Greater Battle Creek Turbidity Monitoring: Update and Additions

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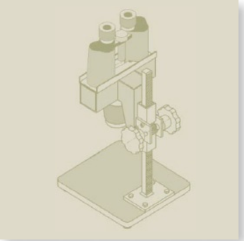

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By Cajun James PhD[1] and Lee MacDonald PhD[2]

1. Introduction

Water quality is an important concern in the Greater Battle Creek Watershed because of the presence of threatened chinook salmon and steelhead in Battle Creek and downstream areas. The total drainage area of the Greater Battle Creek Watershed (or more specifically, the Upper Battle Creek Hydrologic Sub-area) is 237,800 acres or about 370 square miles, and Battle Creek ultimately drains into the Sacramento River about midway between Redding and Red Bluff (Figure 1). The uppermost portion of the watershed is generally under federal management, either the Lassen National Forest (LNF) or Lassen National Park (LNP) (Figure 1). Over the last decade very little timber harvest has taken place on the LNF, but there is a large legacy network of unpaved roads and historic harvest units. Most of the land from about 3000-5000 feet in elevation is owned by Sierra Pacific Industries (SPI), and is actively managed for timber production. Within this elevation zone there also are some smaller private inholdings, and these are used primarily for timber production, orchards, wineries, grazing and small ranchettes. The areas below 3000 feet are almost entirely privately owned and subjected to a variety of uses, including grazing, irrigated pasture, and vineyards.

Bailey Creek is one of the sub-watersheds within Battle Creek, and since 2002 SPI has been monitoring turbidity and other water quality parameters at three locations in the Bailey Creek watershed (CAL Watershed 2.2.1) (Figure 1). A summary report of the turbidity and water quality data from these three stations was submitted to the Regional Water Quality Control Board and other state agencies in July 2011 (James, 2011). Intense public interest regarding the potential effects of timber harvest activities on water quality led to the installation of three additional continuous water quality monitoring stations in three other sub-watersheds in November 2011.

The overall goal of this report is to summarize the turbidity monitoring that is being conducted, and to compare the measured turbidities to commonly-assumed thresholds for adverse effects on salmonids. The specific objectives are to: 1) specify the monitoring objectives for the three stations on Bailey Creek and the three newly-installed stations on South Fork Digger Creek, North Fork Digger Creek, and Rock Creek; 2) document the data collection and quality assurance/quality control (QA/QC) procedures to ensure that the data being collected are valid ; 3) summarize the timber harvest activities upstream of each station and characterize the turbidity data from each of the six continuous water quality monitoring stations; 4) use the timber harvest, precipitation, and turbidity data to both understand the controls on turbidity and the possible effect of timber harvest activities on turbidity and the salmonid populations of concern; and 5) use the results to help guide future monitoring and forest management activities.

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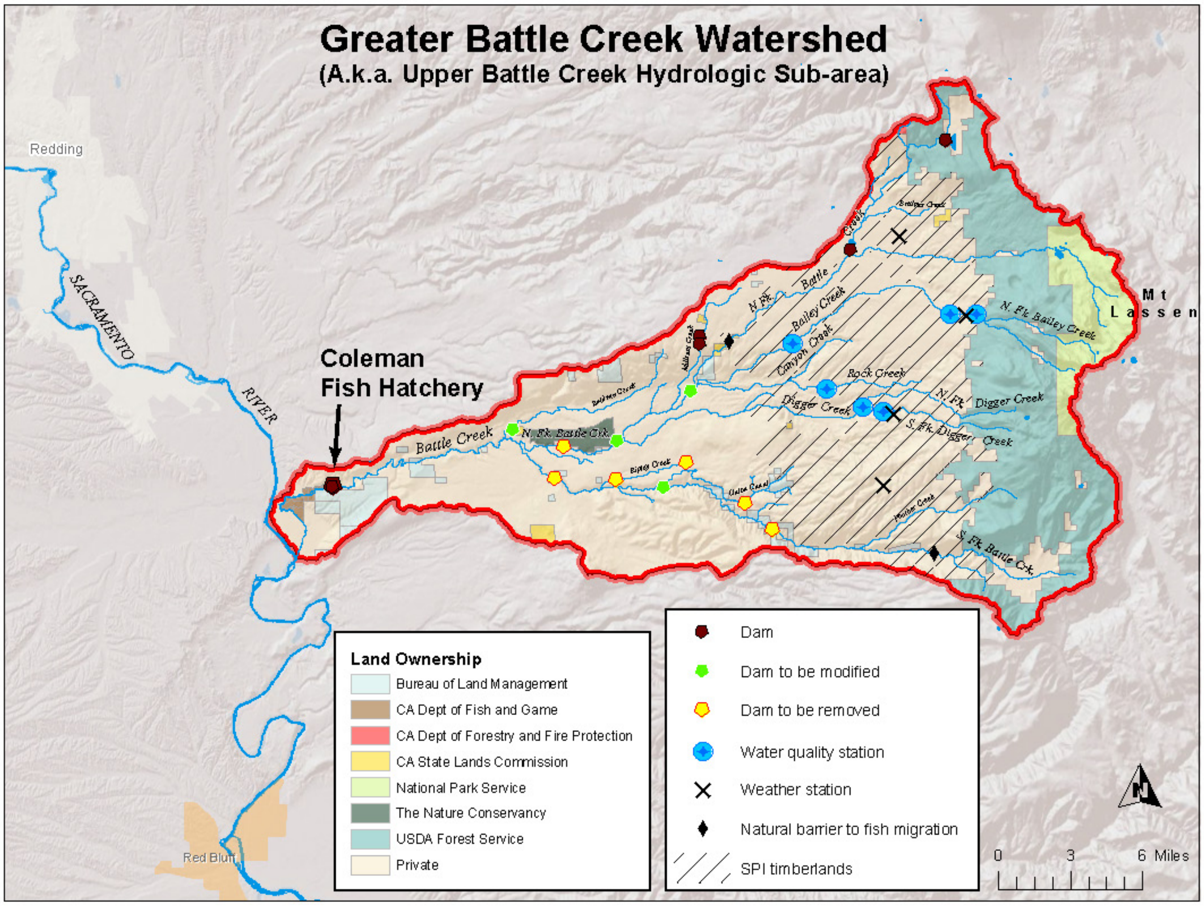

Figure 1. Map of the Battle Creek watershed ("Greater Battle Creek Hydrologic Sub-Unit") showing the stream network, land ownership, SPI water quality monitoring stations, weather stations, current hydropower dams and dams to be modified or removed, natural barriers to fish migration, and the Coleman Fish Hatchery.

2. Study Area

The six water quality monitoring station locations and their respective drainage areas are shown in Figure 2 along with the weather stations and the areas harvested from 1997 to 2011. The harvested areas are divided into pre- and post-2000 as most of the harvesting prior to 2000 was done as selective harvests, while most of the harvests after 2000 were done as clearcuts (even-aged management). The drainage areas in Figure 2 are topographically defined, as a key purpose of this report is to assess the water quality at each station, and the water quality at a station reflects all of the natural processes and anthropogenic activities occurring upstream of that station. For this purpose it is more reasonable to use the true drainage area rather than the CALWATER Planning Watersheds (Version 2.2.1) that are used for used for assessing cumulative watershed effects as required under California Forest Practice Rules. The relationship between the CALWATER Planning Watersheds and the drainage areas used in this report are described in Appendix A, and Appendix A also provides specific data on the amount and type of harvest for each Timber Harvest Plan conducted in each CALWATER Planning Watershed as well as the watersheds used in this report. Given the location of the six monitoring stations, this report focuses only on the upper portion of the Battle Creek watershed where most of the land is managed either by the federal government or SPI.

The primary geology within the study watersheds is volcanic, and the bedrock is a mixture of basalt and andesite. The soils are predominantly in the Cohasset series, which is classified as a loam or clay loam. Other common soil series include the Nanny and Windy soils, which are sandy loams. The overstory vegetation on SPI lands is primarily mixed conifer, with mostly ponderosa pine at the lower elevations and true fir at the higher elevations. The forests above SPI are mostly true fir with some lodgepole pine in the wetter areas.

Annual precipitation is about 55-85 inches, with most of this falling as snow between November and April. The overall annual hydrograph is driven by snowmelt runoff, although rain-on-snow events can occasionally occur in the winter and rain-driven peak flows can occur in the fall and late spring. The volcanic lithology causes many of the streams to originate from springs. Under undisturbed conditions infiltration rates are much greater than rainfall intensities and overland flow is rare.

Most of the area owned by SPI was acquired in 1992. Extensive logging began in the latter part of the 1800s, with much of the initial logging being done by the Walker Family and Diamond International. Ownership passed to the Diamond Match Company and Roseburg Timber, and logging continued prior to its acquisition by SPI. Initially SPI conducted extensive commercial thinning and single-tree selection, along with some shelterwood harvests. Since 2000 the emphasis has been on even-aged management. Most of the logging is ground-based due to the predominantly low-to-moderate slope gradients.

The following sections first describe the Bailey Creek watershed, and the logic behind the establishment of the three monitoring stations established in 2002-2003. This is followed by a description of the other three sub-watersheds where continuous water quality monitoring began in late 2011.

Bailey Creek

There are three continuous water quality monitoring stations within the Bailey Creek watershed. The lowest monitoring station is Lower Bailey Creek (LBC), and this is about two miles east of the western boundary of SPI lands at an elevation of 3720 ft. The area draining to this station is 17,750 acres, or 7.5% of the Greater Battle Creek Hydrologic Sub-Unit, and 46% of this area is owned by SPI (Figure 2; Table 1). The LBC station was established in March 2003 to characterize the water quality emanating from a relatively large, mixed-ownership watershed with some areas of active timber management.

