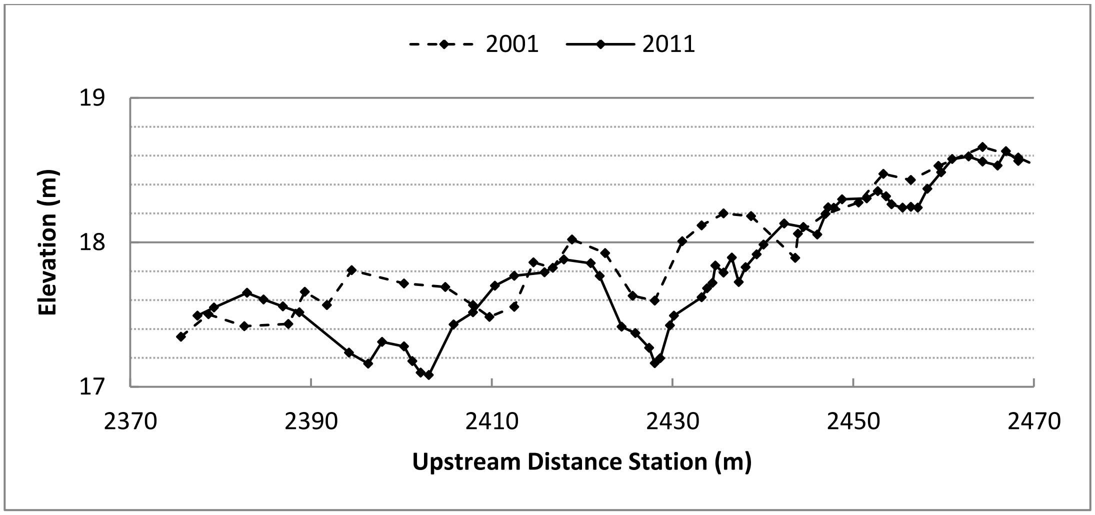

Figure 10: Downstream Reach longitudinal profiles 2001-2011. 2001 source (Davis et al. 2002).

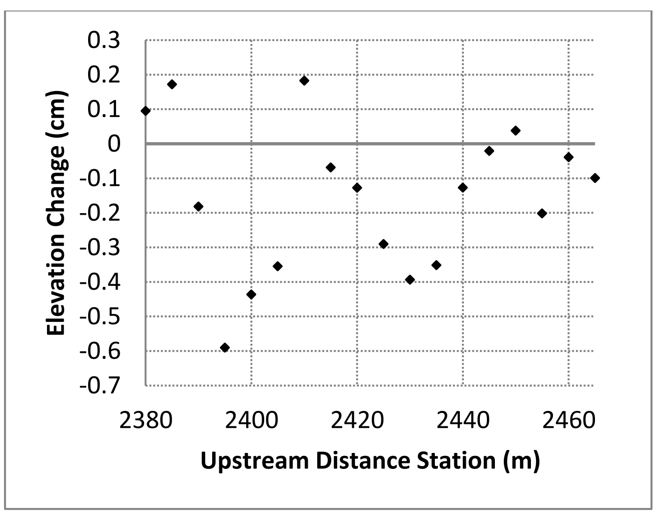

Figure 11: Downstream Reach interpolated elevation change 2001-2011. Datasets matched and interpolated every 5 m (16.4 ft).

Table 11: Downstream Reach results by location.

Distance Station	Description
2466.6-2457.4	• Area of riffles and small steps coming down from the restoration area
~2443-2434	• Monterey pine logs from Restoration Reach anchored to right bank trees for fish habitat.
~2435-2428	• Area of new bank erosion since 2001 survey.
2428	• Deepest pool in reach 2.9 m (9.5 ft).
2421.3-2407	• Large riffle area.
2403	• Second deepest pool in reach 2.4 cm (7.8 ft).
2400.6	• Left bank 30 cm (1 ft) pipe outflow into creek.
2395	• Highest degradation in reach 65 cm (2.1 ft).

In 2011, substrate data was not collected in the lowest 40 m (131 ft) of the reach, so the comparison is limited to the upper 52 m (170.6 ft). In addition, different methods were used to characterize substrate in the two surveys. In 1999, Collins et al. (2001) made visual median diameter (D50) estimates for the entire channel, whereas the method used in 2011 was based on a visual estimate of the substrate surrounding each point. In 1999, a majority of sediment was sand and gravels (58%), while in 2011 75% was cobbles and boulders (Table 12). The difference between boulders was large, with 4% in 1999 and 41% in 2011. It seems likely that this material has been recruited from the Restoration Reach, given the large number of boulders placed during the restoration and the current distribution of substrate which shows the percentage of boulders increasing downstream (Figure 9 p. 54). Additionally, the higher gradient of the restoration area, especially at the lower end, provides the transport capacity to move larger material into the Downstream Reach. However, once there, the lower gradient lacks the transport capacity to keep moving it downstream so it is dropping out. Photo 10 shows the Downstream Reach at ~2438 m where boulders are present.

Table 12: Downstream Reach substrate 1999 and 2011.
1999 data source Collins et al. (2001)

	1999	2011
QC	0%	0%
Silt	4%	0%
Sand	27%	3%
Gravels	31%	19%
Cobbles	8%	34%
Boulders	4%	41%
Vegetation	0%	2%
Concrete	27%	0%

Photo 10: Downstream Reach at ~ 2438 m.

