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Potential impacts of groundwater withdrawal and wildfires along the Big Sur River : an assessment of Oncorhynchus mykiss habitat

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Potential Impacts of Groundwater Withdrawal and Wildfires along the Big Sur River: An Assessment of *Oncorhynchus mykiss* Habitat

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by

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Abstract

Oncorhynchus mykiss **(steelhead trout) are a federally threatened species currently found in the Big Sur River in Monterey County. Dam construction, culverts, water diversions and sedimentation are leading causes in habitat degradation for steelhead. A recent capstone study found that near-stream groundwater wells were extracting enough water to cause a decrease in surface flow, generating motivation for this study. The Basin Complex and Indians fire of 2008 burned 84% of the Big Sur watershed creating the potential for elevated fine sediment yields. Post-wildfire sediment yield increases from background conditions to an unknown level at an unknown magnitude. The threat of continuing sedimentation generated the motivation to monitor watershed response to the 2008 fire. This study looked at post-wildfire sediment yield from the Basin Complex and Indians Fire and potential impacts of groundwater withdrawal. Discharge measurements were taken above and below a well field to determine if a loss of surface flow was occurring. There were no detectable changes in surface flow below the well field. The precision of our study was between 0.028-0.113 cms (1-4 cfs), which is substantially more than the maximum pump capacity of one well in the study reach 0.002 cms (0.058 cfs). To monitor post-wildfire sediment response, six transects were reoccupied from previous studies. Pebble counts were taken at each transect and compared to results from previous years. The Big Sur River continues to experience post-wildfire sedimentation as a result of the Basin Complex fire of 2008. Five transect sites showed a decrease in the** D_{50} **particle size. The decreases in size ranged from 45-193 mm between the 2008 and 2010 studies. Four out of six sites resurveyed have strongly impaired substrate for *O. mykiss* embryo survival. The lack of other impacts to the watershed suggests that the sediment fining that continues to occur is a result of the 2008 Basin Complex and Indians fire.**

Introduction

Threats to Steelhead Populations

Steelhead populations have dropped significantly on the coasts of California and Oregon and many steelhead populations throughout southern Oregon and California retain a threatened or endangered status (NMFS 2007). Mis-managed watersheds such as the poor construction of dirt roads, culverts, dams, reservoirs and water diversions lead to the destruction of riparian zones and valuable *O. mykiss* habitat (Kondolf 2000). The latter of those threats has been documented to cause dry reaches along the Carmel River in Monterey County during late summer base-flow conditions (Kondolf et al. 1986). Because of the inherent need of steelhead to migrate, the physical barriers created by dams, culverts and roads pose significant threats to steelhead populations. Excessive fine sediment delivery from poorly constructed dirt roads, clear-cut forestry and intensive agriculture decrease the available spawning habitat for steelhead, remove the food source for their young, and alter emergence timing for embryos. In central

California, steelhead populations have declined from historic annual numbers of 7,750 to less than 500 (NMFS 2007). Furthermore, the four largest watersheds in the coastal central California region have experienced *O. mykiss* declines of 90% (NMFS 2007). The need for water is universal, and creating allocations for all parties seems to be a difficult task. Human populations tend to dwell extensively near waterways and modify riparian habitats to fulfill their need for water (Sala et al., 2000). In areas where water is not abundant, or water use exceeds natural sustainability, water becomes a limiting factor for steelhead trout (*Oncorhynchus mykiss).*

Big Sur River and Watershed

The Big Sur River is located in the Santa Lucia Mountains in Monterey County and drains a watershed area of 157 km^2 (60.78 mi^2)(Figure 1) (Stanley, 1983). The Big Sur River can be subdivided into two reaches. The lower reach extends from Big Sur Gorge at Pfeiffer Big Sur State Park to Andrew Molera State Park at the Pacific Ocean. The upper reach extends from the Big Sur gorge upstream, to the headwaters. The lower reach is frequented by tourists and provides domestic water for residence and habitat for steelhead. Pfeiffer Big Sur State Park is the limit of anadromy for steelhead trout. Based on 60 years of data, the river has an annual mean flow of 2.06 cms (73 cfs) (USGS 2010). The lowest recorded flow during the 60 years was .18 cms (6.5 cfs) in 1991. On average, base flow conditions in the Big Sur River from August-November range from 18-42 cfs. A rain gage in Pfeiffer State Park receives an average annual rainfall of 109 cm (43 inches). The highest recorded precipitation was 70 inches in 1941; the lowest recorded rainfall was 18 inches in 1923. Precipitation in the Big Sur area increases with elevation and the average annual precipitation in the upper reach is 50 inches (Stanley, 1983). The Big Sur River provides all the water for residents, tourists and businesses located in the area. How residents and businesses obtain this water is determined by the complicated California water law and the decisions of the State Water Resource Control Board (SWRCB).

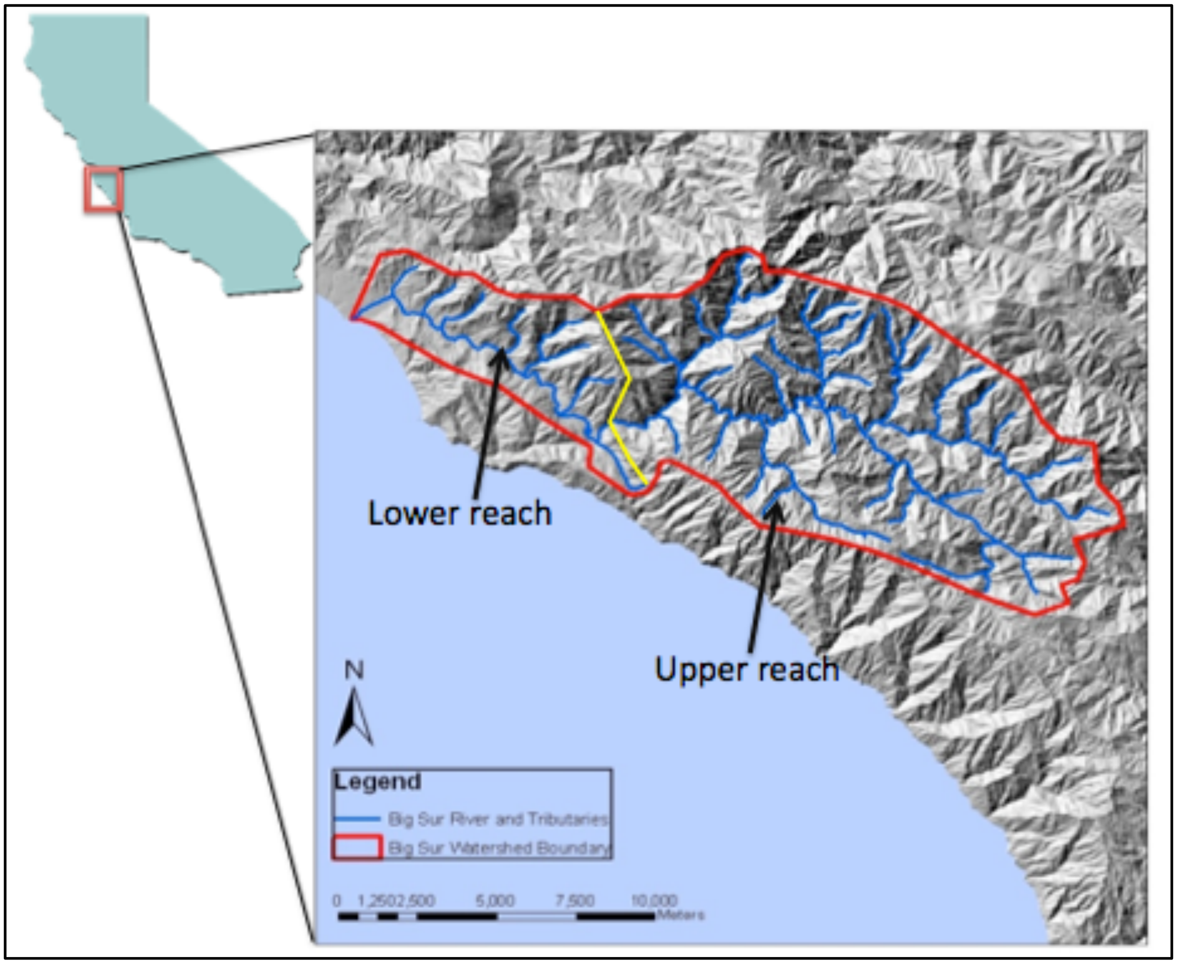


Figure 1. Map of the Big Sur River, tributaries and watershed extent. The studies for this project were conducted in the lower reach.

Relevant Policies

In 1983 the county of Monterey adopted the Big Sur Protected Waterway Management Plan (WMP) in an effort to preserve the cultural, scenic and natural resources found in the Big Sur Area (Big Sur Land Use Plan, 1996). The values and policies within the Big Sur WMP were incorporated in 1996 with the Monterey County Local Coastal Land Use Plan (LUP). Stated in the LUP is “The County's basic policy is to take a strong and active role in the stewardship and safeguarding of Big Sur's irreplaceable natural resources. Where there are conflicts, protection of these national resources is the primary objective with definite precedence over land use development” (Big Sur Land Use Plan 1996). Also included in this plan under the specific habitat requirements is the statement that no development shall affect stream flow in such a way that diminishing water levels result in loss of plant or animal life. A large portion of the LUP discusses the importance of the natural state of streams to plants and wildlife in the area. The Big Sur LUP clearly sets forth terms for maintaining these stream systems and prevents or discourages the excessive use of ground or surface water, inter-watershed transfers of water and degradation of water quality and/or quantity (Big Sur Land Use Plan, 1996). Combined, the Big Sur Waterway Management Plan and the determination of local residents' desire to maintain an "urban-free" environment, make development along the Big Sur area difficult.

California Water Laws

California has a unique system for allocating water. Water rights in California are broken into two categories: riparian and appropriative. Riparian rights are established by owning land adjacent to a riparian habitat (river, stream, lake, pond etc). This method is a first-come-first-served system. Those who establish rights first can choose the amount of water they need and have an established seniority over those who gain rights later. Appropriative rights are based on an application process. An application is submitted to the SWRCB for review and if approved, one can begin diverting water at a specified amount. The diversion amount is typically given in acre-feet per year (afy), not by amount per day or season. During high winter flows, there is enough water to supply the needs of residents in Big Sur and plant and animal species of the river. Problems arise during the summer months and base flow conditions if water has been over-allocated. Although not conducted at or near base-flow conditions, a capstone study in 2008 found significant decreases in flow (Table 1) during a three-day study in a reach of the Big Sur River with three commercial wells and two residential wells located along the banks (Maher, 2008). The 2008 study measured differences in discharge between two transects (Figure 2). The BSRI operates two wells and Clear Ridge Mutual Water Association operates one well (Maher 2008; SWRCB 2010).

Date	Q (cfs) Upstream of well field	Q (cfs) Downstream of well field	Difference in CFS	% Difference in CFS
March 22, 2008	122.32	98.21	-24.07	-19.7
March 26, 2008	100.89	92.85	-8.03	-7.96
April 6, 2008	83.25	69.87	-13.3	-16.1

Table 1. Table showing total change in surface flow between Clear Ridge and BSRI wells during a 2008 capstone study (Maher 2008).

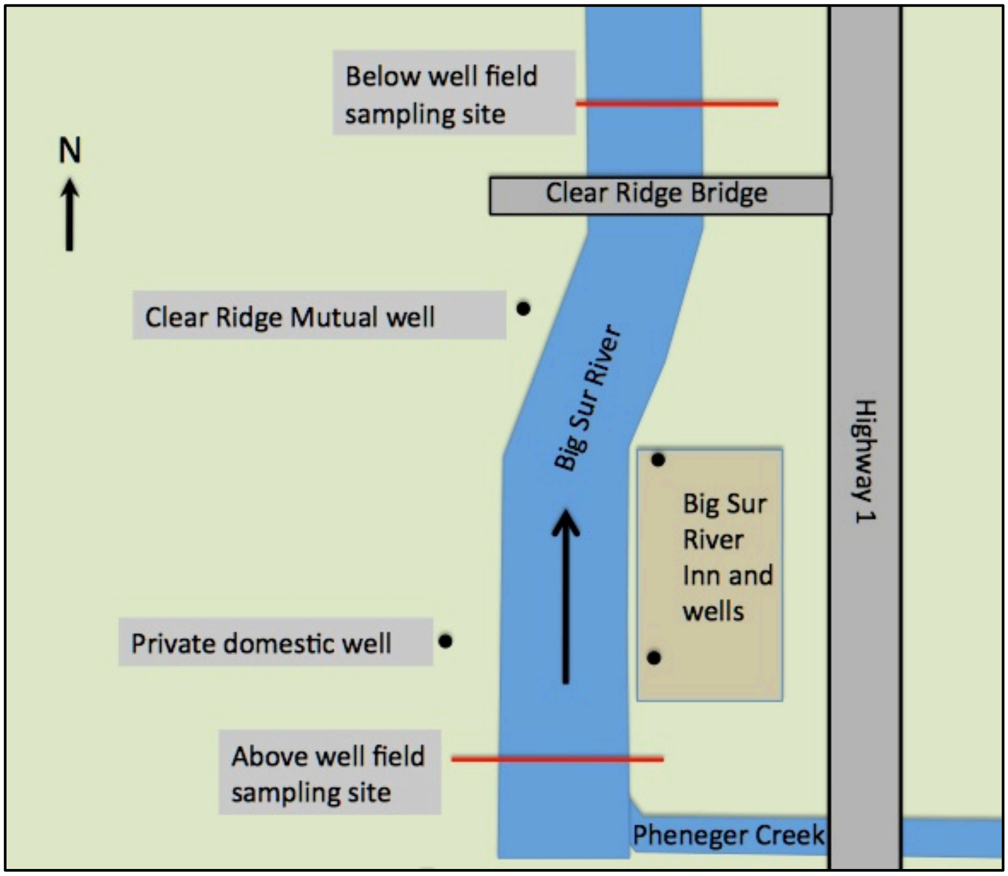


Figure 2. Schematic of sampling sites in relation to wells.