The highest water quality monitoring station is Upper Bailey Creek (UBC), and this is on the eastern boundary of SPI ownership at an elevation of 5,040 ft (Figures 1 and 2). The total area draining to this location is only 7,760 acres, and this is almost entirely under federal management (Table 1). This station was established in September 2002, and the intent is to assess the amount and quality of water coming into the lands owned by SPI.

The third water quality monitoring station is the Upper Bailey Creek 2 station (UBC2), and this is about two miles downstream of the UBC station at an elevation of 4,760 ft. The drainage area at UBC2 is 9,282 acres, or 20% greater than the area draining to UBC. About 54% of these additional 1,522 acres are owned by SPI (Table 1), and this station was installed in September 2002 to primarily assess the effects of three clearcuts with a total area of 46 acres that were established along the mainstem of Bailey Creek immediately downstream of UBC. These clearcuts had 75-foot buffers in accordance with the forest practice rules in effect at that time, and the harvesting was done in October 2002, or just 1-2 months after the UBC2 station began operating.

Flows at the upper two stations are perennial, while flows at the LBC station are more seasonal. The reduction in flow with increasing drainage area suggests a complex subsurface flow system due to the volcanic geology.

Two weather stations were installed to measure precipitation, temperature, and other meteorologic variables in September 2002. One station is about two miles north of Bailey Creek and the other is between UBC and UBC2 (Figure 2).

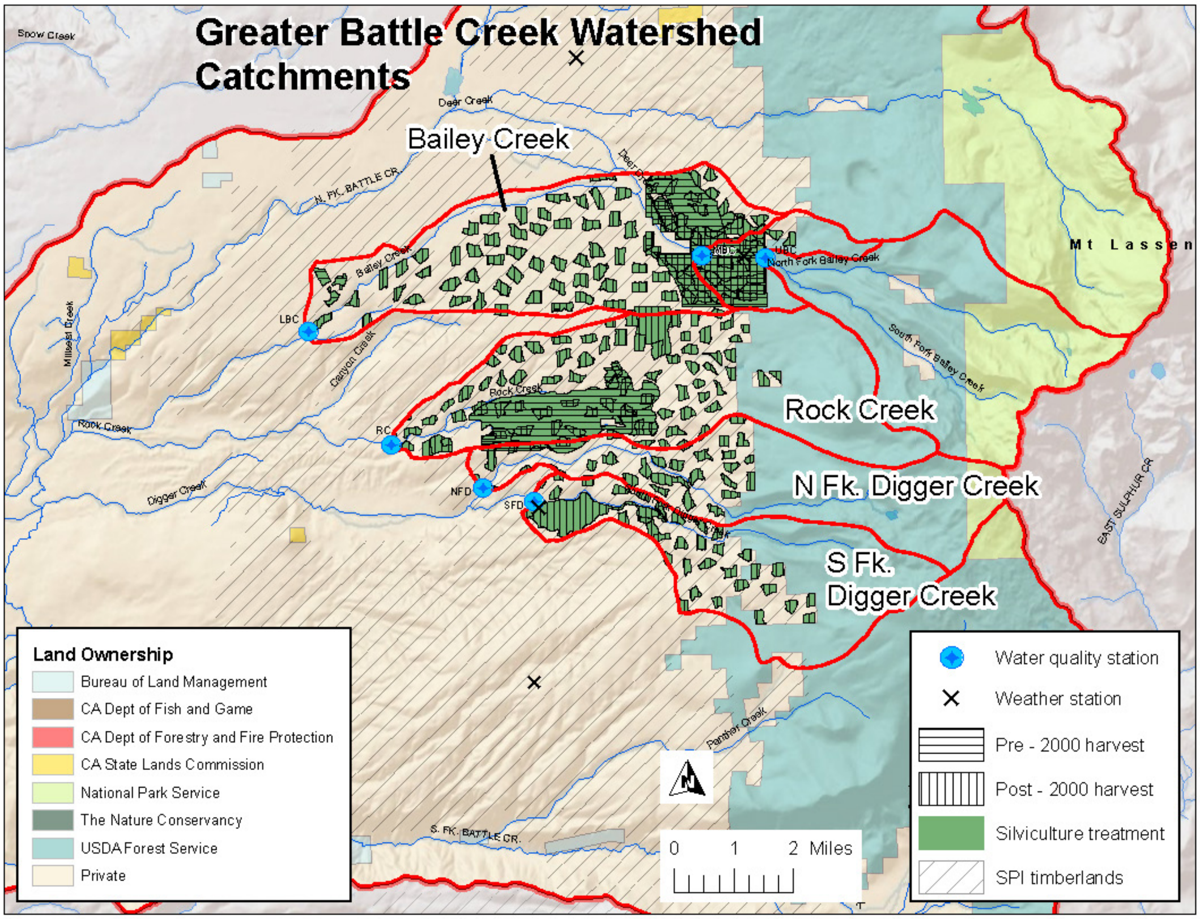

Figure 2. Map showing the six continuous water quality monitoring stations, four weather stations, and the areas harvested by SPI before and after the year 2000. The watershed boundaries in red show the areas draining to each water quality monitoring station.

Table 1. Drainage area in acres, percent SPI ownership, and percent non-SPI ownership for the six continuous water quality monitoring stations being operated by SPI.

Location	Total drainage area (acres)	SPI ownership	Non-SPI ownership
Lower Bailey Creek (LBC)	17,750	46%	54%
Upper Bailey Creek 2 (UBC2)	9,282	9%	91%
Upper Bailey Creek (UBC)	7,760	<1%	100%
South Fork Digger Creek (SFDC)	6,180	48%	52%
North Fork Digger Creek (NFDC)	6,321	41%	59%
Rock Creek (RC)	9,674	64%	36%

Digger and Rock Creeks.

In fall 2011 another three water quality monitoring stations were installed in the middle portion of the Battle Creek Watershed along with a weather station (Figure 2). From south to north the water quality stations are on the South Fork of Digger Creek (SFDC), North Fork of Digger Creek (NFDC), and Rock Creek (RC). Each of these is near the western edge of SPI property, and the proportion of SPI property in these three watersheds ranges from 41% for the North Fork of Digger Creek to 64% for Rock Creek (Table 1). Given the active timber management taking place on SPI lands within these watersheds, the purpose of these stations is to document the quality of the water leaving SPI property. A before-and-after design to assess the effects of timber harvest was not possible because of the long-standing and extensive timber harvest that has been taking place in these watersheds (Figure 2; Tables 2-6). Each of these stations was installed in November 2011, and this report will summarize the turbidity data collected from November 2011 through 14 February 2012.

Qualitatively, Rock Creek appears to have more spring-dominated inflow and more consistent flows than the South and North Forks of Digger Creek. Rock Creek also tends to have a predominantly cobble substrate, while the upper portions of Digger Creek have a coarser bed.

3. Data Collection, QA/QC, and Analysis

Turbidity is measured at 15-minute intervals at each monitoring station using YSI model 6820 multi-parameter sondes with model 6126 turbidity sensors. At five sites water levels are measured using Design Analysis H355 gas bubblers. Water levels at the South Fork of Digger Creek are measured using a built-in vented YSI pressure transducer with a full-scale range of 30 feet. Both the turbidity sensors and the water level recorders feed into Design Analysis H350XL dataloggers. Power is provided by 12-volt batteries as most of the sites have dense canopy cover rendering solar panels ineffective. Each site is visited weekly to check that the data are being recorded and swap out batteries as needed. During these visits the recorded water levels also are checked against a permanent staff gage with a resolution of 0.02 feet. All of the sonde and water level data are recorded onto compact flash cards that are brought back to the lab on a weekly basis. The data are then uploaded into a database for error checking and long-term archiving as described below.

Once a month the turbidity sensors and the pressure transducer are swapped out with a newly-calibrated unit, or sooner if a check of the data indicates a problem. Prior to being deployed the turbidity sensors are calibrated by taking YSI standards for 0 and 100 NTU, and then creating 0, 50, and 100 NTU solutions for a 3-point calibration. At this time the wiper on the turbidity sensor also is replaced. YSI technical representatives generally visit SPI's equipment lab at least annually and on an as-needed basis to provide training and technical support on calibration, QA/QC procedures, etc. If a sensor cannot be calibrated or repaired in the SPI lab, the sensors are sent back to YSI for repair or replacement. YSI, Design Analysis, and Campbell Scientific provide technical review of the data logging programs in order to ensure both accuracy and maximum efficiency with respect to battery power.

Discharge is manually measured with a pygmy current meter and a digital readout from Scientific Instruments each time the turbidity sondes are changed in the Bailey Creek watershed. Velocity and depth measurements are made at one-foot increments across the stream, and the calculated flows from each measurement are summed to obtain the total discharge. Sufficient measurements have now been made to develop a stage-discharge relationship for each of the three monitoring stations, but the resulting flow data have not yet been fully processed and therefore will not be included in this update. Similar discharge measurements have yet to be made for the two stations on Digger Creek and the station on Rock Creek.

About 5-10% of the hourly turbidity data at the Bailey Creek stations are missing, usually due to battery failures or rejection during the QA/QC procedures. Missing data also can be caused by sensor failures, macroinvertebrates, or physical disturbance of the sondes by abrupt changes in flow or sediment deposition during severe storms. There have been no failures at the Digger or Rock Creek sites during the roughly 100 days of data collection being reported here.

