CUMULATIVE WATERSHED EFFECTS OF TIMBER HARVEST AND OTHER ACTIVITIES

BATTLE CREEK WATERSHED, NORTHERN CALIFORNIA

July 3, 2012

Prepared for the

Battle Creek Alliance, Manton, CA

Prepared by

Tom Myers, Ph.D.

Hydrologic Consultant

Reno NV

Tom_myers@charter.net

TABLE OF CONTENTS

TABLE OF FIGURES

EXECUTIVE SUMMARY

The Battle Creek watershed in northern California has been logged for decades, but commencing in the 1990s the harvest method has become predominately clearcutting. This has led to concern that turbidity, a measure of the amount of fine suspended sediment in the streamflow, and stream embeddedness, the amount of the stream bottom clogged with fine sediment, is increasing in stream reaches in the watershed that are important to salmonids, which have been shown to be sensitive to any increase in sediment transport.

This study completes a cumulative watershed effects (CWEs) study of the watershed, in an attempt to identify areas that are being most affected by logging. The study uses all of the available data to develop a conceptual flow and transport model to help in interpreting the current CWEs and to predict how the watershed may evolve into the future.

The watershed receives an average of 48 inches of precipitation per year, of which about 19 inches becomes streamflow, which includes 9.6 inches of baseflow. If discharge to evapotranspiration along the streams is included, the total groundwater recharge averages about 12 in/y. Therefore, about 29 in/y remains for evapotranspiration from the watershed through the trees, either due to interception and its subsequent evaporation, evaporation from soils, or transpiration from the vegetation canopy. The ratio of high to low return interval floods and the relatively high baseflow indicates that Battle Creek is a baseflow-controlled stream. Baseflow correlates with precipitation as much as three years in the past, which reflects a long groundwater flow path from recharge to stream discharge. Streams dominated by groundwater would naturally have less sediment, because groundwater discharge does not erode the land surface, so increased sediment in the stream is a significant cause for concern.

Sediment moves through the watershed along with the flow, with soils being the primary source. The stream network and stream flows move the sediment from the hillslopes through the watershed. Rainsplash, overland flow, and channelized flow cause most of the erosion. Vegetation cover affects erosion and sediment transport from a site by decreasing the energy of the raindrop hitting the ground and slowing the overland flow velocity. Overland flow will erode rills and gullies after reaching a threshold. The watershed has variable slopes, with some flat uplands and steeper canyon sides, leading to variable sediment production.

The most obvious change caused by logging is a change in the vegetation cover which could possibly change the 29 in/y of precipitation that is returned to the atmosphere by this canopy. The generally accepted change is that annual yield increases, whether through additional surface runoff or increased recharge leading to more baseflow. The breakdown between the two depends on soils, compaction, whether roads provide pathways to the drainages, and more. An alternative is that rapidly reestablishing vegetation cover in a clearcut could evapotranspire more of the precipitation and cause less baseflow in the stream.

The evidence regarding streamflow on Battle Creek is not clear. Annual yield varies with the present and previous year’s precipitation; there is not sufficient detail in the measurements of either flow or precipitation to detect changes due to management. However, several factors indicate that logging

should increase extreme floods, which in this watershed are most frequently due to rain on snow events, such as in January 1997. Open areas increase short-term snow depth and also allow more rainfall to fall on the snow. If the open areas lead to more rapid melt of a larger snowpack on saturated or frozen soil, the runoff will definitely increase. A repetition of January 1997 on the current logged areas could result in a much higher runoff and more erosion and sediment in the stream from a similar return-interval storm event.

Sediment transport occurs mostly during runoff events. This means that the total sediment load from the watershed is probably not too high, but 1960s' data, before extensive clearcut logging, indicates that sediment transport is highly variable even for a given flow rate and that small sediment predominates even during high flows. The sediment transport rate therefore likely depends on the actual watershed area generating the runoff, as to whether it has a sediment source either due to natural conditions – soils, slope, low natural vegetation cover, or higher precipitation – or to anthropogenic conditions such as timber harvest or roads which decrease flow travel time.

Turbidity is generally low during baseflow unless increased groundwater flow increases flow in drainage ditches due to raised shallow groundwater levels or it moves fine sediment stored in the stream during high runoff events. High shallow groundwater levels causing roadside ditch flow were observed during a watershed tour in April 2012. Sediment that settles during runoff may be moved by baseflow leading to increased turbidity and embeddedness.

In pre-development conditions, most streams are in a dynamic equilibrium with the sediment load introduced to them. If that load sufficiently changes, the stream system will pass to a new equilibrium. Because equilibrium is generally dynamic, changes in the watershed may have to surpass a threshold for major changes to occur, such as rejuvenation which is a base level change that causes erosion or stream headcutting to move through the watershed. Small changes such as increases in the sediment load entering the stream system can be reflected in the stream morphology, such as embeddedness, pool depth, or pool spacing. Steep streams, such as some of the upper reaches in this watershed, can pass some additional sediment without any effects becoming obvious until the gradient flattens at the downstream end.

Significant changes in the flows can also affect the stream equilibrium. Increased flood flows increase the channel width by eroding channels and passing more sediment from in-channel sources. Decreased flow allows sediment to settle out forming sediment bars. Changes in channel-forming flows could have larger or longer-term impacts on watershed conditions. Increased baseflows may cause higher turbidity even during low flows if the channel sediment balance changes.

Small-sized sediment affects turbidity and embeddedness whereas larger sediment affects pool quality parameters, such as depth. For this reason, slope and flow rate control depth more than management. Data analyzed herein shows that turbidity and embeddedness increase along the stream reaches that are being logged. Considering small areas only ignores the cumulative impacts downstream, as shown by the correlation of turbidity measurements along the stream reaches with upstream reaches. As sediment from affected subwatersheds mixes in the downstream direction, the amount of sediment in the streamflow and on the stream bottom increases. The increase in sediment and turbidity in a downstream direction indicates that studies of CWEs must consider the entire watershed.

There is too little data on the watershed to make informed decisions about future watershed management. To partly compensate, a numerical model based on the conceptual model presented herein could be developed to simulate the current and future flows and turbidity. The modeling could be similar to that completed by Kuras et al. (2012) to simulate changing watershed conditions with past and future climate conditions. A watershed water balance model that estimates runoff around the watershed could be used with empirical sediment transport and CWE data to estimate changes in flows and sediment transport due to logging. The model could estimate the risk of the watershed reaching the threshold conditions that could cause major changes to the sediment and water budget relations.

Also, ongoing data collection efforts by Battle Creek Alliance should be continued and expanded. Sediment data should be collected at the USGS gaging station near the mouth of the watershed, to be compared with the 1960s data and to monitor change into the future. Aquatic habitat data as collected in 2001 and 2002 should be replicated at short time intervals to monitor short term changes. Monitoring that occurs on greater than 10 year cycles cannot detect the changes caused by sediment waves moving through the watershed.

INTRODUCTION

The Battle Creek watershed in northeast California drains the west side of Lassen Park and enters the Sacramento River downstream of Redding, CA. The watershed has a history of logging, but the practice has expanded and its intensity has increased to be primarily clearcutting since 1998 (James and MacDonald 2012). The increased logging has led to concern that it will degrade the watershed further (CalFire 2011; Kier 2009; Tussing and Ward 2008; Ward and Moberg 2004; Napper 2001). Kier (2009) provided a detailed literature review relating directly to the Battle Creek watershed that can be summarized as logging and road development increases the sediment load in the streams and that the sediment load has caused poor fine sediment and pool habitat conditions.

Sediment transport and turbidity has negative effects on most salmonid species (Walters et al 2009; Suttle et al 2004). There is a linear relationship between embeddedness and sediment storage in pools and the survival of juvenile steelhead (Suttle et al 2004). There would seem to be no threshold below which turbidity is harmless (Suttle et al 2004). Sediment transport that occurs at high frequencies tends to be most important (Walters et al 2009), possibly because of its chronic effect.

Cumulative watershed effects (CWEs) are combined effects on watershed processes of all activities in a watershed (Reid 2010; Dunne et al. 2001). These impacts include direct effects such as construction in the stream and indirect effects from land management, including timber harvesting (Wohl 2006). Timber harvesting affects sediment, water temperature, large woody debris in the streams (LWD), water quality, physical aquatic habitat, and stream flows (Kuras et al. 2012; Klein et al. 2011; Reid 2010, Litschert and MacDonald 2009; Reid and Lewis 2009, 2007). The focus of the CWEs concerns hydrology, including low and peak flows, water quality (Binkley and Brown 1993) primarily including turbidity (as an analogue for sediment transport (Kunkle et al. 1971)), and stream morphology parameters including pool frequency and depth, width/depth, embeddedness and percent fines. Best management practices (BMPs) are frequently employed to decrease the impacts, but are often less effective than desired (Klein et al. 2012; Rashin et al. 2006; Dunne et al. 2001).

The purpose of this study is to assess the current cumulative watershed effects of logging in the Battle Creek watershed, to assess the appropriate scale for considering CWEs on this watershed, and to develop a conceptual model to assist in predicting future CWEs from future logging. Concerns are primarily with changes in flow and sediment discharging into the stream. Stream quality includes physical habitat changes as the stream transports, or attempts to transport, the changing flow and sediment loads.

BATTLE CREEK WATERSHED

The Battle Creek Watershed drains an area of about 357 square miles, to the Battle Creek below Coleman Fish Hatchery near Cottonwood gage (#11376550), on the east side of the Sacramento River in Shasta and Tehama Counties in northern California (Figure 1). The watershed extends westward about 35 miles from its highest point of 10,457 feet at the top of Lassen Peak at the south end of the High Cascades to its confluence with the Sacramento River at about 335 feet elevation in the northeast end of the Sacramento Valley. Annual precipitation exceeds 125 in/y on top of Lassen Peak and is less than 30 in/y on the west end near the gaging station (Figure 1). The average over the watershed is 48 in/y, an amount determined by weighted averaging of the zones on Figure 1.

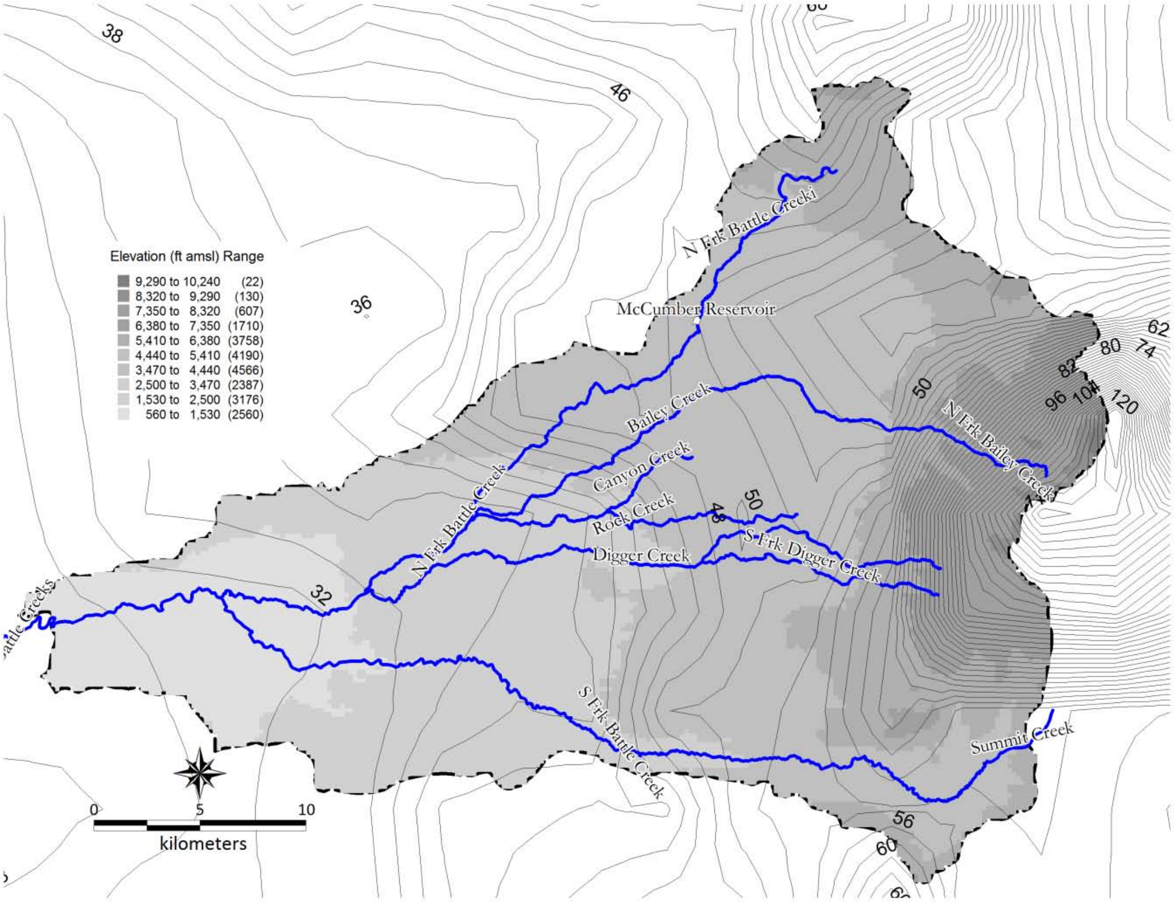

Figure 1: Battle Creek watershed, with average annual precipitation contours in 2-inch increments for 1971-2000 from PRISM (Daly et al 1994; http://www.prism.oregonstate.edu/docs/overview.html#reference) and elevation range based on 30 m DEM data.

The steep slopes of the South Fork of Battle Creek largely define the southern portion of the watershed (Figure 2). The steepest portions of the watershed are in the east on the western slopes of Lassen Peak. Steep subwatersheds that drain to the North Fork Battle Creek are Digger, Rock, and Canyon Creek; Bailey Creek is relatively less steep (Figure 2). Other steep areas occur in the northeast and northwest portions of the watershed. The northeastern part of the watershed displays relatively minor evidence of fluvial erosion which results in a relatively low drainage density for this portion of the watershed; this can be seen in the rapidly changing slopes north of Bailey Creek on the east side of the watershed.

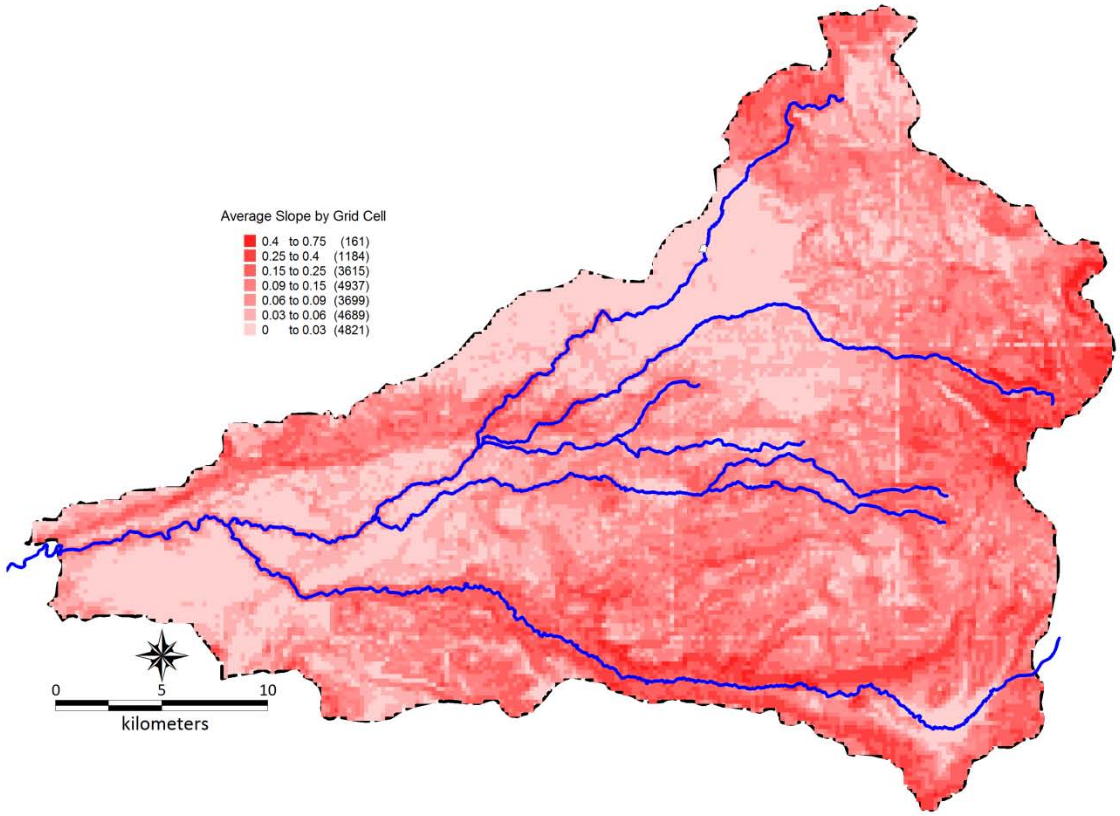

Figure 2: Battle Creek watershed average slope.

Almost the entire Battle Creek watershed lies in the Cascade Range geomorphic province (Bailey 1966; CGS 2002) which includes many flows of basalt, basaltic andesite, dacite, and rhyolite that include Lassen Peak, a dacite plug dome. Andesite outcrops prevail through the watershed (Figure 3). Some faults occur south of the South Fork of Battle Creek, but the bulk of the watershed does not have significant mapped faults, which should be expected due to the volcanic flows which cover the watershed.

