

Central Coast Watershed Studies





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100 Campus Center, Seaside, CA, 93955-8001 831 582 4696 / 4431 Post-Fire Baseline Monitoring of Big Sur River Lagoon: November/December 2008

CSUMB Class ESSP 660:

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Executive Summary

The Basin Complex Fire of 2008 burned over 90% of the Big Sur watershed. Preexisting geologic conditions make the region especially prone to erosion and slope failure, particularly following wildfire. The combination of topography, geology and anticipated rains make about 80% of the watershed prone to debris flows. Excess sediment and large woody debris will probably impact the entire lower Big Sur basin, including the lagoon at the mouth of the river. Impacts can best be understood in the context of baseline monitoring that captures the extant environmental characteristics before the impacts occur. This study provides a set of observations that can be used to measure impact and recovery following the 2008–2009 rainy season. The monitoring parameters include topographic survey, sediment character, channel margin position, and photography. The study covers the mouth and head of the lagoon.

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1 Introduction

1.1 Background

The Big Sur Watershed in the Santa Lucia Range of central California was impacted by wildfire during summer 2008. Based upon previous wildfire events in the region, and early rain events in the 2008–09 water year, the Big Sur tributaries and main stem will be impacted by excess runoff and excess sediment yield. Public infrastructure, private property, businesses, and natural resources are now at risk as the winter rainy season approaches. This report provides an account of baseline environmental conditions for the Big Sur Lagoon at the mouth of the Big Sur River (Fig. 1).



Figure 1: General study area.

Declining environmental conditions from post-wildfire slope failures in California are jeopardizing habitat for steelhead trout (*Oncorhynchus mykiss*). California steelhead, listed as threatened under the federal Endangered Species Act, are sensitive to environmental changes. Historically, rivers in California have supported large numbers of steelhead. Current population estimates are significantly reduced from their historic highs. Factors attributed to the population decline include the destruction of freshwater habitat. Researchers and experts in California agree that water quality problems and

freshwater diversions are exacerbating steelhead habitat concerns (Hecht, 1981; Bond, 2006). The 2008 statewide wildfires are further threatening steelhead habitat from excessive soil yields and debris flows. This report will document baseline conditions in the Big Sur River Lagoon in California, a known steelhead habitat located below an intensively burned watershed.

The Big Sur River Lagoon is a 17-acre riverine estuary positioned at the mouth of the Big Sur River. The lagoon, located 26 miles south of Carmel-by-the-Sea, receives input from the Big Sur River and the surrounding 150 km² watershed. Tidal mixing and wave action from the ocean also contribute to the lagoon. The Big Sur River and lagoon are recognized steelhead stream habitats. In 2005, the National Oceanic and Atmospheric Administration (NOAA) identified this body of water as critical habitat for steelhead trout (70 FR 52488). Estuaries on the California Central Coast are important for steelhead (Bond, 2006) and other aquatic taxa. Estuaries provide a point-of-entry for winter spawning events, a transitional zone for smolts to acclimate to the marine environment and habitat for juveniles. Water quality in the lagoon can greatly influence juvenile success. Generally, steelhead prefer low temperatures, low salinity and high dissolved oxygen (Smith, 1990; Bond, 2006).

Wildfires can cause soils to be hydrophobic. Hydrophobic soils have the potential to cause exaggerated runoff and intensify soil erosion. In 2008, the Big Sur River headwaters experienced a wildfire burn to 92% of the watershed. The United States Geological Society (USGS) reported the Basin Complex Fire of July 2008 produced moderate to high soil burn throughout the catchments. Potential influence from wildfires can include changes in water chemistry from additions of ash, accelerated sediment yield, debris flows, landslides and loss of vegetation. A report from the Burned Area Emergency Rehabilitation (BAER) team stated the Big Sur River was at serious risk during any significant winter storms for the next three years from fire related issues (USDA, 2008).