North Fork Reach Results

The North Fork tributary drains a highly developed 6.13 km^2 area through a 30.5 m (100 ft) long, 2.4 m (8 ft) diameter, concrete culvert (Amato 2003). The culvert discharges into the creek approximately 67 m (220 ft) upstream from the confluence with the Middle Fork of San Pedro Creek. While the survey covered 97 m (318 ft), results below the confluence were not included in the analysis because they are influenced by the Middle Fork. Overall the left bank is steeper than the right bank (vertical in many areas), with more Quaternary clay on the left bank and alluvium and vegetation on the right bank.

The slope of the channel bed has not changed since 1999 (Table 13) when measured as a gradient. However, when calculated by linear regression there was a slight increase. The gradient measurement was calculated twice, the higher number is from the base of the culvert, and the lower number begins at the channel bed at the end of the culvert apron.

	Channel Bed Slope (m/m)	Channel Bed Slope (linear regression)	Water Surface Slope (linear regression)
2011	2.0% or 3.0%	2.76%	1.98%
1999	2.0% or 3.0%	2.61%	Not Available

Table 13: North Fork Reach slopes 1999 and 2011. 1999 data source Amato (2003).

The longitudinal thalweg profile indicates (Figure 12), and the estimate of elevation change as determined by interpolated data from the two matched datasets confirms (Figure 13), a pattern of continuing degradation throughout most of the reach. The mean elevation change was -19.6 cm (-0.6 ft) over the past 12 years with an annual rate of change of -1.6 cm (-0.5 ft).

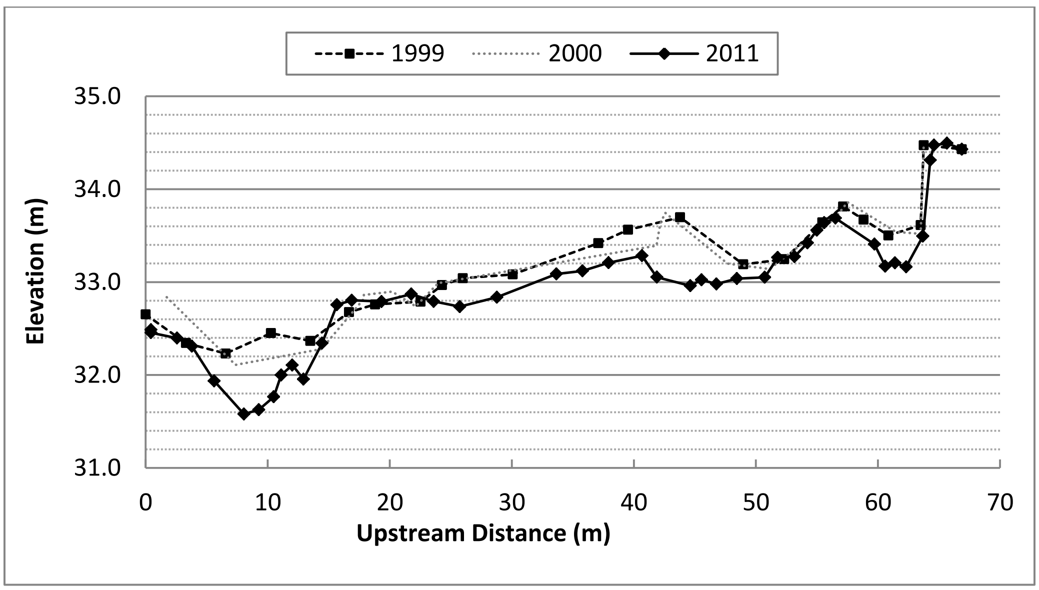

Figure 12: North Fork Reach longitudinal thalweg profiles 1999-2011.
1999 data source Amato (2003).

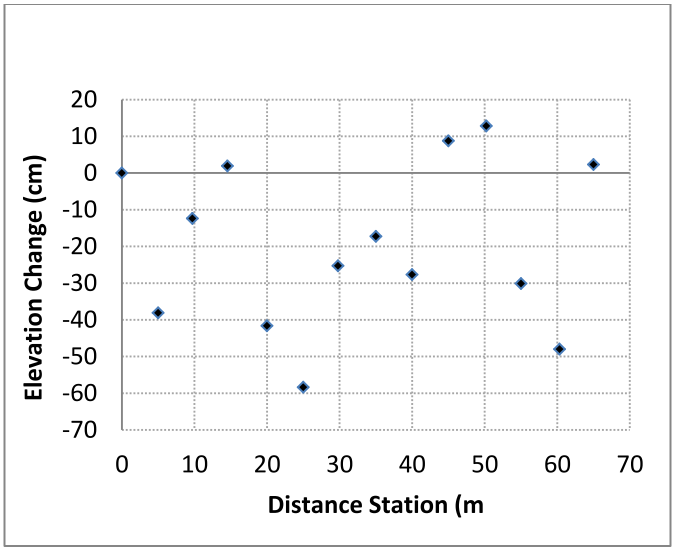

Figure 13: North Fork Reach interpolated elevationchange1999-2001.
Computed from interpolated matched points every 5 m.

