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Introduction

Coastal Lagoons are a hydrologic phenomenon that characterizes many small watersheds in northern California. As a working definition, a coastal lagoon is a body of water separated from the ocean by a barrier, but still connected intermittently to the ocean through one or more restricted inlets (Kjerfve 1994). Coastal lagoons can vary in salinity depending on this connectivity to the ocean and can therefore be characterized by dramatically different salinity in different times of the year (Kjerfve 1986). The intermittency of ocean-lagoon connectivity is driven by hydrologic processes in the ocean and on land. In particular, ocean wave action deposits sand, which creates an isolating sand barrier between the ocean and lagoon. Water that fell to the ground as rain, is constantly moving downhill through coastal watersheds, and the level of discharge impacts the stability of the sand barrier (Kjerfve 1994). In addition, observations by scientists and community members alike have indicated that high flows, and high flows at high frequency in particular, can open the sand barrier and re-establish the connection between watershed and ocean. When low summer flow regimes provide too little flow to displace sand deposited at the mouths of estuaries, a sand bar will form (Schwarz and Orme 2005). That sand bar will exist until a pulse of water, probably during the first large winter storm provides the necessary force to breach the barrier (Scherz and Orme 2005).

Coastal lagoons are found on all continents, and make up 13% of the coastal areas worldwide (Kjerfve 1985). Mediterranean climates, characterized by low summer flows and pulses of winter rain, are common locations of coastal lagoons. For this study, we will focus our interest on coastal California, which is home to several coastal lagoons. While coastal lagoons are common, many of the larger river systems (Klamath River, Eel River, Sacramento River) outflow into estuaries, and not lagoons. Therefore, the presence of coastal lagoons seems to be characteristic of small and medium coastal watersheds.

As ecosystems, coastal lagoons are often highly productive, and provide a heterogeneous habitat for developing animals and plants (Kjerfve 1994). Certain aquatic species are adapted to salinity variability, and these species can take advantage of variable lagoon habitat for important life history stages. A notable example of this adaptation is the ability of salmon and steelhead to maintain homeostasis in marine, estuarine and freshwaters. In California, juvenile steelhead have been observed residing in estuaries or lagoons of the Garcia River, Mattole River, San Gregorio River, Waddell Creek, Pescadero Creek, Navarro River, Redwood Creek, and the Russian River (Coots 1973, Hofstra 1983, Higgins 1995, Puckett 1976, Smith 1990, Taylor 1990, Zedonis 1993, Cannata 1998, Fuller 2011).

Creation of sandbars fundamentally alters the flow of nutrients and organic material in watersheds. Instead of detritus flowing out to the ocean, lagoons serve as an organic matter sink, providing increased food availability to benthic invertebrates and planktonic communities (Scherz and Orme 2005). Increased abundance of invertebrates provides greater food access to fish, and salmonids feeding in lagoons have been shown to have faster growth rates and larger size at time of migration to the ocean (Bond et al. 2008, Hayes et al. 2008). Previous studies have demonstrated that smolt size is a strong predictor of both steelhead and coho ocean survival (Bond et al. 2008, Holtby et al. 1990) During summer low flows, upstream habitat may be unsuitable and less productive for developing steelhead, and the presence of coastal lagoons provides enhanced habitat (Hayes et al. 2008). This fish behavior highlights the importance of coastal lagoons to salmonids.

Management of coastal lagoons lacks consistency and is quickly becoming an important consideration in the face of declining salmon populations in California, and in particular, declines of steelhead across their range (Busby 1996). Steelhead populations in California are divided into six distinct population segments, and for this study I will examine the population segment known as the Central California Coastal Steelhead. This study compares characteristics of four coastal creeks, three of which are sites of intermittent lagoons. With headwaters occurring in the Santa Cruz mountains and outlets in and around Monterey Bay, these creeks have traditionally supported populations of steelhead, and share common climate, invertebrate species, and riparian vegetation (Hayes et al. 2008, Hayes et al. 2011).

Hydrologic variability in general, and the process of lagoon forming and destruction in particular, influence the ecology of stream systems. Recent research into the Scott Creek watershed, estuary, and lagoon show intriguing benefits of this habitat variability. The intermittency of the Scott Creek estuary enhances the survival rates of developing steelhead that use the lagoon (Bond et al. 2008). In addition, the presence of the lagoon provides for varied life-histories and genetics within the steelhead population, in amount of time spent in freshwaters, number of trips to the ocean, and the use of the seasonally closed area during important times of year (Pearse et al. 2009, Hayes et al. 2011). This diversified life history may help buffer against local disturbances, as different elements of the steelhead population are in different locations do to variation in life-history characteristics.