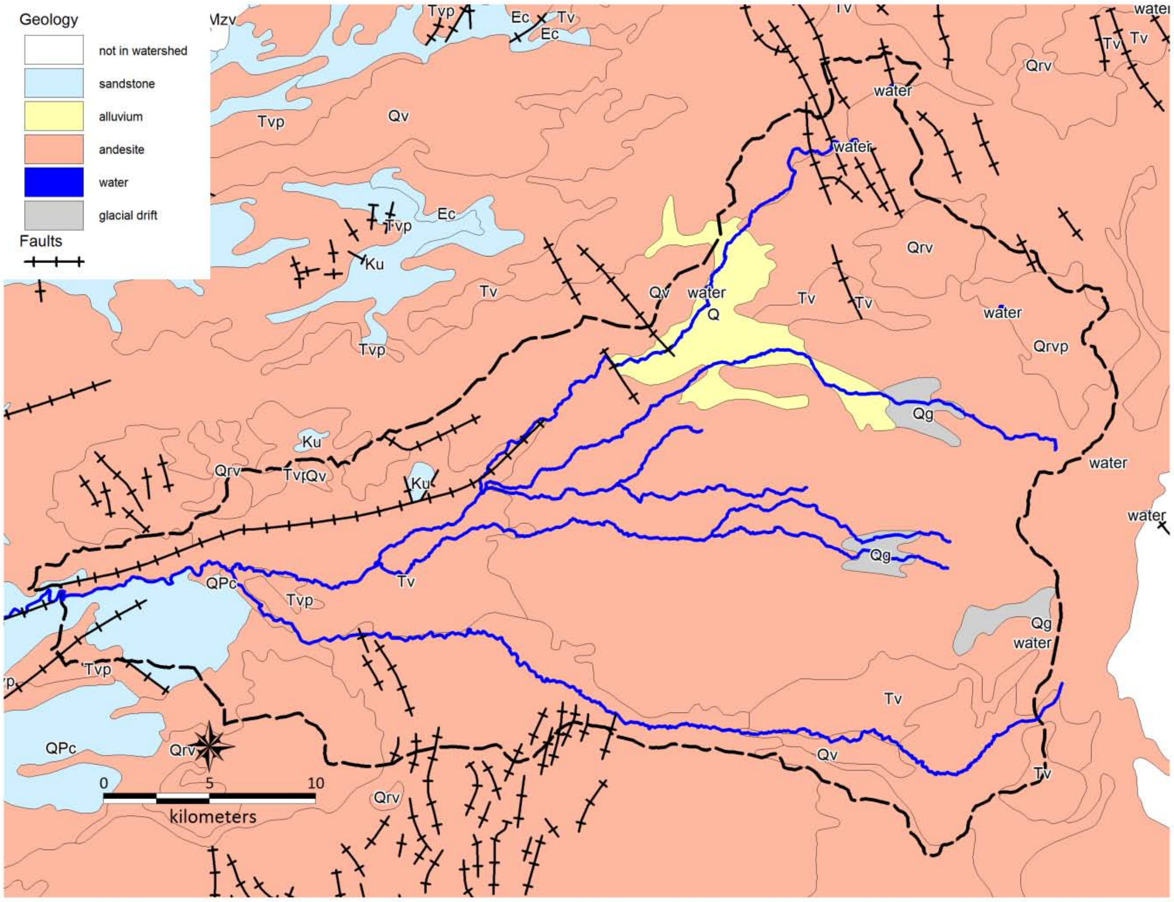

Figure 3: Battle Creek watershed geology and rock type.

Soils in the watershed consist of two associations, 1) the Cohasset-Windy-McCarthy association and 2) the Jiggs-Lyonsville- Forward association (USDA 1967, 1974). The Cohasset-Windy-McCarthy soil association consists of thin to moderately-thick soils that mantle gentle-sloping to rolling ridges capped by lava flows and very steep slopes on mountains of volcanic rock. The soils are generally dark brown to dark reddish brown, derived from andesitic to basaltic rock, and support vegetation that includes ponderosa pine, Douglas-fir, white fir, sugar pine, and black oak. These soils are mostly north of the west-flowing Digger Creek, in the Bailey and Canyon Creek subwatersheds. The Jiggs-Lyonsville-Forward soil association mantles broad, gentle-sloping ridges and steep slopes that flank incised watercourses. The soils are mostly light gray, are derived from rhyolitic to dacitic rock, and support vegetation that includes ponderosa pine, white fir, sugar pine, Douglas-fir, and incense cedar. These soils are mostly south of Digger Creek, in the Upper Digger Creek and Panther Creek planning watersheds. The Battle Creek watershed has low drainage density, or a lower ratio of channels to watershed area, because of the volcanic soils.

The watershed has a history of logging since late in the 19th century. Napper (2001) listed 27 timber sales that had occurred in the watershed between the 1950s and late 1990s. Satellite photography from

1998 shows essentially no clearcutting in the watershed (Figure 4). Extensive clearcutting appeared east of Shingletown in the Bailey Creek subwatershed by 2004 (Figure 5). At least several dozen areas are apparent in the photo. Between 1998 and 2004, about 2300 and just over 400 acres had been clearcut in the Bailey Creek and Rock Creek subwatersheds, respectively (Table 1). By 2010, clearcutting had expanded north further into the North Fork Battle Creek subwatershed and south into both forks of Digger Creek; about 1000 acres had been cut in Digger Creek subwatershed (Figure 6 and Table 1). Table 1 does not include acres cut in the North Fork Battle Creek subwatershed specifically because James and MacDonald (2012) did not provide that logging data. "SPI is responsible for approximately 79 percent of the 33,100 acres under THP within the watershed during the time period spanning from 1997 to 2010. Approximately 67 percent of the total THP area has been harvested using even-aged silviculture…Fifty-four percent of the even-aged harvesting is within the five planning watershed assessment area." (CalFire et al 2011, p 18).

Figure 4: Satellite imagery from 9/12/98 obtained from Google Earth by Battle Creek Alliance.

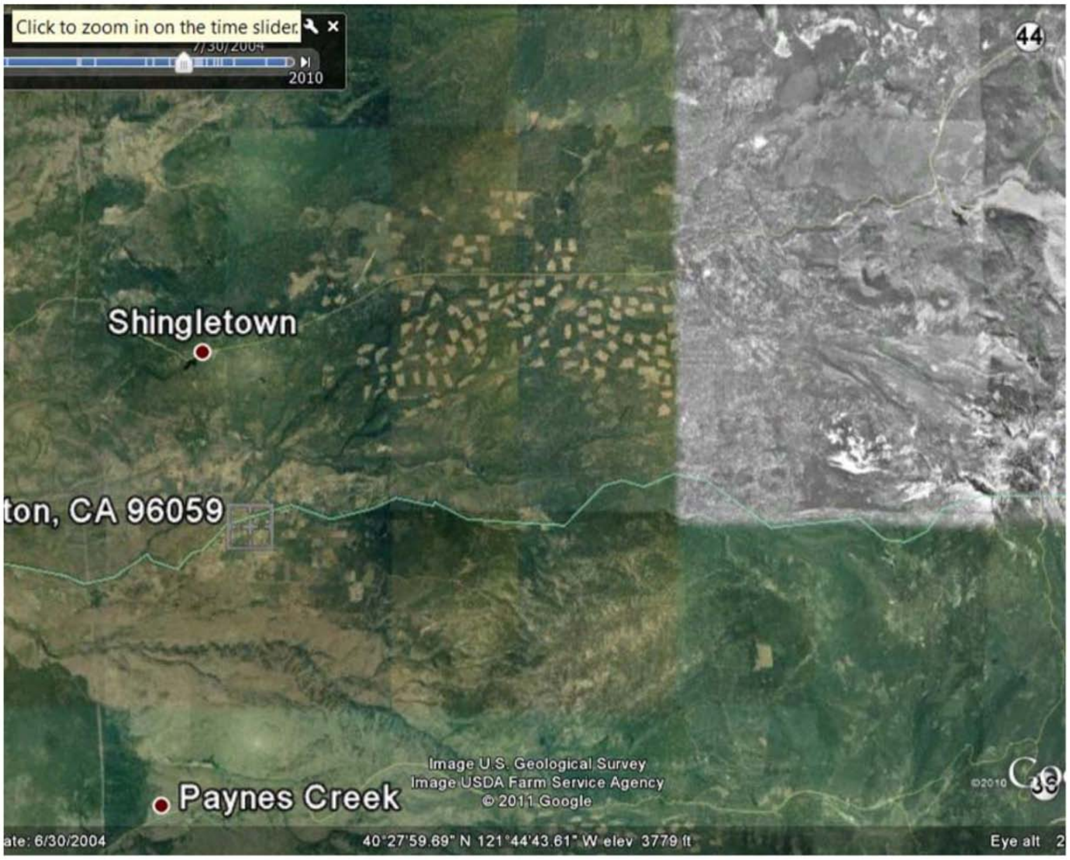

Figure 5: Satellite imagery from 6/30/04 obtained from Google Earth by Battle Creek Alliance.

Table 1: Years and acres logged by clearcut, shelterwood, group selection, or shaded fuel break (James and MacDonald 2012)

	LBC	UBC2	S Frk Digger	Nrth Frk Digger	Rock Creek
1998					28
1999					
2000	900				
2001					
2002	970	216			48
2003	174				357
2004	166				
2005					
2006			42	13	
2007	18		432	73	1169
2008			154	426	79
2009			373		
2010	465	270	85		
2011	374	163			
Total	3067	649	1086	512	1681
Subwatershed Area (Acres)	17750	9282	6180	6321	9674
% Cut	17.3	7.0	17.6	8.1	17.4

Figure 6: Satellite imagery from 8/01/10 obtained from Google Earth by Battle Creek Alliance.

METHOD OF ANALYSIS

A flow gaging station near the mouth of the Battle Creek watershed, the Battle Creek below Coleman Fish Hatchery near Cottonwood gage (#11376550), has operated since 1961 year-round with some exceptions. January 1997 is missing, which is unfortunate because that period contains a flood that has allegedly caused a substantial sediment inflow to the system (Ward and Moberg 2004). The USGS also took grab samples of various water quality parameters between 1961 and 1970, including sediment concentration, sediment size distribution, specific conductivity (SC). Other gaging stations have operated within the watershed, but they have monitored only low flows and diversions. Detailed analysis of the diversions is beyond the scope of this study, but powerplants divert a substantial portion of the flow at times of the year. These diversions appear to be half or more of the total flow, with instream flow requirements. Gage #11376550 includes all of the flow from the watershed, after the diversions have returned to the river.

I analyzed the gage data for annual and monthly flow statistics and flow frequency rates. I also established a relation between sediment concentration (Qs) and flow rate (Q) and between SC and Q for the 1961 through 1970 period. Additionally, I consider the sediment size distribution as a function of Q and Qs. Battle Creek has a high baseflow as a proportion of its peaks, therefore I determined the correlation of annual flow and annual baseflow (September and October) with annual precipitation at four locations – Manton, Shingletown, Coleman, and Lassen Peak. Annual precipitation data was obtained from PRISM (Daley et al 2004) as suggested by Dunne et al. (2001). The annual precipitation series had missing data in a few years, presumably due to the factors used by PRISM to estimate precipitation at a point being incomplete. These were estimated with regression among the locations.

Turbidity is an analogue for suspended sediment, with relationships between the two estimable on a case-by-case basis (Kunkle et al 1971); turbidity best represents fine sediment (Bolda and Meyers 1997). Suspended sediment is related to runoff but also to change in the watershed so that a direct relationship between flow events and sediment will not necessarily manifest. Threshold events cause the change. Threshold can be either rejuvenation, a base level change that causes erosion or stream headcutting to move through the watershed, due to high flows or can be a change in low flows that can cause changes in the base-flow channel.

The Battle Creek Alliance has collected turbidity data since 12/30/09. They collect data throughout the watershed (Figure 7) on randomly selected days with all sites being sampled on the same day. There is no attempt to assure the data collection occurs at the same time or that samples are from a given slug of water traversing the stream network. CSPA (2011) provided some peer review and quality control to the data set. I analyzed this data graphically for trends between stations and completed correlation analysis among all sites. Additional data has also been collected since 2002 at three sites on the Bailey Creek subwatershed (James and MacDonald 2012). This report reviews that report and utilizes useful information from it.

TerraAqua collected stream morphology data in 2001/2 at about 50 sites in the watershed (Figure 7) and replicated the data collection at ten of the sites in 2006 (Ward and Moberg 2004; Tussing and Ward

2008; Keir Associates 2009). This report independently analyzes the stream morphology data and also reviews the analyses completed in these references.

Statistically testing for relations between stream conditions and watershed factors for the entire watershed above the stream site, as done by Ward and Moberg (2004), might violate assumptions about the independence of observations (Van Sickle 2003). For example, road density encompasses the entire watershed above the point for which the measurement is meant to apply, except for areas excluded above reservoirs. Each successive point downstream also encompasses the watershed above the point, including the watershed already included in other independent variables (Ward and Moberg 2004, p 15).

I also visited the watershed on April 11, 2012, during a light rainstorm, to see the sites at which the Battle Creek Alliance had been collecting turbidity data. The visit was a windshield survey of the watershed to look at hydrologic features and sediment transport visible from the county roads. The streams were lightly turbid due to the rainfall. No water samples were collected for use in this study.

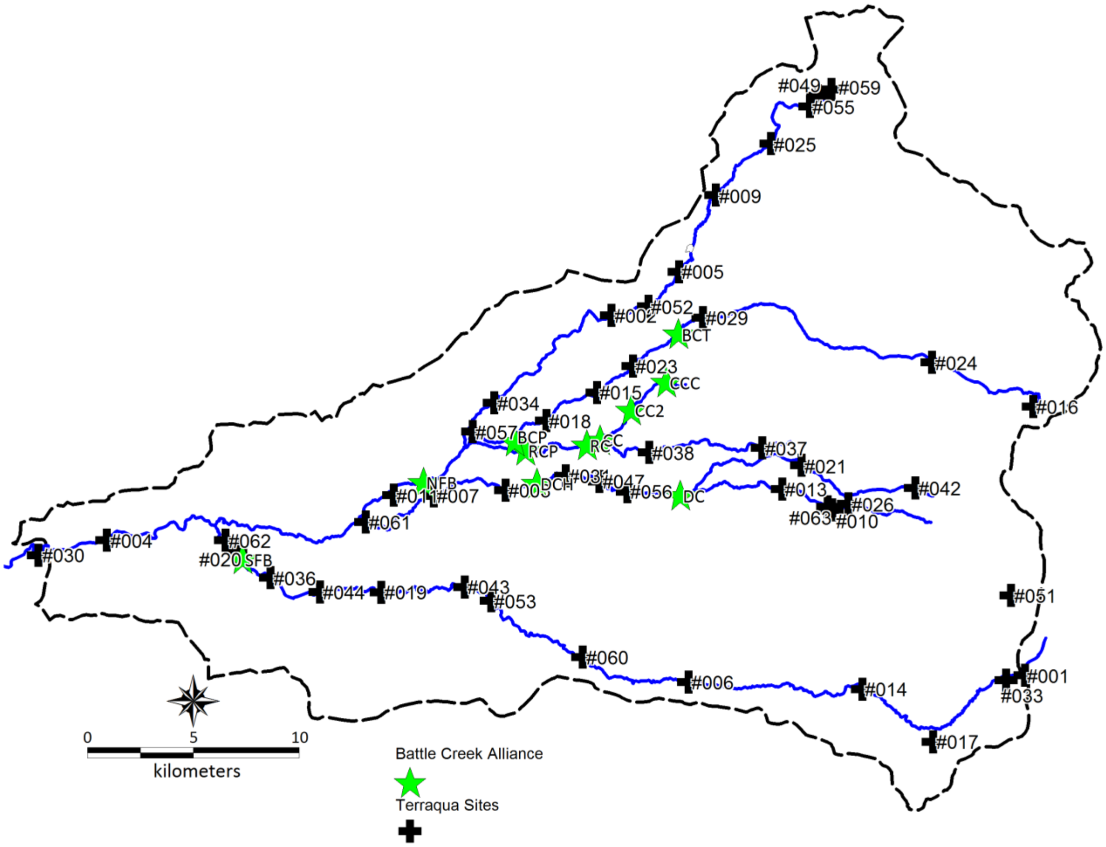

Figure 7: Battle Creek Alliance turbidity monitoring sites and sites sampled for aquatic habitat by Ward and Moberg (2004).

RESULTS

Stream Flow, Sediment and Turbidity Data

The annual yield from the watershed averages 502 cfs with an inter-annual variation of from about 240 to over 900 cfs (Figure 8). Over a 357 square mile watershed, the yield is 1.59 ft/y or 19 in/y. The average monthly flows vary from about 252 cfs in September to over 700 cfs in March (Figure 9). Flow usually peaks from January through March and reaches its minimum from August through October (Figure 9). Rainfall causes much of the runoff from the watershed, with rain on snow events causing the highest runoff, therefore anytime that rainfall peaks can have significant high flows. The highest runoff months are the months during which the antecedent moisture and snow cover in rainfall zones are the highest. The low flow period generally occurs after a period of little rainfall, so rainfall early in the water year runs off only at lower rates than it does during the wetter periods later in the winter and spring.

Both the differences in storm events and watershed conditions are reflected in the mean, median, and standard deviation of the average daily flows by month (Figure 9). For all months, the mean exceeds the median because occasional high flows cause the average to be higher than the median; the difference is highest during mid-winter months because the watershed has not wetted sufficiently to increase the average daily flows but the storms that occur cause high runoff. The highest average flow occurs in March because large storms coinciding with a wet watershed are most likely in March. The median flow is highest from March through May due to wet antecedent conditions but the average flow decreases through that period. The high variability reflected by standard deviation of the flows during winter reflects these watershed factors.

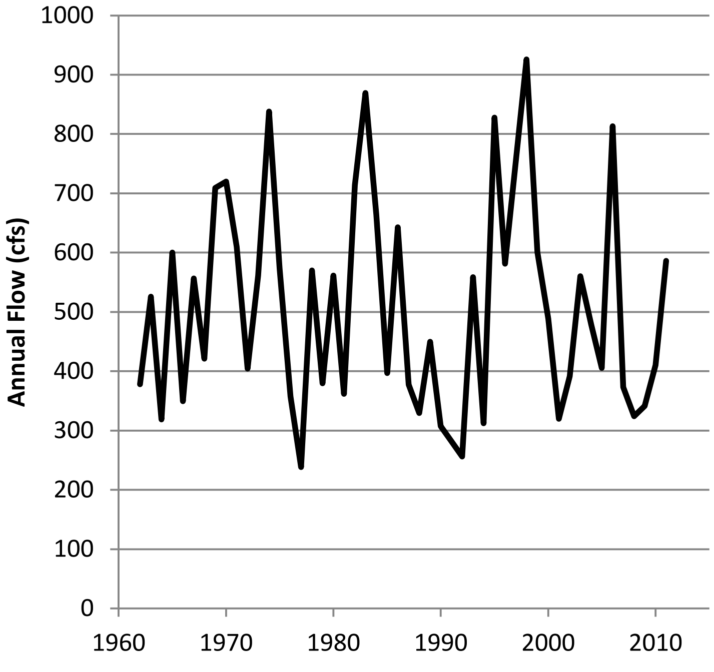

Figure 8: Annual flow rates from 1961 through 2011 for the Battle Creek below Coleman Fish Hatchery near Cottonwood, 1961-2012

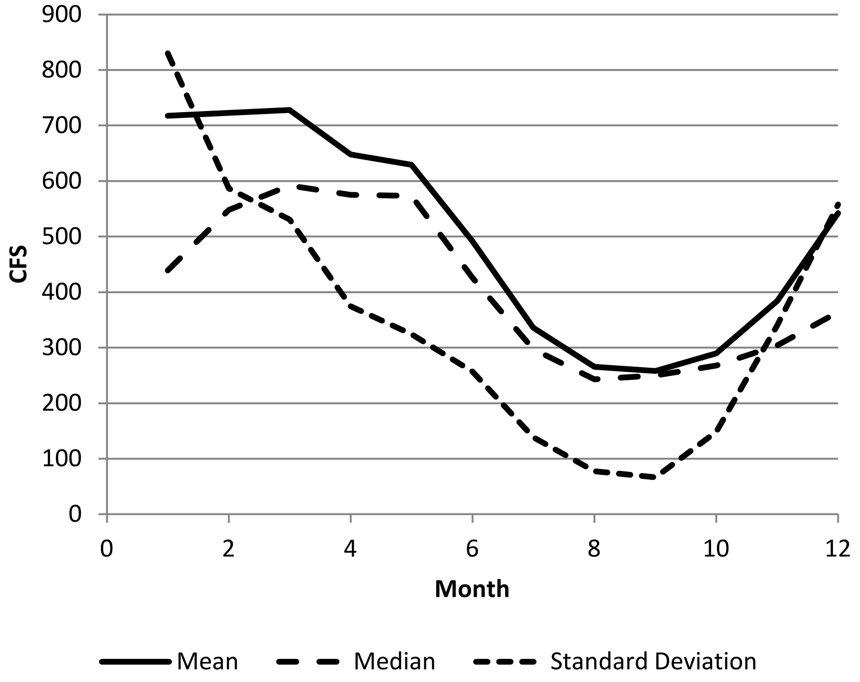

Figure 9: Flow statistics for average daily flow at the outflow to the Battle Creek watershed, # 11376550.