Three weather stations have been installed in or near the monitored watersheds, and there is another weather station about three miles south of the Digger Creek monitoring stations (Figure 2). The two stations in and adjacent to the Bailey Creek watershed were installed in July 2002. The third station on the South Fork of Digger Creek was installed in November 2011 (Figure 2). At a minimum, each station measures precipitation, air temperature and relative humidity, wind speed and direction, and soil moisture. Sensors and the data loggers were purchased from Campbell Scientific Instruments. Precipitation is measured with a Texas Instruments tipping bucket rain gage, and these have a resolution of 0.01 inch. During winter a snowfall adapter is placed on top of the rain gage, and this contains anti-freeze so that snow can be measured as it falls and a thin layer of oil to stop evaporation.

All of the meteorological data are automatically downloaded by a low band radio network every few hours to a Microsoft Access database, as the data are used for fire weather assessments. Diagnostic queries are automatically run on the incoming data, and questionable or missing values are immediately flagged and identified through an automated email notification system. The data from each station also are periodically graphed and reviewed as part of the regular QA/QC process. Each site is visited at least twice each year, and on an as needed basis according to the regular data reviews. Temperature and relative humidity sensors are sent to Campbell Scientific for calibration every two years, while the anemometers are calibrated in house approximately every year. The tipping bucket data are aggregated into hourly and daily precipitation values.

The 15-minute turbidity data were averaged for each hour, and a daily average also was calculated for each day with at least 12 hours of valid turbidity data. The percent of hourly and daily mean values falling into different turbidity classes was determined for each site and each calendar year. The turbidity classes of 0-5 NTU and ≤25 NTU follow the classes used in Interagency Task Force Report on sediment production and delivery in the Battle Creek Watershed (ITF, 2011), with 0-5 NTUs representing the level of turbidity imperceptible by the human eye (often referred to as visible turbidity range), and ≤25 NTUs indicating no long-term adverse effect on salmonid feeding or other activities (Sigler et al., 1984). Hourly and daily values greater than 25 NTUs were placed into classes of 26-50 and 51-100 NTU to indicate the relative exceedance above the presumed 25 NTU threshold for potential adverse effects on salmonids. For each site we also identified each day with at least one mean hourly turbidity value greater than 25 NTU for each site. For these days we determined the number of hours with a mean hourly turbidity value greater than 25 NTU, as the duration of high turbidities is critical for determining the potential effect on salmonids (Sigler et al., 1984; ITF, 2011). The number of hours per day with turbidity values greater than 25 NTU was plotted as a frequency distribution for each station.

4. Results

4.1. Timber Harvest History from 1997-2011

Bailey Creek

Since 1997 about 60% of the SPI ownership draining into the LBC monitoring station has been subjected to some form of timber harvest, and some areas have been subjected to more than one harvest. Most of these timber harvest activities have taken place as selection harvest, commercial thinning, clearcuts, or shaded fuelbreak harvests (Table 2). All of the selection harvest and commercial thinning on SPI lands within the LBC watershed occurred in 1998, and this covered 1804 acres or 22% of SPI's ownership but only 10% of the total area draining to the LBC station. At least 528 acres of commercial thinning was done on the Lassen NF in 2006-2007, but data on all the timber harvest operations in the Lassen NF were not available (Table 2). SPI has clearcut a total of 2101 acres, primarily from 2001 to 2004, and these represent 26% of the SPI ownership above the Lower Bailey Creek station, and less than 12% of the total watershed area (Table 2). Shaded fuelbreaks were cut in 2010 and 2011, and these covered 839 acres or 10% of the SPI ownership (Table 2).

For the area draining to the Upper Bailey Creek 2 station, 695 acres of SPI land were harvested as selection cuts in 1998 (Table 3), prior to any water quality monitoring. The three clearcuts in 2002 covered 216 acres or 26% of the SPI ownership above this station, but this is only 2.3% of the total area draining to the UBC2 station. As noted above, 528 acres within the Lassen NF were commercially thinned in 2006-2007. In 2010 and 2011, 433 acres were harvested as shaded fuel breaks, and this represents 53% of the SPI lands above the UBC2 station, but only 10% of the total watershed (Table 3).

Table 2. Acres harvested in each year from 1997 to 2011 by silvicultural treatment for the area draining into the Lower Bailey Creek water quality monitoring station. * indicates that the acres harvested were on the LNF rather than SPI ownership.

Silvicultural Trtmt.	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
PCT/Mastication										31*					
Commercial thin		91								448*	80*				
Clearcut				900		911	174	116			18				
Selection		1713													
Shelterwood rmvl.						59									
Group selection								50		22*					
Shaded fuelbreak														465	374

Table 3. Acres harvested in each year from 1997 to 2011 by silvicultural treatment for the area draining into the Upper Bailey Creek 2 water quality monitoring station.

Silvicultural Trtmt.	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
PCT/Mastication															
Commercial thin															
Clearcut						216									
Selection		695													
Shelterwood rmvl.															
Group selection															
Shaded fuelbreak														270	163

Digger and Rock Creeks

SPI records indicate quite different patterns of timber harvest over time in the South Fork of Digger Creek, North Fork of Digger Creek, and Rock Creek watersheds (Tables 4-6). For the South Fork of Digger Creek watershed there are no records of any timber harvest being conducted until 2006 (Table 4). From 2006 to 2010 there were 650 acres of clearcut and 432 acres of shelterwood removal, and these account for 37% of SPI's ownership in this watershed, but only 18% of the total watershed area above the South Fork monitoring station.

In the North Fork of Digger Creek watershed there has been relatively little timber harvest except for 482 acres of clearcuts between 2006 and 2008 (Table 5). During this period there were also 61 acres of commercial thinning and 30 acres of shelterwood removal (Table 5). Altogether these 573 acres represent 22% of the SPI ownership in this watershed, but only 9% of the total watershed area, and on a proportional basis this is only half of what was harvested in the South Fork of Digger Creek.

The Rock Creek watershed has both a higher proportion of SPI ownership (64%) and a higher proportion of timber harvest activities than the Digger Creek watersheds. The timber harvest activities took place in two main phases. The first phase was in 1997-1998, when just over 1400 acres were subjected to commercial thinning along with 228 acres of selection harvest and 25 acres of clearcutting (Table 6). Altogether these nearly 1700 acres represent 27% of SPI's holdings in this watershed and 18% of the total watershed area. The second phase was between 2002 and 2008, when 1485 acres were clearcut, with nearly 80% of this occurring in 2007 (Table 6). During this period group selection took place on another 171 acres and commercial thinning on 55 acres. Hence this second phase of harvest represents covered just over 1700 acres, or almost exactly the same proportion of SPI ownership and total watershed area as the area harvested in 1997-1998.

Table 4. Acres harvested in each year from 1997 to 2011 by silvicultural treatment for the area draining into the South Fork of Digger Creek water quality monitoring station.

Silvicultural Trtmt.	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Commercial thin															
Clearcut										42		154	373	81	
Selection														4	
Shelterwood rmvl.											432				
Group selection															
Shaded fuelbreak															

Table 5. Acres harvested in each year from 1997 to 2011 by silvicultural treatment for the area draining into the North Fork of Digger Creek water quality monitoring station.

Silvicultural Trtmt.	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Commercial thin	127										8	53			
Clearcut										13	43	426			
Selection															
Shelterwood rmvl.											30				
Group selection															
Shaded fuelbreak															

Table 6. Acres harvested in each year from 1997 to 2011 by silvicultural treatment for the area draining into the Rock Creek water quality monitoring station.

Silvicultural Trtmt.	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Commercial thin	1411	33									55				
Clearcut		25				48		186			1169	79			
Selection		228													
Shelterwood rmvl.															
Group selection								171							
Shaded fuelbreak															

4.2. Turbidity Data

Bailey Creek

The nine years of turbidity monitoring have yielded 1673 valid days of record for LBC, 3159 days for UBC, and 3181 days for UBC2. The much smaller number of days from the LBC site is due to the absence of streamflow during much of the summer and early fall.

The data from the three stations in the Bailey Creek watershed show that the water coming into and leaving SPI lands generally has very high clarity (Figure 3). The data from UBC show that 89% of the mean daily turbidities are ≤5 NTU. Perhaps more importantly, only 16 days or 0.5% of the mean daily turbidities at UBC were ≥25 NTU, which has been suggested as the threshold for impaired feeding for salmonids (Sigler et al., 1984; ITF, 2011). The highest mean daily turbidity was only 62 NTU.

A comparison of the three stations indicates that the highest turbidity values were at the LBC site, as only 82% of the mean daily values were less than 5 NTU as compared to 89% for UBC and 94% for UBC2. Nevertheless, only 0.7% of the mean daily values exceeded 25 NTU. These results do not necessarily mean that the water quality is poorer at the LBC site, as this site is characterized by a lack of summer flows when turbidity values are typically very low. Hence the data at the UBC site is primarily from the winter wet season, which is when almost all of the high turbidity events occur, and the higher frequency of high turbidities at LBC could just be a function of the fact that there are much fewer low flow days with low turbidity values. To eliminate this bias in the data it would be necessary to compare just the values from the three sites for those days when there are valid data from all three sites, but this is beyond the scope of this report and not really necessary given the overall low turbidities being reported (Figure 3).

A comparison of the two upper stations indicates that turbidities at the UBC site were slightly higher than the turbidities at the UBC2 site, as 8% of the daily mean values at UBC were less than 5 NTU as compared to 94% at the UBC2. Similarly, 0.5% of the days at the uppermost station had mean turbidity values greater than 25 NTU as compared to just 0.3% at the UBC2 site (Figure 3). The slightly better water quality at the station two miles downstream of UBC might be considered surprising given that the UBC site is at the upper edge of SPI property, while the UBC2 station is within SPI lands where active timber harvest has been occurring (Table 3). These results suggest that the 216 acres of clearcuts in 2002 and the 270 acres of shaded fuelbreak harvest upstream of the UBC2 station had no adverse effect on instream turbidities.