While the benefits of coastal lagoons for salmonids include greater food availability and faster growth rates (Hayes et al. 2008), there are also more direct implications of coastal lagoons. For Scott Creek, Pescadero Creek, and Soquel Creek, the formation and destruction of seasonal lagoons dictates migration behavior. The storm that breaks through the sand bar and re-establishes connectivity between the lagoon and the ocean is important to both adult salmon returning to spawn and young salmon swimming out to the ocean. Neither migration can occur until this storm event.

For this research project, I capitalized on a new flow gauge on Scott Creek to examine a major spring storm event on central coast watersheds. Emerging ecological research indicates that the hydrologic dynamics associated with intermittent estuaries are important to steelhead development and survival (Bond et al. 2008, Hayes et al. 2008); however, what hydrologic characteristics are important to actually opening coastal watersheds (breaching sand bars) to steelhead migration and closing it (creating sand bars) to allow for favorable development habitat? In urbanized watersheds, such as Soquel and Pescadero are there ways in which managers can mimic natural flow regimes in order to preserve the timing and duration necessary for sand bar creation and breaching under suitable environmental conditions? This study uses an exploratory approach to compare Santa Cruz mountain watershed responses to a major spring storm, and to identify novel metrics to consider in improving sand bar management.

Methods

Site Selection

The central coast was selected as the study area for this hydrologic investigation because it contained four watersheds with headwaters in the Santa Cruz mountains, where state and federally owned land provides relative protection to urbanization. In addition, three of four watersheds (Pescadero Creek, Scott Creek, and Soquel Creek) generate sand bars and lagoons during the low flow summer months (Table 1). Finally, for each watershed, existing data including discharge volumes and rainfall gauges, could be obtained either through USGS (Pescadero Creek, San Lorenzo River, and Soquel Creek) or the Santa Cruz NOAA office (Scott Creek).

Pescadero Creek is the northernmost watershed in the study (Figure 1). The creek winds down through the mountains while draining 46 square miles and enters the ocean at Pescadero State Beach. The town of Pescadero, home to a small number of people (750), is still a source of runoff and other urbanizing effects in the low-elevation reaches of the creek. After several years of mass steelhead die-offs when the sand bar on Pescadero Creek breaches, the local community is hoping to prevent further kills. To this end, Pescadero citizens and local fisherman are engaged in understanding the steelhead die-offs and improving sand bar management.

Scott Creek is south of Pescadero Creek (Figure 1) and is a watershed that drains 27 square miles of relatively un-urbanized land. The lower parts of the watershed are used for agriculture, and the upper areas of land are logged. A discharge gauge was installed in Scott Creek during 2011. Part of the reasoning for this study was to take advantage of the opportunity to compare a low-urban, recently gauged site with a few neighboring sites that have been gauged for a long time and have urbanized towns in their watersheds.

The San Lorenzo River is the most urbanized site in the study. While the San Lorenzo begins in the Santa Cruz mountains, it winds past Felton, the northern section of Scotts Valley and finally, through downtown Santa Cruz. Much of the downtown area is heavily channelized, and while several re-introductions have been attempted, wild Steelhead have yet to return to the headwaters of the San Lorenzo River.

Similar to the San Lorenzo River, Soquel Creek is highly urbanized in the low-elevation sections, as it moves through the town of Capitola. However, the density of buildings, roads, and people in Capitola is noticeably less that that of Santa Cruz, and the degree of channelization near the lagoon is not as extensive as in downtown Santa Cruz. Soquel Creek continues to support a Coastal California steelhead run as of this paper.

Table 1. Hydrology characteristics of study sites

Site	Mean annual flow per watershed area (cfs/ mi^2)	Watershed Area (mi^2)	March peak flow per watershed area (cfs/mi^2)
Soquel	1.06	40.2	2.41
Pescadero	0.92	46	2.13
San Lorenzo	1.10	115	2.33
Scott Creek	?	27	?

Steelhead use the central coast region for multiple life-history stages (Sogard 1992). The first major storm in the region between January and March of a given year provides a cue for some steelhead to start their migration from marine waters to headwater spawning grounds, though life-histories do vary (Hayes et al. 2011). The presence or absence of sand bars during such a storm is important to the start of the salmon migration. Late winter and early spring storms are also cues for out-migrating smolts, which are young steelhead leaving freshwater to enter the ocean. However, not all young steelhead leave for the ocean during their first year. Some steelhead remain in the headwater streams throughout the spring, and then migrate to the coastal lagoon in early summer (Hayes 2011). Here they find higher food availability, grow quickly, and increase their chances to survive an ocean migration (Hayes et al. 2008).

Comparing Hydrologic Characteristics

To investigate the variability in watershed hydraulics between central coast watersheds, I first obtained flow and rain data for the four watersheds: Pescadero Creek, Scott Creek, San Lorenzo River, Soquel Creek. Pescadero Creek, San Lorenzo River. Flow measurements were downloaded from United States Geologic Survey (USGS), and rainfall measurements were downloaded from the NOAA website and from the Department of Atmospheric Sciences at University of Utah. Flow rates in the following figures were created by dividing stream flow by watershed area.