More than 60 percent of all daily flows are between 200 and 600 cfs (Figure 10), although a histogram has a long tail reflecting high flows. The highest daily average flow was 10,900 cfs, recorded on January 16, 1974, but less than 10 percent of daily flows exceed 1000 cfs. Significantly less water runs off this watershed than other watersheds of similar size for a similar amount of precipitation as shown by the ratio Q100/Q2, the 100-year to 2-year flood, equaling 4.44. This is a very low ratio compared to the regional value 5.75 (CalFire 2011). This is likely due to the volcanic soils and is reflected by a low drainage density which also corresponds to less runoff (Mosley and McKerchar 1993).

Histograms of daily flow by month, presented in Appendix A, show the two distinct flow regimes which had been suggested by Figure 9. August through October has essentially no high flows and most flows are less than 400 cfs. Sixty-eight percent of September has flow between 200 and 300 cfs. During the remaining months, the low flows are higher and there is higher runoff. July and November are transitional months from the high variability, runoff months of December through June to the baseflow-dominated months of August through October. The average of the medians for August through October, 254 cfs, is adopted as the baseflow runoff from the Battle Creek watershed. Using the methods of Myers (2009) and Cherkauer (2004), the average recharge for a watershed of 357 square miles is 9.6 in/y. This does not account for the baseflow that would be lost to riparian vegetation and wetlands through the watershed, therefore the total of discharge and loss would require a recharge rate closer to 12 in/y.

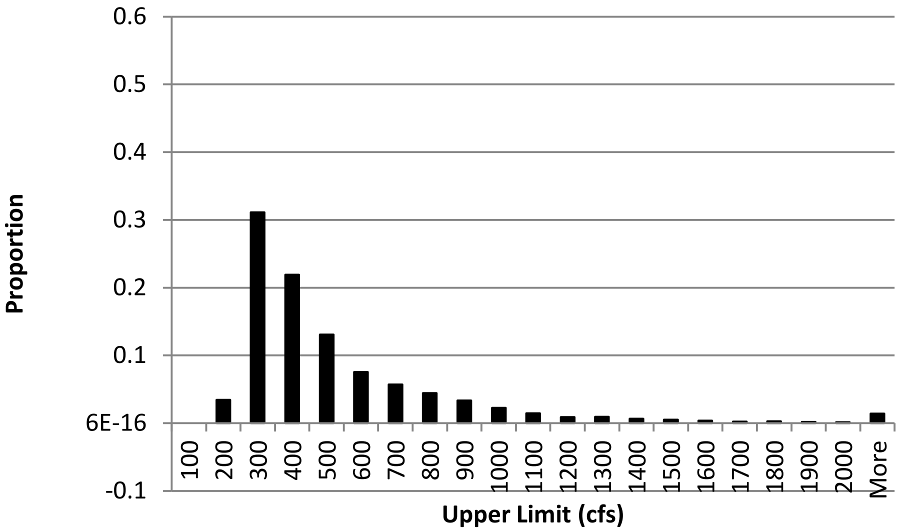

Figure 10: Flow frequency histogram for Battle Creek below Coleman Fish Hatchery near Cottonwood, 1961-2012

Only during two years did the average annual flow fall below 300 cfs, including the classically dry 1977 and 1992 (Figure 8). The longest higher flow period occurred during the late 1990s with four years having above average annual flow. Between 2000 and 2011, average annual flow exceeded average during just three years. This period is not obviously as dry as 1986 through 1994, which had just one year exceeding the average. The first nine years of record are close to average although with a slight increase in flow up to 1970.

Annual yield likely varies with PRISM-generated annual precipitation (Figure 11) which, for Manton CA, shows a significant cycling with time with variation from less than 50 to more than 160 cm. After reaching a small surplus in 1945, the cumulative annual precipitation for Manton reached a deficit of almost -200 cm in 1992, after which the deficit started to rapidly dissipate and reach a peak surplus in 2006 before trending downward. This suggests precipitation is below the average in more years than it is above it; several of the highest precipitation years since 1933 occurred since 1992. The deficit also recovered partially in the year leading to 1983, the second highest flow year in the data base, but afterwards plunged to its 1992 deficit. Annual runoff varies less than the precipitation (Figure 11).

Based on trends in the long-term precipitation deficit (Figure 11), precipitation in the first third of the 20th century apparently is less than during the more recent period. However, since 1961, the thirty-year moving averages at sites in and near the watershed (Figure 12) demonstrate relatively stationary conditions. At Manton and Coleman, the 30-year average in 2011 is several cm higher than in 1961, while higher at Shingletown the average is almost the same and at Lassen Peak it has decreased (Figure 12).

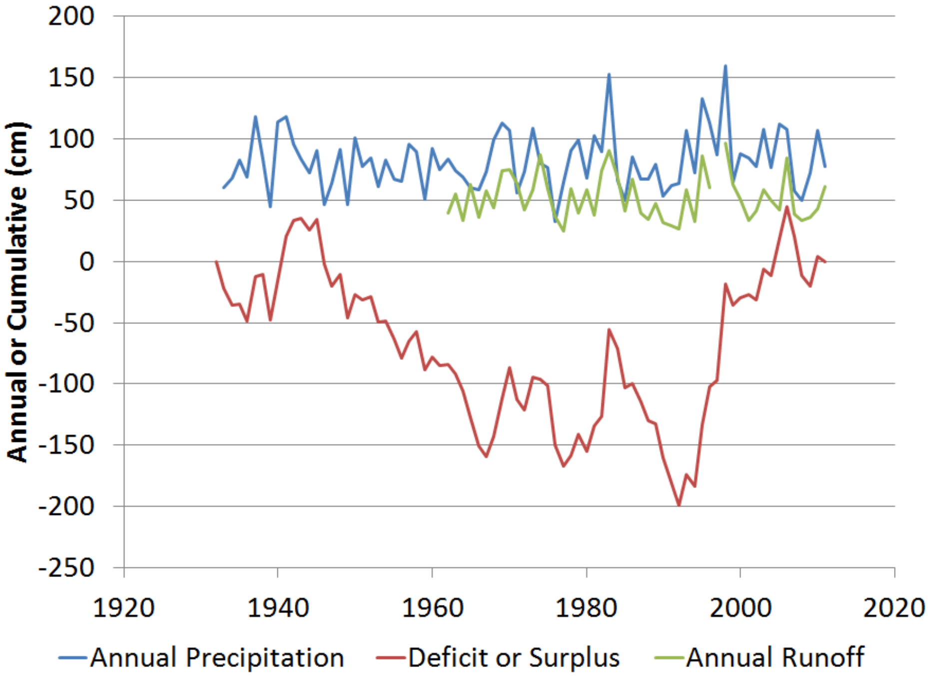

Figure 11: Annual precipitation and cumulative deficit, Manton CA, and annual flow at Battle Creek below Coleman Fish Hatchery near Cottonwood gage. Annual precipitation as generated with PRISM.

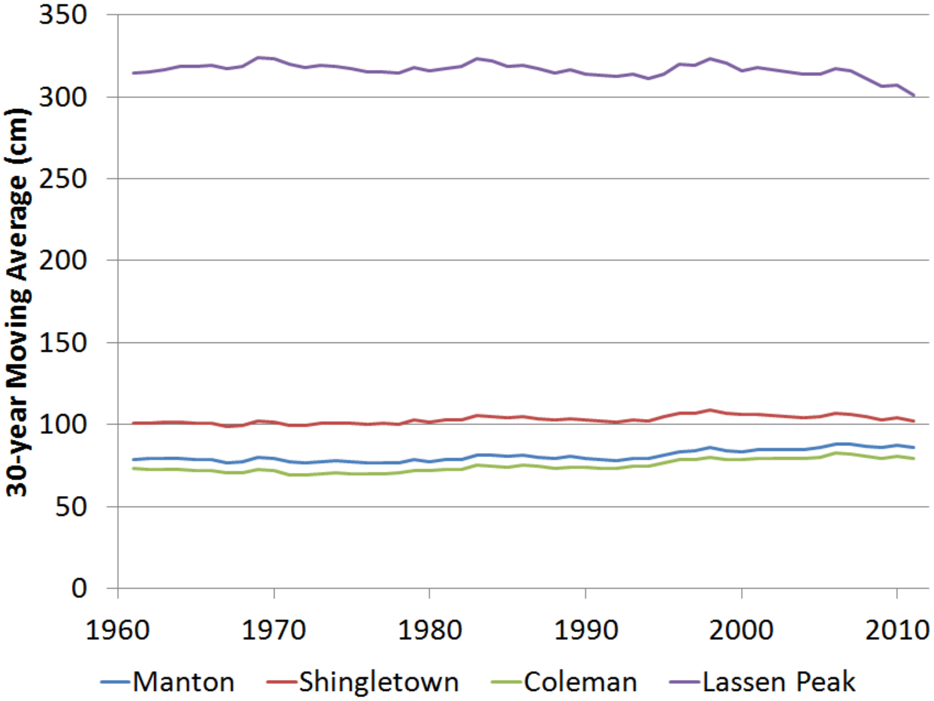

Figure 12: 30-year moving average precipitation for four stations. All data from PRISM.

The smaller variability in runoff (Figure 11) suggests that flow may depend on previous years' precipitation. Multiple regression of annual flow with annual precipitation is significant for lag-0 and lag-1 annual precipitation, meaning that the previous year explains a significant amount of the variation in the annual runoff. However, it is possible that baseflow depends on longer lag precipitation. The coefficient of a multiple regression of average flow for August and September, representing the groundwater-dependent baseflow, with previous years' annual precipitation was significant for lag-0 (p=10-14), lag-1 (p=0.005), and lag-3 (p=0.025) and for lag-2 was just insignificant (p=0.131). Many factors influence this relationship, but correlation with previous years' precipitation reflects the long flow path for base and substantial groundwater storage in the watershed[1]. As noted above, the average baseflow equals a recharge rate of about 9.6 in/y.

Flow counts are the number of flows for a given year that are less than a given percentile for the entire period of record (Perry 2007). The flow count data (Figure 13) reflects the trends in the precipitation data, with flow counts for the lower percentile flows associating with low precipitation periods. The two highest counts for the fifth percentile occur in the lowest precipitation years, 1976 and 1992. However, the 1992 count exceeds the 1976 count by more than 50 even though 1976 was the drier precipitation year; in fact 1990 and 1991 were drier (Figure 11) but they only had a few days with less than the fifth percentile. Low flow periods became longer and more frequent as the long-term precipitation deficit increased. The year 1976, being extremely dry, had almost no high flows, and had 344 days with flow lower than the fiftieth percentile, which are about 20 more than in 1992. Other count data for less than the fiftieth percentile reflect the annual precipitation trends. The annual precipitation predominantly controls the lower flows, but the lowest flows occur after multi-year precipitation deficits which reflect the lag-3 correlation. The year 1964 demonstrates how high flows depend more on shorter-term storm flow, with highest recorded peak in December but more than 50 days with flows less than the fifth percentile. The presence of a low flow plateau below which flows have never dropped and a very small range in the bottom five percent of flows indicates a large regional aquifer that connects the headwaters to the main stream channel through a long groundwater flow path.

Numerous diversions for powerplants probably have a small effect at high flows but may divert a significant amount of water around some stream reaches during low flows. Ward and Moberg (2004) suggested the effect would be "negligible" at the watershed scale but possibly "significant" at a site-specific scale, with respect to stream morphology or aquatic habitat variables. Ward and Moberg are apparently arguing that the diversions may affect sediment conditions near the diversion even if they are not relevant at a watershed scale.

---

[1] Flows for August and September were used because they best reflect baseflow without substantial runoff; October flows average higher because of a few years with runoff.

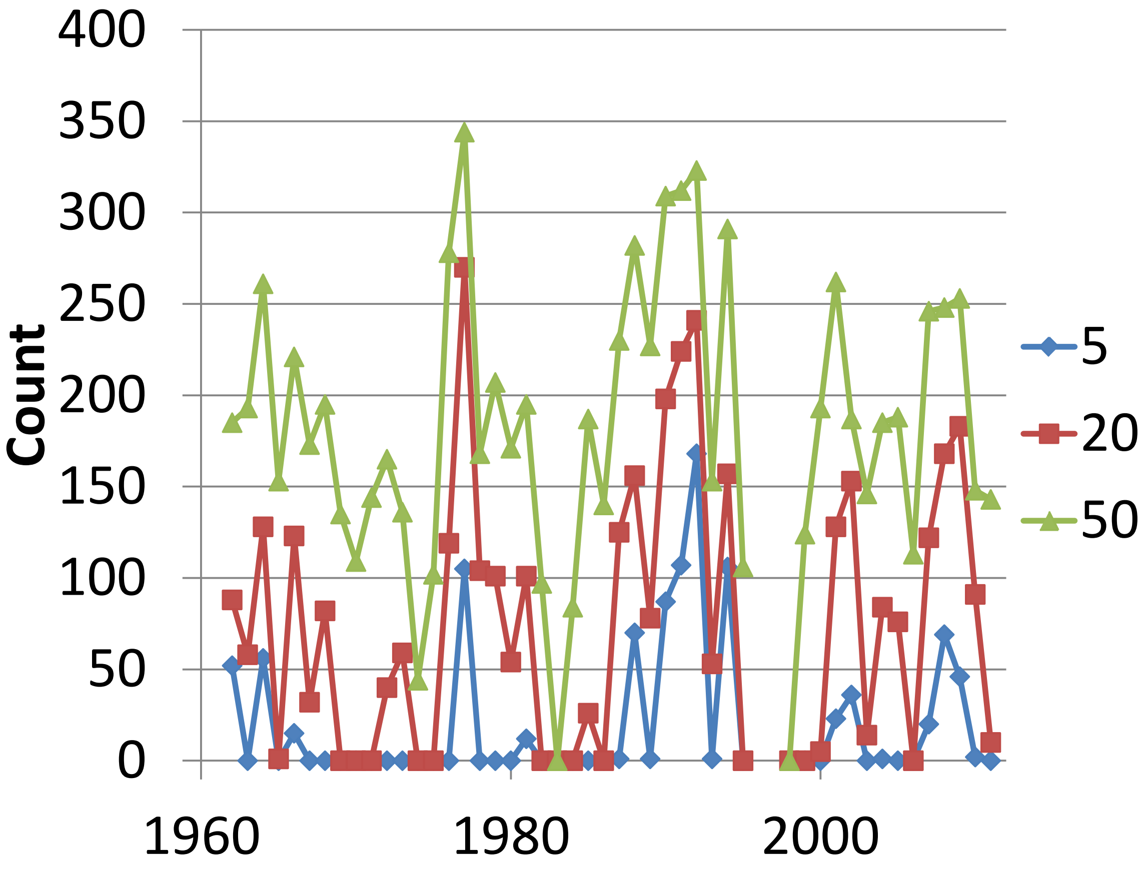

Figure 13: Count of the fifth, twentieth, and fiftieth percentile flows. The count is the number of days that the flow is less than the percentile as determined for the entire data set.

The 1962 through 1970 period, when the USGS collected water quality data, including suspended sediment, had relatively average flow (Figures 8 and 11). The sediment data should be representative of sediment relations on the watershed without the influence of substantial management changes or floods and droughts. Between about 200 and 700 cfs, the suspended sediment concentration clusters below about 13 mg/l (Figure 14), with some exceptions. The exceptions include various observations up to just higher than 40 mg/l. There is also a very slight trend toward increasing concentration with flow, equivalent to about 2 mg/l from 200 through 600 cfs. The trend probably reflects the increased transport capacity with increased flow rate mobilizing sediment within the stream banks, including a low flow channel. The slight increase in flow toward the end of the 1962-70 period probably explains the slight increase in suspended sediment concentration also seen through the period (not shown). The exceptions to the cluster of low sediment concentration at lower flows (Figure 14) include periods with runoff occurring during low flow periods.

The sediment concentration began to increase more significantly at flow rates above about 600 cfs which reflects that the flow includes more runoff which would include more sediment.

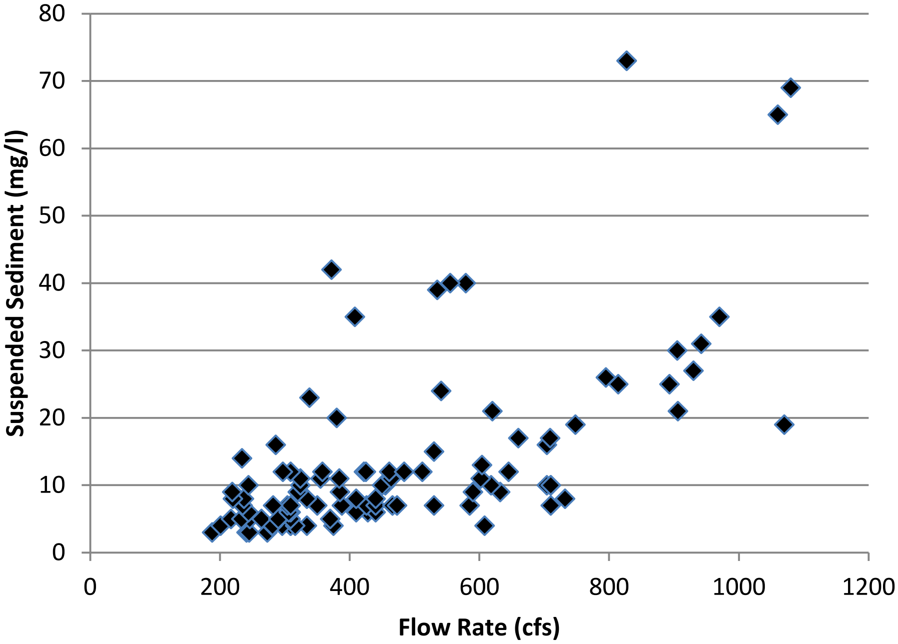

Figure 14: Relation of suspended sediment with flow rate concentration for Battle Creek below Coleman Fish Hatchery near Cottonwood, 1961-2012. At least a dozen observations beyond the end of the axes are not included because they likely represent flood events.

