SWAMP
Surface Water
Ambient Monitoring
Program

Final Technical Report | 2016

2015 Battle Creek Watershed Hydrology And Sediment Assessment

Jameson E. Henkle
Professor Gregory B. Pasternack
Dr. Andrew B. Gray
University of California, Davis

SWAMP-MR-RB5-2016-0003

March 2016

CALIFORNIA
Water Boards

www.waterboards.ca.gov/swamp

2015 Battle Creek Watershed Hydrology and Sediment Assessment

Final Report January 2, 2016

Prepared for:

State Water Resources Control Board

Region: Central Valley

364 Knollcrest Drive; Suite 206

Redding, CA 96002

Prepared by:

Jameson E. Henkle

Professor Gregory B. Pasternack

Dr. Andrew B. Gray

University of California, Davis

Executive Summary

Battle Creek is a mountainous forested catchment whose aquatic ecology has been affected by a history of anthropogenic activities, including land use and engineered water resource infrastructure – both of which continue today. In light of laws and policies that express the will of society, it is imperative that best practices be used to maintain the physical and chemical aspects of the watershed in a good condition to support local and regional recovery of anadromous salmonids to biological good condition (*sensu* California Fish and Game Code Section 5937) and obtain the ecosystems services they provide. When available in the proper abundance and composition, sediment is a key component for healthy aquatic habitat affecting ecosystem functions. However, when present in excess, sediment can impair water quality, ruin aquatic habitat, and even cause acute and/or chronic illnesses in aquatic organisms. As a result, catchments subjected to historic and on-going anthropogenic impacts should be outfitted with a nested array of water discharge and sediment flux monitoring stations to track conditions. When collected over sufficient duration, water and sediment data from a nested array may be used to ascertain baseline and impacted conditions relative to standards established for different water quality criteria and ecological functions. In addition, state and federal agencies provide a number of standard methodologies for sediment impact assessment involving relatively rapid approaches drawing on professional judgement and comparative conditions.

Sediment dynamics in the Battle Creek watershed were investigated through review and re-analysis of historic studies and their data sets, in combination with data obtained through the field operations of the current study. Existing information was reviewed in terms of landscape attributes, anthropogenic changes, natural disturbances, hydrology, sediment, geomorphology, and management actions. In addition, all available water and sediment data were analyzed to yield updated results and new findings about hydrology and sediment flux. Based on this historical analysis and pilot scale monitoring of water and suspended sediment conducted by the authors during 2015, it was determined that there is a near total lack of data to support sediment impact assessment methods. Although a limited amount of information is available to track benthic macroinvertebrate species abundance and diversity as a water quality indicator, overall, this study found that wholly insufficient data exists to perform any existing method of sediment impact assessment. Thus, the status of the watershed is largely unknown.

Battle Creek has a minimal water monitoring network and, apart from this brief study and private efforts in the uplands, no operational sediment monitoring network. This precludes the ability of environmental managers to determine the status of sediment with respect to modern standards. Instead, there is much speculation and assumption regarding sediment production controls based on anecdote in the absence of understanding any natural baseline. Lack of investment in sediment studies appears to be causing harm to stakeholder collaboration.

Suspended sediment was found to be highly suitable for monitoring in Battle Creek using traditional methods to ascertain the central tendency of sediment flux processes. For example, the data show that a small number of very large storm events can dominate the total annual sediment flux. Also, the spatial distribution of precipitation patterns in Battle Creek produces unique responses in streamflow and sediment transport for the South and North Forks of Battle Creek, even though they are adjacent. Comparing data collected in 2015 to historical data yielded some contradictory findings. Suspended sediment concentration was found to be generally similar today as in the past for any given discharge, except perhaps at the highest discharges for which few samples exist among all years of data collection. However, the total sediment load observed in 2015 was notably higher than in the past for similar flow regimes. More data needs to be collected and more consistently through time to arrive at firm conclusions.

Over the last decade geospatial data has become widely available at no cost for the United States and is of sufficient quantity, quality, and resolution to greatly aid the understanding of the landscape processes responsible for generating sediment and delivering it to the stream network. Concomitant with the rise of geospatial data, hydrologists and geomorphologists have developed mechanistic equations that allow for the prediction of which Earth surface process – notably soil creep, sheet wash erosion, channelization, and shallow landsliding – tend to dominate over time in which locations throughout a watershed as a function of topography, climate, soils, land cover, and wildfire disturbance. In this study 14 different scenarios were evaluated to isolate the individual effects of each contributing factor and see how they work together in combination. The final scenario, Model 14, reveals the best comprehensive analysis of the cumulative effects of all factors during wet season conditions to reveal the complex yet organized spatial pattern of landscape processes. This analysis shows that sheet wash erosion is widely occurring in Battle Creek as a result of the soils that are present. Depending on soil conditions locally, wildfire can substantially increase the area of sheet wash as well as initiate gullying. The results also show that landsliding is an important concern for South Fork Battle Creek especially, but is also something that should be evaluated for sections of North Fork and mainstem Battle Creek, as revealed in the maps provided in this report. In the absence of extensive monitoring data, this analysis may be used to guide management in the near term, but into the future it is best utilized as a hypothesis that subsequent field observation can evaluate to reveal the opportunities and constraints of such geospatial analysis in reality. Nevertheless, today models are widely used to aid environmental management and this new analysis brings forward novel ideas about landscape processes in Battle Creek for careful consideration.