Using flow and rain data, I was able to determine metrics for timing and duration of flow dynamics. To compare watershed responses to large winter storms amongst central coast watershed, I examined the first major winter storm of the year, which for 2012 occurred in mid-march (13 March – 25 March). Prior to this storm, Scott Creek maintained a closed estuary. My approached explored several hydrological metrics. I calculated the lag-time between peak of rainfall and peak flow, as a metric to determine the flashiness of the system. This was calculated by subtracting the time at peak rainfall (inches/hr) from the time of peak stream flow (cfs) (See Figure 5). Additionally, I identified peak flow and base flow for each watershed during the time in question, which equates to the highest recorded flow and lowest recorded flow during a storm. These two values allowed me to calculate a variable I will refer to as <u>time at elevated flow</u>. In doing this study, I am suggesting the use of this variable as a way to understand the importance of timing and duration of flow in relation to sand bar destruction. The <u>time at elevated flow</u> is defined in the context of a storm. It is calculated by subtracting the time where base flow begins to rise during a storm from the time at which the stream flow returns to base flow. In this way, time at elevated flow integrates the magnitude and duration of the increased flow rate (Figure 5).

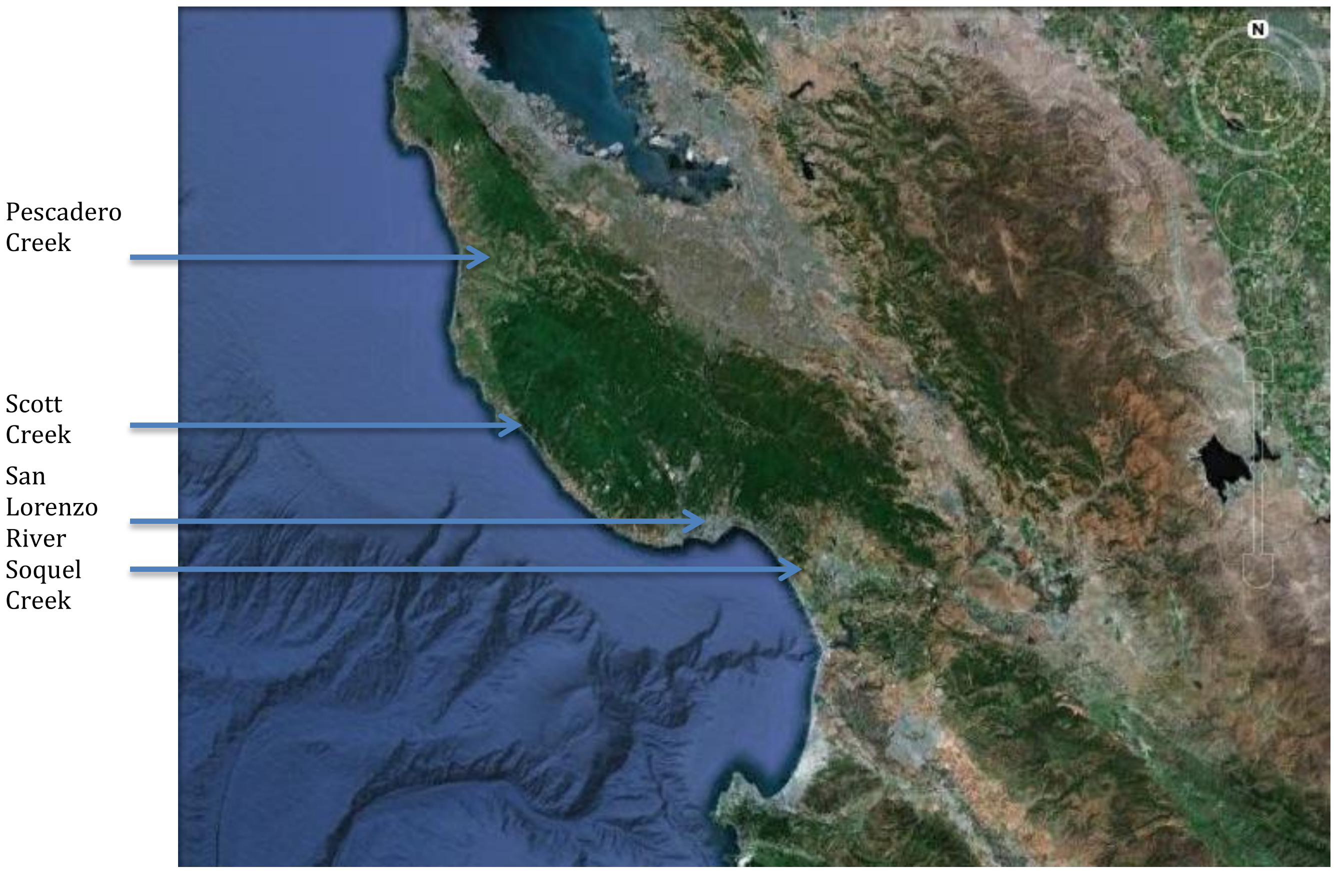

Figure 1. Map of Monterey Bay, Santa Cruz Mountains and watershed study sites, including Pescadero Creek, Scott Creek, San Lorenzo River and Soquel Creek.