It should be noted that the Lassen NF did have 528 acres of commercial thin in 2006-2007 and 31 acres of pre-commercial thin and mastication in 2006. In theory these activities could have reduced the quality of water coming into the UBC station, which might then have eliminated any difference between UBC and UBC2 (i.e., the effect of the timber harvest on the Lassen NF and its resulting effect on turbidity at UBC compensated for the effect of the SPI timber harvests upstream of the UBC2 monitoring station). However, this supposition is unlikely given the differences in the type of harvest activities on SPI lands and the Lassen NF. The absence of any clear effect of timber harvest on overall turbidity values is consistent with the results and conclusions for the Battle Creek watershed by the interagency task force (ITF, 2011). A more detailed analysis of the year-by-year variability in turbidities as well as the type, amount, and intensity of precipitation would be needed to provide further insights into the presence or absence of a specific effect of individual timber harvest plans on turbidity values at UBC and UBC2, respectively.

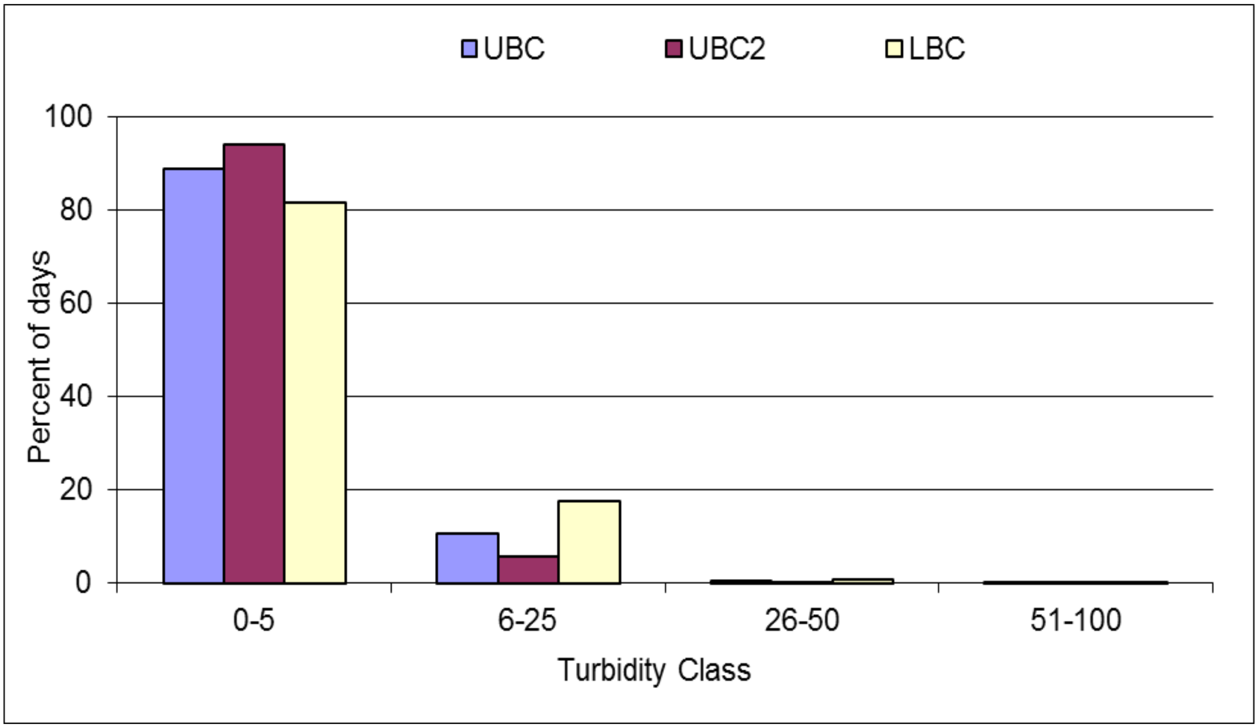

Figure 3. Frequency distribution of the mean daily turbidities by turbidity classes for the three long-term monitoring stations on Bailey Creek.

The grouping of mean turbidity values into classes as shown in Figure 3 is only one way to display the data, and this classification is limited in that it does not indicate the frequency of different values within each class. A potentially better way to display the data is to plot all of the turbidity values as a cumulative frequency distribution, similar to a flow duration curve. For the Bailey Creek stations this turbidity duration curve clearly shows the percent of values that are less (or greater) than a given turbidity (Figure 4). These cumulative frequency plots quickly show that turbidities are generally highest at LBC and lowest at UBC2. The cumulative frequency distribution also shows that the greatest differences between the three sites occur in the moderate turbidity events of around 4-15 NTU, which occur around the 80th to 98th percentiles of the cumulative frequency distribution. Figure 4 also shows that turbidities are roughly similar in absolute terms for all three sites for the lowest or cleanest part of the turbidity duration curve, and the differences tend to diminish during the highest turbidity, lowest frequency events (Figure 4). The latter point is further illustrated by the fact the highest daily turbidity at the "cleanest" station, UBC2, was 51 NTU, while the highest daily turbidity at the most turbid site (LBC) was only slightly higher at 62 NTU.

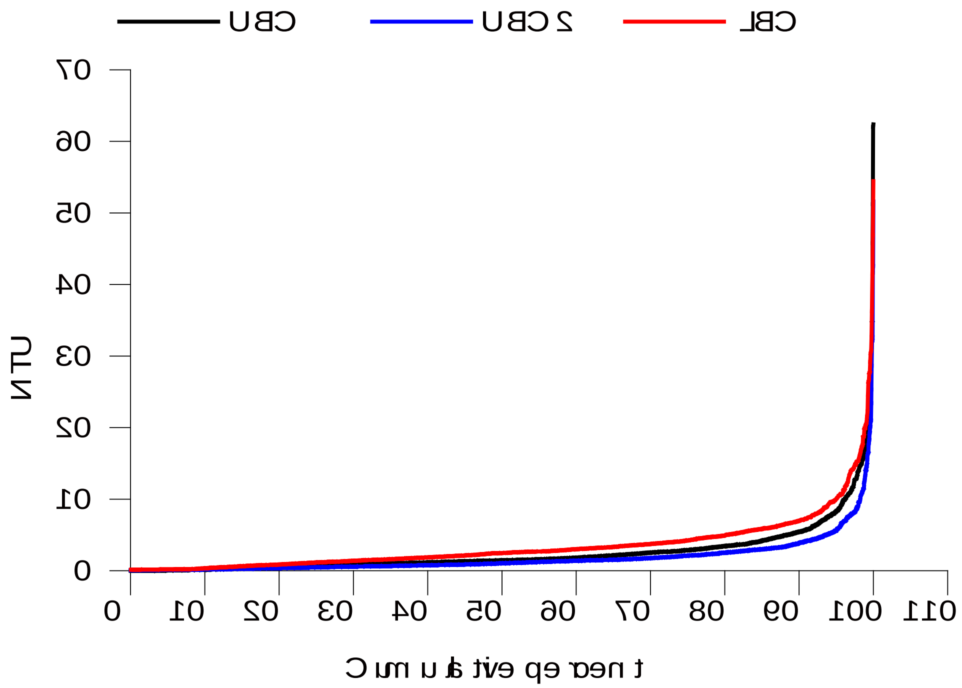

Figure 4. Cumulative frequency distribution of mean daily turbidities for Upper Bailey Creek (UBC, n=3,159), Upper Bailey Creek 2 (UBC2, n=3,181), and Lower Bailey Creek (UBL, n=1,673).

A common concern is whether the use of mean daily turbidity values might obscure or hide the presence of higher but short duration turbidity values. For this reason we also calculated the frequency of mean hourly turbidities by the same turbidity classes used in Figure 3. A comparison of the frequency of mean daily and mean hourly turbidities for each station and each turbidity class shows virtually no differences between the mean daily and mean hourly data (Figure 5). A close examination of the data indicates that the proportion of days that fall into the 0-5 NTU class is about 0-1% greater than the proportion of hours. Conversely, the proportion of hours in the higher NTU classes are higher than the proportion of days, but the absolute values generally differ by only a few tenths of a percent. This means that both the daily and hourly data provide similar estimates of the percent of time that turbidities fall into the different turbidity classes. As might be expected, the biggest differences between the mean daily and mean hourly data are for the maximum turbidity values. The maximum mean hourly turbidities for the entire period of record at each monitoring station was 152 NTU at LBC, 207 NTU at UBC2, and 217 NTU at UBC. While these values are around three times the maximum daily means, these hourly maximums confirm that the highest hourly turbidities in Bailey Creek are relatively low compared to many other locations, such as northwestern California (Klein et al., 2011).