There is insufficient data at this time to conduct state-of-the-art analyses that go beyond central tendency to explain how climatic, hydrological, and land cover / land use factors control the variation of sediment flux about the expectation – something that has been demonstrated for other watersheds for which longer term suspended sediment data have been collected. A comprehensive monitoring plan is recommended to include a multiscalar approach to suspended sediment monitoring at gages targeting both North Fork Battle Creek (NFBC) and South Fork Battle Creek (SFBC) above, within, and below the perimeter of the Ponderosa wildfire, as well as Mainstem Battle Creek. It is recommended that permanent turbidity monitoring stations be installed at MSBC, NFBC, and SFBC and that suspended sediment grab samples be collected for sediment rating curve development. These sites are key for understanding the total sediment flux in Battle Creek and relative rolls of the north fork and south fork subbasins. Turbidity stations would provide detailed data on sediment transport during storm events and could be used to quantify the effects of surface runoff and streamflow on sediment transport over a range of flows. A further study connecting the link between the magnitude and duration of precipitation at current precipitation gages and the response in sediment transport at proposed monitoring stations would help to characterize how weather patterns are affecting fluvial processes in Battle Creek. A computational model as recommended by Myers (2012) developing a sediment budget in Battle Creek would help identify sources of fine sediment relative to the hypotheses generated by the landscape process modeling performed in this study. Taken together, the conceptual model presented by Myers, the landscape processes geospatial model from this study, and a complete sediment budget for the basin would aid in water resource and habitat management.

Preferred Citation: Jameson, H.E., Pasternack, G.B., Gray, A.B. 2015. 2015 Battle Creek Watershed Hydrology and Sediment Report. Prepared for the Central Valley Regional Water Quality Control Board. University of California, Davis.

Table of Contents

List of Tables

List of Figures

Acronyms and Abbreviations

AMP	Adaptive Management Plan
BCA	Battle Creek Alliance
BCWA	Battle Creek Watershed Assessment
BCWC	Battle Creek Watershed Conservancy
BCWG	Battle Creek Working Group
CDEC	California Data Exchange Center
CDWR	California Department of Water Resources
cfs	cubic feet per second
CNFH	Coleman National Fish Hatchery
CSPA	California Sportfishing Protection Alliance
EMDS	Ecosystem Management Decision Support
GIS	Geographical Information Systems
KA	Kier Associates
kSAT	saturated hydraulic conductivity
LiDAR	Light and Detection Radar
NHC	Northwest Hydraulic Consultants
NRCS	National Resources Conservation Service
NTU	Nephelometric Turbidity Unit
PG&E	Pacific Gas & Electric
POM	particulate organic matter
SC	specific conductivity
SPI	Sierra Pacific Industries
SSC	suspended sediment concentration
TNM	The National Map
TRPA	Thomas R. Payne & Associates
USBR	United States Bureau of Reclamation
USDA	United States Department of Agriculture
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
WSS	Web Soil Survey
WY	water year

1 INTRODUCTION

Battle Creek is a mountainous catchment draining ~ 368 mi^2 (953 km^2) of the southern Cascade Range within the Sacramento River watershed (Figure 1). The larger Sacramento River basin has experienced a decline in anadromous Pacific salmonid populations in response to cumulative anthropogenic impacts, including land use and water infrastructure development. The Coleman National Fish Hatchery was established on Mainstem Battle Creek in 1943 as part of a regional network of hatcheries to mitigate the effects of habitat degradation and declining fisheries populations in the Sacramento River basin. Battle Creek provides an enormous opportunity for recovery of native fish populations due to its unique geology, hydrology and habitat suitability for spring and fall run Chinook salmon as well as other anadromous fishes. Therefore, it is imperative to maintain the physical and chemical aspects of the watershed in a good condition to support local and regional recovery of anadromous salmonids to biological good condition (*sensu* California Fish and Game Code Section 5937; Börk et al., 2012) and obtain the ecosystems services they provide.

When provided in the proper abundance and composition, sediment is a key component for healthy aquatic habitat affecting ecosystem functions. Sediment is delivered from hillslopes to stream channels via Earth surface processes, such as landsliding, sheet wash, and channelization. Rivers transport sediment downstream with streamflow in response to precipitation events. The roles of streamflow and sediment load are important for understanding how geomorphic processes ultimately affect water quality and anadromous Pacific salmonid population viability in Battle Creek.

The Battle Creek watershed hydrology and sediment report herein is a comprehensive analysis employing multiple methods to assess the geomorphic processes affecting streamflow and sediment dynamics. Funding is provided from the California State Water Resources Control Board (Agreement 12-105-150). The primary goal of the assessment was to gather together all existing information relevant to assessing the status of sediment and its potential impacts as well as conduct pilot-scale efforts to develop new data and analyses in support of such an assessment. Given the historical and ongoing investments in restoring Battle Creek, a geomorphic process-based understanding of the factors affecting water quality will aid in sustainable decision-making for water resource management in Battle Creek.