Debris flow prediction can rapidly assess areas of concern in post-fire regions. Cannon et al. (in press) analyzed landscape features in a Western mountain setting using a Geographic Information System (GIS) platform to model debris-flow potential. The model successfully predicted debris flows based on estimated rainfall, severity of the burn and site variables such as slope and elevation in a specific catchment. The Big Sur River drains the western portion of the Santa Lucia Range. Federal and State reports forecast catastrophic slope failure and debris flow events in the surrounding range (Cannon, 2008; USDA, 2008). These events could deliver excessive sediment yields and large woody debris yields to the lagoon and beach area. A model of the watershed region will identify areas of concern above the lagoon and assess the potential of debris flow into the lagoon.

1.2 Steelhead and Other Species of Concern

The Big Sur River lagoon provides seasonal and year-round habitat for many fishes and invertebrates several of which are federally endangered and threatened species. In 2005 the Big Sur River was identified as critical habitat (70 FR 52488 – 52627) for steelhead trout (*Oncorhynchus mykiss*), which is listed as threatened under the federal Endangered Species Act.

Steelhead utilize the river mouth and lagoon in various parts of their life cycle. Unlike the Carmel and Salinas Lagoons that remain closed to the ocean for several months of the year, the Big Sur Lagoon mouth is perennially open in average water years because of the robust perennial flow from the generally undeveloped watershed. During the winter and spring, the sandbar which provides a barrier between the freshwater river and the ocean is fully breached. This process is critical in the temporal cycle of the lagoon and allows access for adult steelhead to migrate from the ocean to freshwater for spawning as well as access for juvenile steelhead to enter the ocean (Bond 2006). After the winter rains, the sandbar gradually builds and river mouth narrows. High tides and high surf during low flow times create a seasonal mildly saline lagoon. Throughout the summer and fall the lagoon becomes a rearing habitat for steelhead and provides a brackish environment where steelhead undergo smolting. Smolting is the transitional phase in which steelhead acclimate to salt water from freshwater conditions. Juvenile steelhead usually rear 1 to 2 years in the freshwater river before smolting and entering the ocean (Bond 2006).

Other species of concern observed near the Big Sur lagoon include California red-legged frog (*Rana draytonii*) and western pond turtle (*Actinemys marmorata*).

1.3 Summer 2008 Fires in the Big Sur Watershed

The combined Basin Complex and Indians Fires burned approximately 240,000 acres in several watersheds of the northern Santa Lucia Range (USDA 2008). Using GIS layers from Rosenberg (2001), USDA (2008) and Cannon (2008) we describe the watershed geology, and estimate the extent and severity of the burn in the Big Sur Watershed.

The Big Sur watershed is a WNW-facing, structurally-controlled drainage network that drains 151 km² of steep mountainous topography (Table 1; Fig. 1).

Table 1: Geometry of Big Sur Watershed						
151 km ²						
elongate						
Dendritic with local fault control						
wnw						
27 km						
4500 m						
0.17						
4800						

The watershed is underlain by 85% metamorphic rock, 19% igneous rock, and 15% sedimentary rock and recent deposits (Fig. 2). Five percent of the watershed is covered by existing historic landslides (Fig. 3), and there are slopes with high potential for landslides throughout the watershed (Fig. 4). The region has steep hill slopes and the bedrock is both deeply weathered and pervasively fractured and faulted, resulting in ubiquitous high erosion potential (Fig. 5).



Figure 2: Basic Geology of the Big Sur Watershed (GIS data from Rosenberg (2001)).



Figure 3: Historic landslide deposits in the Big Sur Watershed (GIS data from Rosenberg (2001)).



Figure 4: Landslide susceptibility in the Big Sur Watershed (GIS data from Rosenberg (2001))



Figure 5: Erosion Potential (GIS data from Rosenberg (2001))

Figure 6 and Table 2 show the burn severity distribution in the Basin Complex Fire. Cannon et al., (in press) have found that the moderate-to-high burn severity areas generate the majority of debris flows during post-fire rains events; 65% of the Big Sur watershed falls in that category.

Table 2: Burn Severity in the Big Sur Watershed (GIS data from USDA	A (2008))
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Severity	Area (km ²)	Percent of watershed
Low	22	16%
Low	26	19%
Moderate	65	46%
High	27	19%
total burned	139	92%
total mod+high	91	65%



Figure 6: Burn severity of the Basin Complex fire. See Table 2 for more details. (GIS data from USDA (2008)).