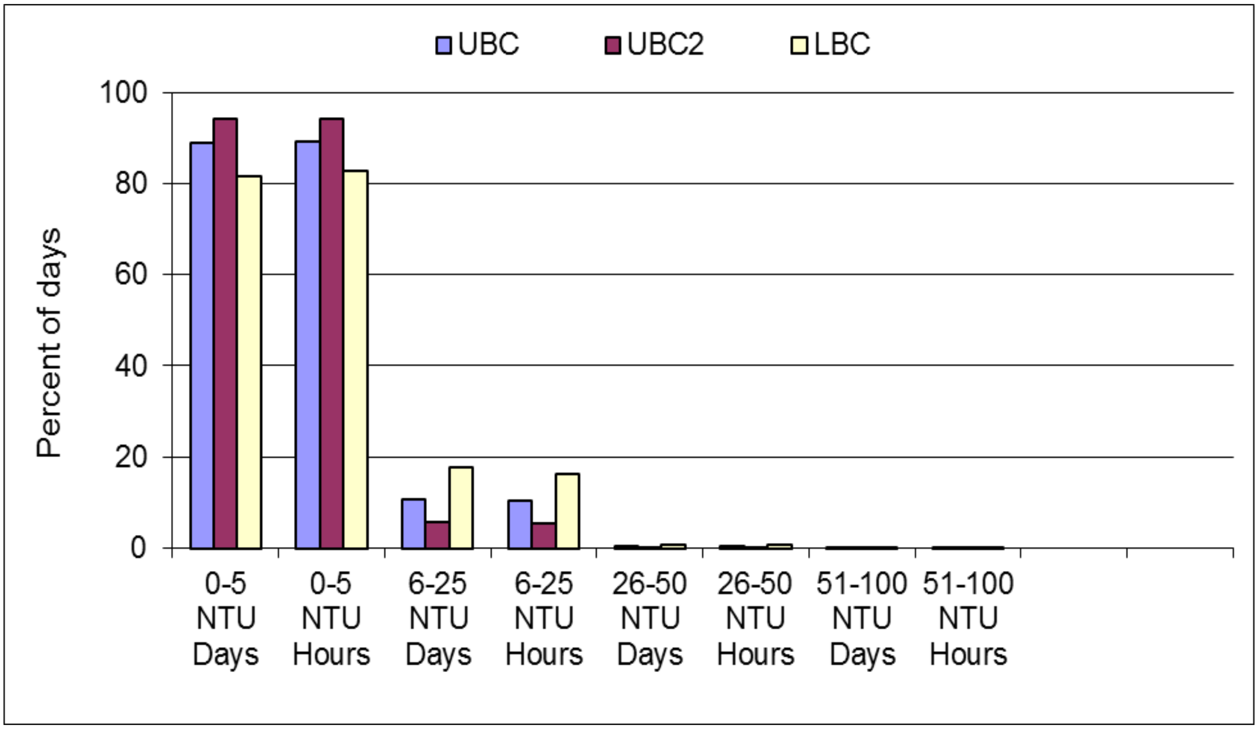

Figure 5. Comparison of the frequency distributions of mean daily and mean hourly turbidities by turbidity class for Upper Bailey Creek, Upper Bailey Creek 2, and Lower Bailey Creek.

Both the magnitude and the duration of high turbidity values are of concern with respect to the health and reproduction of salmonids. Laboratory studies have shown that high turbidities can affect coho salmon feeding, weight, length, growth rates, density, emigration, and possibly gill-tissue damage after 3 to 5 days. Laboratory trials lasting from 14 to 21 days indicated that turbidity values as low as 25 NTU can reduce fish growth. Newcombe and McDonald (1991) summarized the negative effects that high turbidity and suspended sediment values can have on salmonids and their habitats.

Figures 3-5 show that turbidity values ≥ 25 NTU generally occur about 0.5% of the time in Bailey Creek, but these do not indicate the duration of these high turbidity levels, or how they may vary between years. The duration of high turbidity values was approximated by determining the number of hours per day with mean turbidity values ≥25 NTU for each day when there was at least one mean hourly turbidity value ≥25 NTU. The resulting frequency distributions for the number of hours with turbidity values ≥ 25 NTU are plotted as Figures 6-8. For Lower Bailey Creek there were 75 days that had at least one mean hourly value ≥ 25 NTU, and 83% of these days had less than eight hours with mean turbidity values of at least 25 NTU (Figure 6). Only four days had 15 or more hours with turbidity values ≥ 25 NTU, and every day had at least one hour with turbidity values below 25 NTU. These data indicate that turbidity values ≥25 NTU typically last for only a small proportion of each day.

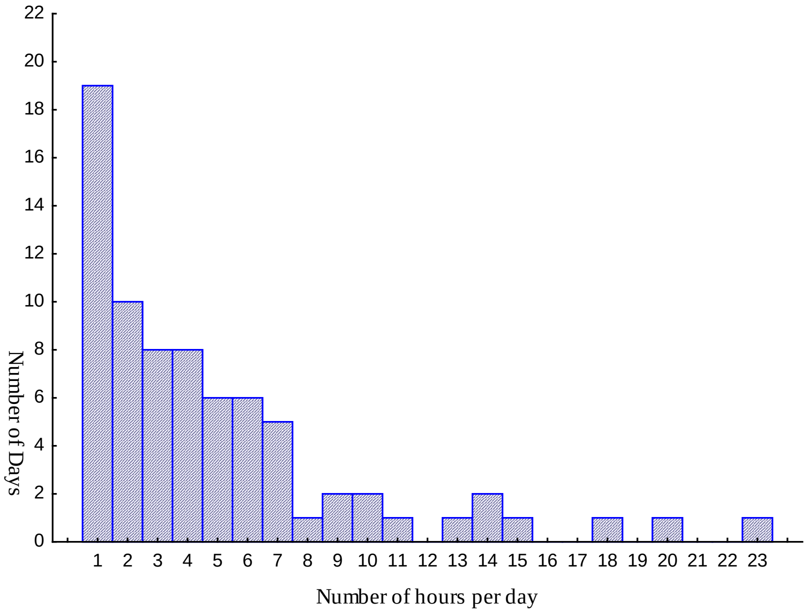

Figure 6. Frequency distribution of the number of hours per day with mean hourly turbidities ≥25 NTU for Lower Bailey Creek 2 (n=75 days). The data for the 1598 days that did not have any mean hourly turbidity values ≥25 NTU are not shown.

At the Upper Bailey Creek station there were 81 days with at least one mean hourly turbidity value ≥25 NTUs. Again there were relatively few hours per day that had ≥25 NTUs (Figure 7), as 43% of the days had only one or two hourly values ≥25 NTUs. No day had more than 21 hours with NTU values ≥25 (Figure 7).

The UBC2 station had the lowest frequency of high turbidity values, as only 53 days had at least one mean hourly turbidity value ≥25 NTU. The frequency distribution of hours with high turbidities was less skewed than the other two sites, but most days still had less than 10 hours of turbidity values ≥25 NTU (Figure 8). The mean number of hours per day with ≥25 NTUs was only five hours, and the maximum number of hours was 15 (Figure 8).

Taken together, these data show that high turbidity events in the Bailey Creek watershed are very short-lived, and only three of the 8013 days with valid records had 20 or more hours with mean turbidity values ≥25 NTU. All of these durations are much shorter than the duration of high turbidities that were shown to adversely affect salmonids in laboratory studies, and the implication is that the magnitude, frequency, and duration of high turbidity values in Bailey Creek are much too low to adversely affect salmonids.

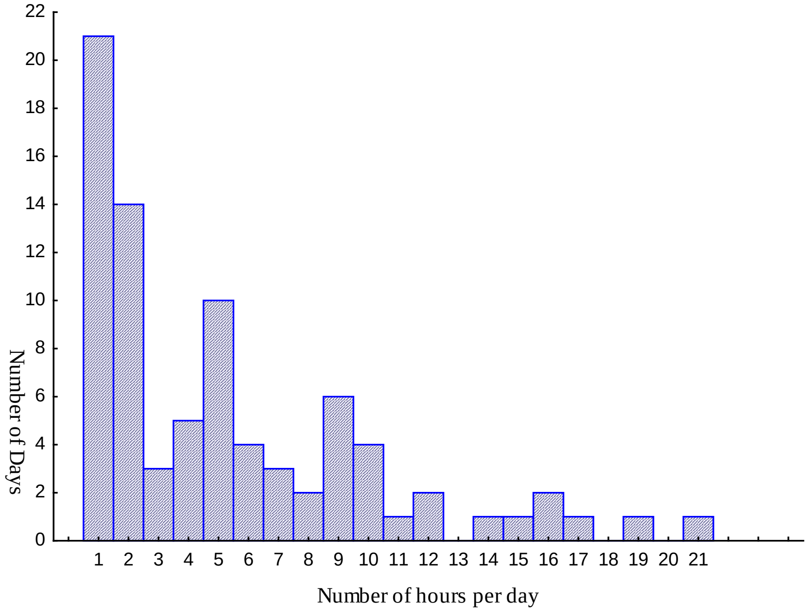

Figure 7. Frequency distribution of the number of hours per day with mean hourly turbidities ≥25 NTU for Upper Bailey Creek (n=81days). The data for the 3078 days that did not have any mean hourly turbidity values ≥25 NTU are not shown.

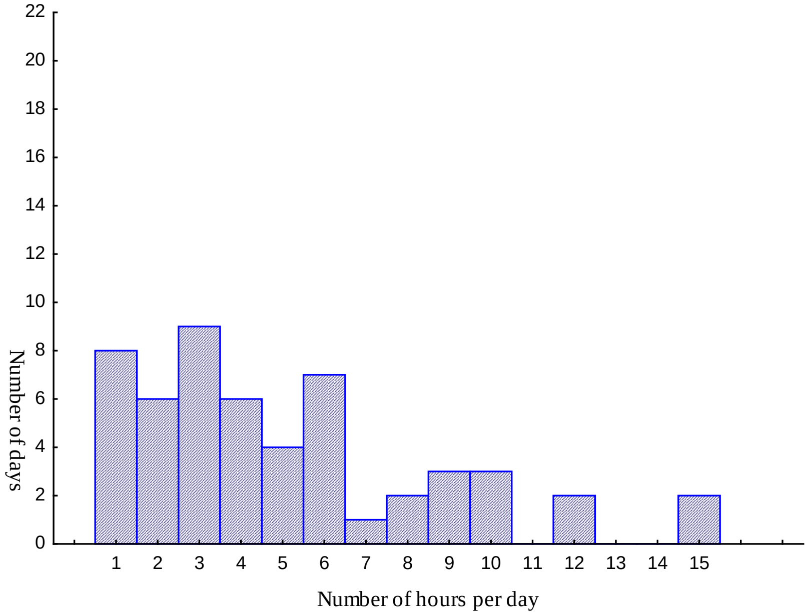

Figure 8. Frequency distribution of the number of hours per day with mean hourly turbidities ≥25 NTU for Upper Bailey Creek 2 (n=53 days). The data for the 3128 days that did not have any mean hourly turbidity values ≥25 NTU are not shown.