The scope of this report includes a broad-based literature review about sediment, including a review of sediment impact assessment methodologies (Section 2), an existing information literature review for the Battle Creek Watershed addressing all geomorphic, sediment, streamflow, and related published studies (Section 3); an evaluation of the major data gaps in the existing literature that impede the ability to make sound assessments and management decisions (Section 4); a hydrological history analysisto update past studies with the latest data from the watershed (Section 5); an analysis of new sediment and associated water quality data in comparison with the pre-existing data to the extent feasible (Section 6); a novel GIS-based analysis showing the spatial pattern of landscape physical processes throughout the watershed and under different conditions (Section 7); a description of a variety of supplemental tasks that were done as part of the project (Section 8); an evaluation of sediment impacts in the Battle Creek Watershed (Section 9); and recommendations for future directions (Section 10). The development of long-term monitoring strategies addressing data gaps is a key component for continued understanding of physical stream characteristics in relation to baseline conditions thus provided. Table 1 presents an accounting of how each project task in the contracted scope of work was accomplished.

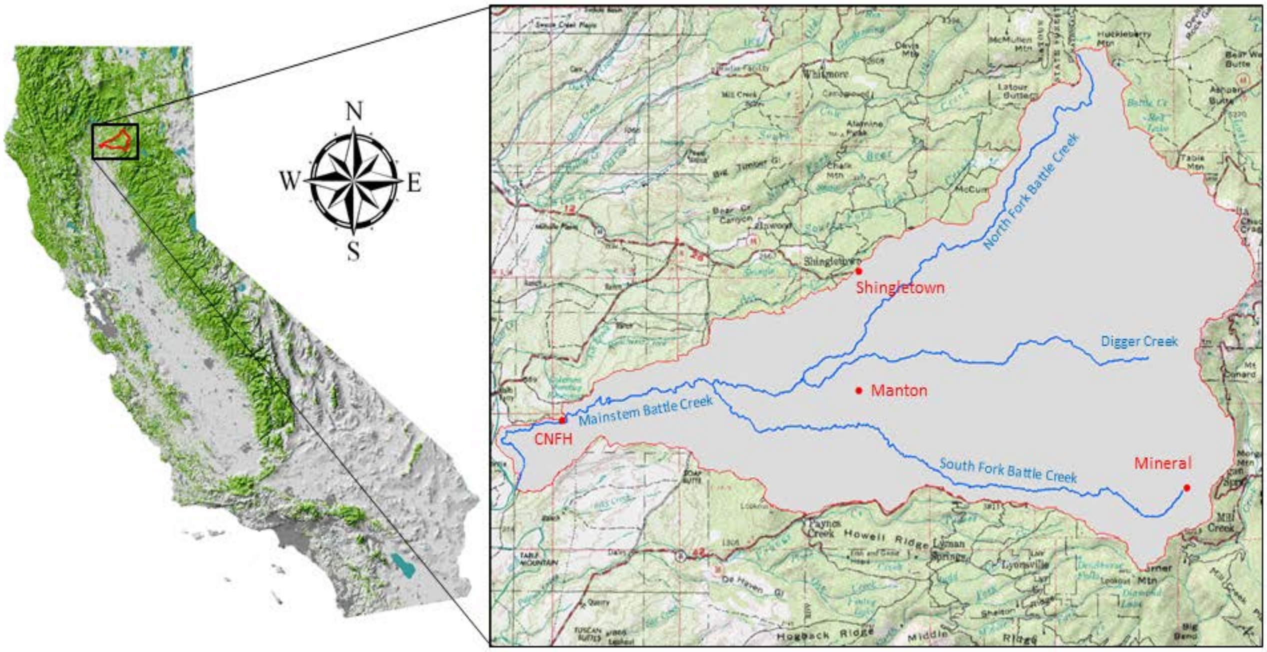


Figure 1: Location map for Battle Creek Watershed.

Table 1 : Battle Creek Watershed study objectives, methods, and deliverables.

Objective	Method	Deliverable
Literature Review, Compilation, and Synopsis	Obtain all previously published literature and reports related to water quality and the subsequent effects on habitat, biology, and restoration. Summarize existing information and provide synopsis.	Two (2) DVDs containing electronic copies of all literature and reports. Results presented in Final Report.
Water Quality Data Compilation and Analysis	Obtain all available water quality data relevant to streamflow, sediment, and other pertinent water quality parameters. Report data in Excel spreadsheet and include a data quality control process. Analyze temporal and spatial variation within Battle Creek.	Two (2) DVDs containing electronic copies of Excel files with water quality data. Sediment-related results presented in Final Report.
Hydrological History Analysis	Use available gaging station data from CDEC and USGS to evaluate temporal hydrological effects on sediment processes associated with hydrological history.	Results presented in Final Report.
GIS-Based Landscape Processes Analysis	Retrieve geospatial data to produce maps of the spatial pattern of susceptibility to landsliding, gullying, sheet wash erosion, and soil creep using the equations of Dietrich et al. (1993).	Two (2) DVDs containing ArcGIS Geodatabase electronic files. Results presented in Final Report.
Water Year 2015 Field Monitoring	Collaborative field campaign monitoring turbidity and suspended sediment transport for water year 2015. Digital photography and time-lapse photo-documentation. Field visits and meetings with Water Board and other entities involved in Battle Creek.	Two (2) DVDs containing digital photographs and Excel spreadsheets with turbidity and SSC monitoring. Results presented in Final Report.
Sediment Impact Evaluation	Utilizing results from previous objectives and new data collected in this study, use new technologies and scientific methods to assess and characterize the spatial and temporal patterns of erosion and sediment impacts.	Results presented in Final Report.
Data Gap Identification	Review results from all previous steps and identify potential data gaps and how these gaps affect evaluation of sediment impacts. Recommend additional monitoring needs.	Results presented in Final Report.