Slope failure and debris-flow generation are the primary risk in the first few years following a fire in the Big Sur basin. Debris flow risk has been modeled in other parts of the country with reasonable success (Cannon et al. in press). The Cannon et al. (in press) model was used on over 850 sub-watersheds of the Basin Complex fire (Cannon 2008). Cannon (personal communication, 2008) supplied model data in GIS format so that we could estimate risks within sub-regions of the Bain Complex Fire perimeter. Analysis of 141 sub-watersheds composing the Big Sur watershed indicates that approximately 80% of the Big Sur watershed is at high risk of developing debris flows through increased erosion or slope failures (Fig. 7 and Table 3). The model figures might underestimate the true risk owing to the naturally weak substrate of the northern Santa Lucia Range (Figs. 5 and 6). Lions Creek draining Ventana Cone has the highest risk of a very high volume debris flow (red watershed in Fig. 7)



Figure 7: Debris flow risk of the Big Sur watershed See Table 3 for legend details (GIS data from Cannon (2008)).

Table 3: Debris Flow Risk in the Big Su	r Watershed	(GIS (data	from	Cannon	(2008);	Risk
method from Cannon et al. (in press)).							
				-			

Combined		%chance	of	number	of	sub-	area	% of
Risk (Fig. 7)	Volume (m ³)	event		basins			(km2)	watershed
6	0-1,000	>80%				1	0	0%
7	1,001-10,000	>80%				101	26	18%
8	10,001 - 100,000	>80%				37	86	57%
9	>100,000	>80%				2	10	7%
				total are	a at	risk	123	81%

In summary, the combination of steep topography, pre-existing weak substrate and broad distribution of moderate to severe burns in the watershed strongly indicate that short term negative consequences are in store for the Big Sur River and lagoon. Exacerbating the high risk is the 30-year time lag since the previous large burn in the watershed. The long time frame since the previous fire has allowed the growth of a thick regolith layer that can now be mobilized by slope failure and erosion.

1.4 Study Objectives

Steelhead habitat in the lagoon is susceptible to degradation. Burnt regions in multiple catchments in the surrounding watershed will generate runoff that will change the topography and bathymetry thus affecting steelhead habitat. The objectives of this report are to document baseline conditions for the immediate and long-term post-fire changes in physical habitat of the mouth of the Big Sur River and lagoon. Baseline monitoring can detect changes in environmental features that serve to act as an indicator for possible threats to the lagoon. These data and report will be provided to State Parks to be used for management of the area. The chief data products are total station surveys to show local channel morphology, GPS survey showing the present channel margins in relation to past channel positions, channel-bottom sediment characteristics, and an archive of digital photography from various perspectives.

We focused our attention on two parts of the lagoon. On November 13 and December 4 we worked at the mouth of the lagoon (Fig. 2). On November 20, we worked at the head of the lagoon, the most upstream reach of river that is typically influenced by tides (Fig. 8).



Figure 8: Survey data covering study sites at mouth and head of the Big Sur Lagoon.

2 Methods

2.1 Goals and Approach

The goal of this work is to document environmental conditions existing at the Big Sur lagoon so that anticipated post-fire effects can be better documented. Our intent was to document conditions in the entire lagoon, but time constraints limited our work to the mouth and head. The head was selected because it will be the first to see aggradation as excess sediment enters the lagoon system. There is a break in slope of the water surface where stream flow interfaces with tidally influenced backwater.

2.2 GPS

We collected GPS point data along the edge of the water at the Big Sur River lagoon using a Trimble 2005 series handheld GPS unit. GPS points were collected during the afternoon hours (1200–1530 hours) between November 13 and December 4, 2008.

On November 13, 2008, GPS points were collected along the edge of the water at the Big Sur River mouth (Fig. 2). GPS points collected along the edge of water on November 20, 2008 were taken at the lagoon head (Fig. 2). On December 4, 2008, GPS points were collected between the November 13 and November 20 surveys to connect the two surveys.

For each GPS point location, a substrate type was associated with the point. The substrate categories included: sand (s), mud (m), gravel (g), cobble (c), and rock (r). While this substrate information tells us what substrate was present at the time of the data collection, its application is limited due to the incomplete representation of the substrate across the lagoon using this approach. Those data are not presented in this report.