The Clear Ridge Mutual Water Association has recently gained permission from the SWRCB to continue to operate a well near the Big Sur River. The well is located approximately 35 feet from the southwest bank of the river and is drilled to a depth of 36 feet in the alluvial bank (SWRCB 2010). The well will supply 42 residents with domestic water and water for fire suppression (SWRCB 2010). The Clear Ridge well had been protested by a number of groups on the basis that it would be detrimental to local flora, fauna and private water rights. The protesting parties included: California Department of Fish and Game, Ventana Wilderness Chapter, California Coastal Commission, Sierra Club, Carmel River Steelhead Association and several private parties (SWRCB 2010). A mitigated negative declaration was signed in July 2010, proposing that the presence of the Clear Ridge well alone will have no negative environmental impacts. The mitigated negative declaration (MND) for the Clear Ridge application set the following extraction guidelines based on flow from the USGS gage 11143000 located approximately two miles upstream of the Clear Ridge and BSRI wells (Figure 3).

When the gaged flow is greater than 3 cfs and less than or equal to 4 cfs, the diversion shall not exceed a maximum 24 hour average rate of 0.03 cfs.
When the gaged flow is greater than 4 cfs and less than or equal to 5 cfs, the diversion shall not exceed a maximum 24 average hour rate of 0.04 cfs.
When the gaged flow is greater than 5 cfs and less than or equal to 6 cfs, the diversion shall not exceed a maximum 24 hour average rate of 0.05 cfs.
When the gaged flow is 6 cfs and greater, the well diversion rate will be the pump's maximum capacity of 0.058 cfs.

Figure 3. Guidelines for groundwater extraction set forth by the mitigated negative declaration for the Clear Ridge well located along the Big Sur River (SWRCB 2010).

It should be noted that the low flow levels suggested above are extremely low and have not been reached in over 60 years of continuous monitoring (USGS 2010). The USGS gage located in Pfeiffer Burns Park is the source for the State Water Resource Control Board to obtain flow data for issuing permits and diversion amounts along the Big Sur River. A number of points of diversion exist in between the USGS gage and the Clear Ridge and BSRI wells (Figure 4). The negative declaration report did not consider the cumulative effects of multiple wells within the reach or the pending permit for the El Sur Ranch to divert ~1600 afy near the river mouth (SWRCB, 2010). The report does make note of the distance from Clear Ridge well site to the USGS gage, however nothing is mentioned of the number of other wells between the well and the gage. Given that there are three additional tributaries and a number of wells between the Clear Ridge, BSRI wells and the USGS gage, the amount of water entering the well field is likely different from that at the USGS gage.

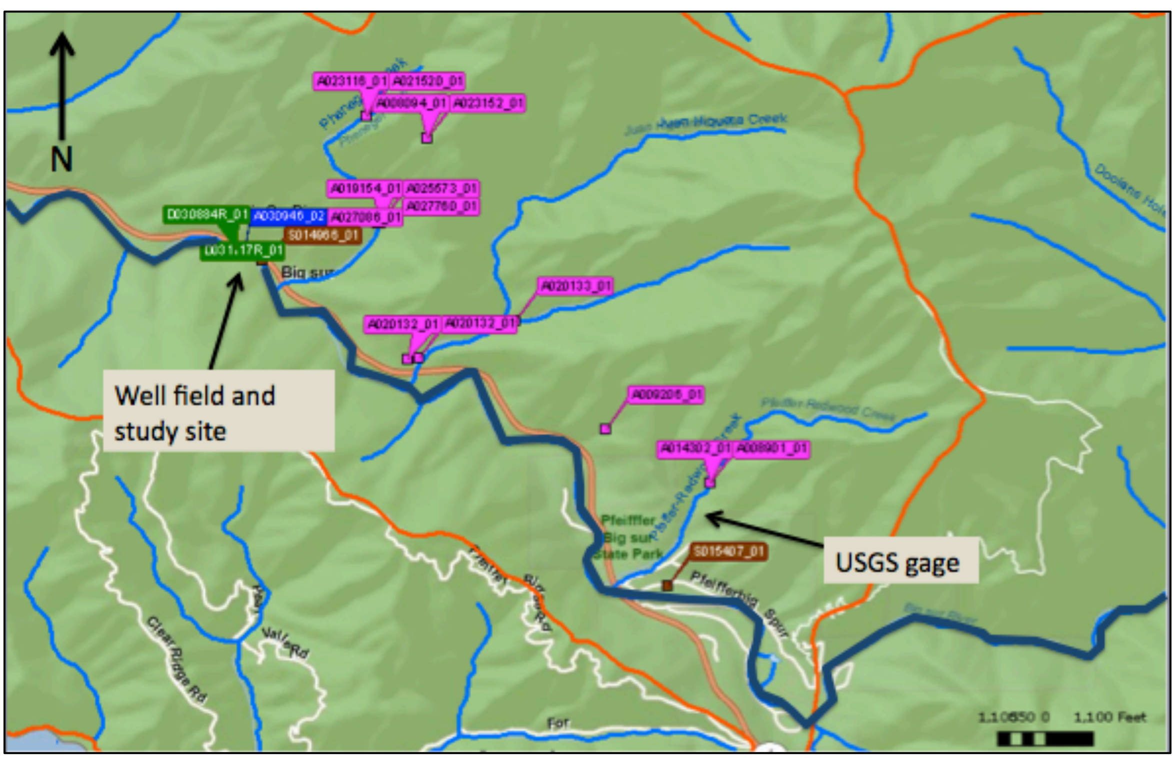


Figure 4. From SWRCB's eWRIMS GIS website showing location of all active wells in between Clear Ridge/ BSRI wells and USGS gaging station.

Endangered Species Act

The Endangered Species Act was passed in 1973 by congress to protect endangered plants and animals. The goals of the ESA are to prevent damage to habitats and ecosystems that harbor listed species, prevent species from staying on the list and prevent incidental "takings" of listed species (USEPA 2010) Two agencies are chiefly responsible for enforcing the act: the U.S. Fish and Wildlife Service and the U.S National Oceanic and Atmospheric Administration (USEPA, 2010). There are two classifications a species can be put into once on the ESA list, threatened and endangered. When a species is listed, state and federal agencies are required to prevent that species from remaining at that status (NOAA 2010).

In California there are a number of distinct population segments of steelhead (Figure 5). The Big Sur River contains the highest relative number of returning adult-anadromous salmonids in the south-central distinct population segment. Recent estimates by the National Marine Fisheries Service (NMFS) in 2007 estimate that there are approximately 500 steelhead returning to the Big Sur River every year. Increasing development along the Big Sur River is increasing the demand for water. Big Sur depends entirely on the river for its water, and an increase in groundwater withdrawal may have negative effects on *O. mykiss* habitat.

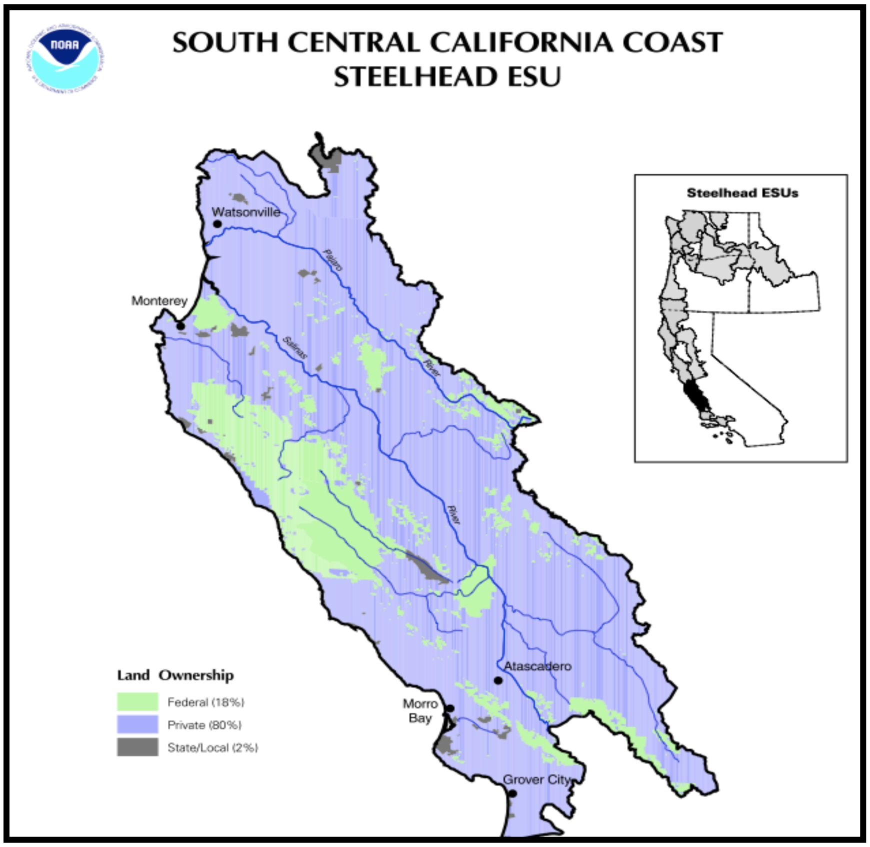


Figure 5. A map of the south-central California steelhead distinct population segment. Source: NOAA 2007

Basin Complex Fire of 2008

In 2008, the Basin-Complex and Indians (BCI) Fires collectively burned approximately 240,000 acres of a number of central California watersheds and 31,000 acres of the Big Sur watershed. Of the total area burned in Big Sur, 84% was classified as having moderate to high burn severity (Figure 6 and Table 2 SEAT (2008)). The fires ignited by lightning strikes in the Big Sur area burned for 24 days (SEAT 2008). Extensive fire suppression near areas where humans dwell can lead to less frequent fires and more catastrophic intense fires (Keeley 2003). Highly flammable undergrowth develops as a result of less frequent burns. Fires are classified by the intensity at which they burn, the area burned, and vegetation lost. A severe burn categorization means strongly hydrophobic soils, majority of leaves crowns and needles burned from trees and little to no vegetation (<20% cover) left on ground (SEAT 2008). Hydrophobic soils form in areas of high burn intensity and effectively repel water from the surface by lowering the infiltration rate. Extremely hydrophobic soils can resist water infiltration for up to several minutes (SEAT 2008). Post-wildfire landscapes lack vegetation and cover which can pose expected hazards due to the increased exposure of soil to direct rainfall. Some of these hazards include: mass-wasting events, increased delivery of sediment to streams and increased run-off. High sediment loads reduce available steelhead spawning grounds and change the channel geometry.