Correlation between elevation change and distance station was tested and rejected using Spearman's test. The correlation coefficient was 0.121 and the single-tailed p-value of 0.340 was greater than 0.05; therefore, it is not significant at a 95% confidence level. All areas were degrading except an ~ 4 m (13.1 ft) area of small steps formed from pieces of broken concrete that have not changed, and an ~8 m (26.2 ft) riffle area where some aggradation has occurred (12 cm where it is highest). Erosion began on the concrete apron (Photo 11); the lip has eroded back horizontally -16 cm (-0.5 ft) and vertically -53 cm (-1.7 ft). Immediately below the apron, the pool has deepened by 33-45 cm (1.1-1.5 ft). After the small steps, where no change had occurred, degradation resumed at the location of a piece of plywood that was found lying across more steps. A 4 m (13.1 ft) long wire fence was located on the left bank, and next to it was a wood revetment of 2.4 m (7.8 ft) that was installed after a recent landslide (Photo 12). Aggradation occurred upstream of the landslide and degradation resumed at the location of the revetment. The deepest degradation, ~70 cm (2.3 ft), occurred approximately 1.5 m (4.9 ft) downstream in a deep pool on a bed of primarily Quaternary clay. Table 14 presents the results by location.

Photo 11: North Fork culvert. Eroded apron at lower center.

Photo 12: North Fork revetment at site of recent landslide

Table 14: North Fork Reach results by distance station.

Distance Station	Description
64.28-63.75	• The culvert apron has eroded back horizontally 16 cm (6.3 in) and vertically 53 cm (20.9 in)
62.3	• Blow the apron, degradation was ~40 cm (15.7 in) in the pool.
56.5-51.8	• Area of small steps
~53.0-52.0	• Plywood in creek
41.9-35.8	• Riffle area that has degraded
21.8-16.9	• Riffle area with some aggradation 12 cm (4.7 in)
19.3-15.7	• Wire fence revetment left bank
14.5-12.0	• Wood bank revetment left bank
10.49	• Deepest degradation ~70 cm (27.6 in)
~2.0	• Location of cross-section

The cross-section (Figure 14) was surveyed at the confluence of the North Fork and the Middle Fork of San Pedro Creek. Facing downstream, it began on the left bank, crossed the Middle Fork, went over the end of the peninsula that separates the two tributaries, and then crossed the deeper North Fork before it reached the right bank. It too mostly showed degradation, with -33 cm (-1.1 ft) vertical degradation on top of the peninsula and -45 cm (-1.5 ft) degradation in the North Fork channel bed. Aggradation occurred 24 cm (0.8ft) from water's edge to right bank. This area was densely vegetated and most likely affected by a small island that was immediately downstream.

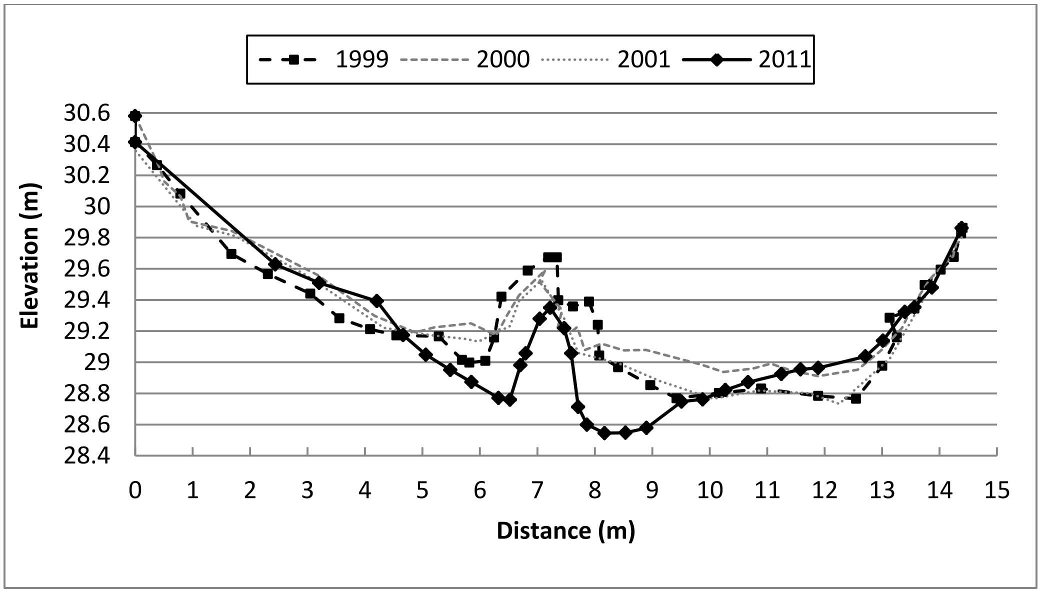

Figure 14: North Fork Reach cross-section 1999-2011.
1999-2001 data source Amato (2003).

There was no comparison substrate data. The substrate, as classified at survey points in 2011, was 41.3% gravels, 34.8% Quaternary clay, 10.9% cobbles, 8.7% concrete and riprap, and 4.3% boulders. Upon further inspection, it appears that most of what was classified as gravels, cobbles, and boulders was most likely derived from eroding concrete from the culvert apron and riprap that lines the area immediately downstream of the culvert. Human impacts were significant near the culvert in terms of garbage. The survey team removed two bicycles, two plastic milk cartons, a shopping cart, and other miscellaneous garbage out of the creek.