2 SEDIMENT LITERATURE REVIEW

This section provides an overview of the literature about fluvial sediments, with an emphasis on those sediments transported in suspension, which are the focus of this study. It also reviews the literature on the impacts of sediment on the environment. Total fluvial sediment is generally subdivided on the basis of whether a given particle is in a state of motion or repose. Fluvial sediments that are not transported over a given period of time are those that were deposited by fluid flow during a previous time period. These sediments are often defined in terms of the geomorphic structures to which they belong, such as channel bed or bank sediments, floodplain sediments, or wetland sediments, etc.

Here we focus on fluvial sediments in motion. Among sediments in motion, these may be divided on the basis of their mode of transport. Section 2.1 summarizes the characteristics of fluvial sediments including their modes of transport, compositions, the role of sediment surface area in the environment, and eventual fate as sediment deposits. Section 2.2 presents the fundamental approaches employed to monitor, measure and characterize fluvial sediments. Section 2.3 delves into the topic of suspended sediment dynamics, or the patterns of changes in suspended sediment magnitudes over time and the controls of these patterns. Section 2.4 then details how suspended sediment flux is estimated.

2.1 Fluvial Sediments

Fluvial sediments are particles of mineral and organic matter transported by water flowing through channelized systems such as rivers and streams (Sundborg, 1967). These particles can be more specifically defined on the basis of their mode of transport and particle size characteristics (Section 2.1.1), and their composition (Section 2.1.2), which have ramifications on their roles in the environment (Section 2.1.3), and their eventual fate (Section 2.1.4).

2.1.1 Bedload and Suspended Load

Total fluvial sediments in transport over a given period of time or through a given spatial domain are known as the fluvial sediment load (Walling and Fang, 2003). Fluvial sediment load is commonly subdivided on the basis of how the downward motion of the particles due to gravity is counteracted, which is to say, the fluvial mode of transport. There are two general fluvial modes of transport: bedload and suspended load. Bedload sediments are the coarsest (largest diameter) fraction of fluvial sediments, which interact directly with the channel bed, essentially rolling, skipping or impacting the channel surface at the end of discreet arcs of trajectory through the field of fluid flow – all of which can be termed as ‘bed supported’ or components of bedload transport (Garcia and Parker, 1991). Bedload sediments are usually the minority component of sediment transport -generally thought to account for only 5–20% of the total fluvial sediment load at most river outlets, although very little data supports this claim (Turowski et al., 2010).

Suspended sediments are a finer (smaller particle diameter) and generally more abundant fraction of sediment than bedload. Rather than requiring direct impingement on the channel bed, suspended sediments are supported by the turbulence of the fluid flow itself (Garcia and Parker, 1991). In other words, the downward motions of particles due to gravitational acceleration are in these cases retarded by the turbulent fluctuations of the flow field, which maintain their suspension. As turbulent fluctuations are essentially counteracting the momentum of settling particles, the settling velocity of a given particle is a critical determinant of how much turbulent intensity is required to maintain its suspension. The major factors inherent to the sediment particles themselves that controls the partitioning of fluvial sediments into bedload and suspended load are those that influence the fall velocity of the particles through a given fluid. Terminal settling velocity (ωs) for an idealized spherical particle through a still fluid is estimated through the following equation:

$$\omega_s = \frac{(\rho_s - \rho_f) g D^2}{18\mu} \tag{2.1}$$

where ρ_s and ρ_f are the densities of the particle and the fluid, respectively, g is acceleration due to gravity, D is the particle diameter, and μ is the dynamic viscosity of the fluid. From this equation it follows that settling velocity increases with increasing particle density and/or diameter. If we assume that mineral particles generally have similar densities, then the major internal (particle specific) factor in determining the settling velocity of a particle becomes particle size (diameter).

Shear velocity, which is essentially the transfer of momentum between layers of fluid flow and is driven by differences in the velocity of the layers of fluid, is one means of describing the conditions that control turbulent intensity (Vanoni, 1975). Due to the natural state of a near 'no-slip' boundary condition at the interfaces between flowing water and the channel bed and banks, shear velocity increases with depth. As particle diameter increases, higher turbulence intensities/shear velocities are required to maintain suspension. Thus, particle concentrations are expected to increase with depth, and the concentration gradient along the depth axis is more pronounced with greater particle size. This is the case for larger particles where shear stresses in the shallower portion of the flow field are generally insufficient for suspension. Indeed the largest particles in motion (bedload) do not have sufficient turbulent intensities to maintain any suspension, but only enough to move them generally along the bed. However, for a flow field of any given characteristics there is also a particle size threshold where particles of a given diameter or smaller are expected to have a uniformed concentration profile with depth, as shear velocities throughout the depth profile are sufficient to maintain suspension (Rouse, 1937).