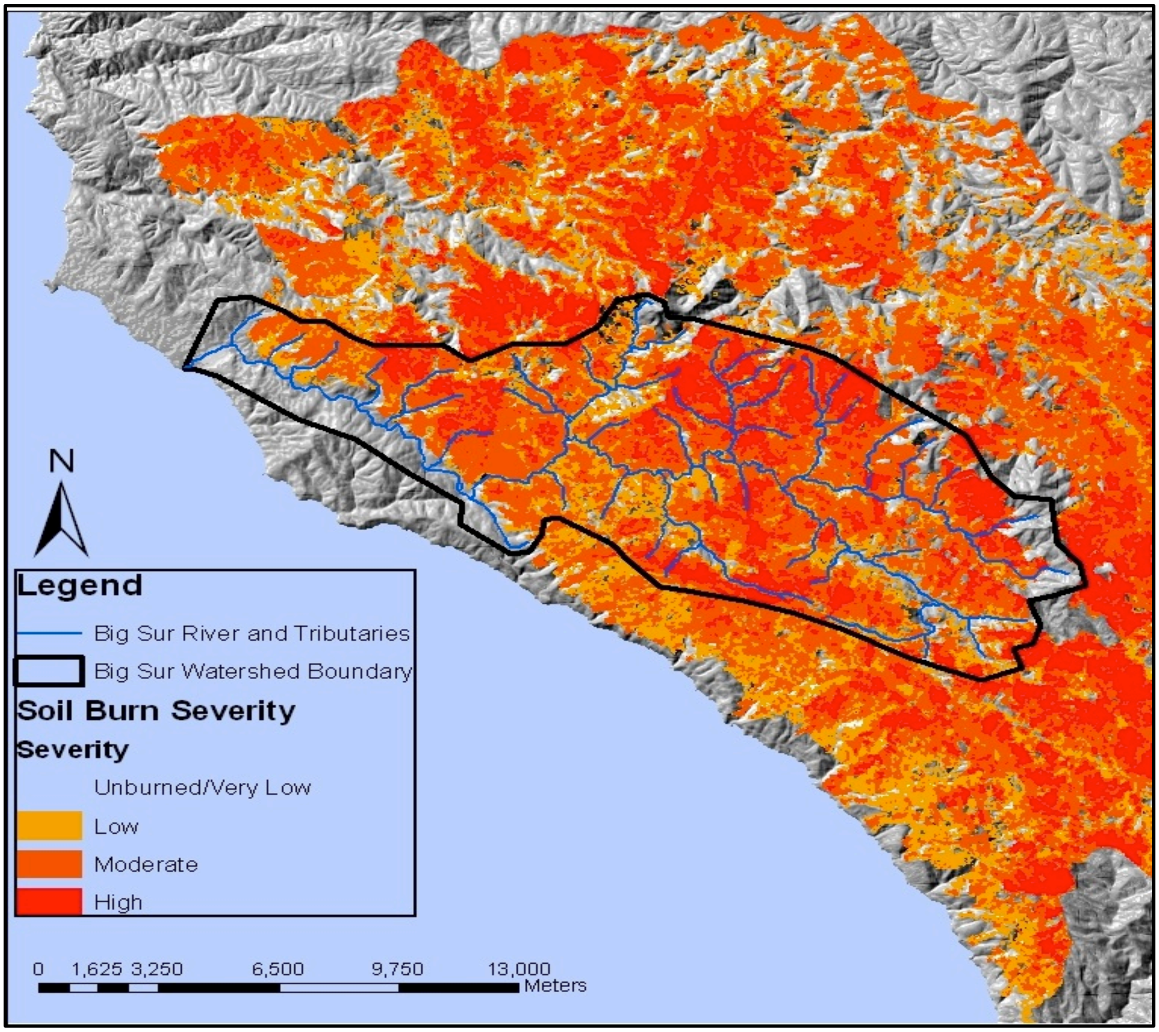


Figure 6. Map of burn severity within the Big Sur watershed.

Burn Severity	% Burned	Hydrophobicity of Soil	Vegetation
High	>80%	Repel water > 40sec	Fully burned or volatized
Moderate	50-79%	Repel water 10-40 sec	Crowns of trees remain, but >50% of needles burned
Low	<50%	Repel water <10 sec	Most plants scorched or singed

Table 2. A brief explanation of burn intensities found in SEAT 2008.

Sediment Pulse, Channel Response and *O. mykiss*

A post-fire study by Miller and Benda (2000) found that after mass wasting events, a pulse of sediment travelled from the wasting site downstream in a wave-like manner. As a result the downstream median gravel size tends to decrease and aggradation occurs through time (Figure 7). Stream aggradation can increase the potential of flooding by decreasing channel capacity (Miller and Benda 2000). Increased potential for flooding is a concern for high value properties businesses and private homes. Channel aggradation temporarily occurs when a river is being supplied with more sediment than it can effectively move. In response to this initial pulse of sediment, streams tend to incise and become characteristically different channels. Aggraded channels frequently flood, as the width to depth ratio is large, whereas deeply incised streams are infrequently topped (Miller and Benda 2000). In addition to changing channel geometry, sediment fining can adversely affect steelhead habitats. Inbar et al. (1998) found that the largest volume of sediment was delivered to a river the first rainy season following after a fire. The amount and volume of sediment discharge is dependent on a number of factors including: soil type, vegetative cover, relief of watershed, burn intensity and burn frequency (Pak et al. 2009).

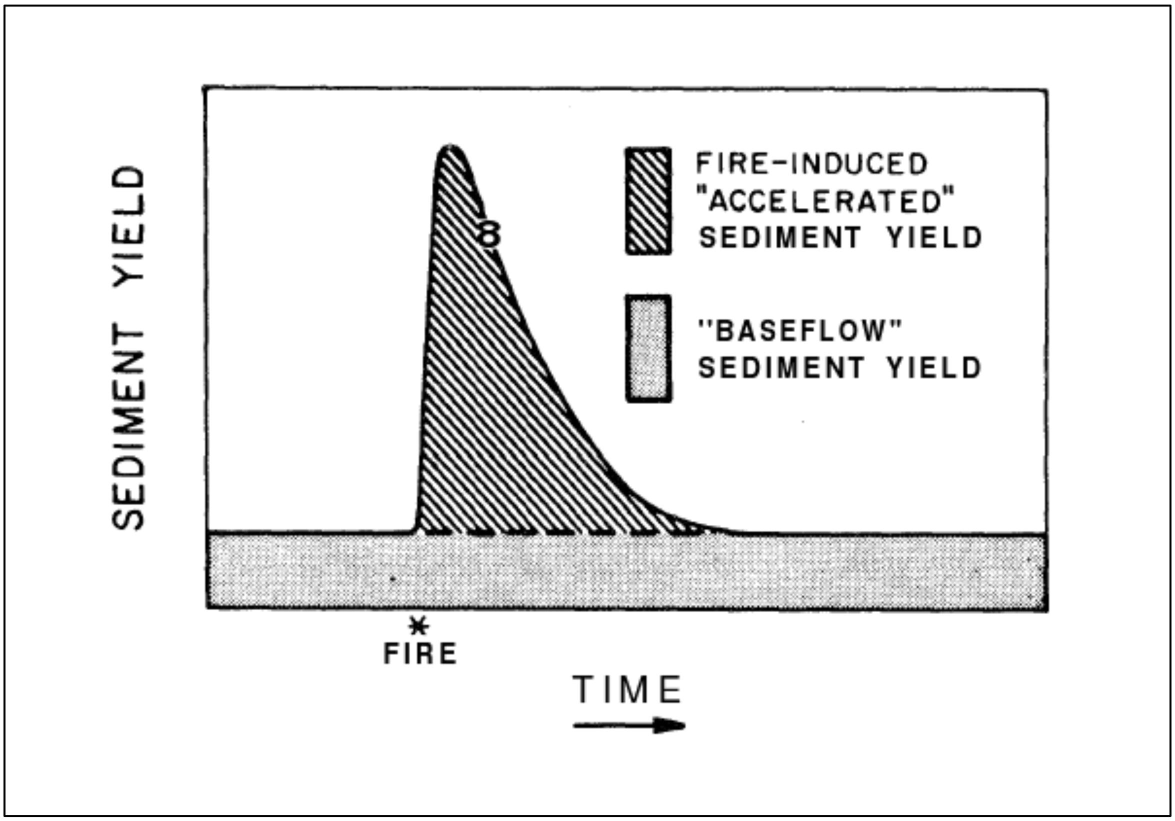


Figure 7. Hypothetical stream response showing accelerated sediment yield over time as a result of fire (Swanson 1981).

Sediment size plays an important role in three reproduction stages of *O. mykiss*: redd (nest) construction, egg incubation and emergence (Kondolff 2000). In addition to the aforementioned stages, sediment also influences temperature, DO of the redd site and emergence timing (Fudge 2008). Fine sediment can suffocate eggs by clogging pore spaces. Figure 8 shows the survival percentage of salmonid embryos given a specific percentage of particles < 6.35mm.

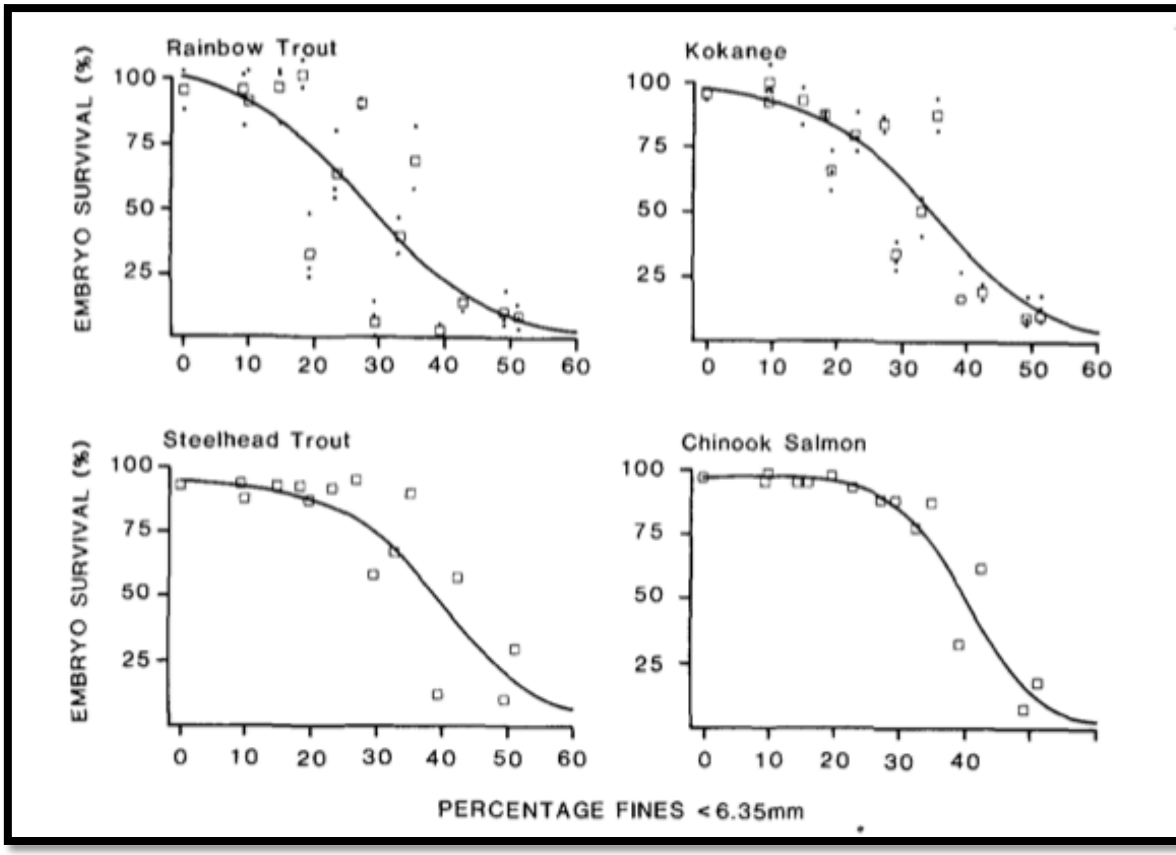


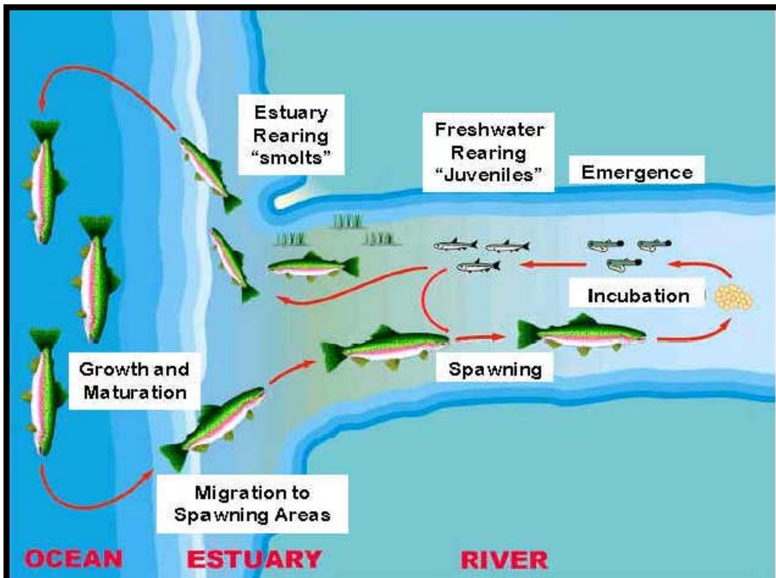
Figure 8. Graph depicting salmonid embryo survival versus percentage of total substrate < 6.35 mm (Machan 1991).