Reach Comparison

Table 15 summarizes key characteristics by study reach, including a characterization of average annual degradation as a portion of bankfull depth. This was done to normalize the data because of differences in the sizes of the three reaches. It was calculated using the degradation estimates derived from the interpolated matched point data and the mean depth regional curve for the San Francisco Bay region (USDA NRCS 2007 p. 11-11). The mean depth regional curves relate bankfull channel dimensions to the size of the drainage area. The result is a dimensionless number for each reach that allows for comparison between them.

The North Fork Reach was the shortest reach analyzed. A larger area was surveyed, but results beyond the confluence were not used because they are influenced by the Middle Fork. The North Fork and Downstream reaches had an equal number of pools (4). However, the ratio of pools per meter was the same for the Downstream and Restoration reaches, and slightly higher for the North Fork (+0.1). Slopes have increased in all reaches, with the highest increase in the Restoration Reach (0.65%) due to the raising of the channel bed. For the Restoration Reach, slope change was even greater at the downstream end, 0.74%. The annual mean rate of degradation was highest for the Restoration Reach at -2.8 cm (-0.09 ft). When annual erosion was estimated as a portion of bankfull depth, the normalized result for the Restoration Reach was much higher (0.93) than the North Fork and Downstream reaches (0.64 and 0.52 respectively).

Table 15: Key characteristics of the three study reaches.
*Based on change since 2001, before the restoration.

	North Fork Reach	Restoration Reach	Downstream Reach
Reach Length	67 m	381 m	92 m
Drainage Area	6.13 km^2	12.7 km^2	13 km^2
Years between surveys	12	3 and 10*	10
Channel bed (CB) slope (linear regression)	2.76%	1.75%	1.45%
Change in CB slope	+0.15	*+0.65%	+0.17
Water surface (WS) slope (linear regression)	1.98%	1.88%	1.29%
Change in WS slope	Not Available	*+0.79%	+0.3%
Pools	4	20	4
Ratio of pools per meter	0.5	0.5	0.6
Annual mean net degradation	-1.6 cm (-0.05 ft)	-2.8 cm (-0.09 ft)	-1.57 cm (-0.05 ft)
Degradation/bankfull mean depth	-1.6/2.5 = -0.64	-2.8/3 = -0.93	-1.57/3 = -0.52

Restoration Reach Step-pool Comparisons

Step pool geometry was assessed using standard step-pool geometry measurements (Abrahams 1995; Chin et al. 2008). However, because techniques for measuring step height and length sometimes differ (Nickolotsky and Pavlowsky 2007), descriptions are provided for clarity and they match the diagram in Figure 3 (p. 28). Length was measured from the top of one log to the next, height was measured from pool bottom to the height of the top of upstream log, and the slope measurement was the gradient between logs. Rock weir steps were not included because their effect was minimal when contrasted with the log steps. Mean log diameter was based on Questa's reported diameter of 0.9-1.2 m (3-4 ft) (Questa 2005a). Mean channel width was based on measurements taken in 2008 (Balance 2008). The $(\overline{\mathrm{H/L}})/S$ calculation reflects the relationship between resistance to flow and step length (Abrahams et al. 1995).

In nature step-pools are dynamic, changing and readjusting after high flow events. This comparison is based on the geometries of idealized step-pools that have reached maximum flow resistance (Table 16). Table 17 provides more detailed information for each step. The $(\overline{\mathrm{H/L}})/S$ for the reach is at the top of the recommended range, 2.03. However, when it is calculated for each step there is a wide range (from 0.35-5.5 with a standard deviation of 1.38) largely influenced by the irregularity of step spacing. The slope is lower than that typically found in nature and neither step length nor step height were found to be correlated with slope. Correlations were tested and rejected using Spearman's test. For step length and slope, the correlation was 0.-324 and the single-tailed p-value of 0.111 was greater than 0.05; therefore, it is not significant at the 95% confidence level. For step height and slope, the correlation was -0.138 and the single-tailed p-value of 0.312 was greater than 0.05; therefore, it is also not significant at the 95% confidence level. The average ratio step height to mean diameter step forming particle was lower than that considered ideal.

When compared with step-pools constructed for other restorations (Table 2 p. 31), the $(\overline{\mathrm{H/L}})/S$ for the Restoration Reach is 2, and it falls within the range of the other projects (from 1 to 3). However, the Restoration Reach slope at 1.8% is much lower (the range for other projects is 2.7-10%), and longer distances occur between steps. At 396 m (1,300 ft) the Restoration Reach is the longest of all of the reported projects. The other projects are 36, 40, 70, 80, and 350 m in length. Water flowing through steps, as in the undercuts in the Restoration Reach, was identified as a problem at East Alamo and Codornices creeks (Chin et al. 2008; Chin et al. 2009).

Table 16: Comparison of Restoration Reach step-pools with the ideal.