Results

The storm used to compare hydrograph characteristics occurred between March 13 and March 25, 2012, and produced 17 inches of rain at Scott Creek (Figure 2). Of this rain, the majority accumulated in the first two days, although the storm did last nearly two weeks. This was a major storm for the region, both in terms of the dramatic increases in flow (Figure 3) and as the storm that broke the Scott Creek sandbar. In additional, the storm recruited significant large woody debris to Scott Creek.

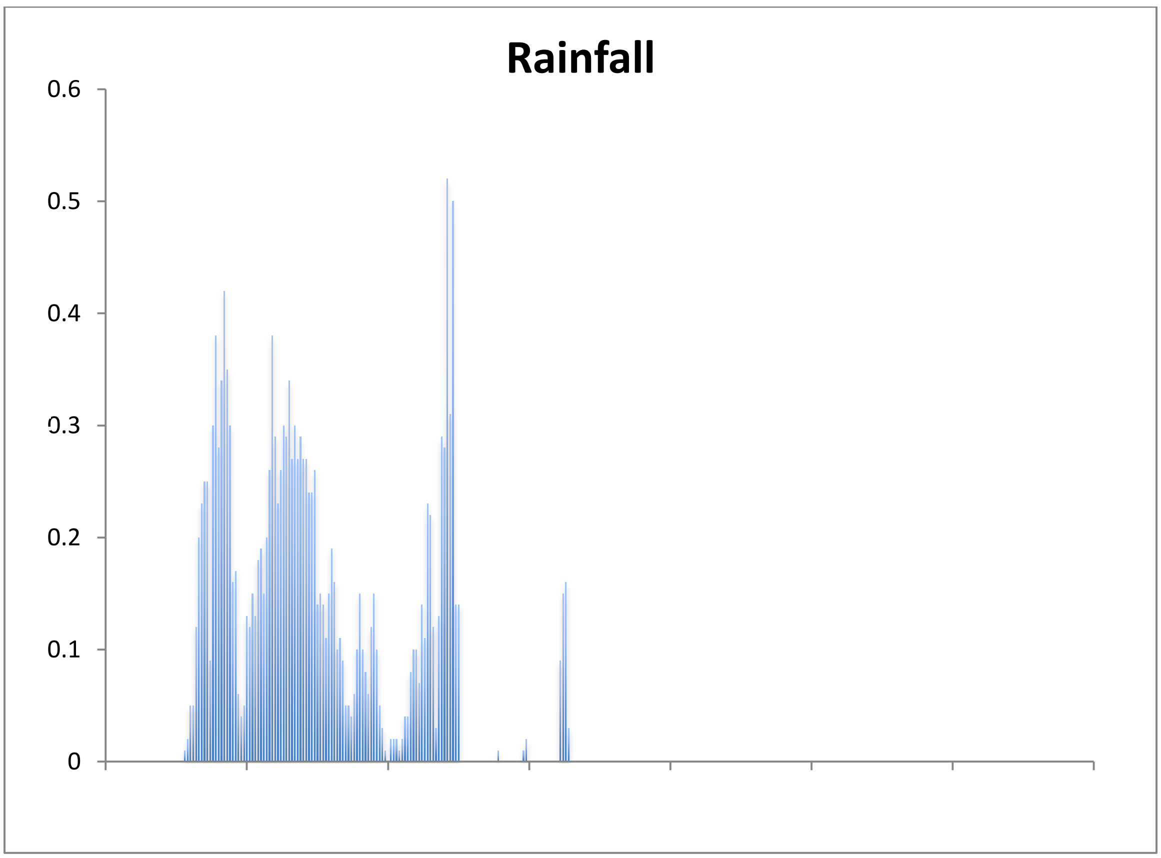

Figure 2. Rainfall (inches/hour) for a major storm that breached the sand bar in Scott Creek in March 2012.