Suspended sediments that display invariant concentration profiles with depth are often labeled as 'washload.' Washload sediment is generally considered to be supply rather than transport limited, as its abundance is not related to the flow field, but rather to sediment erosion and delivery mechanisms (Gabet and Dunne, 2003). Washload has been found to account for the majority of suspended sediment in most rivers of a scale large enough to develop floodplains (Naden, 2010). As suspended sediment is also the major component of total fluvial load, it becomes apparent that most, or at least a very significant proportion, of fluvial sediment flux is controlled by the delivery of sediment to the channel rather than the ability of channelized flow to transport the load. This has important ramifications in the approaches used to investigate the production and transport of suspended sediment at the watershed scale, as it shifts focus from channelized flow characteristics to the mechanism governing the delivery of sediment to the channelized system (see Section 2.3). Note that channel banks can be major proximal sources of washload, especially where lateral migration cuts into floodplains, so washload is not solely an indicator of upland sediment supply.

2.1.2 Suspended Sediment Composition

Suspended sediment can be further subdivided on the basis of particle composition. The primary subdivision is usually between mineral and organic sediments. The mineral component usually makes up the largest proportion of suspended sediment, although proportional contribution between mineral and organic matter can vary widely between rivers and within a given river over space and time (Meybeck, 1982; Hedges et al., 1997). Partitioning of minerals by particle size is commonly observed in suspended sediments and the deposited fluvial, colluvial, and hillslope sediments that ultimately supply the fluvial load (e.g. Blatt, 1967; Nesbitt et al., 1996; Whitmore et al., 2004; Zhou et al., 2015). Larger clasts in the gravel to cobble range (nominally $D \geq 2$mm) are generally pieces of regolith or bedrock from within the watershed, and usually composed of collections of crystals if the source material was igneous or metamorphic, or cemented particles if the source material was sedimentary in origin (Boggs, 1968). Such large clasts are generally transported as bedload in all but the most energetic discharge scenarios (Rouse, 1937). Most suspended sediment in rivers is composed of sand ($63\ \mu m \leq D < 2000\ \mu m$), silt ($4\ \mu m \leq D < 63\ \mu m$), and clay ($D < 4\ \mu m$) particle size fractions (Naden, 2010). Sands and silts are mostly composed of individual mineral crystals or are small clasts of sedimentary rocks composed of even finer grains (Nesbitt and Young, 1996; Whitmore et al., 2004). In the fine silt through clay size fraction most particles are in fact clay minerals, which have mechanically weathered out of sedimentary rocks in the watershed and/or are produced from igneous, metamorphic or sedimentary rocks through chemical weathering processes (Nesbitt et al., 1996).

Organic matter transported in suspension can be further subdivided from several perspectives. A common consideration is the level of susceptibility to microbially mediated oxidation (Hedges and Keil, 1995). Organic materials easily consumed by such processes are considered ‘labile’, while those that resist consumption are ‘refractory.’ The labile component of organic material is mostly composed of particles of relatively recently produced plant material, while refractory particles are often sources from sedimentary regolith materials (i.e. ‘fossil carbon’), or older plant materials that have had the more labile components consumed during the interval between production and entering the fluvial transport stream (Hedges et al., 1997). Labile carbon particles in suspension and in sediment deposits, such as those in a channel, lake or ocean bed exert direct control on the biological oxygen demand (BOD) for a given body of water, and can lead to the development of anoxic conditions detrimental to aquatic biota (APHA, 1993).

Provenance of organic material is also often of interest. Labile organic materials are produced within the fluvial/lacustrine network itself, including most/all of the algal material found in fluvial sediments and a portion of the load of vascular plant detritus (e.g. Etcheber et al., 2007; Goni et al., 2005). Vascular plant material is also delivered to the channelized network from recent vegetation produced in the watershed, and materials that have been incorporated into soils and eventually eroded. Most recalcitrant material is sourced from bedrock, regolith and soil pools within the watershed (Gomez et al., 2004).

2.1.3 Environmental Implications of Fluvial Sediment Surface Area.

Fluvial suspended sediments are important components of the geophysical and bio-geochemical cycles of coupled terrestrial, freshwater aquatic and coastal marine systems. The flux of most solid material from the terrestrial to oceanic spheres is transported through rivers in suspension (Milliman and Meade, 1983; Milliman and Syvitski, 1992). Total surface area scales with an inverse, geometric relationship to particle size for a given unit of mass and a given particle shape. The finest fraction of fluvial sediments (fine silts and clays), all of which are transported in suspension, generally have flattened or platy shapes, as compared to the more spherical shapes of larger particles. The flattened shapes of clay and fine silt particles further exacerbate their impact on the total fluvial sediment surface area. For these reasons suspended sediments also represent most of the surface area of solid material moving through the freshwater and coastal marine aquatic environments (Naden, 2010).