The USGS determined sediment size distribution for the suspended sediment for select observations using either mechanical or settling basin means (Figure 15). Sand ranges from 0.0625 to 2 mm. Most of the flows and associated sediment concentrations reflect runoff events. The lowest flow and sediment concentration event (632 cfs and 9 mg/l) had more than 80% of particles smaller than sand. One other observation with more than 80% less than sand size was for Q=827 cfs, but the sediment concentration equaled 163 mg/l. The third observation with more than 80% sand is for Q = 9340 cfs which had generated the highest concentration at 722 mg/l. This would have been close to 500 mg/l of fine sediment.

The remaining samples have a sand fraction that varies from about 35% to almost 90% of the sample. Only two samples have sediment larger than 1 mm but neither observation is unique for flow (1620 and 1690 cfs) or sediment concentration. Considering the variation in the data, the distribution and concentration of sediment depends greatly on the portion of the watershed producing the flow, including whether it is runoff or interflow.

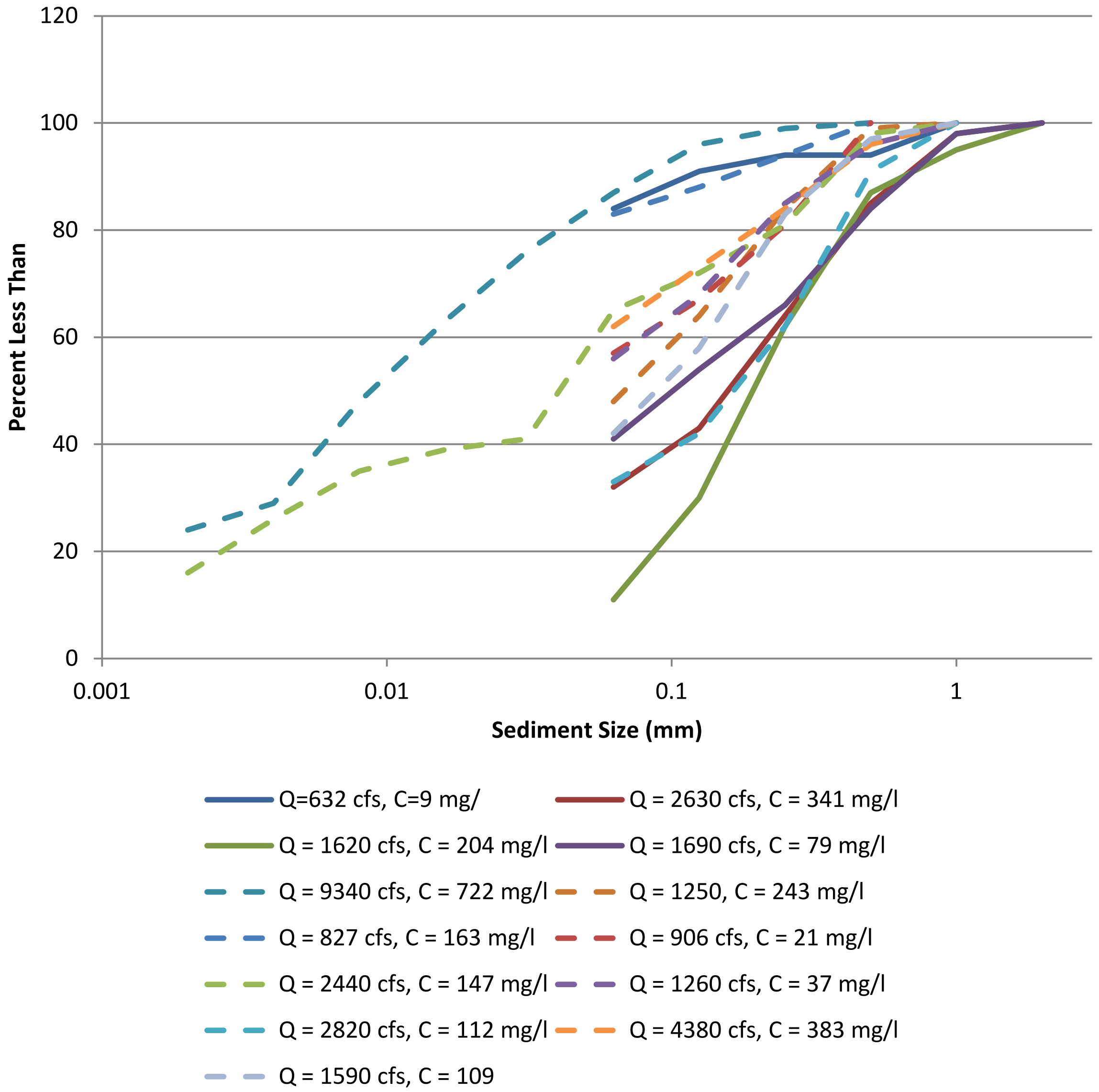

Figure 15: Sediment size distribution, Battle Creek below Coleman Hatchery near Cottonwood gage, 1962-70, sorted by flow rate and sediment concentration. Dashed line represents separation by settling basin.

There are two distinct trends in the relationship of SC to Q (Figure 16); they reflect the mixture of surface and groundwater at less than 700 cfs and of surface runoff at higher flow rates. Up to almost 700 cfs, the SC decreases about 50 microsiemens/cm (uS/cm) at an almost linear rate. At flows greater than 700 cfs, the relationship becomes almost horizontal, showing a further decrease of 20 uS/cm over the next 700 cfs. There is an apparent tendency to approach 70 uS/cm at the limit suggesting that surface runoff averages this rate. Salinity, which SC measures, increases with distance traveled through the groundwater so SC is higher if the groundwater component of the flow is higher as it is at low flows. Surface runoff has fewer dissolved solids so the SC value becomes constant as the flow rate increases. The proportion of groundwater or the average groundwater flowpath decreases as flow rate increases to about 700 cfs, and the proportion of surface water increases. Erosion at high flow which increases suspended sediment does not increase SC because there is less opportunity for any salts to dissolve in the runoff.

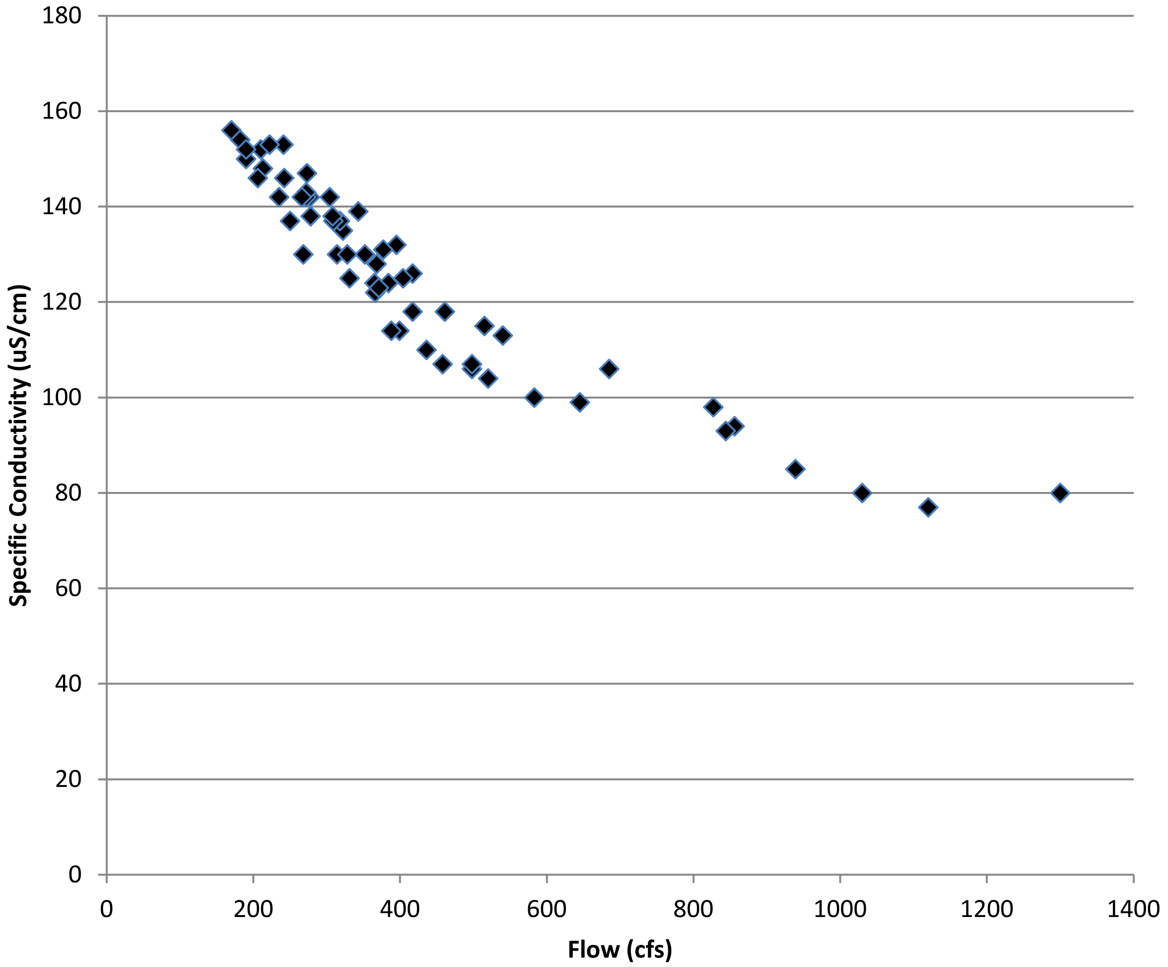

Figure 16: Specific conductivity vs. flow rate at the Battle Creek gage.

Stream Morphology Data

Data analyzed in this report includes data collected by TerraAqua in 2001/2 (Ward and Moberg 2004) and repeated for some stations in 2006 (Tussing and Ward 2008). Concerns about the quality of the data are detailed in the sidebar on this page. The repeated stations were labeled 1 through 11, excepting 8, on Figure 1 in Tussing and Ward (2008). One site (4) is on the mainstem Battle Creek. Four sites (2, 5, 9, and 11) are on the North Fork and two sites (1, 6) are on the South Fork Battle Creek. Three sites (3, 7, and 10) are on the North or South Fork Digger Creek. None were on Bailey or Rock Creek, the subwatershed having undergone most of the logging between 2001 and 2006 (Table 1).

Based on ratings for fine sediment defined in terms of favorability for salmonids for the 2001/2 data (Ward and Moberg 2004), there was significantly more fine sediment in lower gradient reaches but no difference among subwatersheds and no relationship with any of the watershed or sediment source parameters. Reaches with little fine sediment were scattered around the watershed and, conversely, reaches with substantial amounts of fine sediment were not clustered (Figure 17). The amount of fine sediment decreased between 2001/2 and 2006 (Tussing and Ward 2008)

Fine sediment amounts correlated negatively to stream gradient and none of the other watershed or sediment-source variables (Ward and Moberg 2004, p 37). The relationship was most important for stream gradient less than 3.5 percent (Ward and Moberg 2004, p 40). These findings are reasonable and indicate that the high energy reaches do not capture significant small sediment. Overall sediment size, as represented by D50, did not vary with

There is no date provided for the measurements in the dataset. The Battle Creek website indicates the metadata file provides the data acquisition date, but it only indicates that data was collected in 2001 and 2002 (http://krisweb.com/krisbattle/krisdb/webbuilder/metapage_9.htm, site accessed 4/10/12).

Ward and Moberg (2004) indicate they chose not to collect flow data, contrary to the recommendation in the protocol (Gallo et al. 2001; Gallo 2002). They do indicate they collected data during low-flow conditions, but without a collection date this is difficult to verify. Battle Creek low flows are relatively consistent (Figure 9), but pool depths and the fine sediment distribution would depend on the exact flow rates (Figure 15). Data not collected at the same flow rate would always be subject to concerns as to their comparability.

Data was collected at just six cross sections at each site, based on the original USFS protocols (Gallo 2002). Measurements based on six cross sections are highly variable (Myers and Swanson 1997a).

They chose to not measure the longitudinal profile as specified by protocols (Ward and Moberg 2004, p. 9). Protocol would have required thalweg measurements spaced at 1/5th of the bankfull width. They claim that profile data “at these fine increments was not being used to derive any site-descriptive variables” (Id.). They apparently measured profile to include pool features, but they are not clear as to where points were measured. The error introduced herein is not estimable.

Pools are considered only if they are scour pools. They define a pool as being “longer than the averaged wetted width”, “channel spanning” and being scoured over at least 25% of the surface area (Ward and Moberg 2004, p. 10). This would eliminate plunge pools and backwater pools from consideration. Because scour pools are a form of vertical meander and serve to dissipate energy, ignoring pools formed by LWD or rocks may miss some of the pools. An additional error regarding pools is that TerraAqua classified pools as low-gradient sections that “provided biologically significant fish habitat” with the selection dependent on “professional judgment” (Id.). Pool measures in Ward and Moberg (2004) are fraught with potential uncertainty.

any of the individual watershed or sediment source factors, including stream gradient. There was an increase in particle size between 2001/2 and 2006 for both response and transport reaches, but it was largest in the transport reaches. That gradient does not explain the D50 indicates that only a fine-grained proportion of the sediment load transports at low stream gradients. The D50 had a significant model with a factor including all of the watershed and source terms. This may reflect the fact that the source terms tended to have their highest values for sites in the middle of the watershed.

The lack of a significant relationship of sediment variables with watershed conditions, including those related to management may reflect that watershed factors are not independent variables (Van Sickle 2003). The general conclusion is that overall sediment conditions are poor (Kier 2009) and there is no difference among subwatersheds, therefore similar factors could be affecting the entire watershed. These include long-term management prior to 2001 and the general effects of the 1997 flood. The data collection precedes much of the short-term clear-cutting that has occurred during the 2000s.

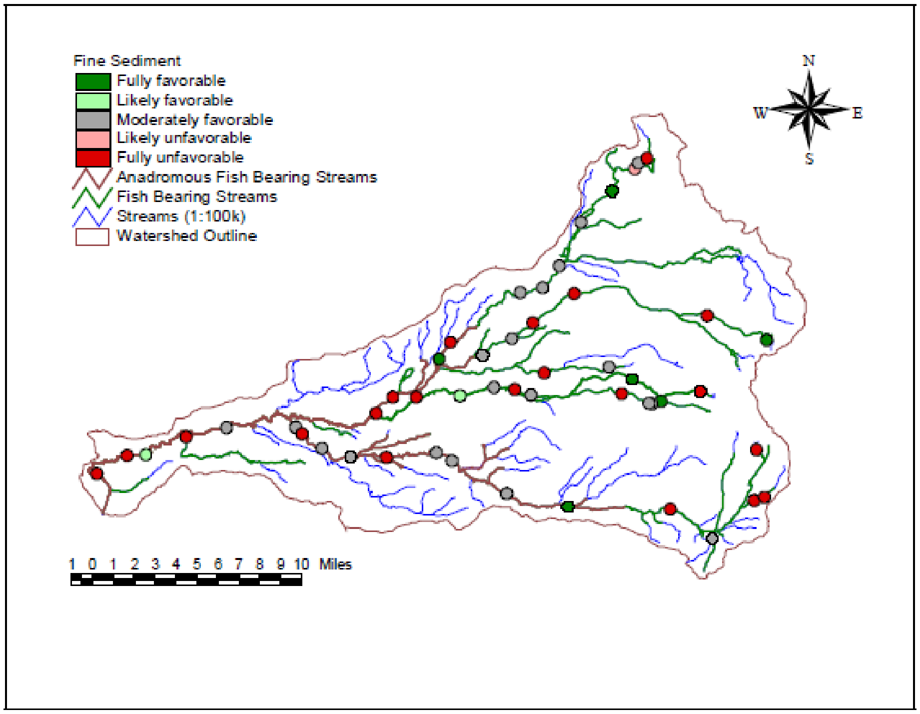

Figure 6. Map depicting EMDS truth values for fine sediment goal at sample sites within Battle Creek watershed.

Figure 17: Snapshot of Figure 6 from Ward and Moberg (2004) showing the distribution of fine sediment conditions, rated as favorable to unfavorable for salmonids, within the Battle Creek watershed.

Ward and Moberg (2004) found that the frequency of scour pools was favorable for salmonids only for reaches with a wide bankful width (Figure 10, Ward and Moberg 2004). A favorable pool frequency would be more than 30 pools per 100 m for channel width less than 2 m (Id.); for channel width greater than 20 m, favorable frequency would be less than 2 pools per 100 m (Id.). The database contained pool reaches with 6 or fewer pools per 100 m for channel width less than 15 m. Favorable pool frequencies therefore cluster at the downstream portion of the watershed (Figure 18), because the bankfull channel is wider and the required pool frequency is lower for the reach to be favorable. There was a slight increase in the number of pools at resampled sites between 2001/2 and 2006.

“Natural” pool spacing in meandering streams is about 7 channel widths. In steeper streams with primarily plunge pools controlled by rocks and LWD, the pool spacing is about 4 channel widths (Richards 1985; Myers and Swanson 1997 b and c). Favorable pool spacing (Ward and Moberg 2004) relies only on scour pools. This means that favorable pool spacing (for salmonids as considered in Ward and Moberg 2004) does not mean natural or hydrologically optimal. Plunge pools spend stream energy so there may be none left for scour pool formation.

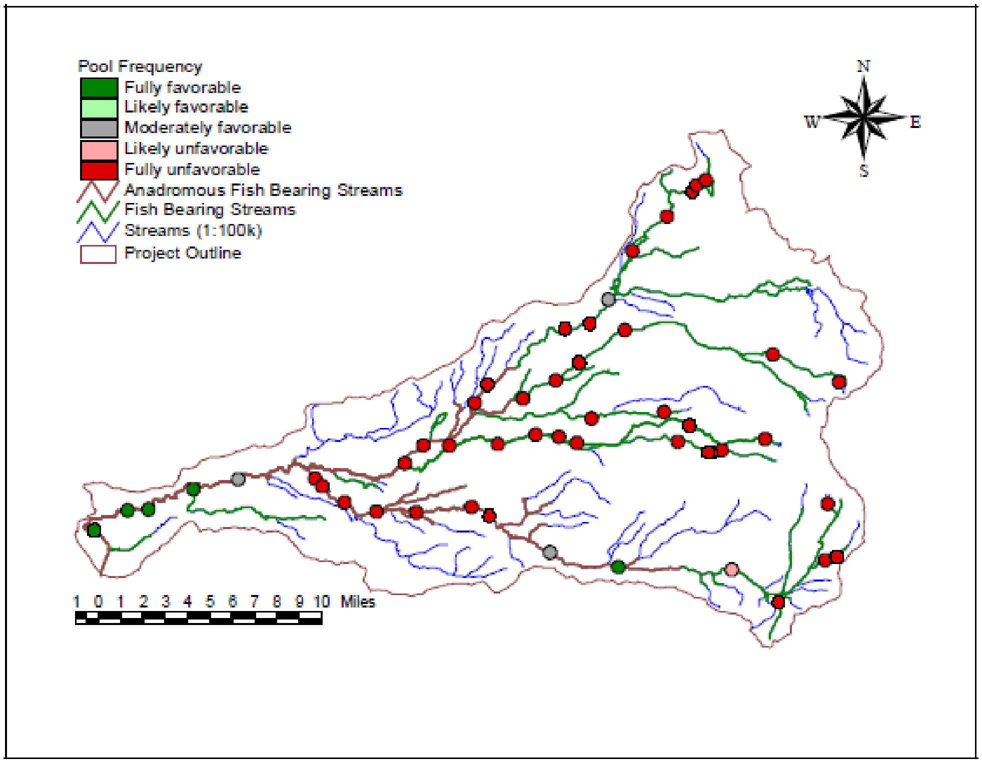

Figure 11. Map depicting EMDS truth values for pool frequency at sample sites within Battle Creek watershed.