The final analysis for the Bailey Creek turbidity data was to assess the annual variability in high turbidity values, and to determine if this can be associated with the pattern of timber harvest or some other factor, such as the amount of precipitation. The percent of days with mean turbidity values ≥25 NTU are shown for each station for each year of monitoring (Figure 9). There is considerable variability in the percent of days with a mean turbidity ≥25 NTU, as the range is from 0.05% at Upper Bailey Creek 2 in 2006 to 3.4% for Lower Bailey Creek in 2008. For all other years and all three stations the maximum number of days with mean turbidity values ≥25 NTU did not exceed 1.6% (Figure 9).

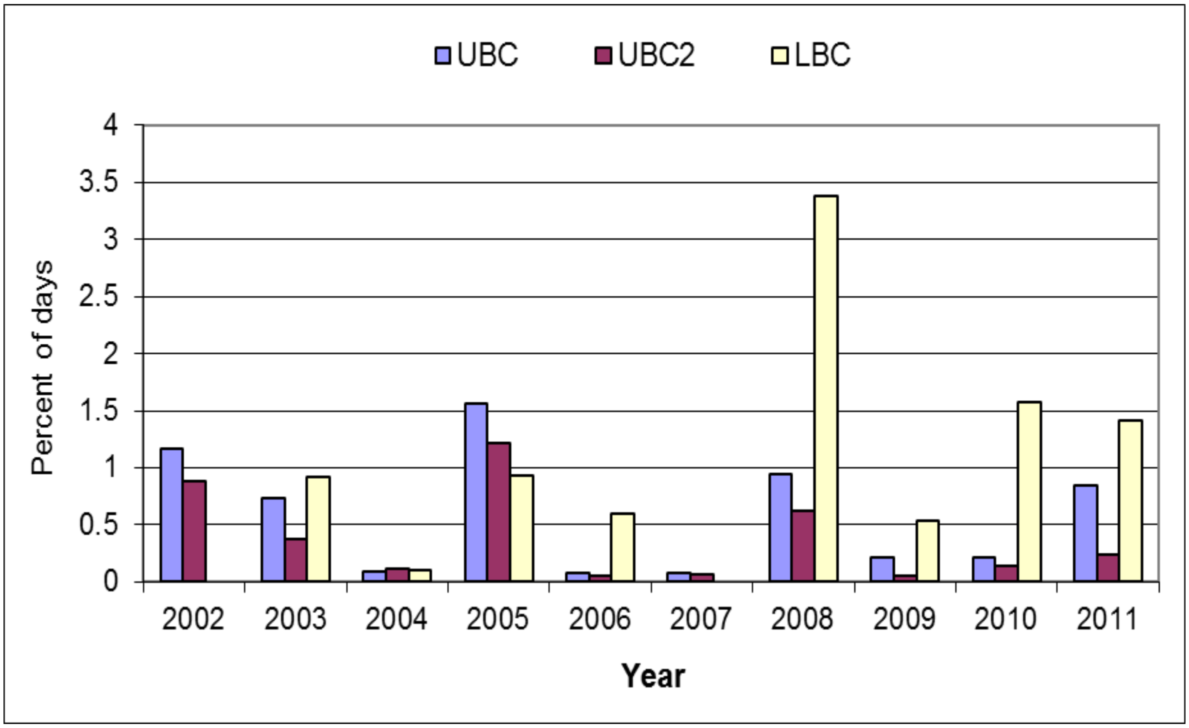

Figure 9. Percent of days with a mean turbidity ≥25 NTU by year for Upper Bailey Creek, Upper Bailey Creek 2, and Lower Bailey Creek.

It should be noted that there is a general consistency between stations for a given year. For example 2005 had a high frequency of high turbidity levels for all three stations, while 2004, 2006, 2007 and 2009 generally had few days with high turbidity values. This consistency between stations suggests that precipitation is a primary control on high turbidities. The mean annual precipitation values from the two weather stations closest to Bailey Creek generally support a relationship between the frequency of high turbidity values and annual precipitation, as 2005 was a high precipitation year while 2007 was a low precipitation year (Figure 10).

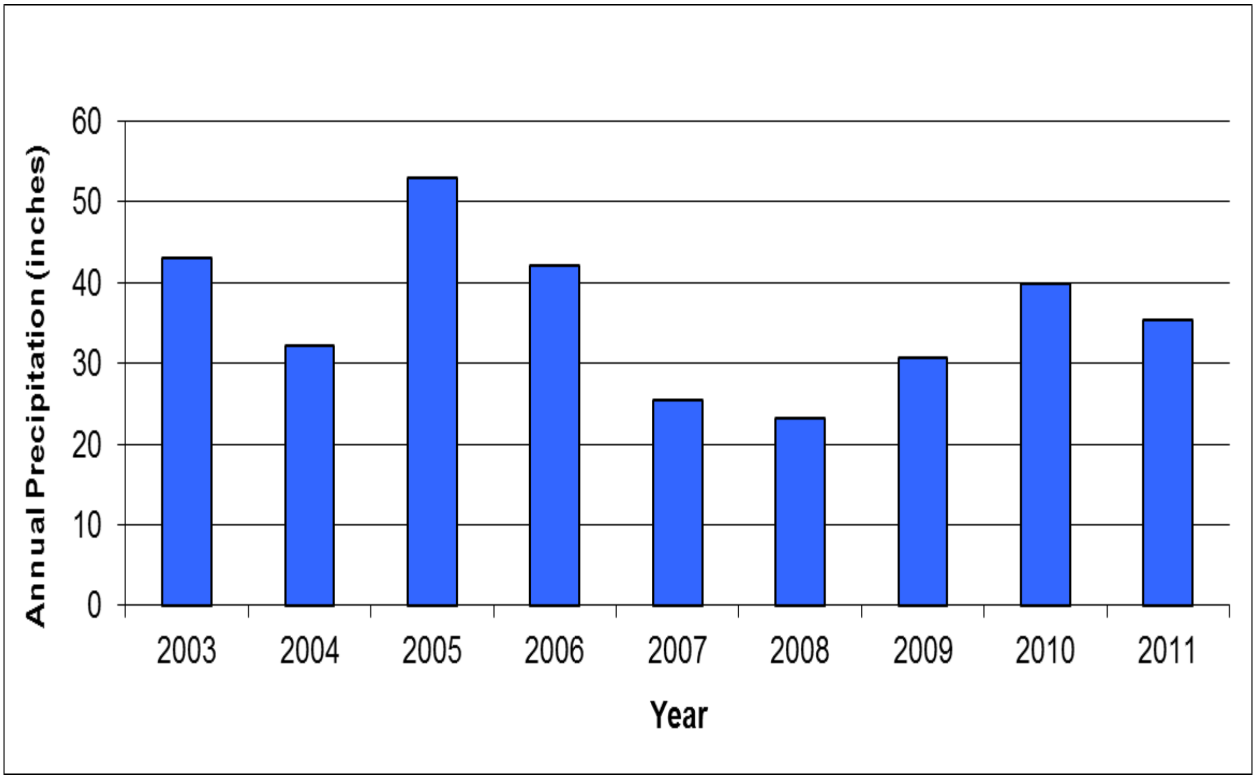

Figure 10. Mean annual precipitation by year within the Bailey Creek Watershed.

The similarity between stations is strongest for 2002-2007, as from 2008-2011 Lower Bailey Creek had substantially more days with high turbidity values than the other two stations (Figure 9). A comparison between these data and the amount of forest harvest does not indicate any clear relationship, as clearcutting in the lower portions of Bailey Creek occurred from 2001-2004 (Table 2). Similarly, the watershed above UBC2 was subjected to 216 acres of clearcut in 2002 and 433 acres of shaded fuelbreak harvest in 2010-2011 (Table 3), but this does not appear to be correlated with the number of days with mean turbidities ≥25 NTUs. The lack of any clear correlation between timber harvest and the number of days with high turbidity values is further supported by the fact that the UBC2 station had the lowest frequency of days with high turbidity values except in 2004, when all three stations had very few days with high turbidities (Figure 9). A better understanding of the relationship between turbidity and precipitation would require a much more detailed analysis of the amount, intensity, and type of precipitation associated with individual high turbidity events, but this is beyond the scope of this report.

North Fork Digger Creek, South Fork Digger Creek, and Rock Creek

The very short record for the three stations installed in late 2011 precludes the type of detailed analysis that was done for the three stations on Bailey Creek. However, the short record does facilitate the use of mean hourly rather than mean daily data, and the frequency of the mean hourly values by turbidity class for each station are presented in Table 7. Again the primary result is that turbidity levels in the water leaving SPI forestlands are very low. For all three stations the mean hourly turbidities were ≤5 NTU at least 95% of the time, and ≤25 NTU at least 99% of the time (Table 7).

The data in Table 7 indicate that turbidity levels in Rock Creek are noticeably higher than in the South and North Forks of Digger Creek, respectively. For Rock Creek there were 14 hours with a mean turbidity greater than 25 NTU, but this still represents only 0.7% of the data. For the North Fork of Digger Creek there were only three hourly values greater than 25 NTU, while the South Fork had no hourly values greater than 25 NTU. The highest mean hourly value recorded at any location was only 81 NTU, and none of the mean daily values exceeded 25 NTU. In terms of duration, none of the stations had five or more consecutive hours with turbidity values greater than 25 NTU. This means that, as in the case of Bailey Creek, high turbidity levels are infrequent, relatively low magnitude, and very short-lived. The low magnitude, frequency, and duration of high turbidities in these three watersheds again indicate that turbidity poses very little threat to salmonids.