Variable	Restoration Area	Abrahams et al. 1995; Chin et al. 2008
Slope	1.80%	Usually >3%
Regularity of step-spacing	Irregular Spacing Median = 19.5m Range = 12.3-51.5m	Regular, scaled to size of channel
Ratio of step spacing to mean channel width	Median 2.57 Range -1.62-6.7	1-4 channel widths
$(\overline{\mathbf{H}/\mathbf{L}})/\mathbf{S}$	2.03 Range 0.35-5.5	1-2 for greatest flow resistance
Step Height	No relationship Median = 0.8m Range = 0.3-1.1	Increase with increasing slope
Step Length	No relationship	Decrease with increasing slope
Average ratio step height to mean diameter of step-forming particle size	Median=0.73 Range = 0.28-1.03	1-1.5

Table 17: Restoration Reach step-pool geometry.

Step Location	% Slope (m/m)	% Slope (Linear Reg)	Step Height (m)	Step Length (m)	Step Steepness (H/L)	Height/Mean Log Diameter 1.1 m (m)	Spacing/Mean Channel Width 7.6 m (m)
Bridge Culvert to Log Weir 1	1.56%	4.42%		15.54			
Log Weir 1 to 2	0.46%	0.56%	0.47	18.59	0.025	0.42	2.45
Log Weir 2 to 3	1.30%	-0.99%	0.88	19.57	0.045	0.80	2.57
Log Weir 3 to 4	0.99%	1.04%	0.73	34.81	0.021	0.67	4.58
Log Weir 4 to 5	1.93%	-0.27%	0.83	14.72	0.056	0.75	1.94
Log Weir5 to 6	1.86%	1.26%	0.81	40.33	0.020	0.73	5.31
Log Weir 6 to 7	2.18%	0.07%	0.61	15.24	0.040	0.55	2.01
Log Weir 7 to 8	1.15%	-0.26%	0.78	29.41	0.027	0.71	3.87
Log Weir 8 to 9	2.19%	3.00%	0.31	23.47	0.013	0.29	3.09
Log Weir 9 to 10	1.67%	-0.41%	1.01	28.80	0.035	0.92	3.79
Log Weir 10 to 11	2.43%	1.06%	0.73	19.51	0.038	0.67	2.57
Log Weir 11 to 12	1.36%	1.52%	1.13	51.05	0.022	1.03	6.72
Log Weir 12 to 13	1.52%	-1.71%	0.82	12.34	0.067	0.75	1.62
Log Weir 13 to 14	4.81%	3.61%	0.81	12.80	0.063	0.74	1.68
Log Weir 14 to 15	2.83%	0.29%	0.95	14.20	0.067	0.86	1.87
Log Weir 15 to End	2.90%	2.94%	0.30	29.69	0.010	0.28	3.91
Total Reach	1.80%	1.75%		380.09			
Culvert to Log Weir 13	1.54%	1.65%					
Log 13 to End	3.31%	1.84%					
Mean			0.75	23.76	0.037	0.68	3.20
Median			0.81	19.54	0.035	0.73	2.57
Sd			0.24	11.14	0.02	0.21	1.49
Total Reach							
$(\overline{H/L})/S$	2.03						

<u>Sources of Error</u>

Many sources of error can occur while surveying longitudinal profiles and stream cross-sections, as well as when comparing data. The most likely sources of error for this study are discussed below. In terms of equipment, horizontal accuracy for the Leica Sprinter 250M is estimated at 50 mm at 100 m distance using the laser distance measurement and 1 mm at 100 m vertical. The digital level's vertical setting was recalibrated using the two-peg method twice during the study to minimize error.

No fixed marker exists for the beginning of the Restoration Reach at the downstream end, and the 2008 and 2011 surveys each used a different downstream boundary. The 2011 survey began in the Downstream Reach and worked upstream. The beginning of the Restoration Reach was determined by the upstream taped distance which was based on the continuation of the 2001 survey which began at Hwy 1. This correlated well with the appearance of the area. The 2008 Balance survey began at the Capistrano Bridge Culvert and worked downstream. They continued surveying until they reached 390 m (1280 ft). This is approximately 6 m (19.7 ft) further downstream than the 2011 survey's boundary, and it includes an area that does not appear to be restored. Because the logs were used as match points, this difference has no effect between the first downstream log and the Capistrano Bridge culvert; it only affects the area below. It does, however, call into question the current length of the Restoration Reach, as determined by the longitudinal profile. Neither of the surveys reached the stated 396 m (1300 ft). The Balance survey was shorter by 6 m (19.7 ft) and the 2011 survey by 15 m (49 ft). This suggests that the longitudinal length of the restored reach is shorter than it was prior to the restoration, which can occur if there was any straightening of the channel.

In terms of the comparison data, horizontal difference for the Downstream and North Fork reaches was not calculated because they both lacked a fixed point at the upper end. In the Restoration Reach, the Capistrano Bridge Culvert and logs were used to calculate distance differences. All but one of the distances between fixed locations was within 0-1.1 m (0-3.6 ft) with a mean of 0.7 m (2.2 ft). However, the distance in the 2011 survey between Log Weirs 11-12 was 4.7 m (15.4 ft) longer than the 2008 data. This is likely due to differences in how the tape was laid around the bend.

The Downstream Reach included the fixed vertical benchmark for both it and the Restoration Reach. In the Restoration Reach, the vertical match between the 2008 and 2011 data was off by 0.99 m (3.2 ft) and adjusted accordingly; the edge of the Capistrano Bridge culvert was used for the match. Not all fixed log elevations are a perfect match, but differences were expected because of variations in where they were measured; some on top and others in the angled notch which is not level and can lower the elevation by up to ~12.7 cm (~0.42 ft). Elevation measurements for the 15 logs matched within 0-12 cm, (0-0.39 ft) with a mean of 5 cm (.16 ft).