Successful incubation of *O. mykiss* eggs depends on adequate pore space to supply sufficient DO and remove metabolic wastes. Adequate space is also required for *O. mykiss* emergence (Fudge T 2008). High loads of fine sediment create "caps" deterring emergence at appropriate times or stopping emergence all together. In certain rivers such as those in central California where migration windows are narrow, late emergence could dictate whether an individual steelhead migrates downstream or becomes a resident Rainbow thereby decreasing the number of steelhead in the area.

Steelhead Trout

Steelhead are an anadromous fish species meaning they spend a portion of their lives in fresh water and a portion in salt water (Figure 9). *O mykiss* is a unique species in that they can migrate downstream and become steelhead or remain in fresh water and become resident rainbow trout. *O. mykiss* are also unique from other salmonids in that they can repeat the spawning process multiple times. Young *O. mykiss* may develop the urge to migrate downstream into a lagoon where they undergo the process of smoltification, the preparation to live in salt water. Size is a significant factor in ocean survival and *O. mykiss* do much growing in lagoon/estuarine environments. Decreased capacity of lagoons from sedimentation may decrease available steelhead habitat. A recent study conducted at Scott Creek, in Santa Cruz County, found that estuaries provide an important nursery habitat allowing small fish to double in size in a short amount of time (Bond et al. 2008).

One essential aspect of sustaining *O. mykiss* populations is the ability to migrate freely both up and downstream. Because *O. mykiss* can remain in fresh water and become resident rainbow or migrate and become *O. mykiss*, the ability to migrate seems to be of paramount importance to the species. Migration typically occurs during the periods of highest flow, December through April. During the summer months, stream flows are at their lowest. Consequently, these are the months with the highest peak demand for water by residents and businesses along the Big Sur River (Stanley 1983). The possibility of creating adverse water conditions for young steelhead and other species of interest increases here as flows can decrease to 18cfs (USGS 2010). The discharge of a river will continue to be at its lowest until a significant runoff event occurs. Unfortunately for inmigrating steelhead the beginning of their inmigration window may overlap with base flow conditions if a significant runoff event has not occurred by December.



Steelhead trout life-cycle.

Figure 9. Steelhead spend portions of their lives in fresh water and saltwater. They undergo physiological changes to allow for life in salt water.

In addition to adequate flow requirements, *O. mykiss* depend on water quality and sediment parameters for breeding, incubation of eggs and emergence of fry. These parameters are different for each stage in the *O. mykiss* lifecycle (Kondolff 2000). Two critical water quality elements are dissolved oxygen (DO) and temperature. Temperature and DO are inversely related. Lower quantities of water heat faster than higher quantities; this becomes a risk during low flows and has the potential to be exacerbated by groundwater extraction (Kondolf et al. 1986). Sediment fining decreases channel capacity and available steelhead habitat. High temperatures are likely to be the most problematic during base flow in this area and may drop DO levels beyond that which can be tolerated by steelhead and their developing progeny.

Potential Impacts of Groundwater Withdrawal

Motivations

The overall study was divided into two components: potential impacts of groundwater withdrawal and sediment fining as a result of the BCI Fire of 2008. Both components of the study were conducted in the context of assessing steelhead habitat. The first portion of the study investigated if groundwater withdrawal is causing a decrease in surface flow along a reach of the Big Sur River (Figure 2). The second portion of the study monitored how the average sediment size was changing along six transects located in the lower reach of the Big Sur River.

Motivation for this portion of the study was brought about by a Big Sur resident who was concerned about potential negative impacts to water availability and loss of riparian habitat as a result of excessive groundwater extraction. Additionally, the capstone study conducted by Maher (2008) found significant decreases in flow below the well field. If the findings by Maher were to occur during low flow or base flow conditions, steelhead habitat could be strongly impaired. The decreases found were on the order of 8-20% during the spring of 2008. The well field of interest has a total 4 active wells.

The goals of this portion of the study were to:

- Determine if groundwater withdrawal is altering surface flow.
- Quantify the change in surface flow if one is detected.
- Interpret findings in the context of local policy, future land-use planning and the ESA

Postulate:

The postulate explored by this study was that summer streamflow downstream of the well field is lower than summer streamflow above the well field.

Methods

Flow data were collected from September through December of 2010 along the Big Sur River near the Big Sur River Inn (Figure 9). Two transect locations were established along the Big Sur River, one above the well field two meters downstream of Pheneger Creek (Figure 10); the second, below the well field at the Clear Ridge bridge (Figure 11). Discharge measurements were recorded using a SonTek Handheld Acoustic Doppler Velocimeter (Figure 12). Discharge measurements followed methods set forth by Harrelson et al. (1994). Three to four repeat measurements were taken per transect to establish a mean discharge. Discharge measurements for each cross-section were calculated in the Doppler.

Figure 10. View looking downstream from Pheneger Creek at cross-section. Left and right benchmarks located out of frame.

Figure 11. View looking upstream from Clear Ridge Bridge.

Figure 12. Image of SonTek FlowTracker console.

A Horiba handheld water quality monitor was sporadically used to detect changes in specific water quality parameters. Because changes in temperature, specific conductivity and dissolved oxygen can be potential indicators of groundwater/surface water interaction, these parameters were recorded. Water quality measurements were taken at the upstream and downstream sites. Additionally, samples were taken in the thalweg of runs just downstream of riffles. Samples were internally logged in the Horiba and field book. In total there were six discharge measurements and three Horiba samples were taken. Table 3 shows the left edge of water (LEW) and right edge of water (REW) locations in UTM coordinates. No permanent benchmarks were established for this study.

UTM Coordinates of transect locations		
	LEW	REW
Upstream of wells	607053 E 4014464 N	607885 E 401479 N
Downstream of wells	606884 E 4014749 N	606889 E 4014747 N

Table 3. Upstream (Pheneger Creek) and downstream (below Clear Ridge Bridge) transect locations.

Results

To determine if groundwater withdrawal is causing a decrease in surface flow along the Big Sur River, discharge measurements were taken above and below a well field near the Big Sur River Inn (Figure 2). During the study we found that any changes in surface flow were too small to detect given the precision of our study (Table 5 and Figure 15). Therefore, we cannot say that groundwater withdrawal along the study site is causing a decrease in surface flow. The accuracy of our discharge measurements ranged between 0.028-0.113 cms (1-4 cfs) (Figure 16).

Date	**Pheneger (cfs)**	**Clear Ridge (cfs)**	**Difference (cfs)**	**Percent change**
9/15/10	34.77	36.23	1.46	4.20
9/22/10	30.1	28.21	-1.89	-6.28
10/6/10	25.58	27.85	2.27	8.88
10/20/10	28.48	24.78	-3.70	-13.00
10/30/10	33.64	33.39	-0.25	-0.76
12/1/10	37.68	35.12	-2.56	-6.80

Table 5. Table of discharge (cfs) for sites upstream and downstream of wells, difference in flow and percent change. The red color indicates a calculated decrease in flow between the upstream and downstream site.

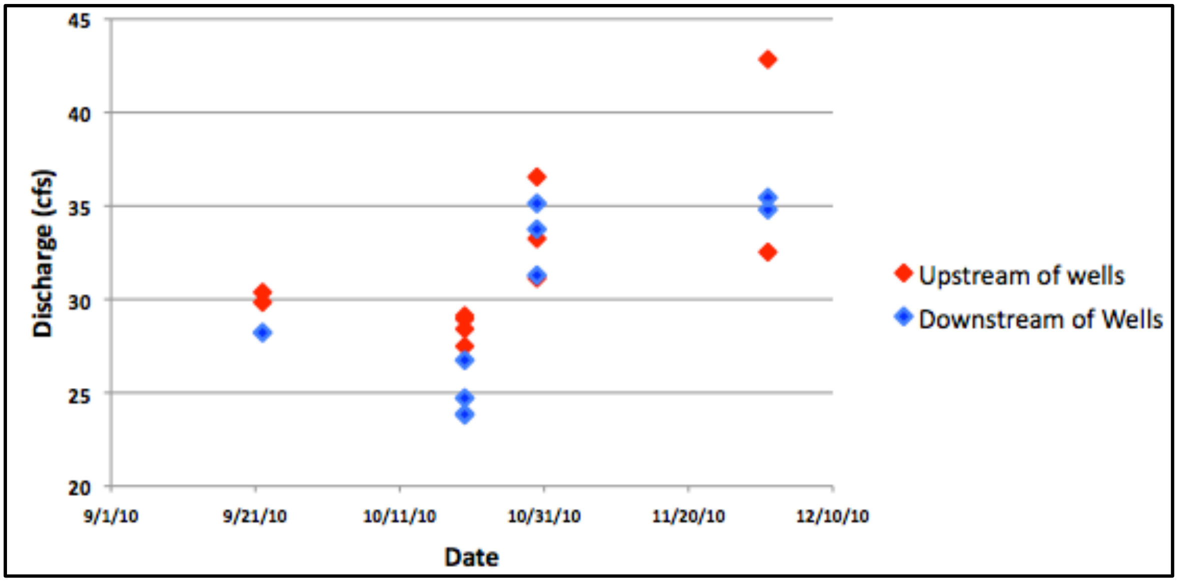


Figure 16. Graph indicating the range of values obtained over multiple measurements resulting in a between-survey precision of ~1-4 cfs.

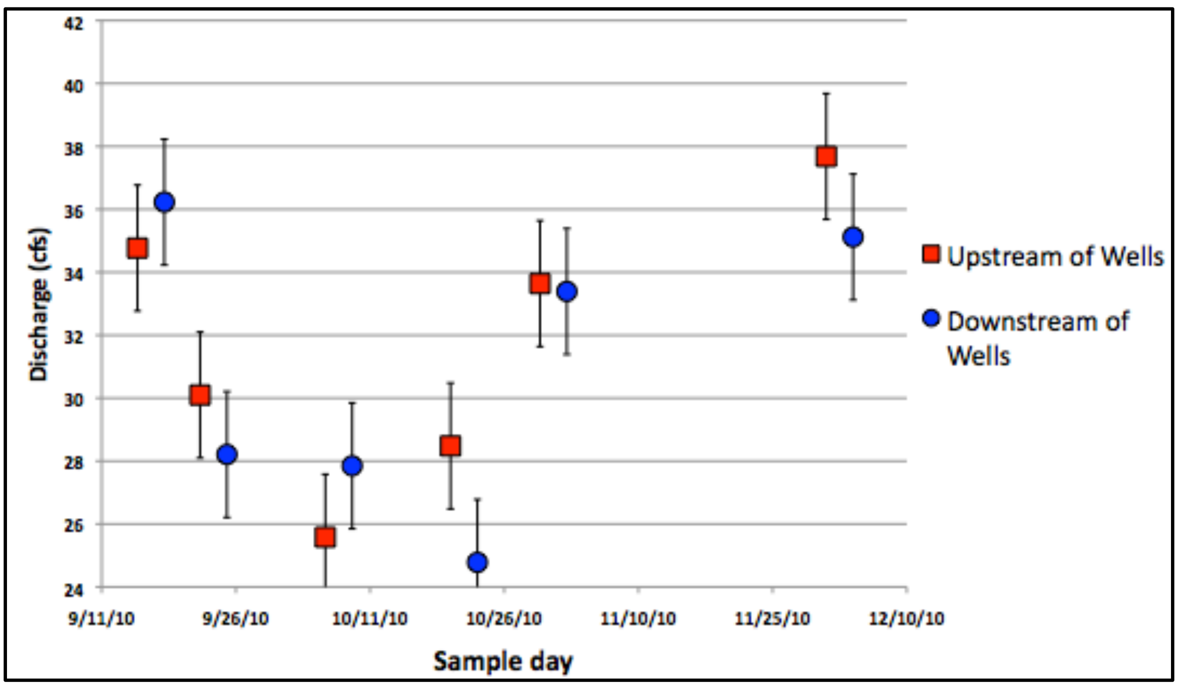


Figure 15. Graph depicting the differences in the upstream (Pheneger) and Downstream (Clear Ridge) transects.

Measurements from the Horiba hand-held water quality monitor showed differences in dissolved oxygen, conductivity (mS/cm), pH, and temperature between the upstream and downstream site (Table 6). The temperature difference of the water ranged from 0.15-0.56 C° between the upstream and downstream site with the downstream temperatures being higher. October 20 and October 30 saw an increase in pH from 0.05-0.48, while December 1 showed a decrease of 1.35. All three sample days with the Horiba showed an increase in the oxidation-reduction potential (ORP). The ORP differences ranged from (20-199 mV). The conductivity of the river increased below the well field on all three days, indicating higher groundwater influence. Conductivity values for October 20, October 30 and December 1 were .004 mS/cm, 0.61 mS/cm and 0.13 mS/cm, respectively. October 20 showed an increase in DO levels despite an increased temperature and December 1 showed a decrease in DO by 6.24 mg/L.