Table 7. Number of days sampled and number of hours by turbidity class for the water quality monitoring stations on Rock Creek, North Fork Digger Creek, and South Fork Digger Creek.

Water quality station	Number of days with valid data	Number of hours in each turbidity class			
Location		0-5 NTU	6-25 NTU	26-50 NTU	51-100 NTU
Rock Creek	88	2010	81	10	4
North Fork Digger Creek	89	2109	18	2	1
South Fork Digger Creek	104	2475	13	0	0

5. Discussion

The in-stream monitoring data consistently shows that the surface streamflows coming into and leaving SPI forestlands have very low mean daily and mean hourly turbidity values. The results also showed that the duration of periods with turbidity values greater than 25 NTU never exceeded 23 hours, and were typically less than 6-8 hours. Hence the magnitude, duration, and frequency of high turbidities do not seem to pose any threat of a chronic, negative impact on salmonids.

Results from this report are entirely consistent with the turbidity grab samples collected near the Coleman Fish Hatchery by the US Fish and Wildlife Service (USFWS) from 2002 to 2010[3]. The data presented in this report also are very consistent with the grab samples

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[3] Presentations using the USFWS turbidity data from Battle Creek were made by Drew Coe of the Central Valley Regional Water Quality Control Board to the Board of Forestry Monitoring Study Group on 23 February 2012, to the Battle Creek Working Group on 17 May 2012, and by Dr. Cajun James to the California Board of Forestry on 6 December 2011.

collected at 12 locations in the Greater Battle Creek watershed by the Central Valley Regional Water Quality Control Board (CVRWQCB) in 2011-2012[4].

Taken together, the results indicate that the historic and recent timber harvest activities in the areas studied are not having a significant adverse effect on water quality. This conclusion is consistent with the recent Interagency Task Force investigation, which found no indication that timber harvest is having an adverse effect on water quality in the Battle Creek watershed (ITF, 2011).

The lack of any adverse effect from timber harvest on water quality may be largely attributed to the use of best management practices (BMPs) as required by the California Forest Practices rules and the additional management practices implemented by SPI (Interagency Task Force Report, 2011: James 2011). More specifically, the ITF report (2011) cited five BMPs that were regarded as particularly effective in limiting surface erosion and sediment delivery from harvest units, and these were:

1. Strategic skidding and effective drainage (e.g., waterbars) to limit the amount and concentration of surface runoff and erosion;
2. Contour ripping in harvest units to reduce compaction, increase infiltration, and decrease slope length by creating closely-spaced berms;
3. Harvest practices that maintain high surface cover;
4. Routing sediment-laden runoff to areas undisturbed by heavy machinery;
5. Presence of riparian buffer strips (WLPZ's) to facilitate infiltration and slow or capture surface runoff and sediment.

In the Greater Battle Creek Watershed SPI consistently does soil ripping along the contour on clearcuts prior to planting. The purpose is to break up the compaction from past logging, increase growth rates, increase infiltration, and impede potential sediment movement by creating berms that are typically 7-10 ft. apart and can be more than a foot high. When whole tree harvesting is employed and the chips are being sold as biomass for cogeneration, the associated landings are covered with a minimum of at least 4-6 inches of chips, and this protects the soil surface from sealing and rainsplash. The ITF report noted SPI clearcuts typically had 50% to 75% ground cover (ITF, 2011), and this amount of cover is sufficient to greatly reduce surface runoff and erosion (e.g., Larsen et al., 2009).

Roads and stream crossings are another major source of sediment, and Timber Harvest Plans require SPI to evaluate and improve the road network and existing water course crossings. The closing and relocation of streamside roads, combined with crossing improvements, are one of the most effective ways to reduce road sediment production and delivery. The combined effectiveness of these hillslope and road practices is indicated by the fact that turbidity levels at the UBC2 water quality monitoring station, which is well within SPI property, are generally lower than for the water coming into SPI property from the upper watershed.

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[4] Presentations using the CVRWQCB Greater Battle Creek turbidity monitoring in 2011-20102 were made by Drew Coe of the Central Valley Regional Water Quality Control Board to the Board of Forestry Monitoring Study Group on 23 February 2012 and to the Battle Creek Working Group on 17 May 2012.

The ITF report (2011) did find that some road crossings, road segments, tractor crossings, and landings that had not been chipped could serve as sediment sources (ITF, 2011). Some of the most problematic roads and road crossings are on shared or public access roads, as these cannot be gated off during wet weather and they often are subjected to high traffic loads. One positive outcome of the ITF study (ITF, 2011) is the greater recognition of public roads as an important sediment source to certain streams, such as Canyon Creek. This has led to partnerships between Shasta County, Tehama County, and SPI to assess and improve some of the most problematic road sections identified in the ITF (2011) report.

Monitoring is an essential component to management, but this can be done at many different levels (MacDonald, 1993). Perhaps the most effective monitoring is the "open-eye, open-mind" monitoring to ensure that BMPs are being properly implemented, and to ensure that they are continuing to function as designed (MacDonald, 2000). Collecting long-term, instream water quality data is expensive, so both private companies and regulatory agencies need to carefully weigh the costs of different types of monitoring relative to their potential to protect and improve water quality. The water quality information collected from SPI's network of long-term monitoring stations is extremely useful for assessing: 1) temporal and spatial variations in water quality; and 2) linkages between the measured values, management activities, and key controlling processes, such as the amount and type of precipitation. However, different types of monitoring data must be collected and analyzed in order to understand both site-specific and larger-scale effects. Different types of data also are needed to help inform the public, regulatory agencies, land managers, and scientists as to on how different management activities are likely to affect water quality under different site conditions. Regular reviews of the data being collected are needed to determine what combination of on-site and instream monitoring techniques will be most effective to further protect and improve water quality and aquatic habitats. In the case of the Greater Battle Creek Watershed, the consistently low turbidity values suggest that the installation of additional water quality monitoring stations is likely to provide only limited benefits. Potentially more benefits could be gained from on-site assessments of specific BMPs and management activities--such as roads, vineyards, or grazing--that are more likely to directly affect water quality than carefully conducted timber harvest operations. Nevertheless, SPI is committed to long-term instream data collection to help ensure that the combined effect of their management activities do not adversely affect water quality and the salmonid species of concern.

6. Conclusions

The Greater Battle Creek watershed is considered an important source of clean water and habitat for threatened steelhead and chinook salmon. The areas between 3000 and 5000 ft elevation are largely owned by Sierra Pacific Industries (SPI) and intensively managed for timber production. There is considerable public concern over the potential adverse effects of forest management activities on water quality and salmonid fisheries. SPI has been continuously monitoring instream turbidity at three locations in the Bailey Creek watershed since 2002-2003, and three more stations were installed on different sub-basins in late 2011. Turbidity levels at all six stations are consistently low, as mean daily turbidity values are less than 5 NTU at least

82% of the time, and less than 1% of the mean daily turbidity values are above 25 NTU. High turbidity values tend to be more frequent in wet years, and do not show any apparent relationship with the amount or type of timber harvest. The typical duration of high turbidity values is less than 6-8 hours, and no days had continuous turbidity values greater than 25 NTU. These results are consistent with other turbidity data and other studies done in the Battle Creek watershed. The low frequency and duration of elevated turbidity values indicate that turbidity is not a threat to the salmonid species of concern. The lack of a clear effect of timber harvest activities can be attributed to the effective implementation of Best Management Practices and the relatively benign site conditions in terms of topography and soils. Future monitoring should focus on identifying and improving specific problems, particularly near-stream roads and road-stream crossings.

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Appendix A

CALWATER Planning Watersheds vs. Catchment Areas

Under the California Forest Practice Rules CALWATER (2.2.1)*[5] Planning Watersheds must be used when planning forest management activities and assessing cumulative impacts within Timber Harvest Plans (THP). The monitoring stations described in this report were established to characterize flows and water quality in a given watershed in accordance with the monitoring objectives. They were not established to meet a specific regulatory objective relating to the Forest Practice Rules or a given THP. Since the measured turbidity levels represent the integration of all of the natural processes and anthropogenic activities taking place upstream of that location, the drainage areas used in this report represent the total area draining to each water quality monitoring station. We recognize that these drainage areas differ from the CALWATER Planning Watersheds, so the purpose of this appendix is to provide cross-links between these two sets of watersheds.

Figure 11 shows the location of the water quality and weather monitoring stations relative to the CALWATER Planning Watersheds. A comparison of Figure 11 to Figure 2 indicates how the CALWATER Planning Watersheds differ from the areas draining to each water quality monitoring station. In Bailey Creek, all three of the SPI water quality monitoring stations are inside the Bailey Creek Planning Watershed, although the uppermost station, UBC, is only slightly downstream of the outlet for the Blue Lake Canyon Planning Watershed. The lowest SPI station on Bailey Creek (LBC) is well upstream of the outlet of the Bailey Creek Watershed as designated by CALWATER (Figure 11). Similarly, the Rock Creek monitoring station is well within the Canyon Creek Planning Watershed, while the stations on the North and South Forks of Digger Creek both fall inside the Upper Digger Creek Planning Watershed (Figure 11).

This means that the drainage areas represented by the three SPI monitoring stations in Bailey Creek represent a combination of the Blue Lake Canyon Planning Watershed plus some portion of the Bailey Creek Planning Watershed (Table 8). The recently established monitoring stations on Rock Creek and the tributaries of Digger Creek also represent only a portion of the Canyon Creek and Upper Digger Creek Planning Watersheds, respectively. The percentages of each CALWATER Planning Watershed represented by each of the SPI water quality monitoring stations are shown in Table 8. These data show that the Upper Bailey Creek station can be used to represent the Blue Lake Canyon Planning Watershed, but none of the other monitoring stations correspond to the outlet of a Planning Watershed.