We imported our GPS points into ArcMap 9.2 in State Plane NAD 1983 projection in order to create a Big Sur River lagoon watercourse boundary file. We then projected this layer file onto aerial photos of the Big Sur River lagoon from 1994, 2003, and 2007. This allowed us to compare movement of the river channel over time.

2.3 Bathymetry and Topography

Three-dimensional topographic data were collected using Topcon 211 and Topcon 3002 total stations. The 3002 instrument is capable of collecting XYZ data with or without a prism reflector, which increased survey efficiency during our first date during low tide. All other surveys used a prism pole with both instruments. Using a 2.5 meter prism pole allowed "blind" areas to be correctly surveyed and provide access to areas submerged by water (bathymetry). Points were collected on random transects across the river channel at major breaks in slope. Beach profile data were collected at various locations that seemed to indicate a break in slope across the planar surface.

The total stations were referenced to semi-permanent benchmarks at both the lagoon mouth and lagoon head. We assigned an NEZ location of 0, 0, 100 (m) to each benchmark and selected distant objects to set false north at each site. Original survey data are available from the first author. Total station precision was checked by shooting identical points with each total station. Closing errors were typically 0.02 m root mean square.

Data were downloaded from the total station to personal computer for post processing. We decided to keep the data in its project reference framework, rather than shifting and rotating the data cloud into the state plane projection used with the GPS data due to time limitations. Given the reproducibility of the reference framework, future surveys using identical setup inputs and benchmarked locations can provide precise time series datasets for comparison.

The survey of the lagoon head on 11/20/2008 was combined with survey data collected on 11/11/2008 by students in the undergraduate Geomorphic Systems class at CSU-Monterey Bay.

Filtered text files were imported into ArcGIS 9.2 where a raster was created using the Inverse Weighted Distance (IDW) tool in spatial analyst. Spatial Analyst extension was used to subtract the elevation differences between the repeated surveys at the lagoon mouth from 11/13/2008 and 12/4/2008.

2.4 Sediment Analysis

Multiple pebble count transects were performed at both the lagoon head (Fig 9) and mouth (Fig. 10). Sediment transect counts were performed in the river bed and adjacent bars and banks. Randomly chosen individual particles were measured at their intermediate axis with a metric ruler. Fine particles <2mm were counted, but sand and mud particle sizes were estimated based on field observations and not measured. Percent fines, arithmetic mean and standard deviation were calculated for each transect, lagoon head, mouth, and all locations to help determine baseline lagoon conditions. Pebble counts were tallied into particle size classes. Percent pebble counts were graphed into histograms.



Figure 9: Sediment transects at the Big Sur lagoon head location. TH2 is located on a riffle, and TH4 goes across a cobble bar.



Figure 10: Sediment transects at the Big Sur lagoon mouth.

We conducted a Kruskal-Wallis test for nonparametric data on the unclassified pebble measurements to examine the variability between transects at both the head and mouth of lagoon. Adjacent transects were tested for differences using a Wilcoxon rank sum test. In order to make recommendations for follow-up monitoring, we conducted post hoc power analyses. Statistical analyses were conducted using R Statistical Package (R Development Core Team 2008).

2.5 Photo-monitoring

Many documentary oblique photographs were shot. These include both single scenes at various scales and multiple-photo panoramas of broader regions. These photos were neither benchmarked nor scaled to quantify change; they will be useful to demonstrate gross qualitative changes in environmental characteristics at the lagoon mouth and head.

2.6 Other data available for this study

All original data sets to be used for post-fire runoff comparisons are archived with Dr. Douglas Smith in the Division of Science and Environmental Policy at CSU-Monterey Bay.

3 Results

3.1 Bathymetry and Topography

Post-processed field data were imported into GIS where a raster was created using the Inverse Weighted Distance (IDW) tool in spatial analyst. The resulting maps illustrate surveyed locations and interpolated points. Figure 11 shows topography of the lagoon mouth on 11/13/08.