Soquel Creek, San Lorenzo River, and Pescadero Creek all have some urbanization in the low elevations of their respective watersheds. During the March 2012 storm, the slope and shape of each hydrograph is qualitatively similar (Figure 3). In addition, the discharge in each system was similar in several quantifiable ways. First, the initial peak discharge, standardized by watershed area, for each watershed occurred within 8 hours of each other (between 11:15 am and 7:15 pm, March 14, 2012). Secondly, the second and larger peak in discharge occurred within an even narrower window (Figure 3). Between 11:45 pm and 2:00 am on March 16 and March 17, 2012, respectively, San Lorenzo River, Pescadero Creek and Soquel Creek were at peak discharge for the storm. Soquel Creek had the highest peak flow, followed by San Lorenzo River and Pescadero Creek (Table 1, Figure 3). The similarity in the timing of peak flows (per watershed area) in these systems is accompanied by a similarity in lag time between peak rainfall rate (inches/hour) and peak flow rate (cfs).

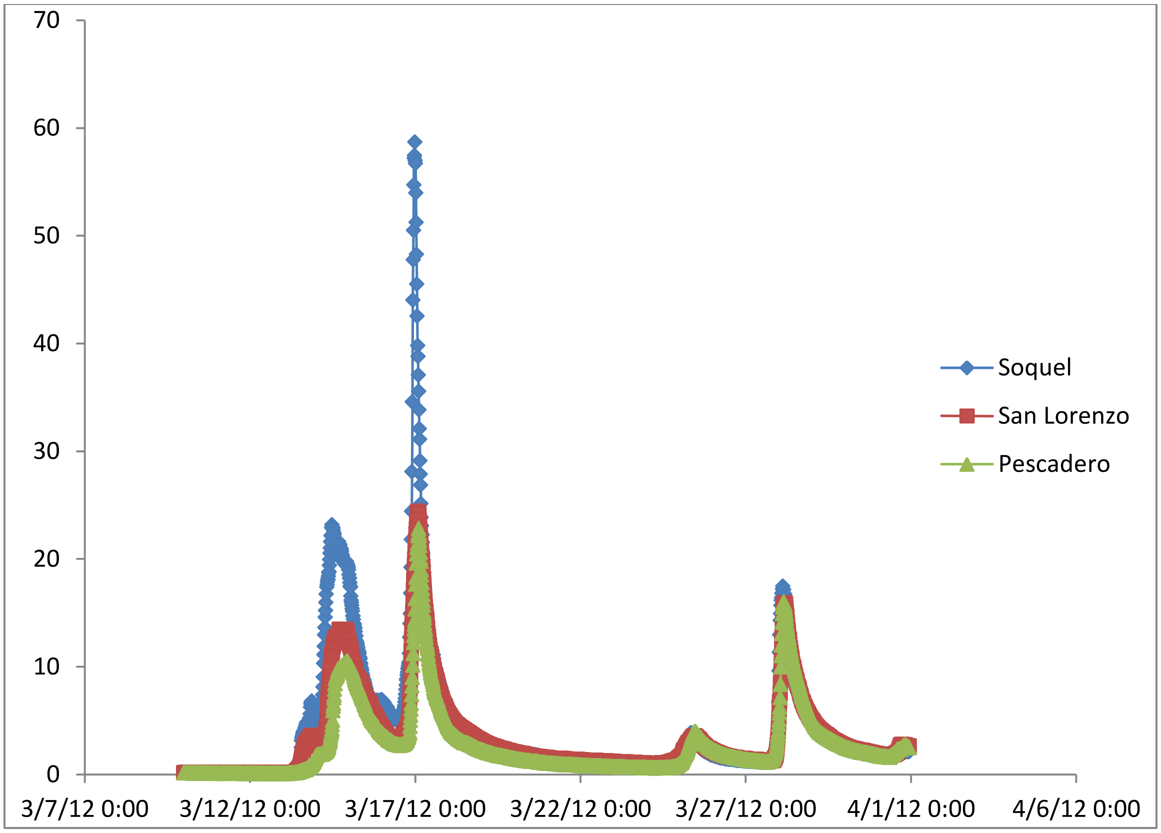

Figure 3. Discharge measured at USGS gauges in Soquel Creek, San Lorenzo River, and Pescadero Creek during a major storm in March 2012.