Figure 18: Snapshot of Figure 11 from Ward and Moberg (2004) showing the occurrence of favorable to unfavorable scour spool frequency values.

The residual pool depth correlated with watershed factors, as should be expected, but not the sediment source factors (Ward and Moberg 2004, p 43), indicating that geomorphology and flow rate controls pool depth. Only after a major sediment wave moves through the system should one expect to find a significant relationship with the factors that cause the sediment wave. The pool depth in 2006 was less than in 2001/2.

The lack of correlation with sediment-source variables may be due to the variables being a cumulative variable for the watershed above this point. Independent variables as defined in this way are not independent of each other. The in-stream factors vary however with stream gradient, a localized control. Other factors could be more useful explainers if they represented only the relevant watershed above the site.

Watershed channels have multiple channels at a dozen of 49 survey sites in the watershed (Figure 19). Bailey Creek has a substantial reach with multiple channels and the downstream end of Battle Creek has two sites. Tussing and Ward (2008) indicated that multiple channel sites in this watershed are not unusual based on previous surveys, which they did not reference, although they did note that Gallo et al (2001) indicated that multiple channel sites are unusual. Multiple channels can indicate braided channels which usually result from large sediment loading in the watershed. Kier (2009) argued persuasively that having 12 of 49 sites with multiple channels is a clear sign of too much sediment reaching the watershed and also provided references that link such multiple channel formation with logging, due to increased sediment. Because the 1997 flood could have caused a significant sediment wave (Ward and Moberg 2004), it is essential that the multiple channel sites be studied in detail with respect to their formation and age.

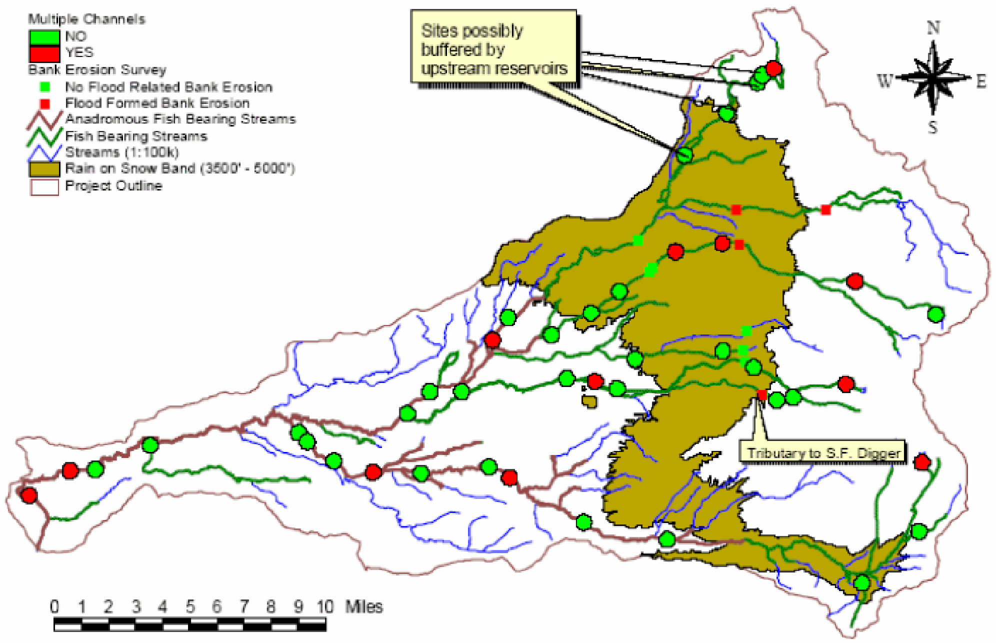

Figure 3. Battle Creek reaches exhibiting multiple channels (red dots) indicative of aggradation and cumulative effects are widespread throughout the watershed. From Terraqua (2004).

Figure 19: Snapshot of Figure 3 from Kier (2009) showing the location of multiple channels.

The downstream reach of Battle Creek has optimal LWD (Figure 20) and fully favorable pool frequency (Figure 18). Two sites have multiple channels and unfavorable LWD (Figures 19 and 20) but this does not necessarily indicate a correspondence between the two factors. Virtually all of the mid reach areas on all tributaries have fully unfavorable pool frequencies but since the distribution of LWD input in this region varies from fully unfavorable to likely favorable, it is impossible to relate pool frequencies through the watershed to LWD input. Unfavorable ratings for LWD on the North Fork Battle Creek and Bailey Creek may correspond with areas that had been logged (Table 1 and Figure 4) prior to the 2001/2 sampling (Ward and Moberg 2004) study. The riparian vegetation through the mid range of the watershed is mostly small trees with some open reaches (Figure 21). The different classification of LWD does not apparently correspond with the riparian classification since all LWD categories occur within small tree riparian areas. Several sites with fully unfavorable LWD coincide with riparian reaches without trees.

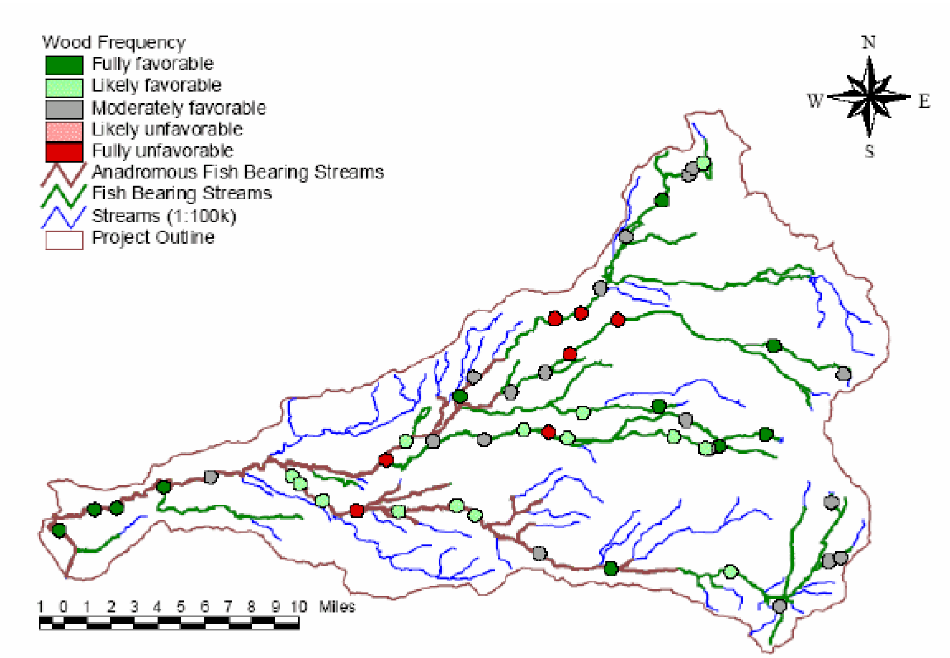

Figure 6. Frequency distribution chart based on EMDS ratings for large woody debris. Red dots show the "fully unfavorable for salmonid production" ratings at seven sites, green dots the "fully favorable" rating sites.

Figure 20: Snapshot of Figure 6 from Kier (2009) showing the distribution of ratings for large woody debris.

Although some stream morphology data had been resampled in 2006, the interpretation of the data has not been very useful. The year 2006 had the third highest average flow rate of any year since 1961 at 813.4 cfs whereas 2001 and 2002 were both below average (320 and 392 cfs, respectively). Because the subwatersheds with the resampled sites had not been significantly logged in the intervening periods, changes are primarily due to recovery from the 1997 flood and the high flows of 2006, which would have flushed the fine sediment. The resampled sites provide little insight into potential changes due to logging.

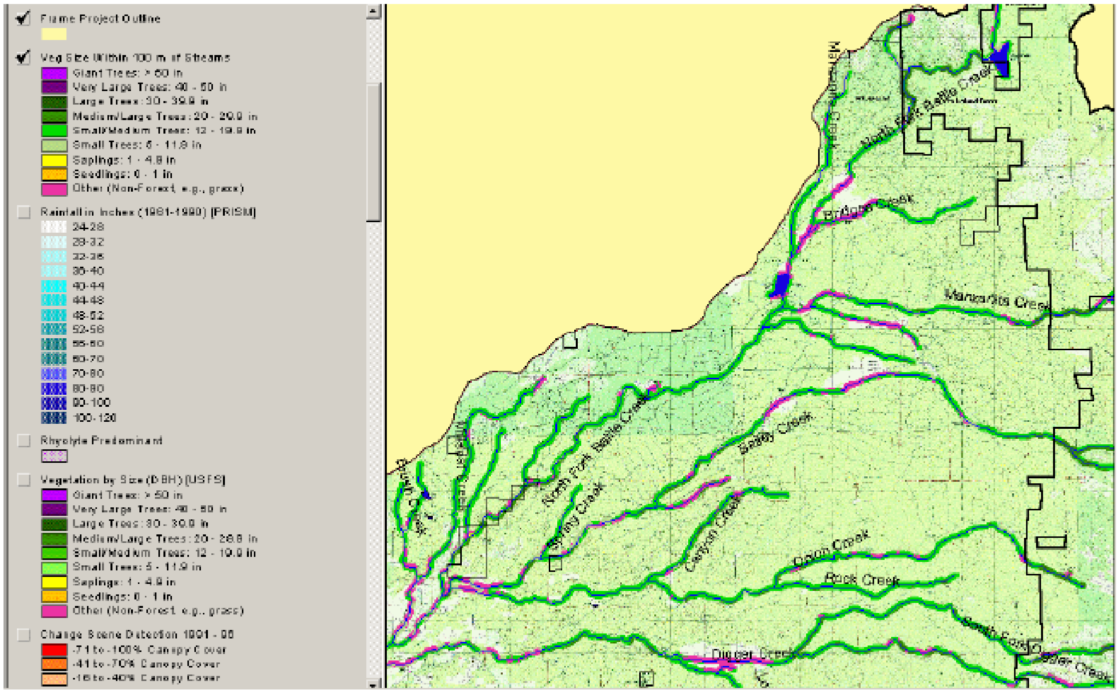

Figure 8. This map shows Landsat derived vegetation data provided by the U.S. Forest Service based on a 1996 image (Warbington et al., 1998). The buffer zones are 100 meter band on each side of the stream at a one hectare scale and the area displayed is similar to that of Fisk et al. (1996).

Figure 21: Snapshot of Figure 8 from Kier (2009) showing the distribution of Landsat derived vegetation types.

Turbidity Data

Battle Creek Alliance (BCA) has collected over two years of spot turbidity measurements along the various subwatersheds of Battle Creek. The turbidity data in Figure 22 for each of the BCA sites are presented as lines for clarity on the figures, not to suggest that turbidity varies linearly between dates. The NFB site most consistently has higher turbidity (Figure 22A) except at very low turbidity values during the summer; SFB turbidity is higher at baseflow in summer.

Rock Creek and Bailey Creek are very close to each other but Bailey Creek drains a larger subwatershed. For most of the turbidity graphs with comparable data (Figure 22B), the downstream sites, RCP and BCP have turbidity higher than the upper sites. Turbidity on Digger Creek (Figure 22C) is much less than the other sites; turbidity at sites on Digger Creek tends to increase in the downstream direction for only part of the period of record, with DCH having higher value, by just a few NTU, during the late summer and fall 2011. Canyon Creek has the highest turbidity overall with its most downstream site, CC, being just above the confluence with Rock Creek; during runoff, the CC turbidity values often exceed 20 and are as high as 80 NTU. These values are almost double the values at sites just upstream. Also, the CC turbidity values apparently affect the values at the Rock Creek site (Figures 22D and 22B)

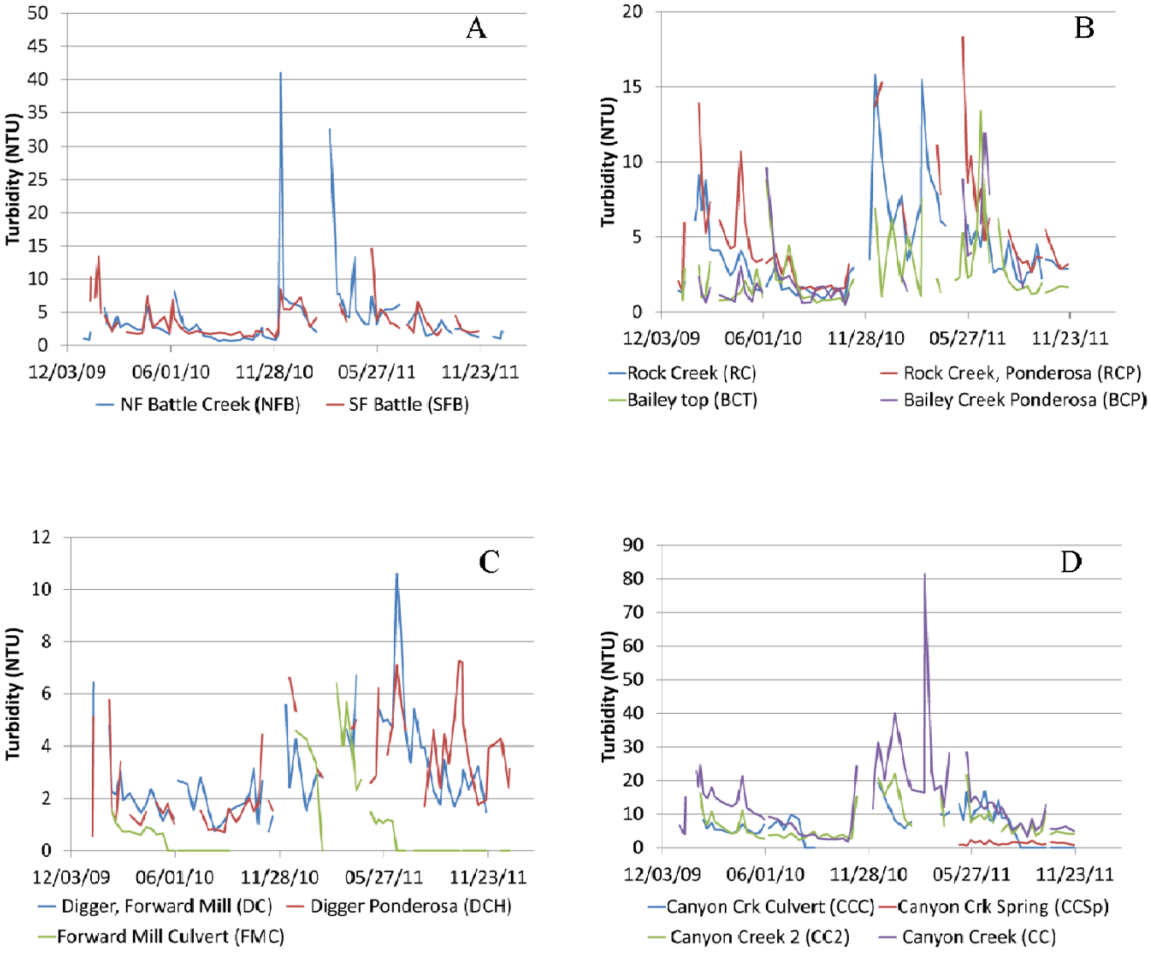

Figure 22: Time series of turbidity data collected by the Battle Creek Alliance at sites throughout the Battle Creek watershed. See Figure 7 for the site maps.

The highest correlation among BCA turbidity sites are among sites on the same stream, as would be expected (Table 2). Site CCSP, a spring, has little correlation with any site as it does not vary much with runoff. Sites on Rock Creek correlated closely to sites upstream on Canyon Creek. The high correlation of NFB with RCP shows how variation in headwater streams affects the turbidity over a much larger watershed than is monitored at one site; this relation holds between many headwaters' and lower turbidity sites. The high correlation of SFB, RCP, RC, and CC with flow shows the influence of high runoff in controlling turbidity from the sites. The modest correlation of NFB and SFB, even with substantially different management and soils, demonstrates a need for considering the impacts of management over the entire watershed.

Table 2: Correlation matrix between turbidity values at Battle Creek Alliance sites and with the daily flow rate from the Battle Creek near Coleman Fish Hatchery gage.

	DC	*DCH*	*FMC*	*CCC*	*CCSP*	*CC2*	*CC*	*RC*	*RCP*	*BCT*	*BCP*	*NFB*	*SFB*
DC	1.00												
DCH	0.65	1.00											
FMC	0.28	0.55	1.00										
CCC	0.55	0.78	0.69	1.00									
CCSP	0.15	0.07	-0.40	-0.49	1.00								
CC2	0.49	0.70	0.77	0.84	-0.10	1.00							
CC	0.43	0.61	0.66	0.44	-0.18	0.95	1.00						
RC	0.50	0.59	0.83	0.38	0.37	0.76	0.78	1.00					
RCP	0.50	0.63	0.48	0.24	-0.11	0.89	0.89	0.79	1.00				
BCT	0.61	0.51	0.51	0.52	-0.04	0.41	0.44	0.34	0.30	1.00			
BCP	0.69	0.67	0.24	0.45	0.04	0.46	0.39	0.33	0.42	0.69	1.00		
NFB	0.36	0.62	0.65	0.48	-0.09	0.89	0.66	0.58	0.82	0.50	0.72	1.00	
SFB	0.45	0.52	0.20	0.47	-0.18	0.64	0.67	0.49	0.80	0.32	0.49	0.53	1.00
Flow	0.68	0.56	0.47	0.36	-0.04	0.68	0.70	0.71	0.85	0.53	0.69	0.48	0.72

Industry Turbidity Data

James and MacDonald (2012) analyzed turbidity data collected at three locations on Bailey Creek since 2002. Stations Lower Bailey Creek (LBC), Upper Bailey Creek (UBC) and Upper Bailey Creek 2 (UBC2) are located at 3720, 5020, and 4760 feet amsl, respectively. LBC, UBC, and UBC1 have a 17,750, 7760 acres, and 9282 acres of drainage, respectively. LBC does not have flow during summer and early fall[2] and therefore has only about 2/3rds of the turbidity measurements of the other stations. LBC has the most land subject to timber harvest (Table 1).