Figure 11: Total station data interpolated into a raster image of the lagoon mouth using Inverse Distance Weighted averaging. Colors correspond to elevation zones where light green and light blue correspond to lowest elevations and red areas represent higher elevations. Red boundary is a user-created line to clip the raster to fit the data points. Points are in a local arbitrary reference frame. Red and white areas have greatest elevations and light green and light blue have the lowest elevations. Rocky cliff extends upward in upper left and bottom of the image. A horizontal sand spit runs parallel to the shore and constricts the lagoon mouth

Higher areas (red) are located across the mouth in the form of a partial lagoon barrier or river mouth spit, along with the bluff backed beach and cliff where total stations were setup. The deepest areas (light green to light blue) appear at the base of the bluff nearest the ocean, where highest wave energy occurs, and the upper part of the lagoon system behind the gravel bar. A plug of sediment provides hydrologic control over freshwater outflow into the ocean. At the lagoon head, a riffle just before the big bend marks the approximate endpoint of saltwater influence (Fig. 12).



Figure 12: Lagoon head survey at a sharp right bend in the river channel. Colors correspond to elevation zones. Lght tan correspond to low elevations while purple and white areas represent higher elevations. Water elevation during survey approximately located along purple/sandy color interface. Arrow indicates flow direction. A gravel point bar was present at the white colored area, with water flowing outside in the tan areas.

A resurvey of the lagoon mouth on 12/04/08 maps natural variability within the system Given good point density and overlapping transects between repeated surveys (Fig. 13), comparison of elevation values could quantify variability at the lagoon mouth. Raster subtraction of the survey dates 11/13/08 from 12/04/08 (Fig. 14) yielded approximate change over 3 week period that included several days of large surf

This is a highly dynamic system with observed changes over a 3 week period without fire impact.



Figure 13: December 4, 2008 total station data point cloud and interpolated raster plotted on top of November 11, 2008 clipped raster. Both rasters were clipped using appropriate user-created mask. White corresponds to the higher elevations and dark green corresponds to the lower elevations. Color ramp used for each survey dataset is identical, providing the ability to qualitatively examine variability within the system.



Figure 14: Raster subtraction of November 11th and December 12th clipped datasets plotted over muted November 11th interpolated raster. Point cloud from both surveys are shown. Changes in areas with low point density are less defendable than those with greater point density. Depth changes are in meters and warmer colors indicate erosion while cooler colors indicate accretion.

3.2 GPS

The result of the GPS points collected and the GIS mapping is a delineation of the current lagoon edge at the Big Sur River lagoon. This layer file can be used as a baseline for the location of the lagoon edge. The series of maps (Figs. 15, 16 and 17) illustrates the movement of the Big Sur River channel between 1994 and 2007. This series of maps shows that the position of the channel has rapidly changed, even in the absence of high sediment loads imposed by fire impacts. Figure 17, the Big Sur River lagoon layer file projected onto a 2007 Google image, provides a reasonably accurate representation of the current location of the Big Sur River lagoon, as the projection error is estimated at only half a meter based upon our local comparison with optical survey data. The layer file, created from GPS point data taken in November and December 2008, can be used as a baseline for comparison with future post-fire impact surveys.



Figure 15: GPS position of channel margins plotted on 1994 aerial photograph.









3.3 Channel Sediment Characteristics

Arithmetic mean and standard deviation results are given in Table 1 for each transect and overall average. Figures 18 and 19 show histograms of percent pebble counts for each particle class size on each transect. The mean is approximately shown as a black circle hovering above the appropriate size class, with a black triangle representing the mean calculated with the fine particles removed (<2mm). With the exception of TH3, all histograms show a bi-modal distribution of particle sizes with a strong fines spike <2mm. The fines are present as a thin veneer on framework grains and as interstitial fill. The Big Sur transects range from poorly sorted to extremely poorly sorted when the fines are included.

Table 1: Percent fines, arithmetic mean and standard deviation for sediment transect particle measurements (mm). Green column includes all measurements, and the orange column does not include fine particles in the calculations (<2mm). "TM#" transects are from the Big Sur lagoon mouth analyzed on Dec. 04, 2008, and the "TH#" transects are from the Big Sur lagoon head analyzed on Nov. 20, 2008. Averages for the lagoon head and mouth locations as well as all transects are located at the bottom.