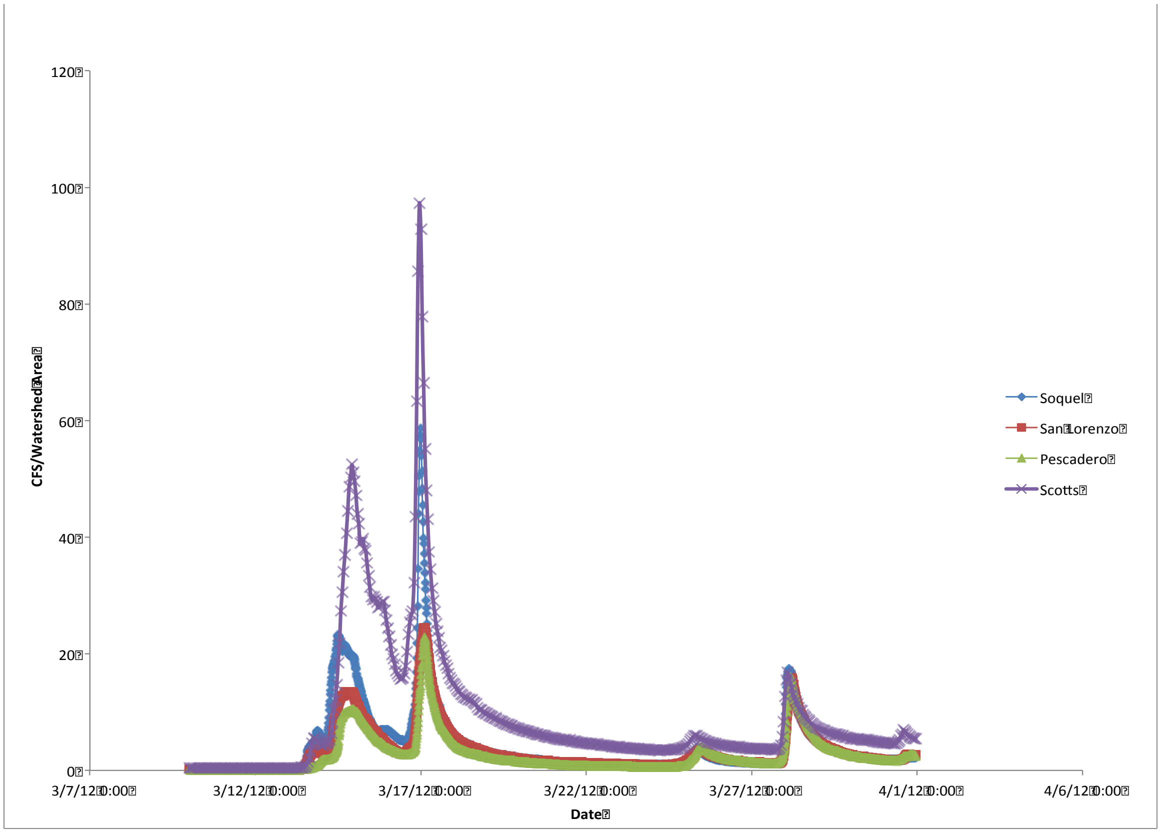

Figure 4. Hourly discharge measurements from Soquel Creek, San Lorenzo River, Pescadero Creek, and Scotts Creek during a major storm in March 2012.

When examining Scott Creek specifically, I calculated a 29 hour lag-time between peak rainfall rate and initial peak discharge (Figure 5). The Scott Creek lag-time was 5-12 hours longer than the lag-time associated with Soquel Creek, San Lorenzo River, and Pescadero Creek. For the secondary, and higher peak discharge, the four watersheds were within 7 hours of each other (Figure 4), with Scotts Creek slightly later than the other three watersheds. For this high peak, Scott Creek had a lag-time of 80 hours, while Soquel Creek, San Lorenzo River, and Pescadero Creek ranged from 73-78 hours.

Comparing the length of time each creek spent at an elevated flow rate (see Methods for definition) showed that Scott Creek watershed behaved differently from the other sites. During the March storm, Scott Creek discharge increased and remained elevated for nearly 200 hours (Figure 5). This was the longest time at elevated flow rate for the project. Pescadero (142 hours), San Lorenzo River (138 hours), and Soquel Creek (148 hours) behaved similarly to each other, and different than Scotts Creek.