The earlier North Fork survey was relative, without a known elevation. Both it and the 2011 survey elevation were matched at the edge of the culvert, and a height was set using a GPS reading at the same culvert edge. The GPS was a Trimble GeoXH, with a Trimble Zephyr external antenna and estimated vertical error of 0.3 m (0.98 ft). The two cross-sections were not subject to the same considerations because they began and ended at rebar stakes planted for the earlier surveys.

The distance stations recorded for observed conditions are approximately ± 30.5 cm (1 ft), because they were based on measured distances from taped flags tied to trees when the profile surveying took place. While there may have been some variability in the classification used by different individuals for substrate, the more precise categories of small, medium, and large/coarse were removed from the data analysis to achieve a more consistent result.

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VI. Discussion and Recommendations

The goal of this assessment was to evaluate the current condition of the Capistrano Bridge Fish Passage Restoration Project (CBFPRP), consider its longer term sustainability, and identify downstream effects, if any. Specific research questions asked: 1) has the creek changed since the restoration, and if so how; and 2) are there indications of any threats to the restoration? To place the discussion in context, it begins with a short review of the conditions that led to the restoration. Answers to the research questions are then discussed, starting from the upper sample area, the North Fork Reach, and working downstream. The chapter ends with conclusions and recommendations.

A Brief Review

San Pedro Creek is a perennial stream that drains a 21.2 km^2 (8.2 $miles^2$) watershed in Pacifica, California. Human alterations to the creek began in the late 1780s, and those alterations and the urbanization of large parts of the watershed are responsible for the degradation that has occurred since. In response, the San Pedro Creek Watershed Coalition, formed in 1999, used a science-based watershed approach to study the watershed and focused on identifying underlying problems and creating solutions that targeted them and to restore system function to the creek. While part of the cause of deep incision at the Capistrano Bridge, 4.6 m (15ft), was identified as large, flashy flows coming from the highly urbanized and culverted North Fork tributary, restoration of the reach below Capistrano Bridge was assigned first priority because it created a barrier to fish passage for federally listed migrating steelhead trout. This meant that the underlying upstream problem remained, and that has been a primary concern in this study in terms of the longer term sustainability of the restoration.

Response to Study Questions

The research questions were intended to identify changing conditions and possible threats. Change was observed in all three study reaches, as was expected given that streams are dynamic systems. The challenge lies in differentiating between those changes that may be minor adjustments in equilibrium and those that may signify the potential for accelerated degradation. The discussion will start upstream at the North Fork tributary and work its way downstream.

North Fork

The North Fork has continued to incise since 1999. This was not unexpected given that no measures have been put in place to increase storage in the sub-watershed and lessen the large, flashy flows that discharge from the 2.4 m (8 ft) culvert during storm events. The North Fork is an entrenched tributary cut off from its floodplain; it can only cut down or laterally. When annual net degradation was characterized as a portion of bankfull depth, the normalized result for the North Fork Reach was in between that of Restoration and Downstream reaches (0.93, 0.64, and 0.52). The tall, wooden revetment on the left bank, approximately 54 m (177 ft) downstream from the culvert, has been recently placed to stabilize a landslide that occurred in this steeply banked area. This type of collapse is reminiscent of that which occurred downstream in the reach below

Capistrano Bridge and led, in part, to the need for the restoration. Davis (April 25, 2012 pers. comm.) hypothesized that because the North Fork was developed a decade later than the area near the Capistrano Bridge, bank degradation is happening later. Slope measurements taken at six locations on the left bank between the culvert and the wood revetment in 2012 ranged from 48 to 64 degrees (Davis 2012).

The City of Pacifica currently has an opportunity to increase opportunities for infiltration, or to potentially make the large, flashy flows worse. A new storm drain master plan is under development and expected to be completed in mid-2012 (Pacifica 2012). This planning effort offers an opportunity to reduce flows by implementing alternatives that can increase storage. Alternatively, if storm drain capacity in the North Fork sub-watershed increases, the large, flashy flows would be expected to get worse. How this might affect the restoration is unclear. The restoration was designed for a bankfull of 9.9 m^3/s (350 f^3/s) and it has withstood one storm of 26.9 m^3/s (950 f^3/s) largely intact, although the anchors for the lowest V-shaped log weir failed in this event. In the natural world, step-pool reaches are less sensitive to changes in sediment and discharge than pool-riffle or plane bed reaches (Montgomery and Buffington 1997), which suggests that the restored reach may be more stable than its natural form. The $(\overline{\mathrm{H/L}})/S$ calculation for the entire reach, which reflects the relationship between resistance to flow and step length, is within the typical range of 1 to 2. However, when it is calculated for individual steps there is such a wide range (from 0.35-5.5 with a standard deviation of 1.38), that it raises a question as to whether all of the steps will offer similar resistance. Additionally, none of the other geometric relationships identified in step-pools with maximum resistance were found to hold true in the Restoration Reach. The slope is lower than that typically found in step-pool reaches in nature, neither step length nor step height were found to be correlated with slope, and average ratio step height to mean diameter step forming particle was lower than the ideal.