Suspended sediment surface area has a number of consequences for the aquatic environment, including strong control on the optical properties of water and domination of surface mediated transport (Martin and Meybeck, 1979). Fine suspended sediment absorbs and reflects light, which contributes to turbidity, or the ability of water to attenuate light (APHA, 1992). By reducing the penetration of light into surface waters, turbidity in turn moderates aquatic primary productivity, and contributes to additional effects of on light or vision mediated behaviors of aquatic biota (Mirbagheri and Tanji, 2007; 1981; Bash et al., 2001; MPCA, 2008).

Fine suspended sediments also play a large role in mediating the transport and availability of many substances that are adsorbed to or associated with particle surfaces. Fine sediment particles, particularly those of clay minerals, tend to have negatively charged surfaces which attract positively charged ions (Tisdall and Oades, 1988). Although many chemicals in aquatic systems are transported in solution (i.e. a dissolved state), many others are attracted to the charged surfaces of fine suspended sediments and move through the aquatic environment primarily in association with individual particles and their aggregates. Thus fine suspended sediment dynamics play a large role in the aquatic flux of nutrients, particularly phosphates (Reddy et al., 1999; Bowes and House, 2001; Clarke and Wharton, 2001; House, 2003; Bowes et al., 2005; Warrick et al., 2005), contaminants such as persistent organic pollutants (POPs) (Jones and de Voogt, 1999; Lohman et al., 2007; Zhang et al., 2005), heavy metals (Bryan and Langston, 1992; Macklin et al., 1997; Kronvang et al., 2003; Springborn et al., 2011), and much of the aquatic microbia, including pathogenic bacteria such as E. coli (Harmel et al., 2010; Pandey and Soupir, 2013). These compounds and organisms are very important in terms of water quality, the biogeochemical cycling of nutrients and organic matter from terrestrial to freshwater aquatic and coastal marine environments. Turbidity and surface mediated constituents also play a large role in determining the suitability of surface waters for given water quality criteria in terms of ecosystem services and human beneficial uses (US EPA, 2003a).

The high surface area and surface charge of fine sediment particles results not only in the attraction of other compounds and microorganisms, but attraction between mineral particles as well. Much of the fine sediment fraction, particularly clay minerals, are known to be ‘cohesive’, in the sense that they adhere to one another, generally traveling as aggregates of multiple particles. These aggregates of fine mineral sediments often incorporate organic particles, as well as other surface associated constituents mentioned above. Aggregates develop in soils and can be delivered in aggregated form to the channelized network (Tisdall and Oates, 1989), but fine sediment aggregation and dispersion dynamics are also influenced by the physical and chemical properties of the surface waters through which they are transported (Droppo and Ongley, 1994; Slattery and Burt, 1997; Winterwerp, 2002). Changes in the energetics and dissolved chemical characteristics of surface waters influence the aggregation or disaggregation/dispersion of fine particles by controlling the frequency and energy of particle to particle interactions, as well as the surface charge and abundance and type of surface associated ions (Einstein and Krone, 1962; Mehta et al., 1989). Changes in aggregate size and composition in turn affect settling characteristics of cohesive fine particles (Krone, 1962; Mehta et al., 2014). Aggregates are larger in diameter than their constituent particles, which leads to higher settling velocities despite some offset in this effect due to lower relative densities. After deposition, attraction between cohesive particles also makes them much more difficult to suspend than would be expected from their particle size alone. The stress threshold for initiation of particle motion can increase further with time as compaction and dewatering progress, which can lead to closer association between particles.

2.1.4 Fate of Fluvial Sediments

Although much of suspended sediment is transported by flows that are more than competent to maintain their suspension, portions of the suspended load are deposited within the freshwater aquatic system and onto adjacent terrestrial systems (Owens et al., 1999; Walling et al., 2003). Sediments settle out of suspension when the hydro-dynamics of flow no longer counteract downward motion due to gravity. This generally occurs due to changes in the flow field, and in some instances due to changes in particle characteristics, such as through increased aggregate size. Changes in the flow field in the channelized system itself can lead to deposition of suspended sediments on channel banks, fringing wetlands, and the channel bed (e.g. Smith and Griffin, 1997). As water stage recedes toward the end of a given rainfall runoff event or cluster of events suspended sediments may be deposited during the falling limb of the hydrograph as flow depths and velocities decrease (Walling et al., 2000). Transfer of channelized flow into hyporheic flow, or the movement of waters through the channel bed, can also result in the deposition of formerly suspended sediments in coarser bed sediment matrix (Owens et al., 1999; Boulton, 2007). Vegetation on channel banks and margins can also increase suspended sediment trapping due to increases in roughness, slowing down flows (Arcement and Schneider, 1989).

Overbank flooding, whereby the magnitude of flow exceeds the capacity of the channel and inundates channel adjacent lands such as wetlands and floodplains, generally results in deposition of suspended sediments. Flow depth and shear stresses generally decrease rapidly away from the channel, resulting in the deposition of coarser sediments closer to the channel and finer sediments further from the channel (Asselman and Middelkoop, 1995). A similar process occur when river levees (natural or otherwise) are breached, creating ‘crevasse splay deposits’, with coarser material (including in some cases bedload) deposited near the levee breach or ‘crevasse’ and finer sediments deposited further away as the escaping flow spreads out, becomes shallower and slows (Makaske, 2001). Similarly, channelized flow entering standing water such as lakes or reservoirs also experiences changes in flow characteristics, which generally lead to the deposition of coarser material near the river entrance, with finer materials settling out into in the less hydro-dynamically active portions of the water body, or transported downstream (Blum and Tornqvist, 2000).