The daily average turbidity at LBC exceeds 5 NTU about 20% of all sampled days, or more than twice the percent of days observed at the other sites (Figure 3, James and MacDonald 2012). This indicates that the stream turbidity increases substantially through the logged area, although James and MacDonald (2012, p 10) claim that the lack of summer flows at LBC causes this difference. LBC has 53% of the observations of the upper stations. This they claim could skew the results because it is during low flow periods that turbidity is lowest. However, they also claim that comparing only the values for days that all three stations have flow data is “beyond the scope of this report and not really necessary given the overall low turbidities being reported” (Id.). They dismiss the one simple analysis that could show whether management is causing more turbidity on Bailey Creek, although doing so would probably be a simple exercise; failing to do this extra analysis takes much away from their analysis. If all of the extra proportion of days are considered to have turbidity less than 5 NTU, the LBC bars for percent of days 6-

---

[2] The claim that LBC is frequently dry is disputed by Marily Woodhouse of Battle Creek Alliance who claims that she has never seen Bailey Creek dry at any time. She suggests that the sampling is actually occurring on an ephemeral tributary.

25 turbidity class on their Figure 3 would be cut almost in half, but would still show an increase over UBC2. This would be the extreme case in favor of their analysis because it is not certain that all observations at UBC or UBC2 are below 5 NTU at times when LBC is dry.

The general comparison of three sites in the Bailey Creek watershed (Figure 3, James and MacDonald 2012) is misleading because it does not consider data by year; unless an effect manifests over the entire period of record from 2002 through present, mere comparison of data from each site will reveal nothing. The amount of timber harvest above each side varies yearly (Table 1). Considering that the largest effects on turbidity may occur 10 to 15 years after harvest (Klein et al. 2011), these results should be given little credence.

Consideration of hourly data shows that high turbidity values manifest for a higher proportion of time than suggested by the daily averages (James and MacDonald 2012, p. 12). This is because a daily average may be less than a threshold even though more than half of the day had high turbidity, depending on the skew of shorter-term turbidity data. They do not present actual exceedence values and their Figure 5, which compares the percent of time units in each category for hours and days, is unreadable at the high NTU scale; it should be presented with a logarithmic scale. They suggest that the proportion of hours in higher NTU classes is only a few tenths of a percent (James and MacDonald 2012, p 12), but 0.4% of a year's hours are 35 hours which could be toxic to aquatic biota.

The highest hourly turbidity values are 152, 207, and 217 NTU at LBC, UBC2, and UBC, respectively. Comparison of the hourly data to that of Klein et al. (2011) suggested that "highest hourly turbidities in Bailey Creek are relatively low" (James and MacDonald 2012, p. 13). Their comparison is relatively meaningless because it does not account for the different sediment producing properties of a regime with more rainfall runoff and less snowmelt. It also does not account for the differences in the amount of watershed that has been logged. It does not indicate that management in Battle Creek is somehow better than in the coast ranges because Battle Creek may just be catching up to that level of development.

They also present figures (James and MacDonald 2012, Figures 6 – 8) which show that on no days at either of the sites has turbidity exceeded 25 NTU for all 24 hours. These figures by themselves provide no indication of the overall impacts of turbidity, but they show that even though UBC2 has fewer days with any hour's turbidity exceeding 25 NTU, a greater proportion of the days have more than just one hour. This may reflect the presence of runoff from the rain-on-snow zone which may cause higher flows to last a little longer than just the one or two hours observed at UBC. It would be advantageous to compare actual days to consider the change that occurs along the stream.

CONCEPTUAL FLOW AND SEDIMENT MODEL

A conceptual model of flow through a watershed describes the flow of water into, from, and through a watershed, and all the changes that occur to the water, specifically regarding water quality (Dunne et al 2001). Rainfall and snowmelt is the primary input to the Battle Creek watershed. Water leaves the watershed as flow from Battle Creek, most of which is measured at the Battle Creek gage discussed above, and as evapotranspiration (ET) from streams, lakes, riparian vegetation, and wetlands in the watershed. The elevation zone 3500 to 5000 ft above mean sea level (amsl) in the Battle Creek watershed is a rain-on-snow zone (Ward and Moberg 2004) which can accumulate a deep snowpack but is low and warm enough to have winter or early spring rainfall that can simultaneously runoff and generate snowmelt (MacDonald and Huffman 1995). Many of the largest floods in northern California were rain on snow events (Kattelman 1997), including the New Year's Day 1997 event which included the Battle Creek watershed.

The vegetation, soils, and geology determine how the watershed partitions precipitation among runoff, interflow, groundwater recharge, and baseflow discharge to and flow in streams (Figure 23). The average recharge basinwide equals 12 in/y, accounting for both stream baseflow and likely ET. The average annual rainfall is 48 in/y and the average of all flow from the watershed is 19 in/y. Water balance indicates that 29 in/y is lost to ET from forest canopy and soils, or about 60 percent of precipitation on the watershed.

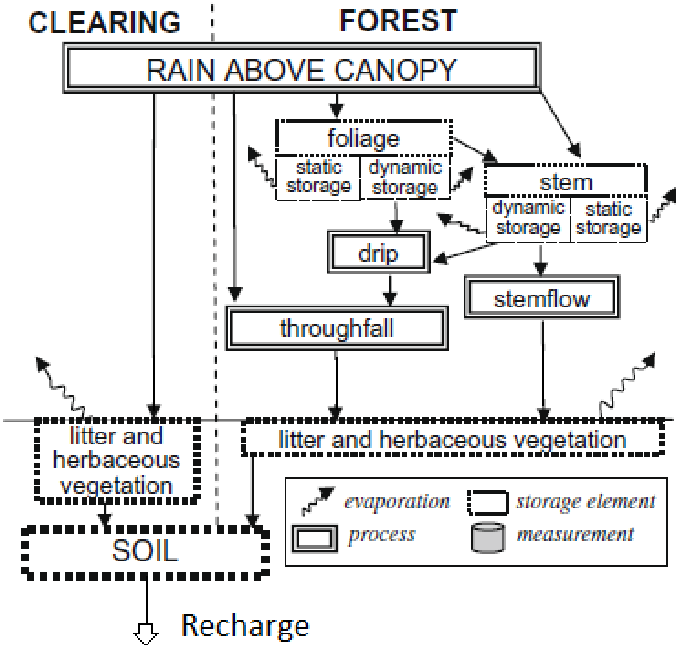

Figure 23: Conceptual model for the water balance through a forest canopy and soil layer. (adapted from Reid and Lewis (2009))

Groundwater dominates the flow through the watershed as exemplified by the high baseflow and exhibited by the large springs observed around the watershed. Some larger springs suggest there could be interwatershed groundwater flow (Winter et al. 2003), which suggests that impacts to one watershed could affect adjoining watersheds. Also, a reported low drainage density due to the soil type also reflects the high groundwater component of the flow.

Assuming a constant climate (a large assumption with climate change) with seasonal and annual variations, the base precipitation and heat fluxes remain stationary through time. Precipitation is either intercepted by the vegetation canopy, the forest canopy in the portions of the Battle Creek watershed being logged, or it reaches the soil surface simply by not being intercepted or by stemflow down the tree trunk. Interception is the portion of precipitation falling in a watershed intercepted by vegetal cover (Singh 1988) and not reaching the ground within a specific time interval (Reid and Lewis 2009). Stemflow is the precipitation intercepted by the canopy that moves to the main stems and flows to the ground.

Interception loss is the difference between total precipitation and that reaching the ground surface through the canopy with the loss being the amount actually lost due to interception (Reid and Lewis 2009, 2007).   It is a portion of the 29 in/y which does not become runoff or baseflow. Interception is an initial abstraction of precipitation after which the remaining precipitation, minus ongoing evaporation from the canopy during the event, reaches the ground (Horton 1919) with annual losses ranging from 10 to 40% of annual precipitation (Maidment 1993) with reports of as much as 59% in an old growth forest (Xiao et al 2000). The 10 to 40% range would be 4.8 to 19.2 in/y, a range well within the 29 in/y lost by the vegetation. During a series of precipitation events, the amount of water reaching the ground depends on the amount of water stored in the vegetal cover between events; the more water that evaporates from the canopy, the less that reaches the ground. The water remaining in the canopy depends on evaporation which depends on the canopy density and the amount of heat reaching the canopy, both of which vary seasonally (Link et al. 2004; Klassen et al 1998). The canopy increases the surface through which evaporation can occur, so the rate may exceed an open water surface evaporation due to the same conditions (Reid and Lewis 2009). Throughfall, the rainfall making it through the canopy, can be highly heterogeneous because of the overlying canopy (Shachnovich et al. 2008). Bark can also store high volumes of rainfall, with the largest most porous bark storing the most (Reid and Lewis 2009). Because precipitation in the Battle Creek watershed tends toward larger events spaced by significant dry periods, annual interception loss is probably closer to 4.8 in/y.

The vegetation cover also transpires water from the root zone back to the atmosphere (Kuras et al. 2012; Xiao et al 2000; Mount 1995; Wigmosta et al. 1994). Water that passes the root zone without becoming interflow to the streams or running off becomes recharge to the groundwater system that underlies the stream network in the watershed, estimated as 12 in/y. Removing the canopy significantly changes the energy and water budget of the landscape (Kuras et al 2012; Dunne 2001; Wigmosta et al 1994) and therefore the recharge and runoff – the entire balance of water flux through the watershed. Removing a vegetation canopy changes the ET loss from the watershed and subsequently the runoff (Kuras et al 2012; Wigmosta et al 1994; MacDonald and Hoffman 1995) and recharge. A logging operation is a threshold event after which the watershed is constantly changing until quasi-equilibrium becomes reestablished. Timber harvesting can contribute to an increase in long return interval peak flows as the amount of harvest surpasses threshold levels (Kuras et al 2012). The ongoing changes lead to significant evolution with time in the flow and sediment production from a watershed (Kuras et al 2012; Reid and Lewis 2009, 2007). The canopy accounts for up to 29 in/y of the precipitation in the watershed which would be the extreme upper limit to the potential increase in flow from the watershed. The decreased canopy can also increase the pore pressure in areas due to decreased interception and ET and lead to soil movement after storms.

Sediment moves through the watershed along with the flow. Soils are the primary sediment source in the watershed, which moves with runoff, with snowmelt, groundwater, and interflow contributing only minor amounts of sediment movement (Mount 1995). Three erosional processes contribute to eroding soils, including 1) rainsplash, 2) overland flow, and 3) concentrated flow and scouring of rills and gullies (Mount 1995). Rainsplash erosion erodes soil by the kinetic energy of raindrops hitting the soil. Rainfall that does not infiltrate runs off, initially as overland flow which erodes more soil and transports it downslope.   Vegetation cover affects erosion and sediment transport from a site by decreasing the energy of the raindrop hitting the ground and slowing the overland flow velocity (Gabet and Dunne 2003). At the point where overland flow reaches a threshold rate, it will erode rills and small gullies further increasing the amount of sediment. Vegetation cover prevents erosion by slowing both rainsplash erosion and overland flow; it also allows additional infiltration while soil compaction decreases the infiltration rate which increases the overland flow. Logging and associated road building removes vegetal cover and decreases the infiltration capacity thereby leading to increased sediment movement from a watershed.

The stream network and stream flows move the sediment from the hillslopes through the watershed. In pre-development conditions, most streams are in a dynamic equilibrium with the sediment load introduced to them (Richards 1985; Bull 1991; Leopold 1994). If that load sufficiently changes, the stream system may undergo changes as it adapts to a new equilibrium. Because equilibrium is generally dynamic, changes in the watershed may have to surpass a threshold for major changes to occur, such as rejuvenation (Bull 1991). Small changes such as increases in the sediment load entering the stream system can be reflected in the stream morphology, such as embeddedness, pool depth, or pool spacing. Steep streams, as occur in the upper reaches in this watershed, can pass some additional sediment without any effects becoming obvious until the gradient flattens at the downstream end.

Significant changes in the flows can also affect the stream equilibrium. Increased flood flows increase the channel width by causing erosion and additional sediment transport of in-stream sediment. Decreased flows allow sediment to settle out forming sediment bars (Benda et al 2004). Changes in channel-forming flows could have larger impact or longer-term impact on watershed conditions (Kuras et al. 2012). Channel forming flows are 1-day, or 7-day or 30-day durations, watershed size dependent. Increased baseflows may cause higher turbidity even during baseflow conditions.

Cumulative Watershed Effects

CWEs in a watershed manifest as changes in runoff and sediment transport, or turbidity (Dunne et al 2001; MacDonald 2000), due to all activities in the watershed; in Battle Creek that is primarily timber harvesting and road building with local impacts due to power plant diversions.

Logging affects the three components of runoff – overland flow, interflow, and groundwater baseflow – differently. Wohl (2006) included forest management as a prime example of a land management activity that can affect the functioning of watersheds and also noted that most mid-latitude streams have been affected by some form of land management, which could also include grazing (Myers and Swanson 1997a, 1996, 1992a and b), agriculture, and urbanization. Forest management affects both the vegetation cover and some properties.

Partial harvesting of up to 30% of a watershed did not affect turbidity, based on spot measurements, in paired watershed studies (Murray et al. 2000), although water temperature was affected. The authors found to their surprise that TDS was less in the harvested watersheds but this should actually be expected if harvesting increases the runoff portion of the flow because a longer groundwater path provide more opportunity to dissolve solids. Logging in small tributaries in humid regions may not affect the mainstream (Benda et al. 2004) because the larger overall area overwhelms the tributary; in effect it washes the impacts away. In arid regions small areas affect the larger drainage area because the heterogeneity in precipitation events causes major impacts to the downstream drainage even from some subbasins. The Battle Creek watershed and runoff regime is in-between – not arid or humid – so that small drainages have little effect until a large event occurs; this would explain the correlation between turbidity in tributary streams and further downstream on the North Fork Battle Creek observed above.

Vegetation can prevent sediment from reaching the streams even if it is once eroded. Buffer strips and rapid regrowth of undercover vegetation can minimize the water quality effects of clearcutting (Aubertin and Patric 1974). Harvesting not with clearcuts and with wide (90 m) buffer strips have minimized sediment delivery to streams (Litschert and MacDonald 2009; Litschert 2009). Treecutting even within the streamside buffers may be acceptable if done properly (Neary et al. 2010). Rashin et al. (2006) found that 10 m was a threshold width for streamside zones, but that for steep canyons it should be much higher.

Lower turbidity in Battle Creek as compared to other logged streams (Bolda and Meyers 1997; Litschert and MacDonald 2009) could reflect the prevalence of baseflow in Battle Creek. However, the increased turbidity and larger sediments sizes for some runoff events demonstrate that logging is not following the necessary BMPs or that it is simply reaching a threshold in some subwatersheds. The watershed could be reaching a threshold.

It can be difficult to ascertain the difference between near-stream and watershed sources of sediment (Naperala et al 2009), so a detailed survey of potential sources and pathways is necessary to discover the source on a site specific basis. The Battle Creek Task Force over five days in September 2011 considered the potential for water quality impacts at 135 sites in the watershed associated with timber harvest operations (CalFire 2011). These sites were clearcuts, road crossings, road segments adjacent to roads, landings, and tractor crossing sites. Some basic findings were that 1), thirty-nine percent of the overall sites delivered sediment to the streams; 2) only one of 55 harvest units delivered sediment, and 3) sixty-nine percent of road crossings, 67 percent of roads adjacent to streams, and 100 percent of tractor crossings delivered sediment to the streams.

CalFire (2011) breaks the data down more, but in general they found that road crossings and road segments were more likely to be significant sediment sources than were clearcut units. They also found that 42 of 58 class I stream segments surveyed had no sediment, with the remainder having low or moderate sediment. This conflicts with the results of Ward and Moberg (2004) and Kier (2009). Class I streams were primarily the mainstem branches of the Battle Creek or Digger Creek Forks (CalFire et al 2011, Figure 15). They linked the lack of sediment production from clearcut harvests to high surface cover remaining after harvest and contour ripping. They also suggest that the riparian buffers trap sediment moving from the clearcut to the streams, which has been found in other studies. Finally they also consider the low stream density in the harvest area limits the opportunity for sediment to reach the streams (CalFire et al 2011, p 43).

The results of CalFire (2011) do not correspond with observations of CWEs made by this author during the site visit, which occurred during a light rainstorm. Roadside ditches and sediment accumulating near roads can increase flows and turbidity (Figures 24-26). However, even paved roads can transport sediment and debris to the stream channels (Figure 27). A road leading to a clearcut in the Canyon Creek drainage was substantially gullied and transporting sediment downstream to the roadside ditch (Figure 28). I observed numerous short roads accessing clearcuts but none had been reclaimed or closed. Another clearcut in the Canyon Creek drainage (Figure 29) also had substantial debris left on it. There were no signs of sediment transport near this clearcut, but the scattered debris and broken soil would increase the infiltration and therefore the shallow groundwater level which with time and increasing clearcut areas can lead to slope failures (Mount 1995).

At the head of Bailey Creek, a clearcut was completely bare and contained substantial erosion due to equipment accessing it (Figure 30). It was a long distance from the stream and sediment eroded from the site would accumulate in the watershed. Again, accumulating sediment at sites around the watershed increases the sediment ready to move downstream. Watershed sediment production is a long-term process and clearcuts with no cover generate sediment which may move for years or decades in to the future.

Figure 24: Shallow swale intercepting interflow in Canyon Creek drainage.

Figure 25: Roadside ditch intercepting and transmitting groundwater to Canyon Creek.

Figure 26: Sediment in roadside ditch in the Canyon Creek drainage.

Figure 27: Sediment source on paved road leading to Rock Creek.

Figure 28: Gullies in road from clear cut in the Canyon Creek drainage.

Figure 29: Clearcut in the Canyon Creek drainage showing lots of woody debris remaining on the ground.

Figure 30: Clearcut at the head of the Bailey Creek drainage showing lots of tire tracks.

More cumulative effects occur in dendritic watershed patterns because the tributary watersheds have similar sizes so the impacts accumulate (Benda et al. 2004). Battle Creek has a pear-shaped dendritic drainage pattern. More confluence effects also occur in the central portion of the watershed where more tributaries draining similar sized watersheds converge (Benda et al. 2004), again as in the Battle Creek watershed. Because of subwatersheds having similar sizes, the CWEs accumulate in a downstream direction. The correlation of turbidity measurements observed in the Battle Creek watershed reflects the downstream propagation of effects. "The overview and case studies indicate that mountain streams must be managed with particular attention to upstream/downstream connections, hillslope/channel connections, process domains, physical and ecological roles of disturbance, and stream resilience" Wohl (2006). In the Battle Creek watershed, CWEs should be considered over the entire watershed.