	% Fines	Wit	th Fines	Without Fines		
Transect	(<2mm)	Mean (mm) Std. Dev. (mm)		Mean (mm)	Std. Dev. (mm)	
TM1	31	24.0	19.6	34.8	12.9	
TM2	38	25.5	26.6	41.3	22.2	
TM3	60	12.0	17.3	29.5	15.3	
TM4	66	23.3	40.4	67.3	42.5	
TM5	43	29.2	33.5	51.0	29.1	
TH1	50	28.7	45.7	57.4	50.6	
TH2	36	52.3	64.3	81.3	63.9	
TH3	0	79.8	51.8	79.8	51.8	
TH4	37	35.7	44.3	56.9	43.9	
TH5	67	9.6	15.7	28.8	13.3	
TH6	12	51.3	34.7	58.3	30.8	
TH7	52	35.5	43.4	73.9	31.9	
TH8	32	45.5	41.6	66.9	32.9	
TH9	8	58.9	28.9	64.1	23.8	
TH10	32	45.2	50.8	66.4	48.7	
TH11	12	64.1	50.9	72.8	47.9	
TH12	4	218.2	159.5	227.3	156.1	
Average M	48	22.8	27.5	44.8	42.2	
Average H	29	60.4	52.6	77.8	49.6	
Average M & H	38	41.6	40.1	61.3	45.9	



Figure 18: Histograms for lagoon head transects showing mean with (circle) and without (triangle) fines. Dashed lines represent standard deviation.



Figure 19: Histograms for lagoon mouth transects showing mean with (circle) and without (triangle) fines. Dashed lines represent standard deviation.

A Kruskal–Wallis test conducted on the 12 pebble count transects at the lagoon head showed significant variability between transects (α =0.05, p=4.491e-14; Fig. 20). The Wilcoxon rank sum test for differences between adjacent transects showed differences between five of the adjacent transects (α =0.05, Fig. 20). The five pebble count transects placed at the mouth of the lagoon showed no variability between transects (α =0.05, p=0.1063) following the Kruskal–Wallis test (Fig. 21).

We conducted post hoc power analyses to determine optimal sampling for future efforts. At the lagoon head, we recommend six well-placed transects to adequately capture the variability of the area surveyed (Fig. 22). Pebble counts within each of these transects should be increased to 105 in order to detect a smallest meaningful difference (SMD) of 30 mm (α =0.05). Increasing the pebble count to lower the SMD below 30 mm would significantly increase sampling effort. At the mouth of the lagoon, pebble counts could be conducted using either three transects of 105 counts each or five transects of 65 counts each to assess the area sampled during the baseline survey (α =0.05). These recommended pebble counts would capture an SMD of 12 mm and 15 mm respectively (α =0.05).



Figure 20. Boxplot of 12 pebble count transects at the head of Big Sur River Lagoon. Asterisk (*) indicates a significant difference (α =0.05) between adjacent transects.



Figure 21. Boxplot of 5 pebble count transects at the mouth of Big Sur River Lagoon. No significant differences between transects were found (α =0.05, p=0.1063).



Figure 22. Pebble count transects at the Big Sur River lagoon head in 2008. Red circles indicate the six recommended transect locations for future surveys.

3.4 Photo-monitoring

A subset of photos is provided here. Figure 23 shows an overview of the lagoon mouth. Figure 24 shows the natural variability in the lagoon mouth following a period of high waves. Changes can be seen in the amount of organic debris in the spit and the shape of the spit following the high waves in late November (Fig. 24). Figure 25 shows a close-up view of the mouth on December 4.

Figure 26 and 27 are views downstream from the right bend at the lagoon head. Figure 28 is the upstream from the lagoon head, immediately above the riffle defining the limit of tidal influence. An initial increase in mud is documented in the substrate along the gravel bar at the Lagoon head (Fig. 29). This mud veneer was not present during a site visit on November 16. Between November 16 and November 20, there was the first significant rain of the water year in the Big Sur watershed. The runoff produced a peak flow of 200 cfs, and apparently brought the first fine-grained sediment yield as well.



Figure 23: Mouth of Big Sur River Lagoon during low tide. (November 2008)



Figure 24: Lower reach, mouth of Big Sur River Lagoon. Time series comparison from November 20th 2008 (left) and December 4th 2008 (right), note kelp deposit.