Alluvium, or deposited fluvial sediment, is a critical component of aquatic and terrestrial environments with far reaching effects for the global biosphere. Much of the most productive soils in the world have developed from alluvium deposited in wetlands and floodplains (Troeh, 2005; Buol et al., 2011). Indeed, the maintenance of wetland elevations in most freshwater, estuarine and coastal settings is highly dependent on fluvial fine sediment fluxes (Krone, 1962; Syvitski, 2008). Fluvial sediments also provide key nutrients, substrate and sediment sources to coastal and benthic communities (Kaul and Froelich, 1984; Hedges, 1992; Lebo and Sharp, 1992;

Kamer et al., 2004). Fluvial sands are also required to maintain coastal beaches (Slagel and Griggs, 2008). However, the deposition of fluvial suspended sediment can also adversely impact ecosystems and aquatic biota through the release of surface mediated constituents that have harmful water quality effects such as the methylation of elemental mercury in wetland sediment deposits (Bryan and Langston, 1992; Boening, 2000; Marvin-DiPasquale et al., 2014) or excess nutrients leading to eutrophication (Horwath et al., 1996; Correll, 1998; Cloern, 2001).

2.2 Monitoring, Measuring and Characterizing Suspended Sediment

Monitoring of suspended sediment generally begins with the estimation of suspended sediment concentration (SSC) for a given location or station in a given surface water body at a given time. Estimating SSC without paired measurement of water Q is 'ambient monitoring', whereas the addition of Q measurements allows for further inquiry into suspended sediment dynamics, suspended sediment flux, and estimation of the processes controlling sediment production and transport (Edwards and Glysson, 1999). Suspended sediment concentration measurement can occur through direct means, which involves the collection and analysis of surface water samples, or by indirectly measuring a proxy for SSC. Water samples collected for direct monitoring of SSC are subsequently processed to determine the mass of sediment relative to water volume. The most widely used proxy for SSC is turbidity, a measure of water's ability to attenuate light penetration (Rasmussen et al., 2009). Many different measurement methods and units have been developed to describe turbidity, but here only the most recent will be discussed. Four turbidity measurement units were encountered as sample data for this project: (i) Turbidity as SiO_2 (mg/L), (ii) Formazine Turbidity Units (FTU), (iii) Nephalometric Turbidity Units (NTU), and (iv) Jackson Turbidity Units (JTU). Of these three NTU and JTU are generally equivalent (Anderson, 2005). Turbidity as SiO_2 is no longer generally measured, and is not easily translated to other systems of turbidity measurement (USGS, 1965, p. 289-290).

Collecting a representative sample or proxy measurement of the sediment that is passing a given station on a river or stream is not a trivial undertaking. For an overview of USGS protocols for field collection of suspended sediment samples from surface waters see Edwards and Glysson (1999). As discussed in Section 2.1, SSC for coarser particles in suspension will vary with the energetics of the flow field. The cross section of channelized flow from bank to bank (normal to the net direction of flow) at a given station on a river contains spatial variations in turbulence and shear velocity, which result in spatial variations in the SSC of coarser particles. This variation in SSC with position in the flow field complicates attempts to obtain a representative suspended sediment sample from a given Q at a given station.

Attempts to monitor suspended sediment at a given station generally fall into two categories: those that explicitly account for variations in SSC within the cross section of flow, and those that ignore it. The most common method used to account for variation in SSC through the flow field is ‘flow integrated sampling’, a technique commonly employed by the most prolific suspended sediment monitoring agency in the US – the USGS (Edwards and Glysson, 1999). Flow integrated samples are collected continuously through depth, usually at multiple points along a transect normal to mean flow direction. Potential drawbacks of this comprehensive sampling scheme include the need for costly specialized equipment, and complex time-consuming sampling operations which generally produce a large sample that requires longer processing time in the laboratory. It is also impossible to know if the amount of time spent sampling each depth is kept equal and velocity differences with depth mean that the amount of flow sampled at each depth is unequal even if sampling time is somehow kept constant. Characterization of a given Q using this approach may also not be possible if the amount of time required to obtain a spatially representative sample is long relative to the time scale of hydrologic change. This problem can be particularly acute in small, flashy systems.

In contrast, the simplest approach for obtaining SSC is the ‘grab sample’, where a single sample is collected from the flow field, generally at or just beneath the water surface at some point along the transect normal to mean flow. A grab sample can generally be considered representative only of the range of particle sizes that are expected to express uniform concentration across the entire flow field. If general information regarding the hydrodynamics of the range of flows likely to be sampled at a given station is known, simple calculations can provide an estimation of the maximum particle size expected to express a uniform concentration under the least energetic flow conditions (Rouse, 1937).