		Temp C°	pH	ORPmV	mS/cm	mg/L DO	Q (cfs)
10/20/10	Pheneger	13.8	8.75	204	0.3	10.68	28.48
	Clear Ridge	14.19	8.8	224	0.304	15.44	24.78
10/30/10	Pheneger	12.37	7.74	227	0.233	11.76	33.64
	Clear Ridge	12.93	8.2	264	0.294	11.04	33.39
12/1/10	Pheneger	8.05	9.23	86	0.281	22.4	37.68
	Clear Ridge	8.2	7.88	287	0.294	16.16	35.12

Table 6. Table showing results from Horiba at both transect locations.

Post-Wildfire Impacts From the Basin Complex and Indians Fire

Motivations

Because the Basin Complex Fire was extremely large and intense, CSUMB faculty and students initiated a program to monitor how the river channel responds to the fire. Numerous models and philosophies exist regarding how a watershed will respond to a fire (Keeley 2003). Approximately 84% of the Big Sur watershed burned at moderate to high intensity (SEAT 2008). Given the high potential for mass-wasting events and large amounts of topsoil being delivered into the Big Sur River, we are monitoring how the watershed is responding to the 2008 fire. Two previous capstone studies have monitored stream response to the BCI fire (Zertuche 2008 and George 2009).

The goals of this portion of the study were to ask:

- Is the Big Sur River still experiencing an increased fine sediment yield from the BCI fire of 2008?
- How have individual sites changed over time? Is there monotonic decrease in sediment size, or a variation about a mean particle size?
- How do our observed results of sediment yield from the Big Sur watershed compare to the hypothetical post-wildfire sediment yield graph?

Postulate:

The experimental design of this portion of the study is to monitor how sediment size is changing at six sites through time. Previous capstone studies have shown continuous sediment fining over the past two years. If we are still on the rising limb of the hypothetical post-wildfire sediment delivery graph (Figure 6), then we should see continued sediment fining.

Methods

A total of 6 benchmarked cross-sections were reoccupied between Pfeiffer Big Sur State Park and the Big Sur River mouth at Andrew Molera State Park (Figure 13). Cross-section surveys of these sites were measured using methods set forth by Harrelson et al. (1994). Pebble counts were obtained employing methods established by Wolman (1954). Previous studies provided a baseline for our data and site locations. GPS coordinates for benchmarks, site photos and descriptions allowed us to accurately reoccupy the sites (Table 4). Buried benchmarks were located using a metal detector.

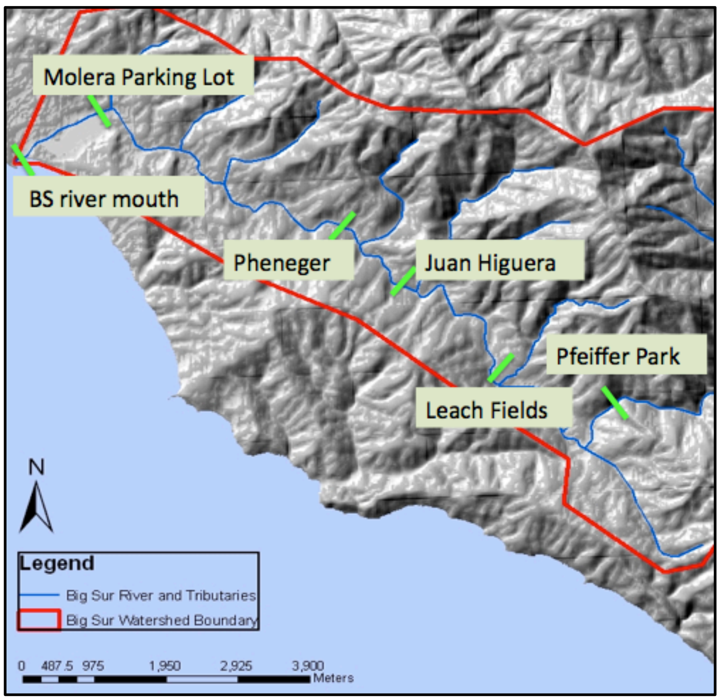


Figure 13. Map of general study area and six transect locations along the Big Sur River**.**

Site	LBM	Center of Cross-Section	RBM
Pfeiffer		**610267 E 4012058 N**	
Leach Field	**608764 E 4013298 N**		**608811 E 4013319 N**
Juan Higuera Creek		**607409 E 4014152 N**	
Pheneger Creek		**606888 E 4014757 N**	
Molera Parking Lot		**603789 E 4016416 N**	
Molera near River Mouth	**602793 E 4015910 N**		

Table 4. UTM coordinates of benchmarks of transect locations along the Big Sur River

For analysis, all data were entered into Excel to create cumulative particle size distribution plots. For the purpose of this study, sediment such as "sand", "mud" or "silt" were placed in a "<2mm" group. To determine if overall fining was occurring, the D_{50} (median) grain size was compared between study years. Pebble count data were entered into a pre-existing Excel spreadsheet formatted to provide statistical analysis of pre-fire impact (2008) and post-fire impact (2010), particle sizes including histograms, and graphs of cumulative particle size distribution (Potyondy and Bunte 2001). GIS layers obtained from the U.S. Forest Service's Burn Area Emergency Response team were projected in NAD 1983 UTM Zone 10N and edited in ArcMap. Burn severity areas within the Big Sur watershed were obtained using these files

Results

To monitor post-fire stream response, we reoccupied six study sites along the Big Sur River. Pebble counts were collected and compared to previous study results. Measurements were recorded at cross-section sites in October of 2008 and October of 2010. The sites at Pfeiffer and Higuera have substantial differences in the three size classes from 2010 when compared to the 2008 study (Figure 17 and Table 7). These results indicate that the overall sediment size in the Big Sur River is continuing to decrease. Although the changes in the Leach field site were not as dramatic as Pfeiffer and Higuera the cumulative percent finer than graph shows an overall decrease in the D_{50} size class. The site located below Pheneger creek near the BSRI and the Andrew Molera State Park parking lot site both demonstrated fining. The Big Sur River mouth at Andrew Molera shows no substantial changes in particle sizes.

Site number	Site Name	2008 Study D_{50} Particle size (mm)	2010 Study D_{50} Particle size (mm)	% Change
1	Pfeiffer BS Park	200	7.5	-96.3
2	Leach Fields	85	40	-53.0
3	Higuera Creek	100	6	-94.0
4	Pheneger Creek	25	110	340
5	A. Molera Parking	200	19	-91.0
6	A. Molera near river mouth	6	5	-16

Table 7. Change in D_{50} particle size for all sites surveyed between 2008 and 2010.

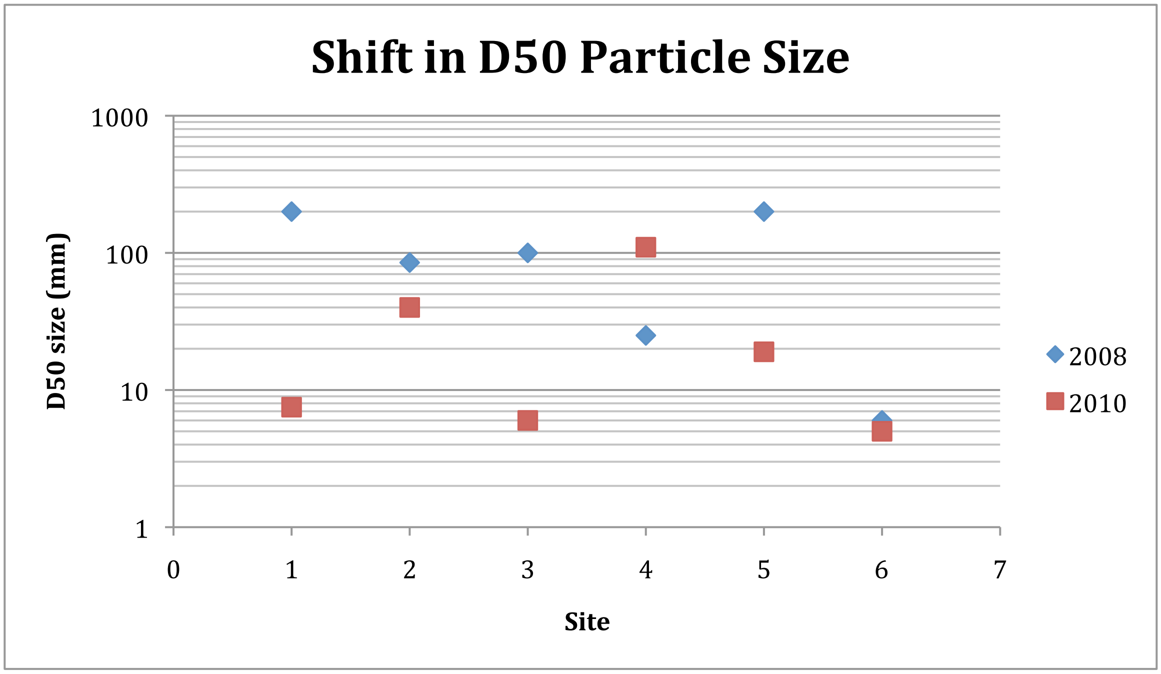


Figure 17. Shifts in D_{50} particle size (mm) from 2008 to 2010. Site numbers correspond to Table 9.

Results from the particle analysis in Pfeiffer Big Sur State Park show a substantial fining across all size classes (Figure 18 and 19). The D_{50} grain size shifted from 200mm to ≈7.5mm after two winters. D_{84} decreased in size from 350 mm to 25mm. The D_{16} shifted in size as well. 2008 reported a D16 value of around 18mm and 2010 found that the D_{16} had dropped to a size somewhere below 2 mm. The largest particle found during the 2010 transect was approximately 300mm, compared to the 1000mm particle found during the 2008 transect. Additionally, in 2008 there were few particles classified as sand, silt or mud (<2 mm). In 2010 the <2 mm size class comprised 30% of all samples. Unfortunately in 2010 we were unable to locate the 2008 survey BMs and were unable to capture any geomorphic change that may have occurred. The cumulative particle size distribution graph for the Leach Field site does not show substantial change in overall particle sizes, however there is a continuous fining between surveys (Figures 20 and 21). The D_{50} particle size decreased between the two survey years from about 85mm in 2008 to 45mm in 2010. The change in size of the D_{84} particles is barely noticeable on the graph indicating a change in less than 5mm. The D_{16} particle size decreased from ≈4mm in 2008 to 2.5mm in 2010. The next site downstream at Higuera Creek showed visible changes in particle size across all classes. The most notable change was the D_{50}, which decreased in size from 100mm in 2008 to 7 mm in 2010 (Figures 22 and 23). The 2008 study found that particles under 2mm accounted for approximately 5% of sediment. A substantial decrease was found in 2010 where particles under 2mm accounted for nearly 20% of all sediment.

Pheneger Creek, located upstream of the Big Sur River Inn, showed an increase in the total number of fine particles counted. Figures 24 and 25 show that no particles less than 2 mm were observed during the 2008 study. The D_{50} and D_{84} particle sizes both increased between survey years by 88mm and 390mm, respectively indicating a general shift in sediment composition throughout this reach. The study site near the parking lot of Andrew Molera State Park showed an overall decrease in particle size over the past two years. The D_{16}, D_{50} and D_{84} all decreased of 10mm, 180mm and 360mm, respectively. Figure 26 shows a large shift in particle size with no sediment larger than 156 mm seen in 2010 when compared to 2008. The 2010 study along the Big Sur River mouth did not find much variation in particle sizes when compared against the 2008 study (Figures 28 and 29). During both survey years the majority of sediment along this reach was mostly sand and fine particles. The D_{50} particle size remained almost constant between the 2008 and 2010 studies, changing from 6mm to 5mm, respectively. Roughly 40% of all sediment at this location was <2mm.