CONCLUSION

Battle Creek has substantial groundwater inflow which maintains a consistent and substantial baseflow. The runoff component of the precipitation is naturally fairly small because the canopy intercepts and evapotranspires much of the precipitation. A very substantial change to the watershed water balance could occur if too much of the canopy is removed. It is unknown how close the watershed could be to such a threshold.

Baseflow depends on precipitation occurring as much as four years earlier, which is also reflected in long-term trends of wetter or drier than average flow. This is good from the perspective of avoiding drought conditions and adapting to watershed conditions. It is not so good from the perspective of moving sediment through the system; small increases in sediment load may easily overwhelm the streams' power to transport it which would allow sediment to build in places, increasing embeddedness and decreasing pool depths. Sediment accumulation would be more of a concern near the west end of the watershed because of its lower gradient near the watershed outlet.

The Battle Creek watershed with its increasing area subject to timber harvest is essentially an uncontrolled experiment in watershed management. Evidence reported and reviewed herein suggests the watershed could be reaching a threshold at which either or both flow or sediment transport from the watershed could increase substantially. The evidence includes:

- The generally poor habitat conditions found in 2001/2
- The lack of improvement by 2006, as reported in Tussing and Ward (2008), not due to that year's high flows
- Increased turbidity through managed portions of the watershed
- Observed sediment in the stream
- Pathways for sediment to reach the streams
- The frequent presence of multiple channels

Except for 2006 the past eleven years have had low flows. The watershed is moving toward disequilibrium slowly but could enter a rejuvenation period as the flow and sediment changes. If flow more commonly reaches 600 cfs, the sediment transport from the watershed could increase substantially. Literature suggests there could be a significant lag time between logging operations and their worst effects; the heaviest logging in the watershed commenced less than 15 years ago and has trended toward more clearcutting. Passing a geomorphic threshold would be manifest by rejuvenation throughout all or portions of the watershed

RECOMMENDATIONS

There is too little data on the watershed to necessarily make informed decisions about future watershed management. To facilitate the lack of data, a numerical model based on the conceptual model presented herein could be developed to simulate the current and future flows and turbidity (Dunne et al 2001; Dunne 2001). The modeling could be similar to that completed by Kuras et al. (2012) to simulate changing watershed conditions with observed climate conditions for the past or for stochastic conditions for the future. A model similar to that proposed by Wigosta et al. (1994) could be utilized. The model could estimate the risk of the watershed reaching the threshold conditions that could cause major changes to the sediment and water budget relations.

It would be useful to continue and expand data collection efforts in the watershed. BCA should continue its turbidity measurements. Sediment data should be collected at the USGS gaging station near the mouth of the watershed, to be compared with the 1960s data and to monitor change into the future. The aquatic habitat data (Ward and Moberg 2004) should be replicated at short time intervals, as done by Myers and Swanson (1996a, b, and c), to monitor the short term changes; it is not possible to monitor changes in habitat caused by sediment waves if monitoring occurs on greater than 10 year cycles. The data collection should have an increased number of transects to decrease the variability of the estimates and to increase the confidence that year-to-year changes are real and statistically significant (Myers and Swanson 1997a).

REFERENCES

Aubertin, G.M., and J.H Patric. 1974. Water quality after clearcutting a small watershed in West Virginia. Journal of Environmental Quality 3(3): 243-249.

Bailey, E.H., 1966, Geology of Northern California: California Division of Mines and Geology (aka California Geological Survey) Bulletin 190, 508 p., 1 Pl., geologic map scale 1:2,500,000.

Benda, L, Poff, NL, Miller, D, Dunne, T, Reeves, G, Pess, G & Pollock, M (2004b) The network dynamics hypothesis: How channel networks structure riverine habitats. Bioscience, 54, 413-27.

Binkley, D., and T.C. Brown. 1993. Forest practices as nonpoint sources of pollution in North America. Water Resources Bulletin 20:729-740.

Bolda, K.S., and W. J. Meyers. 1997. Conducting an long-term water quality monitoring project: A case study on the McCloud River, California. Journal of Soil and Water Conservation 52(1):49-54.

Bull, W.B. 1991. Geomorphic Responses to Climatic Change. Oxford University Press, New York. 326 p.

California Department of Forestry and Fire Protection, California Department of Fish and Game, Central Valley Regional Water Resource Control Board, and California Geological Survey (CalFire). 2011. A Rapid Assessment of Sediment Delivery from Clearcut Timber Harvest Activities in the Battle Creek Watershed, Shasta and Tehama Counties, California.

California Sportfishing Protection Alliance (CSPA). 2011. Letter from Mr. Bill Jennings, CSPA, to Ms. Marily Woodhouse, The Battle Creek Alliance, August 19, 2011.

CGS (California Geological Survey), 1997, (revised 2002), California Geomorphic Provinces: CGS Note 36, 4 p., available on the CGS website at http://www.consrv.ca.gov/CGS/information/publications/cgs_notes/note_36/note_36.pdf

Cherkauer DS (2004) Quantifying ground water recharge at multiple scales using PRMS and GIS. Ground Water 42(1): 97–110

Daly, C., R.P. Neilson, and D.L. Phillips. 1994. A statistical-topographic model for mapping climatological precipitation over mountainous terrain. Journal of Applied Meteorology, 33, 140-158.

Dunne, T.. 2001. Introduction to Section 2 – Problems in Measuring and Modeling the Influence of Forest Management on Hydrologic and Geomorphic Processes. In: Land Use and Watershed: Human Influence on Hydrology and Geomorphology in Urban and Forest Areas. American Geophysical Union, Washington.

Dunne, T.E., and many others. 2001. A Scientific Basis for the Prediction of Cumulative Watershed Effects. University of California Committee on Cumulative Watershed Effects, Wildland Resources Center, Berkeley CA. 103 p.

Gabet, E.J., and T. Dunne. 2003. Sediment detachment by rain power. Water Resources Research 39(1): 1002-1014. Doi:10.1029/2001WR000656, 2003.

Horton, R.E. 1919. Rainfall interception. Monthly Weather Review 47(9):603-623.

James, C., and L. MacDonald. 2012. Greater Battle Creek Turbidity Monitoring: Update and Additions.

Kattelman, R. 1997. Flooding from rain-on-snow events in the Sierra Nevada: In Destructive Water: Water-Caused Natural Disasters, their Abatement and Control: Proceedings of the Conference held at Anaheim, CA, 1996, IAHS Publ. no. 239, p. 59-65.

Kier Associates (Kier). 2009. Aquatic Habitat Conditions in Battle Creek and Their Relationship to Upland Management. Arcata. 33 pp

Klaasen, W., F. Bosveld, and E. d Water. 1998. Water storage and evaporation as constituents of rainfall interception. Journal of Hydrology 212-213: 36-50.

Klein, R.D., et al. 2011. Logging and turbidity in the coastal watersheds of northern California, Geomorphology, doi:10.1016/j.geomorph.2011.10.011

Kunkle, S.H. and G.H. Comer. 1971. Estimating suspended sediment concentrations in streams by turbidity measurements. Journal of Soil and Water Conservation 26(1): 18-20.

Kuras, P.K., Y. Alila, and M. Weiler, 2012. Forest harvesting effects on the magnitude and frequency of peak flows can increase with return period. Water Resources Research 48, No. W01544, doi:10.1029/2011WR010705.

Link, T.E., M. Unsworth, and D. Marks. 2004. The dynamics of rainfall interception by a seasonal temperate rainforest. Agricultural and Forest Meteorology 124 (2004): 171-191. Doi:10.1016/j.agrformet.2004.01.010.

Leopold, L.B. 1994. A View of the River. Harvard University Press, Cambridge Mass. 298 p.

Litschert, S.E.. 2009. Predicting Cumulative Watershed Effects in Small Forested Basin. Dissertation, Colorado State University. 208 p.

Litschert, S.E., and L.H. MacDonald, 2009. Frequency and characteristics of sediment delivery pathways from forest harvest units to streams. Forest Ecology and Management 259: 143-150.

MacDonald, L.H. 2000. Evaluating and managing cumulative effects: Process constraints. Environmental Management 26(3): 299-315.

MacDonald, L.H., and J.A. Hoffman, 1995. Causes of peak flows in northwestern Montana and northeastern Idaho. Water Resources Bulletin 30, No. 1: 79-95.

Maidment, D.R. (Ed.), 1993. Handbook of Hydrology. McGraw-Hill, Inc., New York.

Mosley, M.P., and A.I. McKercher. 1993. Chapter 8. Streamflow. In Maidment, D.R. (Ed.). Handbook of Hydrology. McGraw-Hill, Inc. New York.

Mount, J.P. 1995. California Rivers and Streams, The Conflict Between Fluvial Process and Land Use. University of California Press, Berkeley CA. 359 p.

Murray, G.L.D., R.L. Edmonds, and J.L. Marra. 2000. Influence of partial harvesting on stream temperatures, chemistry, and turbidity in forests on the western Olympic Peninsula, Washington. Northwest Science 74(2): 151-164.

Myers, T, 2009. Groundwater management and coal-bed methane development in the Powder River Basin of Montana. J Hydrol 368:178-193

Myers, T.J. and S. Swanson, 1997a. Precision of channel width and pool area measurements. Journal of the American Water Resources Association 33:647-659.

Myers, T.J. and S. Swanson, 1997b. Stochastic modeling of pool-to-pool structure in small Nevada rangeland streams. Water Resources Research 33(4):877-889.

Myers, T.J. and S. Swanson, 1997c. Stochastic modeling of transect-to-transect properties of Great Basin rangeland streams. Water Resources Research 33(4):853-864.

Myers, T.J. and S. Swanson, 1996a. Long-term aquatic habitat restoration: Mahogany Creek, NV as a case study. Water Resources Bulletin 32:241-252

Myers, T.J. and S. Swanson, 1996b. Temporal and geomorphic variations of stream stability and morphology: Mahogany Creek, NV. Water Resources Bulletin 32:253-265.

Myers, T.J. and S. Swanson, 1996c. Stream morphologic impact of and recovery from major flooding in north-central Nevada. Physical Geography 17:431-445.

Myers, T.J. and S. Swanson, 1992a. Variation of stream stability with stream type and livestock bank damage in northern Nevada. Water Resources Bulletin 28:743-754.

Myers, T.J. and S. Swanson, 1992b. Aquatic habitat condition index, stream type, and livestock bank damage in northern Nevada. Water Resources Bulletin 27:667-677.

Naperala, Troy R.; Jacobson, Brian A.; Cazanacli, Dan; Sinha, Sanjiv, 2009. Integrating Geomorphologic Field Assessment and Watershed Modeling for a Turbidity TMDL. Proceedings of the Water Environment Federation, TMDL 2009 , pp. 1213-1225(13)

Napper, C.O. 2001. Cumulative Watershed Effects, Battle Creek, Analysis of Beneficial Uses and Water Quality Criteria to Evaluate CWE Susceptibility. Lassen National Forest, Susanville CA. 22 p.

Neary, D.G., P.J. Smthurst, B.R. Baillie, K.C. Petrone, W.E. Cotching, and C.C. Baillie. 2010. Does tree harvesting in streamside management zones adversely affect stream turbidity? – preliminary observations from an Australian case study. Journal of Soils and Sediments doi 10.1007/s11368-010-0234-2.

Perry, T.D. 2007. Do Vigorous Young Forests Reduce Streamflow? Results from up to 54 Years of Streamflow Records in Eight Paired-watershed Experiments in the H.J. Andrews ad South Umpqua Experimental Forests. A Thesis submitted to Oregon State University.

Rashin, E.B., C.J. Clishe, A.T. Loch, and J.M. Bell. 2006. Effectiveness of timber harvest practices for controlling sediment related water quality impacts. Journal of the American Water Resources Association 42(5):1307-1327.

Reid, L.M., and J. Lewis. 2009. Rates, timing, and mechanisms of rainfall interception loss in a coastal redwood forest. Journal of Hydrology 375: 459-470. Doi:10.1016/j.jhydrol.2009.06.048

Reid, L.M., and J. Lewis. 2007. Rates and implications of rainfall interception in a coastal redwood forest. USDA Forest Service General Technical Report PSW-GTR-194.

Richards, K. 1985. Rivers: Form and Process in Alluvial Channels. Methuen, London. 361 p.

Shachnovich, Y., P.R. Berliner, and P. Bar. 2008. Rainfall interception and spatial distribution of throughfall in a pine forest planted in an arid zone. Journal of Hydrology 349(1-2): 168-177.

Singh, V.P. 1989. Hydrologic Systems, Watershed Modeling, Volume II. Prentice Hall, Englewood Cliffs, NJ. 320 p.

Suttle, K.B., M.E. Power, J.M. Levine, C. McNeely. 2004. How fine sediment in riverbeds impairs growth and survival of juvenile salmonids. Ecological Applications 14(4): 969-974.

Tussing, S.P., and M.B. Ward. 2008. 2006 Data Analysis Report and Correction to the 2001 and 2002 Watershed Assessment. Prepared for the Battle Creek Watershed Conservancy and the California State Resources Control Board. Terraqua, Inc., Wauconda, Washington. 29 p.

USDA (United States Department of Agriculture Soil Conservation Service and Forest Service), in cooperation with University of California Agricultural Experiment Station, 1974, Soil Survey of Shasta County Area, California: US Government Printing Office, Washington, DC, 160 p., maps, scale 1:20,000.

USDA (United States Department of Agriculture Soil Conservation Service and Forest Service), in cooperation with University of California Agricultural Experiment Station, 1967, Soil Survey, Tehama County, California: US Government Printing Office, Washington, DC, 124 p., maps, scale 1:31,680.

Van Sickle, J.V., 2003. Analyzing correlations between stream and watershed attributes. J American Water Resources Association 39(3):717-726

Walters, D.M., A.H.Roy, D.S. Leigh. 2009. Environmental indicators of macroinvertebrate and fish assemblage integrity in urbanizing watersheds. Ecological Indicators 9:1222-1233.

Ward, M.B. and Moberg, J. 2004. Battle Creek Watershed Assessment: Characterization of Stream Condiions and an Investigation of Sediment Source Factors in 2001 and 2002. Terraqua, Inc.Wauconda, Wa. 72 pp.

Wigosta, M.S., L.W. Vail, and D.P. Lettenmaier. 1994. A distributed hydrology-vegetation model for complex terrain. Water Resources Research 30(6):1665-1679.

Winter, T.C., D.O. Rosenberry, and J.W. LaBaugh. 2003. Where does the ground water in small watersheds come from? Ground Water 41(7): 989-1000.

Wohl, E., 2006. Human impacts to mountain streams. Geomorphology 79: 217-248.

Xiao, Q., E.G. McPherson, S.L Ustin, and M.E. Grismer. 2000. A new approach to modeling tree rainfall interception. Journal of Geophysical Research 105(D23):29173-29,188.

APPENDIX A: Histograms of Monthly Flow Categories for the Battle Creek below Coleman Hatchery near Cottonwood gage.

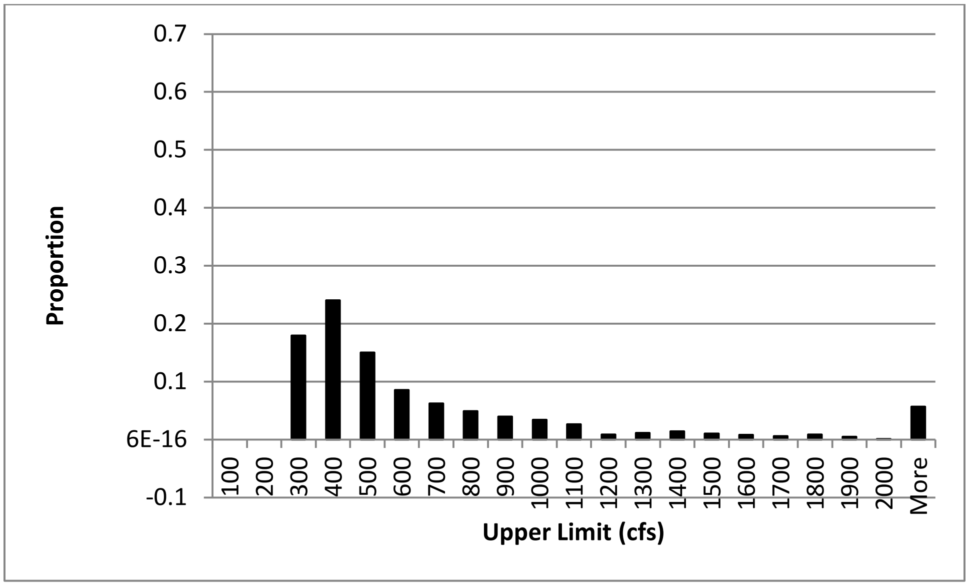

Figure A 1: Flow frequency histogram for Battle Creek below Coleman Fish Hatchery near Cottonwood, January, 1961-2012

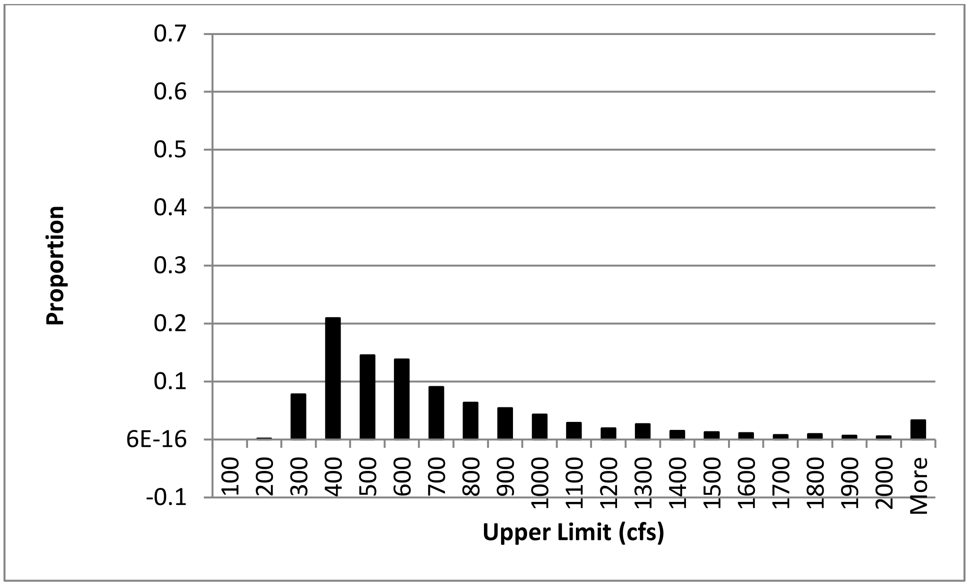

Figure A 2: Flow frequency histogram for Battle Creek below Coleman Fish Hatchery near Cottonwood, February, 1961-2012