Restoration Reach

The stability of the Restoration Reach has improved since the restoration, and the barrier to fish passage has been removed. Previously collapsing banks have been re-graded and stabilized with a dense, three-storied cover of vegetation and with additional toe support and cribwalls where needed. Logs, rock weirs, and root wads have added diversity to the channel that should improve habitat for aquatic species, pools are well-formed, and gravels have been recruited from upstream and distributed throughout the Restoration Reach. The area withstood a major storm event of 950 f^3/s (26.9 m^3/s) largely intact, just months after it was completed, and before the vegetation was even planted. The log weir steps have remained in place, and 11 of the 15 steps are functioning as intended. There are, however, several areas of concern that have been identified including: 1) degradation, 2) underperforming logs, 3) invasive species, 4) human impacts, and 5) aging gabions.

1) Degradation

The profile, cross-section, changes in slope, and observed conditions all indicate degradation. When the Restoration Reach was restored, the entire system was disturbed and a period of adjustment is expected. The Department of Water Resources estimated that stability would be reached after approximately five years (DWR 2005).

However, annual mean rates of erosion and the normalized ratio of annual mean erosion to bankfull depth indicate that it is degrading at a higher rate that the other reaches sampled, including the North Fork which is not considered a stable reach. Because the rates for the Restoration Reach were averaged over a three year period, it is not possible to know whether degradation has occurred equally each year or whether it is tapering off or increasing. Additional monitoring will be required to clarify this situation.

The undercut left bank at the cross-section could be due to a minor perturbation or a sign of lateral widening caused by the increase in stream power from the steeper channel bed slope and the relatively steep bank. If it is lateral widening, it could lead to bank failure in the future. The San Pedro Creek Watershed Coalition expressed concerns about the steep slope and limited floodplain when the restoration area design was adopted by the City of Pacifica (Jerry Davis, May 6, 2012 pers. comm.) Their concern was heightened because of the large, flashy flows coming out of the North Fork culvert. According to Davis, the City chose this design over the one preferred by the Coalition, because set-back walls would have been required and they would have added to the project cost. It is important to resurvey the cross-section and to monitor this situation.

In addition, four localized problem areas were identified during the survey. These include the right bank immediately outside of the culvert where the gravel bar and island are directing the flow to the right bank, the undercut left bank at the cross-section between Log Weirs 10-11, the right bank on the bend between Log Weirs 11-12, and the left bank across from the two lower rock weirs where another pampas grass covered island is directing the flow of water into the bank. It is possible that other areas of lower bank erosion are also occurring, but because root wads and other structures placed to protect the banks limit good visibility, actual measurements need to be taken for confirmation.

2) Underperforming logs

The function of the log steps is to dissipate energy as the water flows downstream, so any dysfunction has the potential to increase the stream power. Submerged logs have little effect, and Log Weirs 8 and 11 were found fully underwater. This effectively creates a step that is 53 m (174 ft) long between Log Weirs 7 and 9, and a step that is 70.6 m (231.6 ft) between Log Weirs 10 and 12. A larger problem is presented by the two undercut logs (Log Weirs 12 and 14) which are located further downstream, and possibly Log Weir 13 which appears to be developing an undercut. The placement of the logs atop boulder-lined trenches may make it unlikely that the undercuts can erode the channel bed surface (Temple, July 20, 2011 pers. comm.), but it is still a possibility. Additionally, water flowing under the logs rather than over the top diminishes their energy resistance. This is especially important in the lower end of the restoration (where the undercut logs are located) because the steep slope increases stream power just above the point where the restoration area ends and joins the remainder of the stream. The undercut logs also have longer periods of drying than those that are fully functioning, which may affect their longevity because longevity is improved when logs are underwater (Fischenich and Morrow 2000). More discussion on the log longevity occurs below.

3) Invasive species

Pampas grass has been identified as a contributing factor in three areas that either are eroding or have potential for bank erosion. It covers the island outside the culvert, which along with the gravel bar is directing the flow to the right bank, as well as the island at the downstream end of the restoration area that is likely causing erosion of the left bank. Pampas grass also flanks the left bank around the bend, narrowing the channel, and possibly eroding the outer right bank. Because of the presence of root wads intended to direct the flow of water away from this bank, it is not possible to tell whether this area is eroding based solely on a visual inspection. While the vegetation survey conducted for the 2008 monitoring (TRA and Balance 2008) mentioned problem invasive species, pampas grass was not among them. This suggests that either its appearance has been recent, it was missed during that survey, or the survey did not cover the areas where the pampas grass occurs. Additionally, there is no evidence that the recommendations from the 2008 monitoring ever occurred. They recommended removal of French broom shrubs (*Genista monspessulana*) and weed control for nonnative Cape ivy (*Delairea odorata*) and poison hemlock (*Conium maculatum*).

4) Human Impacts

The amount of trash noticed in the Restoration Reach was less than that in the North Fork; however, there was trash. The area where it was most noticeable was below the Sanchez Art Center, which is the area with the easiest public access.

5) Gabions

Gabions that were used for bank stabilization before the restoration were left in place. While none that were visible appeared to be failing, they were showing signs of rust and should be watched, especially the gabions on the left bank in the lower restoration area, where the creek is the widest above the lower pampas grass covered island.