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[5] The California Interagency Watershed Map of 1999 (CALWATER 2.2, updated May 2004, "calw221") is the State of California's working definition of watershed boundaries. Available online at http://ceic.resources.ca.gov/catalog/ForestryAndFireProtection/WatershedsCALWATER221.html; last accessed March 26, 2012.

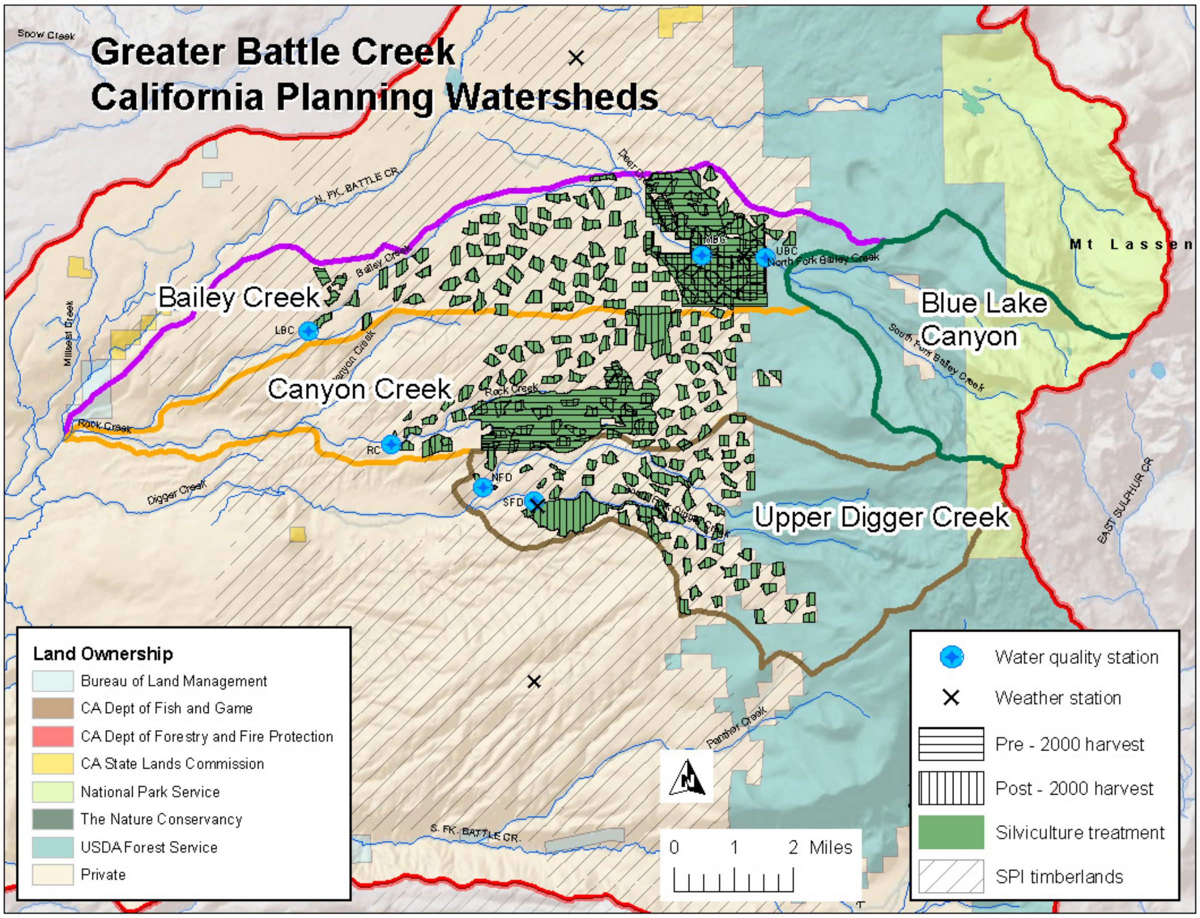

Figure 11. Map of the continuous water quality monitoring stations, weather stations, and the areas harvested by SPI before and after the year 2000. The CALWATER (2.2.1) Planning Watershed boundaries are shown in purple, yellow, brown and green, and in each case the monitoring stations fall within a Planning Watershed rather than at a Planning Watershed outlet.

Table 8. Percent of each of the different CALWATER Planning Watersheds that are upstream of each SPI water quality monitoring station.

CALWATER Planning Watersheds	Percent of each CALWATER Planning Watershed upstream of each SPI water quality monitoring station					
	Lower Bailey Creek	Upper Bailey Creek 2	Upper Bailey Creek	South Fork Digger Creek	North Fork Digger Creek	Rock Creek
Bailey Creek (5507.120201)	74%	12%	<1%	0	0	0
Canyon Creek (5507.120202)	0	0	0	0	0	63%
Blue Lake Canyon (5507.120204)	100%	100%	100%	0	0	0
Upper Digger Creek (5507.120402)	0	0	0	47%	48%	0

Cumulative Impacts Assessment

The assessment of potential cumulative impacts is a necessary component of a THP. In this process the Registered Professional Forester is required to examine the potential combined hydrologic impact from multiple timber management activities within the CALWATER Planning Watersheds covered by a THP. The silvicultural method used, number of acres harvested, soil erosion factors, drainage network, road network , and time period between timber harvest activities are all considered when estimating the potential cumulative hydrologic impact. Tables 2-6 provided the acres treated by year for the areas upstream of each of the SPI water quality monitoring stations, but these data cannot be used to estimate the potential cumulative impact for the CALWATER Planning Watersheds. Table 8 lists the percent of each CALWATER Planning Watershed that was subjected to forest harvest on SPI timberlands for: 1) 1997-1999, when the primary silvicultural treatments were selection cut and commercial thin, and 2) 2000-2011, when the primary treatments were clearcutting and shaded fuelbreaks (see Tables 2-6). This indicates that up to 27% of the Bailey Creek Planning Watershed was subjected to uneven-age management from 1997-1999, while up to 24% of this watershed was subjected to timber harvest in 2000-2011. Relatively intensive timber harvest activities also were conducted on SPI lands in the Canyon Creek Planning Watershed, as 20% of the total watershed was subjected to harvest activities in 1997-1999, and 19% from 2000 to 2011. Fifteen percent of the Upper Digger Creek Planning watershed was harvested between 2000-2001, but the values in Table 8 do not include any timber harvest on the Lassen NF or other private lands besides SPI.

Table 8. Percent of CALWATER (2.2.1) Planning Watersheds harvested on SPI timberlands in 1997-1999 and 2000-2011.

CALWATER (2.2.1) Planning Watershed	Watershed area acres	Percent watershed treated* 1997-1999	Percent watershed treated* 2000-2011
Bailey Creek (5507.120201)	13,664	27%	24%
Canyon Creek (5507.120202)	15,353	20%	19%
Blue Lake Canyon 5507.120204	7,657	0%	0%
Upper Digger Ck 5507.120402	13,222	0%	15%

For comparison, Tables 9 and 10 present the percent of each monitored watershed that was subjected to timber harvest on SPI timberlands in 1997-1999 and 2000-2011, respectively. Again the harvest data are only for SPI lands, and they show that the percent of the catchment that was harvested from 1997-1999 was highest for Rock Creek (18%) and Lower Bailey Creek (11%). From 2000-2011 the maximum area harvested was 18% in both the South Fork of Digger Creek and Rock Creek. The varying results between Table 8 and Tables 9-10 indicate that the estimated cumulative effect will vary according to whether the true hydrologic drainage area is used, or the CALWATER Planning Watersheds. In general the potential magnitude for a cumulative effect will typically decrease as watershed size increases due to dilution, attenuation of peak flows, storage, and other processes (MacDonald, 2000).

These data on the watershed scale are needed for analyzing and interpreting the results of instream monitoring programs, while the analogous data at the Planning Watershed scale are needed for regulatory purposes, and the two sets of data will not necessarily yield similar results because of the differences in the catchment areas being considered.

Table 9. Number of acres upstream of each SPI water quality monitoring station that was harvested on SPI timberlands from 1997 to 1999 by Timber Harvest Plan (THP) number, and the total percent area for all THPs.

THP number	Acres and total percent area harvested upstream of each SPI water quality monitoring station					
Number by county	Lower Bailey Creek	Upper Bailey Creek 2	Upper Bailey Creek	South Fork Digger Creek	North Fork Digger Creek	Rock Creek
2-92-024-SHA					127	1411
2-95-401-SHA	1804	695				
2-97-255-SHA						286
2-98-314-SHA	67	216				
Total percent area	**11%**	**7%**	**0%**	**0%**	**2%**	**18%**

Table 10. Percent of water quality station catchment area harvested on SPI timberlands during years 2000-2011 by timber harvest plan number. The dominate silviculture during these years was evenaged management.

California Timber Harvest Plan Number	Catchment area for water quality monitoring Stations*					
Number by county	Lower Bailey Creek	Upper Bailey Creek 2	Upper Bailey Creek	South Fork Digger Creek	North Fork Digger Creek	Rock Creek
2-99-247-SHA	2087	216				
2-02-185-SHA	75				18	1329
2-03-158-TEH				548	159	18
2-03-162-SHA						362
2-04-181-SHA				537	395	
2-08-052-SHA	839	433				
Percent Catchment Area Harvested 2000 -2011	**5%**	**7%**	**0%**	**18%**	**9%**	**18%**

*Catchment area reported for Upper Bailey Creek 2 is also included in Lower Bailey Creek.