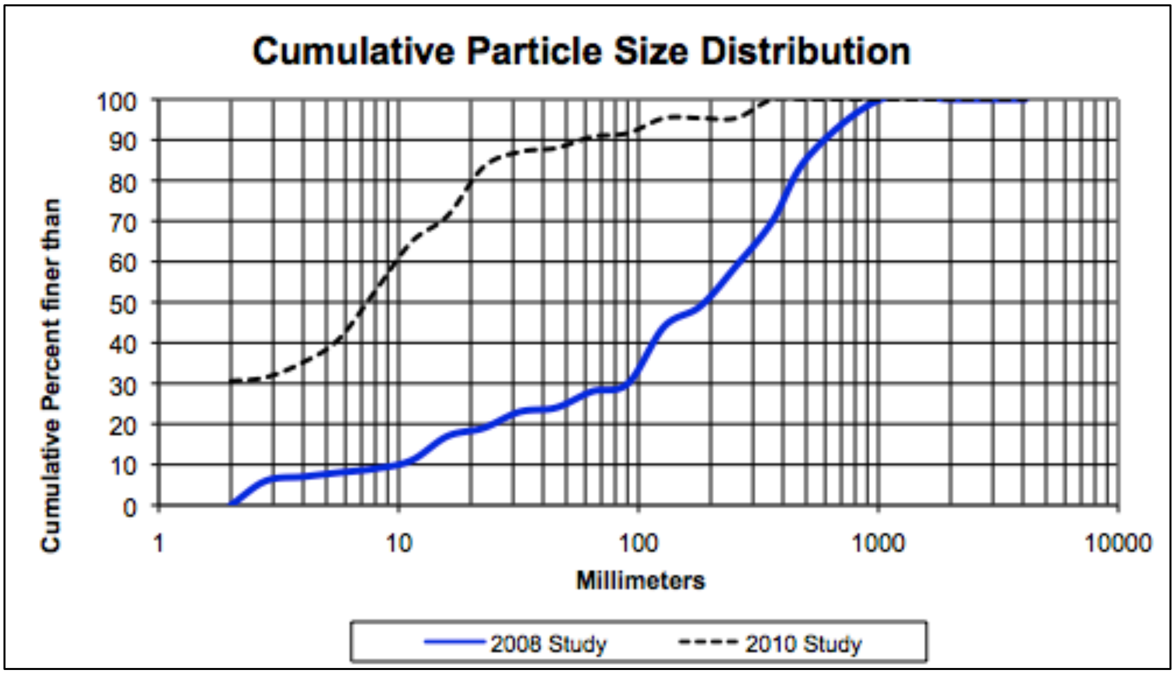


Figure 18. Cumulative particle distribution of sediment at Pfeiffer Big Sur State Park from two studies, 2008 and 2010.

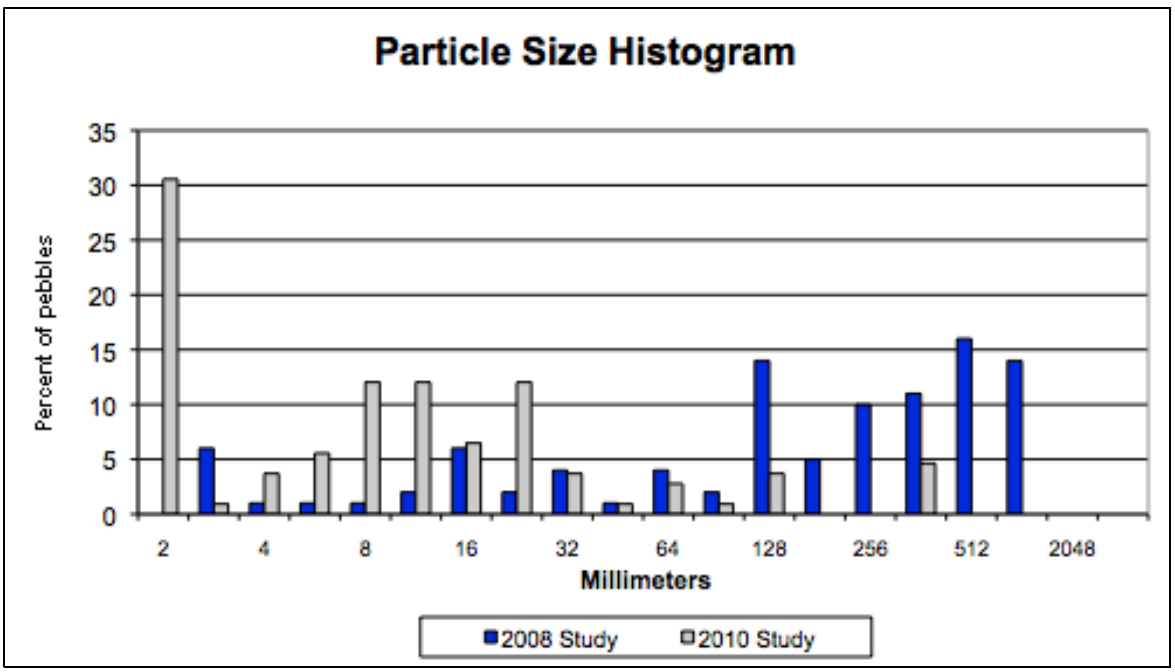


Figure 19. Histogram depicting distribution of particle sizes by percent of total at Pfeiffer Big Sur State Park

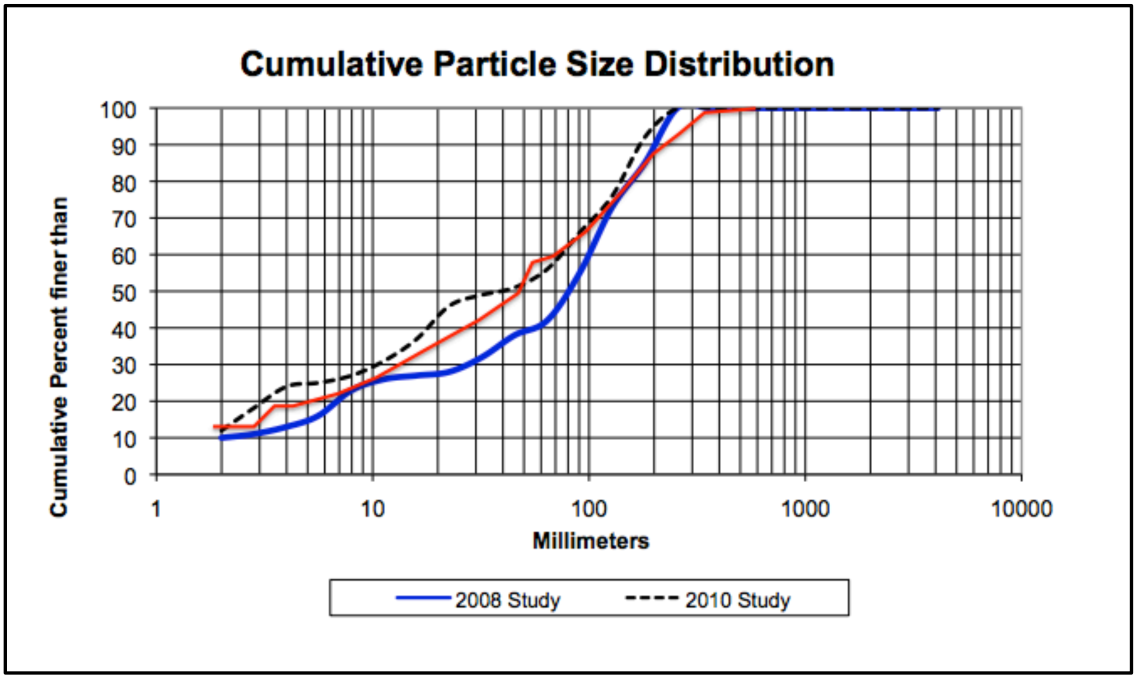


Figure 20. Cumulative particle distribution of sediment at site below Leach Fields. Red line indicates values from 2009 study.

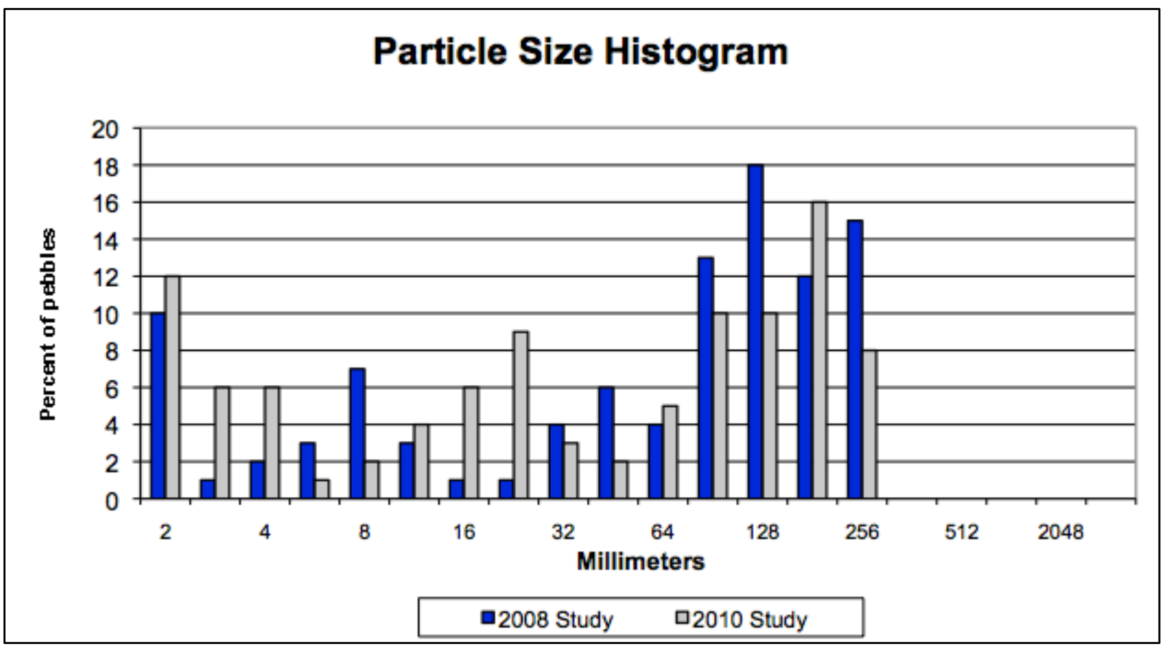


Figure 21. Histogram depicting distribution of particle sizes by percent of total below Leach Fields

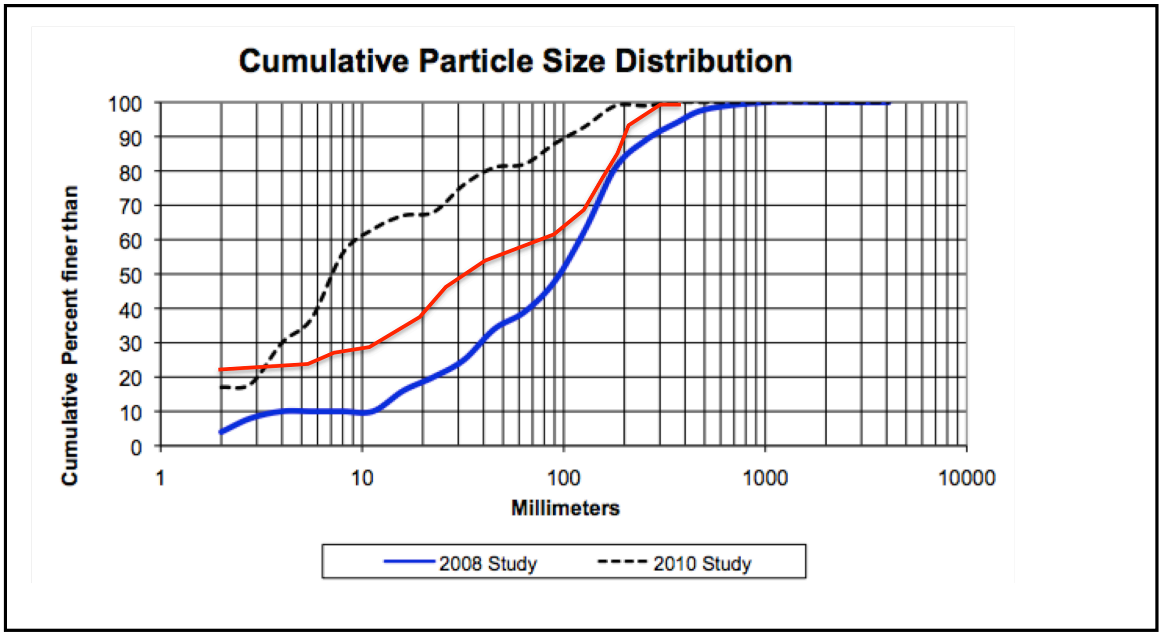


Figure 22. Graph of the cumulative distribution of particles observed below the Higuera Creek along the Big Sur River. Red line indicates study results from 2009.