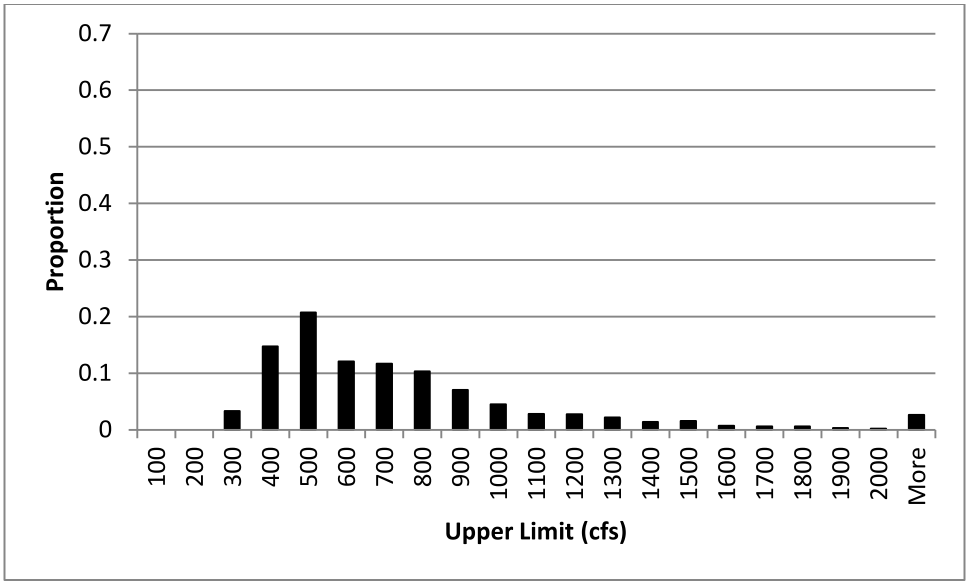

Figure A 3: Flow frequency histogram for Battle Creek below Coleman Fish Hatchery near Cottonwood, March, 1961-2012

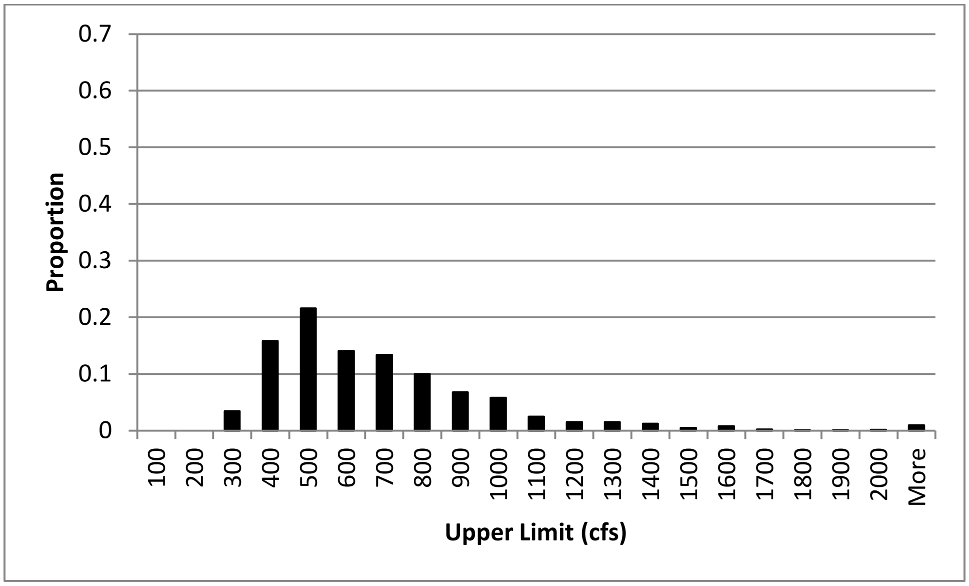

Figure A 4: Flow frequency histogram for Battle Creek below Coleman Fish Hatchery near Cottonwood, April, 1961-2012

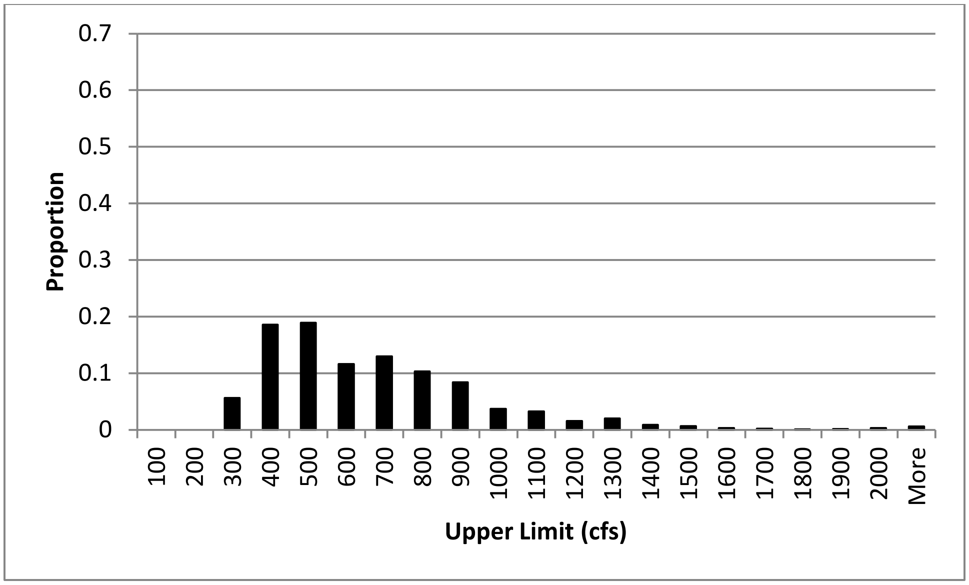

Figure A 5: Flow frequency histogram for Battle Creek below Coleman Fish Hatchery near Cottonwood, May, 1961-2012

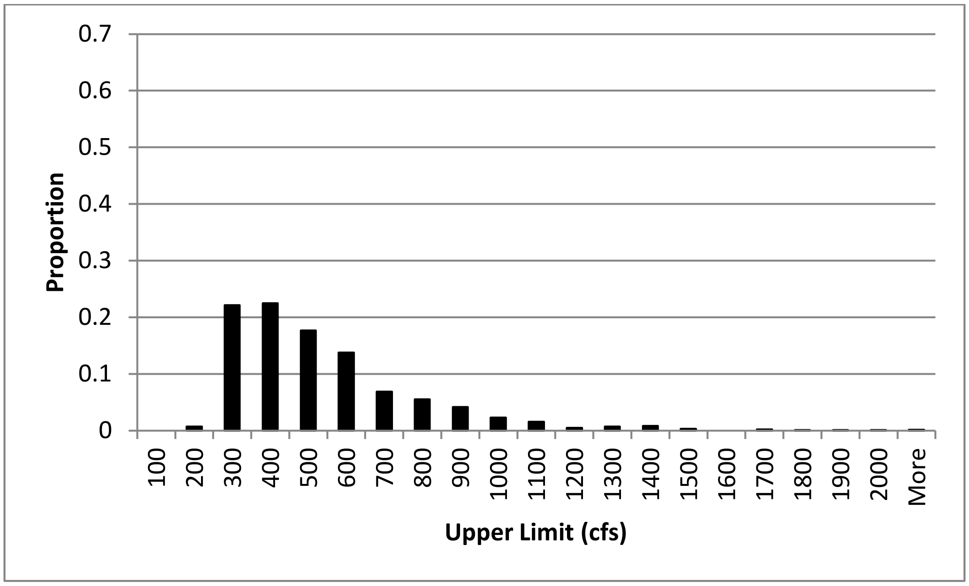

Figure A 6: Flow frequency histogram for Battle Creek below Coleman Fish Hatchery near Cottonwood, June, 1961-2012

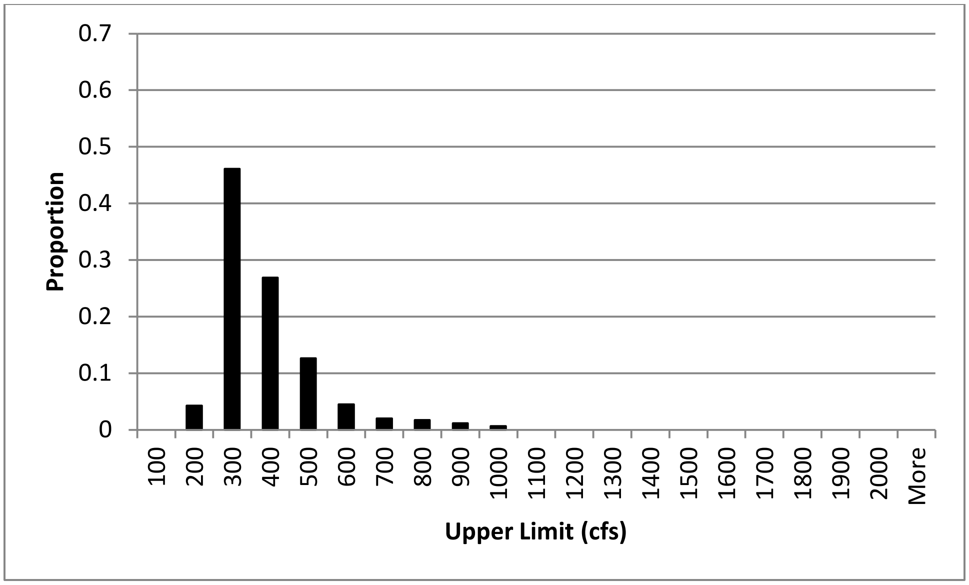

Figure A 7: Flow frequency histogram for Battle Creek below Coleman Fish Hatchery near Cottonwood, July, 1961-2012

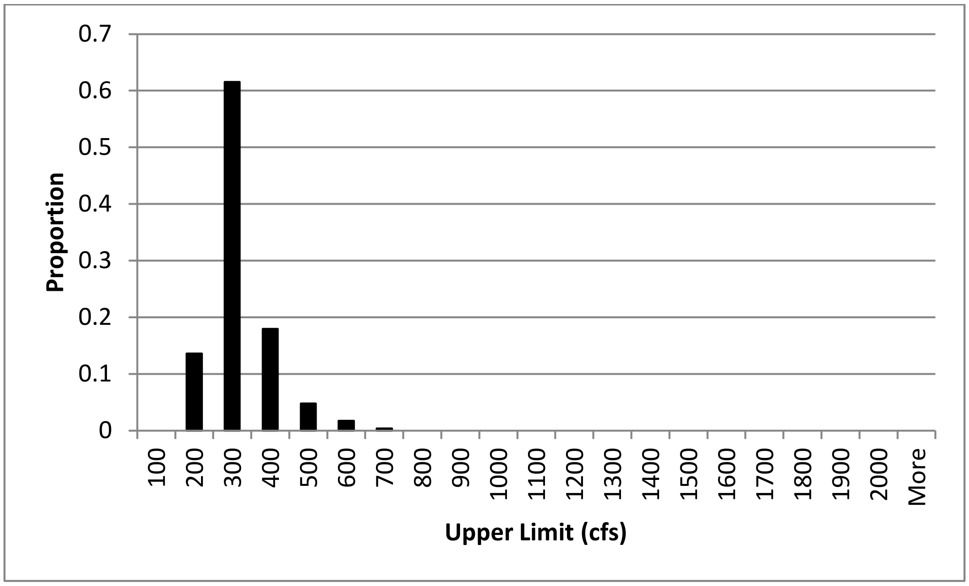

Figure A 8: Flow frequency histogram for Battle Creek below Coleman Fish Hatchery near Cottonwood, August, 1961-2012

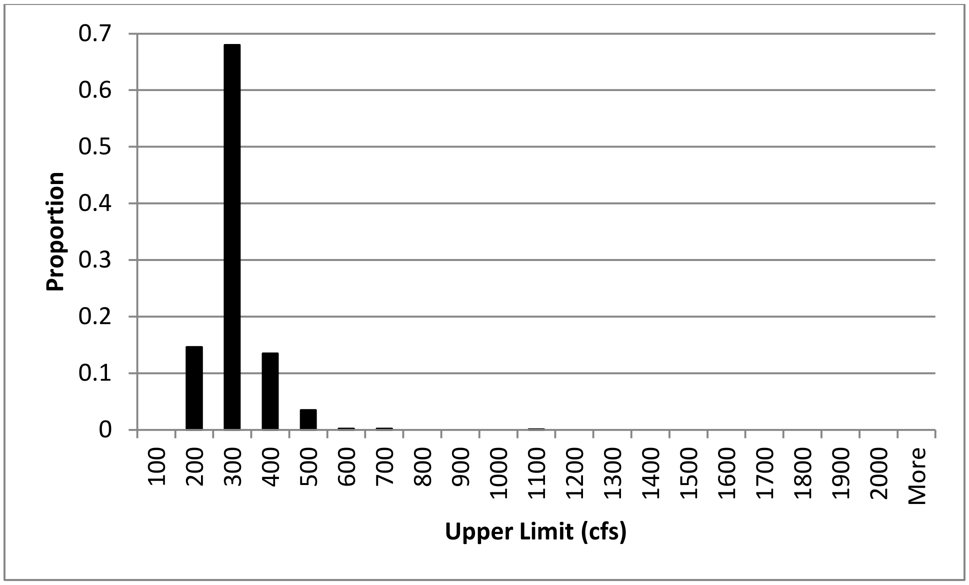

Figure A 9: Flow frequency histogram for Battle Creek below Coleman Fish Hatchery near Cottonwood, September, 1961-2012

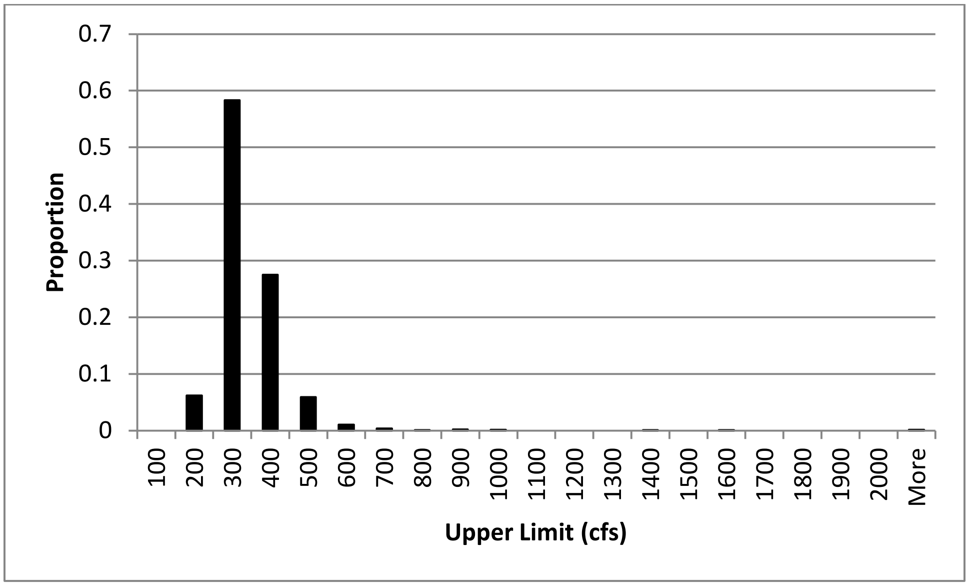

Figure A 10: Flow frequency histogram for Battle Creek below Coleman Fish Hatchery near Cottonwood, October, 1961-2012

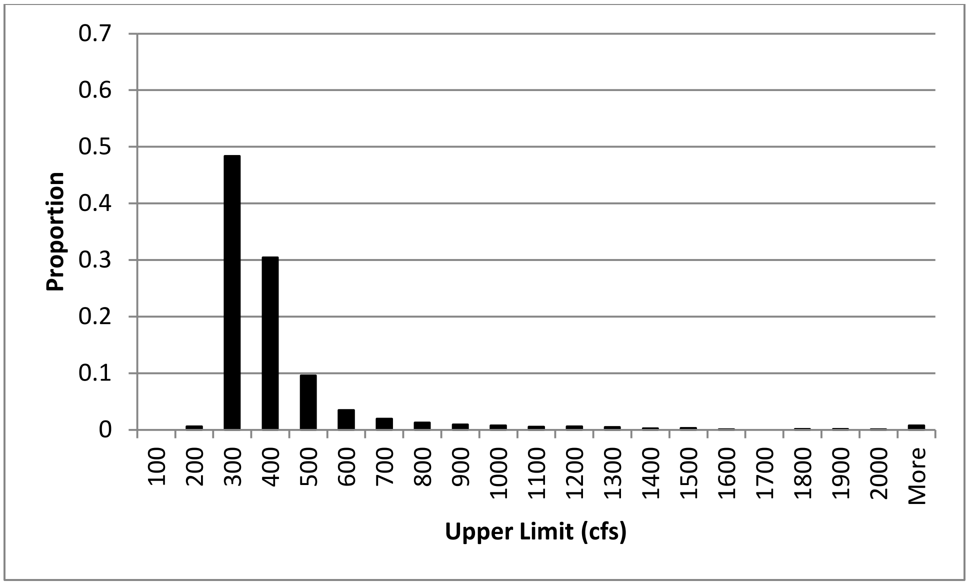

Figure A 11: Flow frequency histogram for Battle Creek below Coleman Fish Hatchery near Cottonwood, November, 1961-2012

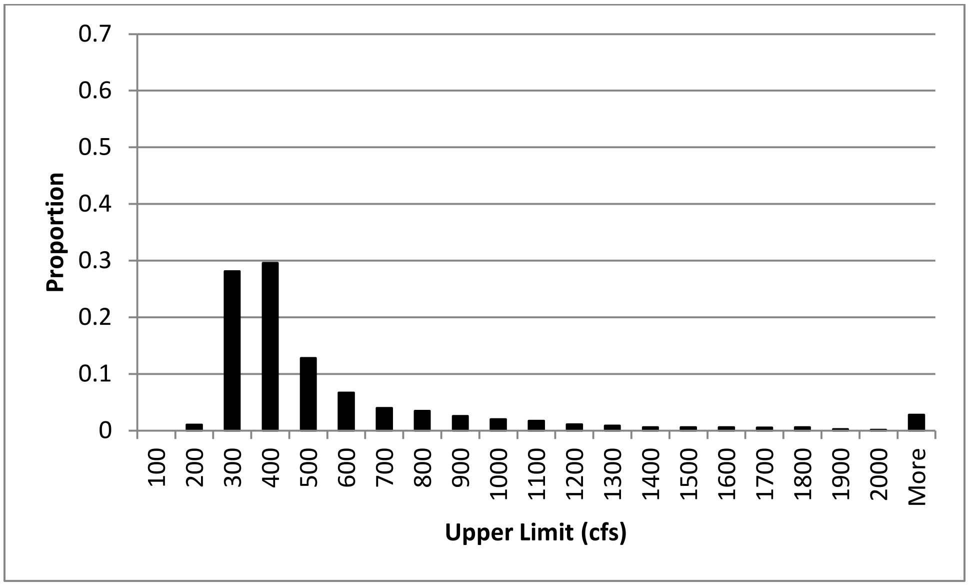

Figure A 12: Flow frequency histogram for Battle Creek below Coleman Fish Hatchery near Cottonwood, December, 1961-2012