Figure 25: Lower reach, point-of-entry of Big Sur River Lagoon mouth and ocean. (December 2008)



Figure 26: Lagoon head. View downstream from gravel point bar (November 2008).



Figure 27: Lagoon head. View downstream across gravel point bar (November 2008).



Figure 28: View upstream of Big Sur River Lagoon. Upstream edge of gravel point bar visible in bottom of photo. Note mud veneer on gravel and along bank (November 2008).



Figure 29: Lagoon head. Various levels of substrate embeddedness at the upstream edge of the gravel bar (November 2008).



Figure 30: Lagoon head. Riffle delimiting the upper boundary of tidal influence in the river. Raw, freshly eroded bank is at apex of sharp right bend (November 2008).

4 Discussion

Baseline data were collected for the upper and lower terminations of the Big Sur Lagoon. Natural variability is great at the lagoon mouth as storms rearrange the river mouth spit geometry, and the lagoon head, where bank erosion is lengthening the river channel.

In keeping with historic post-fire effects, we anticipate an increase in bed load, suspended load, and large woody debris in the system during the 2008–2009 winter. This change has the potential for adverse short-term environmental effects in the lagoon. Channel bottom variability might become reduced as deeper areas are infilled by sediment. Fine sediment will likely cover the framework of coarse gravel.

Recent historic aerial photos analyzed in this study indicate that the mouth of the Big Sur River is typically located adjacent to the rocky cliff at the northern end of the spit. This observation suggests that the mouth position is in decadal-scale steady-state equilibrium, with an "average position" that does not vary through decades.

In contrast, the position of the lagoon head, especially the sharp right bend, is not in decadal-scale steady-state equilibrium with current watershed (or local) conditions. It has monotonically shifted south, gradually increasing the river length and decreasing its average slope. The abrupt change from dense riparian forest to un-forested terrace (Fig. 31) provides the context for a positive feedback between bank erosion and greater shear stress. As the outer bank erodes into the weak terrace materials, the stout riparian bank vegetation downstream from the bend resists any change. The result of this uneven erosion is a gradually decreasing radius of curvature in the bend (Fig. 31). The tighter bend, resulting from this erosion, increases the stream attack angle on the bank and the attendant shear stress on the weak bank (Fig 30). The bend currently has a radius of curvature that is approximately one half the value typically found in unmodified streams of the same size.



Figure 31: Approximate recent positions of the lagoon channel based upon remnant topography of aerial photographs and recent GPS (Figs 15,, 16, and 17).

Based on our analysis of historical aerial photographs, and personal observations through time, we predict continued rapid erosion along the outer bank of the bend above the lagoon head. There are few mature trees with complex root systems or young stream-bank willows along the apex of the bend for stabilization (Figs. 30 and 32). The presence of a high longitudinal water-surface slope, tall bank height, steep bank angle, weak floodplain deposits, and lack of root density on the outer bank of a bend with diminutive radius of curvature (Fig. 31) allow us to predict continued rapid erosion at this point in the river.



Figure 32: Detail of weak floodplain deposits underlying eroding terrace (November 2008).

We also expect increased erosion on the outer bank from increased shear stress ($\tau = \gamma RS$) during large storm events in the post-fire rainy season. Shear stress (τ) is defined as stress which is applied parallel or tangential to a face of a material; in this case the hydraulic stress applied to the riverbank. The components of shear stress are the specific density of water (γ), which is equal to 9800 kg/m³; the hydraulic radius (R) of the channel, and the slope (S) of the water surface. Large storm events will likely transport large amounts of sediment downstream. Sediment deposition on the inner bend of the channel will cause the hydraulic radius (R) of the channel to sporadically increase which will cause an increase in shear stress (τ) on the outer bank of the curve.

Large storm events also transport large woody material. We predict that if large wood makes its way to the lagoon it is likely to pile up and cause a log jam at the upstream bend location due to the extreme curvature in the bend. Shear stress can be extreme where the backed up water finds pathways around the debris.

4.1 Future studies and data needs

We recommend performing a repeat study following the 2008-09 storm season to capture the immediate impacts of the Basin Complex Fire, and studies in subsequent years to mark the gradual recovery to pre-fire conditions captured in this report. Future studies should include the entire lagoon.

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