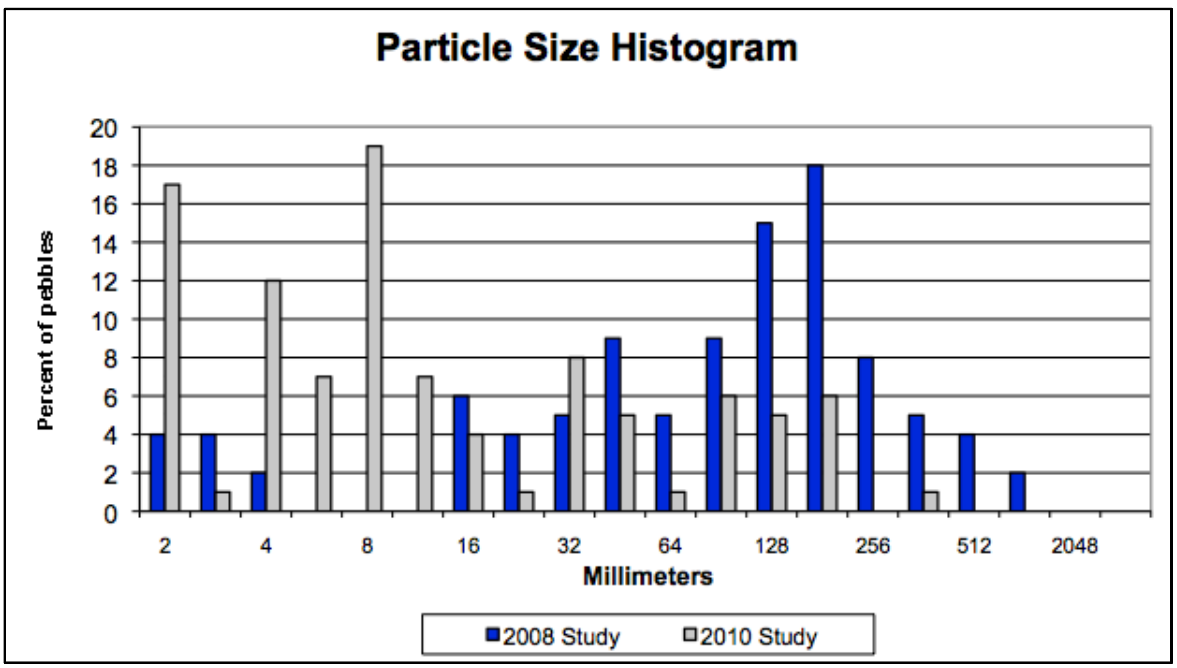


Figure 23. Histogram depicting distribution of particle sizes by percent of total below Higuera Creek.

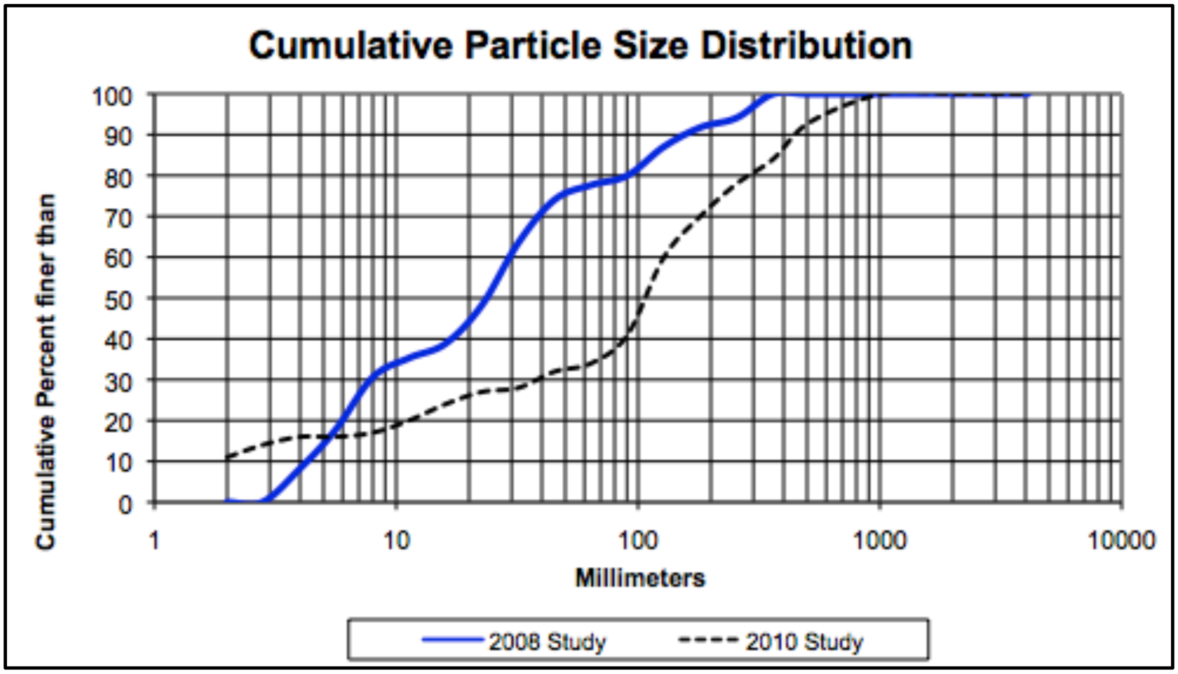


Figure 24. Cumulative distribution of particle sizes below Pheneger Creek near BSRI.

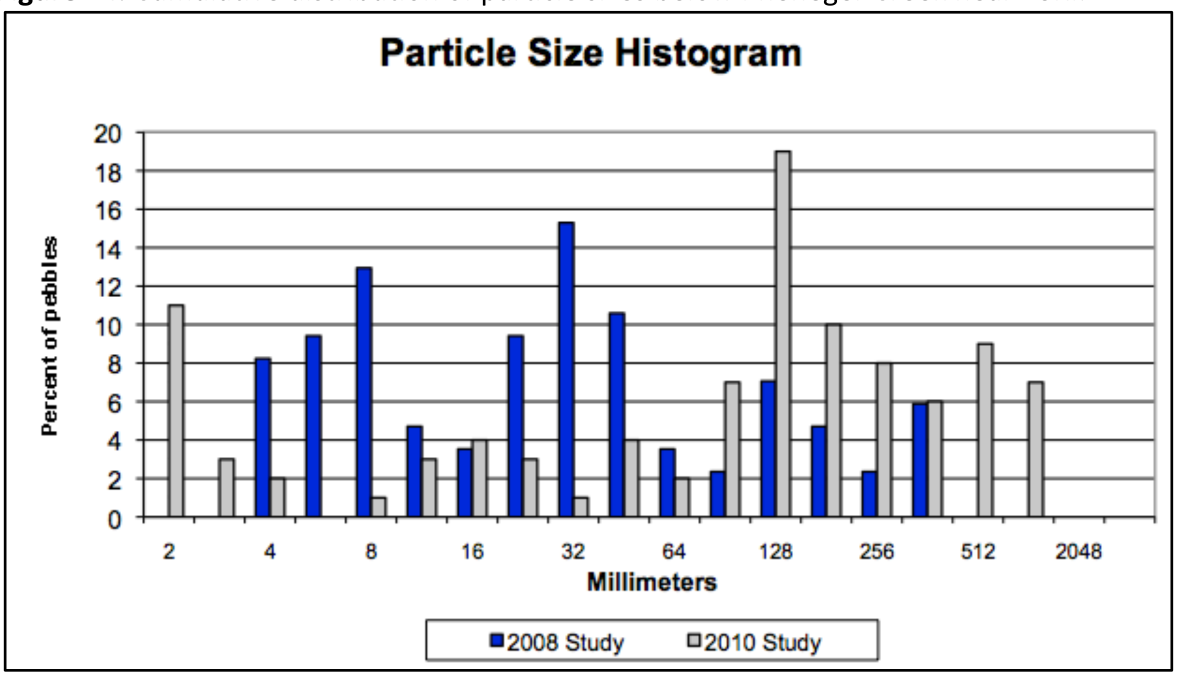


Figure 25. Histogram depicting distribution of particle sizes by percent of total below Pheneger Creek, near BSRI

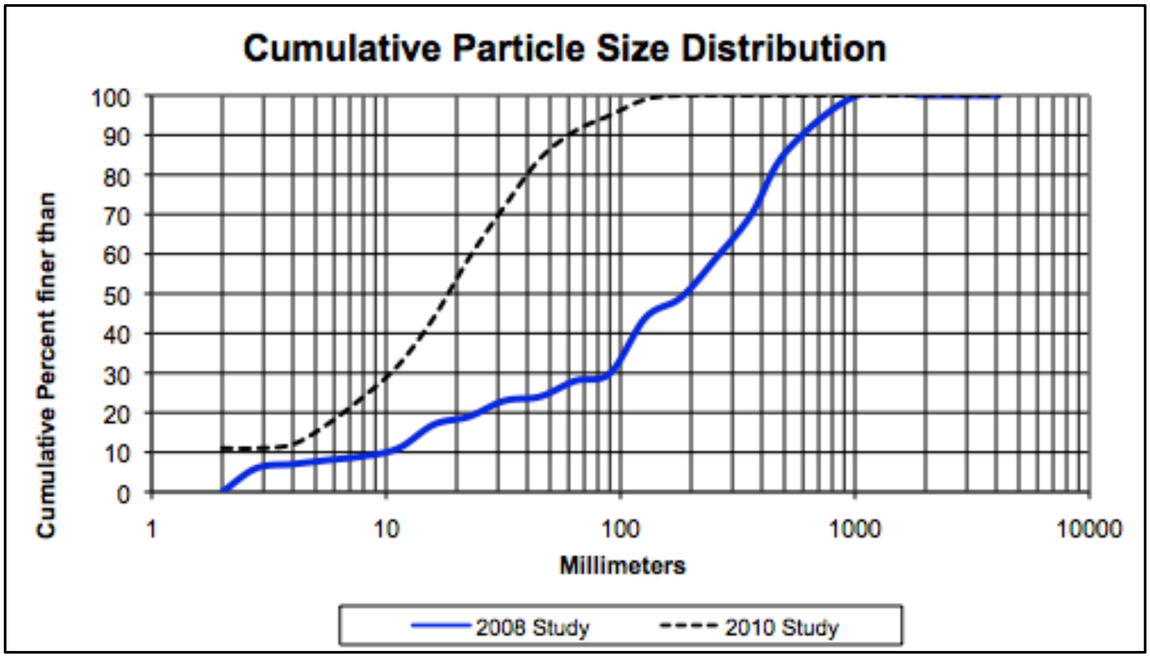


Figure 26. Molera Parking lot cumulative distribution graph of sediment sizes from 2008 and 2010.

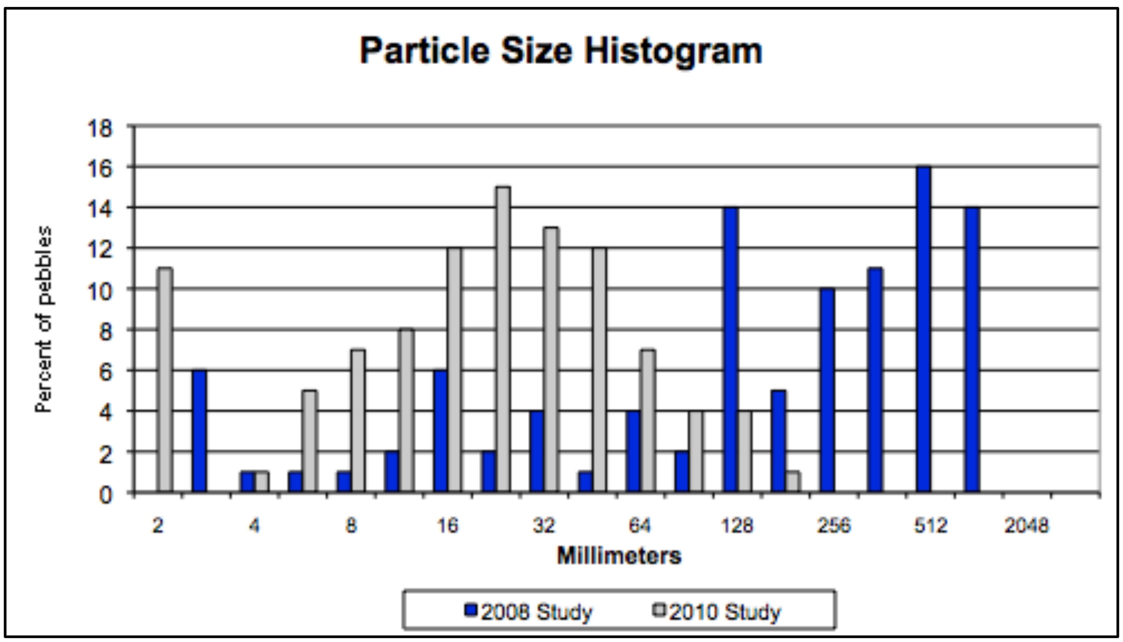


Figure 27. Histogram depicting distribution of particle sizes by percent of total, near parking lot at Andrew Molera State Park.