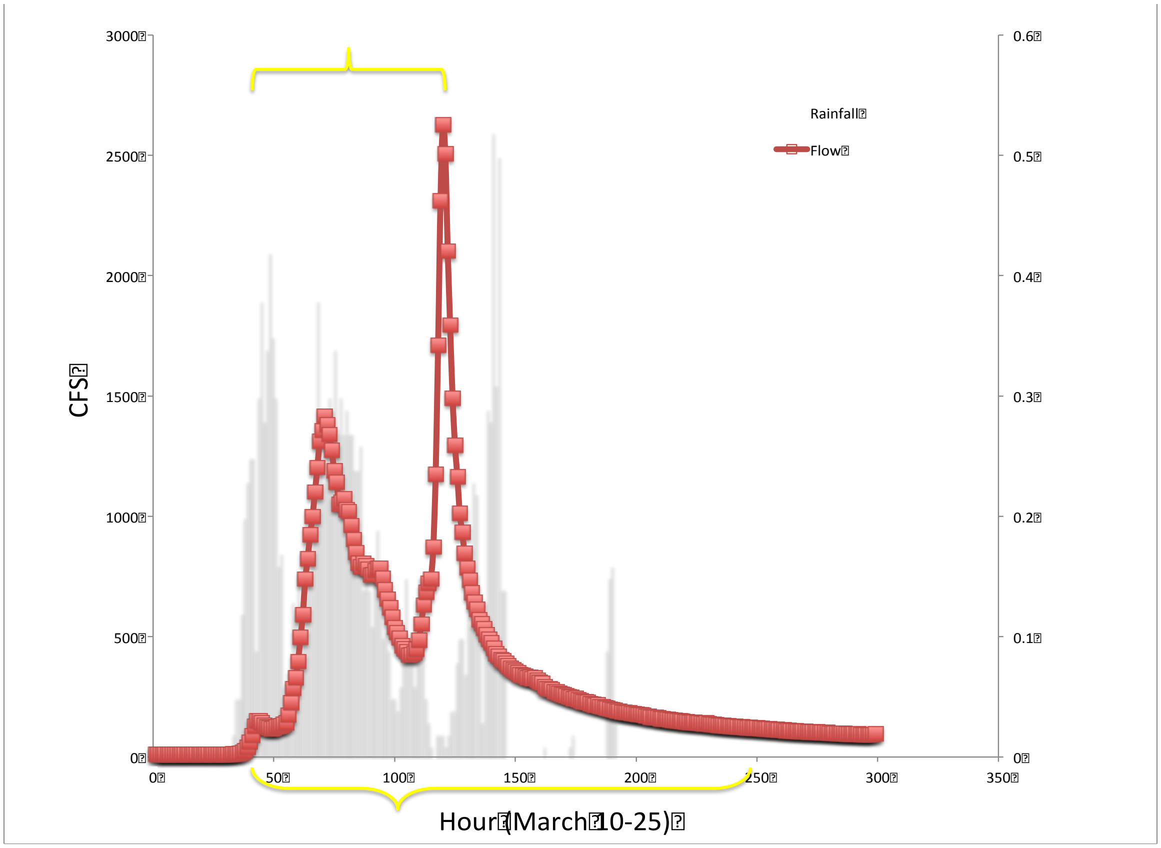

Figure 5. Rainfall (inches/hour) and discharge (cfs) for Scott Creek during a major storm in March 2012. Yellow brackets show 1) lag-time between peak rainfall and peak stream flow, and 2) time at elevated flow

Discussion

Watershed comparison

Graphical analysis revealed similar hydrographs among Soquel Creek, Pescadero Creek, and San Lorenzo River, in particular, slopes of stream flow over time were nearly identical. This is surprising, given the characteristics of these three watersheds: San Lorenzo River and Soquel Creek appear much more urbanized than Pescadero Creek. The similarities in the timing of peak flows for Soquel Creek, Pescadero Creek, and San Lorenzo River suggests that even though these watersheds differ in urbanization and complexity, their peak flows for this storm occurred at the same time and therefore, the function of these watersheds for steelhead timing may be similar. The similarity in duration of peak flows suggests that steelhead attempting to migrate up these watersheds to spawn may be able to do so within the same window and with the same environmental cues.

The addition of Scott Creek to the graphical analysis showed a pattern different than the other three watersheds. In particular, Scott Creek was characterized by a more gradual slope relative to Soquel Creek, Pescadero Creek, and San Lorenzo River (Figure 4). This distinction may be important to sustaining steelhead population in multiple ways. First, a more gradual slope will generate less scouring of upstream macroinvertebrates and young steelhead, which are using the creek as habitat during the winter months. Second, the process of "breaching" the sand bar is highly consequential to steelhead survival (Sloan 2006). The breaching process is a current problem in Pescadero Creek and has been demonstrated to be detrimental to fish in an Australian estuary (Griffiths and West). Since the mid-

1990s the breaching of the sand bar in Pescadero Creek has often been accompanied by massive steelhead die-offs, including seven out of eleven years from 1995-2006, (Sloan 2006), due to the water quality in the creek after the lagoon is breached. Once the lagoon is breached, the upper, highly oxygenated layer of the deep lagoon water is pushed out to sea, leaving a shallow, anoxic layer that harms fish through lack of oxygen. In addition, high levels of hydrogen sulfide in the sediments become suspended in the water column, directly harming fish (Sloan 2006), and increased water acidity increases metal toxicity in the estuary (Huber 2011, personal communication). The Pescadero Creek observations of decreased dissolved oxygen and fish kills are consistent with an estuary study in Australia, where the timing of a sand bar breach resulted in fish kills (Griffiths and West 1999).

The results of my study suggest that these problems seen at Pescadero Creek are due to the timing and duration of the sand-bar-breaching flows, and may be alleviated if the Pescadero lagoon was breached with a hydrograph characteristic of Scott Creek: more gradual and sustained. Sustained flows could act as a buffer to decreased oxygen in the remaining lagoon water.