Downstream Reach

The channel bed and water surface slopes have increased in the Downstream Reach (0.17% and 0.3%). This is likely due to the increase in slope in the Restoration Reach above it (+0.65% channel bed and +0.79% water surface slope), which is even higher at the downstream end. The increase in the percentage of boulders, from 4% in 1999 to 41% in 2011, suggests that the higher slope is providing the transport capacity to move larger material into the Downstream Reach. Once there, the lower slope lacks the capacity to keep moving so the largest materials are dropping out.

Conclusion and Recommendations

Once completed, it is easy to consider a restoration project finished. This is especially so if a project appears stable and the community is pleased with the results. However, this study indicates that the CBFPRP requires ongoing management, beyond the five years suggested in the agreement with the Department of Water Resources (2005). There is also nothing to indicate that the recommendations made after the 2008 monitoring were implemented (TRA and Balance 2008). Either the log weir being undercut at that time was filled and the problem has reoccurred, or it was never fixed. Additionally, this study identified a second log weir with an undercut, a third which is showing signs that it might develop a similar problem, and two upstream log weirs that area residents reported filling-in. The higher relative rate of degradation found in the Restoration Reach over that found in the other reaches studied is troubling. But because the rate was derived from a three-year average, further monitoring is required to know whether it is continuing to degrade or tapering off. Localized degradation and bank erosion identified in the survey may remain just that, or it may be a warning of problems to come. The only way to know for sure is through repeat measurements. Because some erosion may be related to the growth of pampas grass, an assessment should be made as to whether it can and should be removed.

The last minute change from planned rock weirs to log steps saved an estimated $50,000 (Temple, January 30, 2012, pers. comm..), or approximately 2.5% of the total project cost. But has this led to other project effects? Neither rock weir steps nor large, Monterey pine logs are natural in San Pedro Creek. However, the large log weirs placed across the creek stand out more than the rock weirs and have a more unnatural look. Because of their size and linear form, they appear more like hard structures than the rock constructed steps. However, they may also provide more stability given that they are so well fixed in place. Some of the rock weirs shown on the as-built plans appear to have moved, while the log steps have not. The larger log weirs have higher steps and deeper pools, so they dissipate more energy. Given the increase in slope caused by raising the channel bed, this may be important. As it is, the reach immediately downstream from the restoration appears to have eroded in response to the increase in stream power and larger sediment, and had smaller rock weirs been used throughout the project, stream power may be even greater.

Another important question to ask is, “How long will the log structures last?” Longevity estimates for log structures range from 5-15 years (Fischenich and Morrow 2000), to 5-20 years (Roni et al. 2002), and Frissell and Nawa (1992) project an average life-span of 20 years. Frissell and Nawa found high rates of failure and impairments in their study of fish habitat structures in Oregon and Washington, including impairments or failure in all downstream facing V-shaped log weirs, which is the type that failed in the CBFPRP. Bank erosion at lateral margins of log structures was also identified as a common problem. According to Fischenich and Morrow (2000), climate, species, position, and soil contact are the factors that most influence longevity of the logs. Preferred species are cypress, cedar, redwood, and oak; cool and dry climates are best; and submerged logs last the longest. Log longevity decreases with frequent wetting and drying. The California Salmonid Stream Habitat Restoration Manual (Flosi et al. 1998) lists cedar, redwood, and Douglas fir as the best species and spruce, hemlock, white fir and pine as the least desirable. The logs used for the steps and bank stabilization in the CBFPRP are Monterey pine. With the exception of the two log weirs that were underwater, all of the restoration area log weirs have periods of wetting and drying due to the dry summer, wet winter cycle of the Mediterranean climate. The undercut logs are dry for even longer periods and this may impact their lifespan.

This study has focused on the sustainability of the CBFPRP. However, an equally important question to ask is, “How has the restoration impacted the fish?” The restoration was a high priority because it created a barrier to fish passage for migrating steelhead trout, a federally listed species. The barrier has been removed, and there is an assumption that the problem is solved. However, without doing a fish study, the result remains unknown. Finally, it seems important to note that even when using a watershed-based science approach to stream restoration, the availability of funding for particular types of projects and/or threats to endangered species may result in decisions to restore downstream reaches before dealing with underlying projects upstream. However, after this occurs, opportunities to correct underlying problems should continue to be sought.

Recommendations

The following recommendations are made as a result of this study:

1. Implementation of a management and monitoring plan that includes:
    a. Filling in log undercuts and annual inspections to identify and repair any new undercuts that may form.
    b. Removal and/or control of invasive species, especially pampas grass, because it may cause bank erosion.
    c. Repeat longitudinal profiles to determine if degradation is increasing or tapering off.
    d. Repeat the cross-section to determine if the undercut is increasing.
    e. Monitoring of areas identified as potential sites for erosion.
    f. Monitoring of gabions, so they can be replaced if required.
    g. Periodic clean-ups and outreach to neighbors to keep them informed about creek conditions.
2. More research into the use of logs in the construction of steps, especially related to their longevity in a Mediterranean climate.
3. An assessment of ecological recovery of the restoration area to determine, what, if any, impact the restoration has had on fish.
4. Inclusion of storage-increasing alternatives for the North Fork sub-watershed in the new storm drain master plan, and exclusion of measures that would increase storm capacity.

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