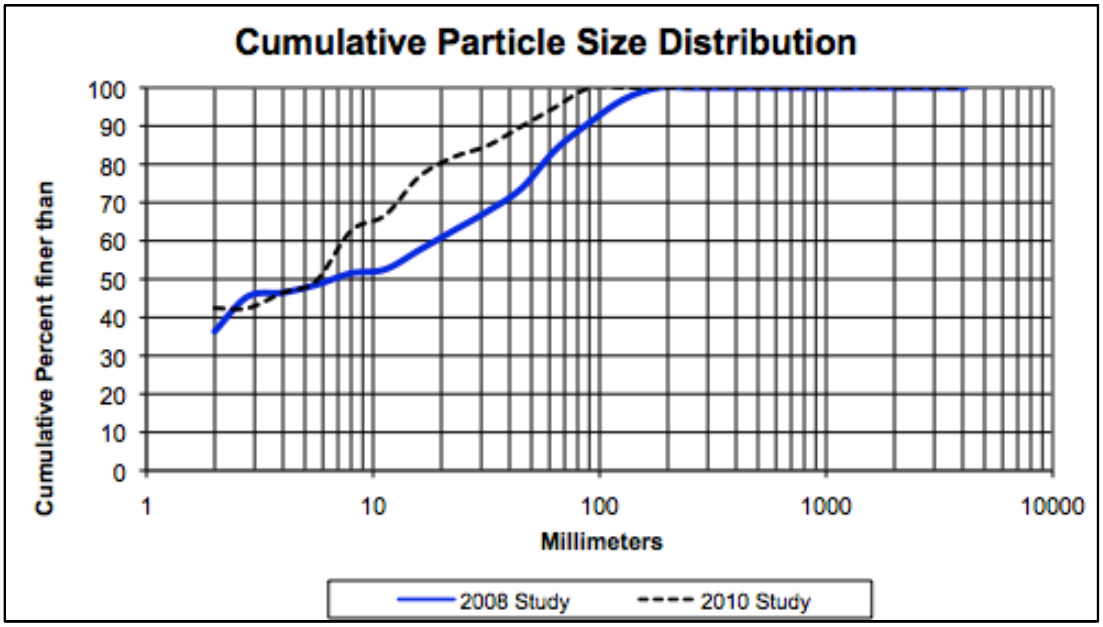


Figure 28. Cumulative distribution of particle sizes between 2008 and 2010 studies at the Big Sur river mouth.

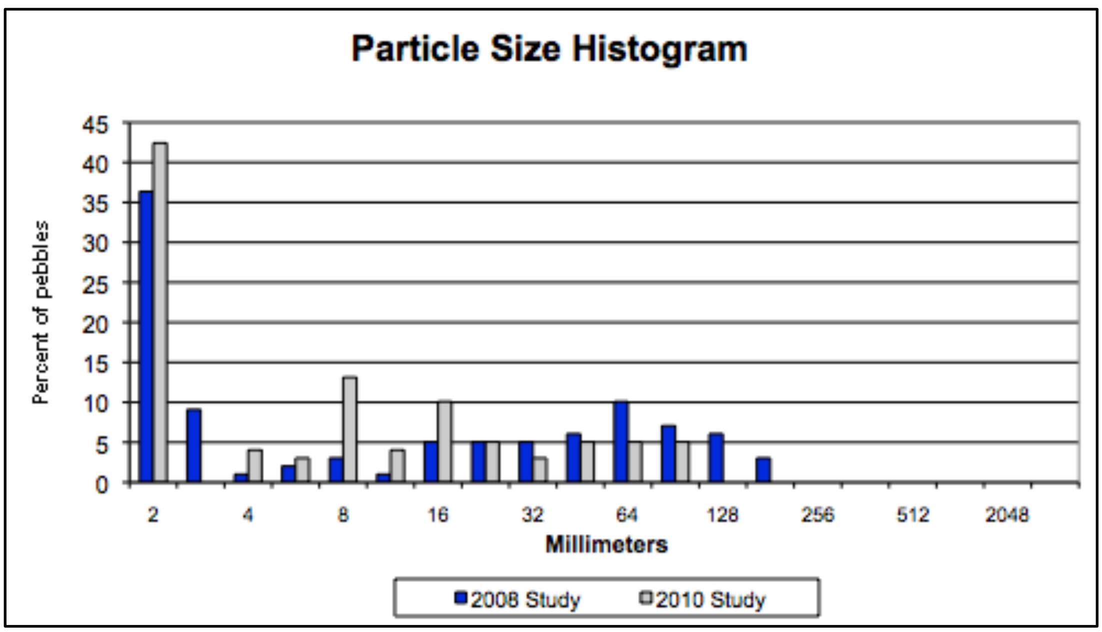


Figure 29. Histogram depicting distribution of particle sizes by percent of total at Big Sur river mouth within Andrew Molera State Park.

Discussion

We were unable to detect any changes in surface flow between the upstream and downstream transects. The maximum pump capacity of the Clear Ridge well within our study site is 0.002 cms (0.058cfs). Our precision in the field is between 0.028-0.113 cms (1-4 cfs), which is orders of magnitude higher than what a single well can pump. Difficulties in the detection of groundwater-surface water interaction arise from our limited precision or the lack of an impact from groundwater withdrawal.

One interesting observation is that our results at near-base flow conditions do not approach the relatively large values found by Maher (2008), whose study was conducted at flows 3-4 times higher than ours. One potential reason for the discrepancy between the two years could be that wells along the study reach extract more volume when more water is available. However, this would mean that the cumulative withdrawal in the 300m-study reach during the 2008 study was in the range of 8-20 cfs. A decrease in flow of 8-20 cfs is unlikely given the maximum pumping capacity of the Clear ridge well of 0.058 cfs. One key component to determining a relationship between groundwater withdrawal and changes in flow is the ability to know when pumps are operating and at what capacity. This information is difficult, if not impossible to obtain. Maher (2008) states the BSRI wells are continuously pumping. Continuous long-term monitoring of discharge is an ideal way to determine the true effect near stream wells have on the surface flow of the river.

The Andrew Molera river mouth site and Leach Field site did not show much change in the D50 particle size range. The Leach Field site did not record a significant fining over the two years since the Basin Complex fire, however the D_{50} particle size decreased from 85mm to 50 mm. This seemingly small change in sediment size may be a result of the natural conditions in this reach. The reach surrounding the Leach Field may be steeper and provide enough shear stress to transport the sediment being supplied. Longitudinal profiles and an increased number of cross-sections in this area would be useful for hydraulic and sediment transport modeling. The cross-section near the river mouth in Andrew Molera also did not show much change in particle size, though this was expected as it is subject to the influence of waves and is the natural depositional area of sediment for the Big Sur River. Steelhead embryo survival declines precipitously when more than 35% of substrate is composed of particles <6.35mm (Figure 7). Overall, the fining of sediment at the four other sites could be potentially detrimental to *O. mykiss* trout.

All sites saw an increase in the fine (<2mm) size particle class. The most dramatic increase of fine sediment was observed in Pfeiffer Big Sur State Park where a 30% increase in fines was recorded and a 96% decrease in the D_{50} particle size was recorded. Upstream of the Pfeiffer site, the river transitions to a steeper gradient, step-pool channel. The lower gradient of the river at Pfeiffer site causes a decrease in water velocity and becomes unable to transport sediment further. This pulse of sediment will likely be transported further downstream in the coming winters. All sites continue to see a gradual, monotonic fining trend, which may still be continuing. Here we are assuming that, given the lack of any other impacts in the Big Sur watershed, the continued fining of sediment is a result of the Basin Complex fire. Uncertainty remains in the timing and magnitude of the peak sediment pulse. Figure 30 is a modified version of the hypothetical post-wildfire sediment yield. This annotated version of Figure 7 displays the three years of post-wildfire monitoring along the Big Sur River with an unknown magnitude or duration of the sediment pulse.

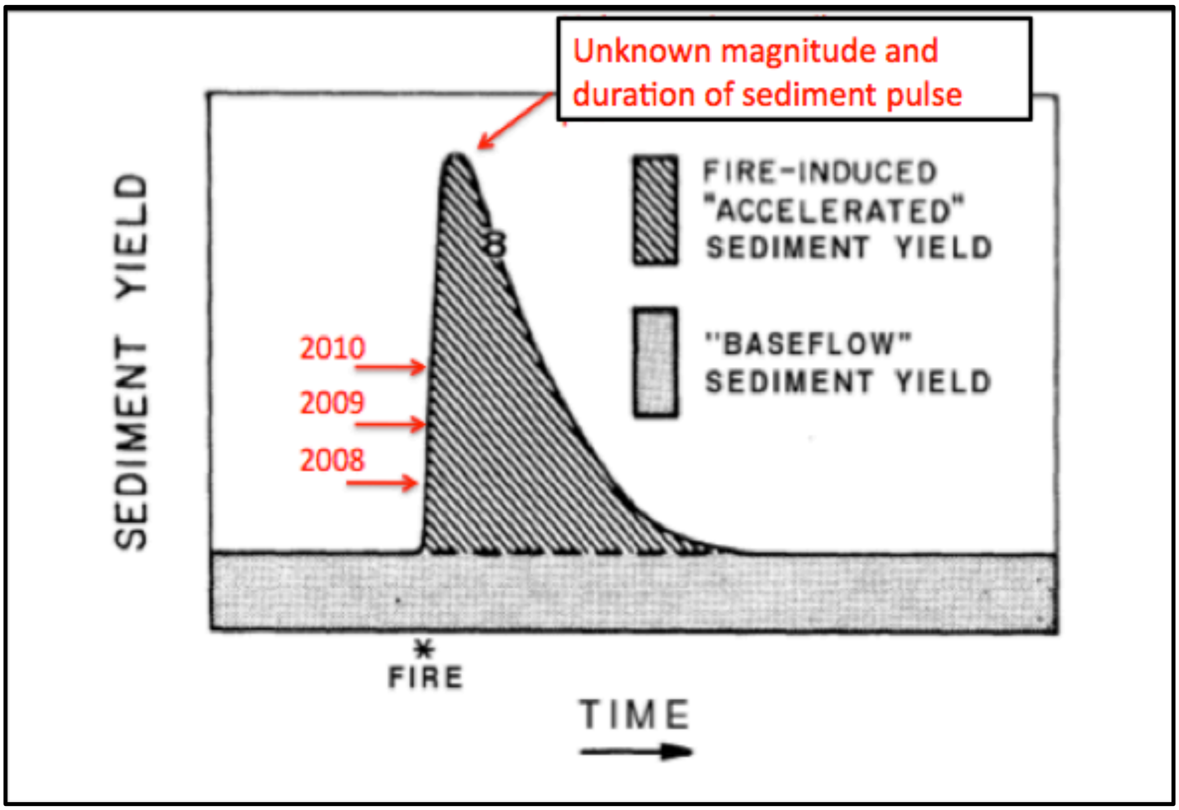


Figure 30. Annotated hypothetical model of post-wildfire sediment yield. This version incorporates the three study years of sediment monitoring after the BCI fires.

Conclusion

Groundwater extractions between Pheneger Creek and the Clear Ridge Bridge are too small to detect. Although we were unable to detect any changes in groundwater withdrawal in our study reach, the cumulative effect of multiple wells throughout the river is unknown. The Big Sur LUP states that developments cannot disrupt natural stream processes. Currently, there are no detectable negative effects from groundwater withdrawal that may pose problems to the riparian ecosystem. Additionally, California water laws state that water must be put to "beneficial use" and diversions cannot affect downstream users. There were no detectable changes in surface flow within the study reach during the course of our investigation. The lack of any discharge reference downstream of the study site can lead to the false assumption that there may be more or less water available for use given the number of tributaries and confluences between the USGS gage and Andrew Molera State Park. Oversights of this nature could pose problems for protecting *O. mykiss* habitat during dry years and base flow conditions. The USGS has installed a gage in Andrew Molera Park, however it is not yet rated for discharge. The addition of the Molera gage will provide a more accurate account of water moving through the Big Sur area. The California Department of Fish and Game is currently conducting in-stream flow requirements in the Big Sur River for *O. mykiss* habitat to determine the minimum flow necessary for *O. mykiss* migration, redd construction and adequate egg incubation water parameters.

Steelhead are experiencing threats to their habitat from the increasing fine sediment loads from the BCI Fire. Four out of the six sites resurveyed have strongly impaired substrate for steelhead trout. The theoretical timeframe of post-wildfire sediment yield is 1-3 years (Swanson 1981 and Inbar et al. 1998). Our study took place on the eve of the third winter and it appears we are still on the rising limb of the theoretical sediment yield graph, suggesting there is a need to continue monitoring the watershed response to fire. The increase in fine sediment throughout the lower Big Sur River may cause a loss of benthic macro-invertebrates, the primary source of food for steelhead young (Suttle et al. 2004). The ESA mandates that government agencies protect and delist endangered and threatened species. The California Department of Fish and Game will find this study useful for their ongoing in-stream flow needs of steelhead.

The information provided in this paper will be of use for establishing future studies on stream response to fire and detecting potential impacts of groundwater withdrawal. By having a solid understanding of the channel geometry, we can predict how the Big Sur River will respond to future fire events and gain a better understanding of the competency of the river to transport fine sediment. A better understanding of potential impacts of groundwater withdrawal can be gained by establishing multiple transect sites and recording discharge on a regular basis, before, during and after base-flow conditions. Extensive surveying of the reach below Pfeiffer Big Sur State Park confluence will allow for precise modeling of the river.

Acknowledgements

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