Specific Management Recommendations

Management of coastal lagoons may require a more focused strategy on flow timing and duration during the sand bar breaching process. Many additional small to medium sized coastal watersheds exist in the region, and the installation of additional gauges in these systems may yield important information to management priorities. In addition, multiple years of Scott Creek data could enhance these analyses.

From a management perspective, one important area of analysis is the conversion of rainfall to stream flow, which can be managed to a certain extent through infiltration and detention. Stormwater planning in small communities such as Felton (on the San Lorenzo River), Capitola (on Soquel Creek) and Pescadero (on Pescadero Creek) can be used to capture rainwater and create more gradual spikes in stream flow patterns. Gradually sloped storm hydrographs benefit aquatic invertebrates through decreased souring of organisms during storms, may decrease the risk of rapid drops in dissolved oxygen after breaching, and may also extend the migration window for Coastal California steelhead.

While some of these communities are small, the watersheds in question are also relatively small, creating an opportunity for strategic stormwater projects to influence infiltration rates, detention capacity, and ultimately the speed of water moving through he watershed. Targeting already established community centers can be an efficient strategy to creating community buy-in for rain garden and retention pond projects. For this project, I have provided initial recommendations for the four watersheds of this study.

San Lorenzo River

The San Lorenzo River will always face the challenges of the urbanized downtown in Santa Cruz, California. Hydrology projects in this area have been progressing for years and are at such a scale that requires extensive stormwater projects. More achievable success can be had in the town of Felton, which is located 12 miles up river from Santa Cruz. The public schools and churches in Felton will have already-established, longstanding communities that may be excited to steward a rain garden project on their property to benefit the watershed. Felton Presbyterian Church and St. John's Church are both within a mile of the San Lorenzo River. The town of Felton could partner with these churches to create small, attractive rain gardens on their properties. San Lorenzo Valley Elementary School, San Lorenzo Valley Middle School, and San Lorenzo High School are clustered in the northern part of Felton, and border San Lorenzo River. With all three schools bordering the river, there is potential for a larger project, and one that students can take ownership of as they make their way up through each grade in school. In addition, these stormwater-retaining rain-gardens can be used as a natural classroom for science classes and enhance the aesthetic nature of the school section of the town. Finally, Covered Bridge Park borders the San Lorenzo River on the southeast and includes a large grass field. Long-term plans to convert this to a dual-use, field and detention pond should be established and implemented as the city is able to invest in public works projects.

<u>Pescadero Creek</u>

For Pescadero Creek, the main problem is in the timing of the sand bar breach. The breaching event often happens earlier in the year than in Scott Creek, and commonly in November or December (Huber 2011, personal communication). As in Felton, the city or county government may be able to find stormwater project opportunities in partnerships with the local churches and public schools. Pescadero Community Church and First Congregational Church of Pescadero may be willing to partner with the city to retain small amounts of water during storms. Again, rain gardens on church grounds may add aesthetic value and watershed enhancement. Pescadero Elementary School also lies within two miles of Pescadero Creek. Schools often have groundskeeping projects ranging from pulling weeds to planting community gardens, and rain gardens on school grounds may be a natural partnership between the community and the elementary school.

Soquel Creek

Soquel Creek watershed has the benefit of a narrow, tree-filled green space that minimally buffers the creek from the town of Capitola. Enhancing this greenspace with trees to increase water interception, as well as utilizing the two public parks, Perry Park and Soquel Creek Park, should be priorities for stormwater projects. The strategic location of the parks, right along the south side of the creek, provide the greatest opportunity for increasing infiltration and detention along the stream corridor. This watershed is more developed than Pescadero, and will require more projects to broaden the shape of the hydrograph during winter storms.

Conclusion

Recent studies in Scott Creek Estuary, Pescadero Lagoon, and the Russian River Estuary point to the importance of coastal lagoons as steelhead habitat (Hayes et al. 2008, Sloan 2006). Prior to these studies, management of these lagoons has received little attention, creating an opening for informing management through the study of the hydrologic processes that shape the timing and duration of sand bar creation in the summer and sand bar breaching in the winter. The large number of small to medium sized watersheds in the central California coast region could be a stronghold for coastal California steelhead populations if lagoons can be managed effectively.

In examining the hydrologic characteristics of these watersheds, I suggest that time at elevated flow and the commonly used metric of lag-time between peak rainfall and peak stream flow as variables to help shape lagoon management. Once there are multiple years of Scott Creek data, further studies could better describe the hydrograph of the "breaching storm" through additional variables. One strategy that was not used in this study, but that I believe has merit, is to use integral calculus to find the area under the curve of the hydrograph during the "breaching storm." This metric may be useful as a management goal for watersheds in the region and is more nuanced in integrating flow magnitude and duration than time at elevated flow.

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