Similarly, in situ sampling apparatuses are also usually installed to collect suspended sediment from a given point in the flow field. In situ sampling approaches generally employ an automated sampler with either multiple chambers installed in the channel, or a pumping apparatus that draws sample water from a hose inserted in the flow field, such as ISCO samplers (Teledyne ISCO Inc., 2007). In some cases simple containers designed to passively fill with sample water just beneath the water surface on the rising limb of the hydrograph (aka single-stage samplers) are deployed (USGS, 1961). Such passive fill bottles are designed not to exchange water and sediment after their initial filling, and several bottles can be deployed at successive elevations in order to capture samples at different stages of the rising limb of the hydrograph.

Turbidity measurements can be performed on water samples using laboratory instrumentation or in the field using optical sensors (i.e. turbidity meters) that can be lowered into the monitored water body, or even installed for continuous monitoring (Rasmussen et al., 2009). Fixed turbidity meters provide the opportunity of collecting higher temporal resolution data over longer periods of time than would generally be practical for an in situ auto collector of water samples, which are limited by sample collection space. This has value, because turbidity fluctuates rapidly over a wide range, warranting more frequent sampling than the 15 minutes commonly used for stage measurement and discharge gaging. The same issues related to spatial variation in suspended sediment concentration through the flow field apply to the point collection of turbidity measurements, illustrating that there is a trade-off between resolving temporal variation and spatial variation- no approach does both.

Characterization of suspended sediment concentration using turbidity is further complicated by the need to transform turbidity measurements into units of SSC (i.e. mg/L sediment). Although SSC is usually a dominant control on turbidity, other factors also contribute to turbidity values, particularly the amount and type of dissolved organic compounds present (Rasmussen et al., 2009). The composition of the suspended load in terms of mineral/organic content, particle size, mineralogy and organic character also play large roles in determining turbidity. For this reason, turbidity-SSC relationships are usually developed on a site specific basis, which may require further refinements if suspended sediment composition effects are significant. Thus, even monitoring regimes that rely extensively on turbidity measurements require collection of suspended sediment samples to develop turbidity-SSC rating/calibration curves.

Actual samples are also required for most sediment composition characterization, with the exception of relatively rare in situ measurement devices, such as flow through particle size distribution systems (Francis et al., 2006). Laboratory analyses can be performed for any of the sediment characteristics mentioned above (see Section 2.1.2) such as mineral particle size distribution (Walling and Morehead, 1987; 1989), mineralogy (Griggs and Hein, 1980), organic content (Tanji et al., 1978), many forms of organic material characterization (e.g. Gomez et al., 2004; Goñi et al., 2005 Leithold et al., 2006) and analyses of trace and bulk geochemistry (Ingraham and Lin, 2002), as well as the characterization of the types and amounts of surface associated materials (Weston et al., 2004). Each approach to characterizing suspended sediment requires additional sample material, which places increased demands on sample number and/or sample size for a given station and Q. Further details on the many different sediment characterization analyses are not provided here, but are prevalent in the literature.

2.3 Suspended Sediment Dynamics

Changes in watershed-scale suspended sediment concentration and flux over time is an integrated expression of the internal and external factors controlling the delivery of water and sediment to a given water body (Walling and Fang, 2003). Internal factors are aspects of the watershed itself, including topography, substrate (geology and soils), channel dynamics, and vegetation. External factors are those that arise from outside of the watershed and exert influence often through fluxes of mass and energy, such as climate/weather delivered moisture and wind, earthquakes, and electromagnetic radiation from the sun. Internal and external factors interact with and influence one another, with external factors such as climate playing a large role in mediating internal factors such as vegetation. Changes in internal and external factors over time lead to changes in the biological and geophysical expression of the watershed, including the delivery of water and sediment to the channel, and the conveyance of both, which in turn controls the concentration and flux of suspended sediments at the watershed scale.

From the previous exposition it becomes clear that watershed-scale suspended sediment dynamics, much like any watershed-scale expression, are integrated expressions of multiple factors. Data-driven, watershed-scale hydrologic analysis must then be a forensic process of inquiry, whereby all of the major factors controlling a given expression are at least considered, if not explicitly tested, to decipher the driving forces behind changes in watershed expression over time (Gray et al., 2014). As mentioned in Section 2.2, the most basic approach to examining suspended sediment is to measure SSC. However, as SSC has been found to highly correlate with the Q of channelized flow, and as Q is perhaps the most common metric obtained when examining stream function, the next step in suspended sediment analysis is to examine the SSC-Q relationship. This analysis involves plotting SSC and instantaneous Q at the time and location of sample measurement/collection in bivariate space as dependent and independent variables, respectively (Helsel and Hirsch, 2002). The dependent relationship of SSC on Q is then described through either a parametric empirical model, most often a log-linear (i.e. power law) relationship, although many other linear to polynomial equations have been utilized, as have non-parametric methods, such as the localized regression technique LOESS (Horowitz, 2003).

Recall that washload abundance (the majority of suspended sediment in many cases) is primarily a supply- rather transport-limited phenomenon, which suggests that the practice of estimating SSC through Q would be rather unsuccessful. However, SSC is measured as the solid mass of suspended sediment per unit volume of the water-sediment mixture, and as such is inherently dependent upon water supply to the channel from the simple perspective of concentration or dilution. Moreover, the internal and external factors that collude to produce runoff in a watershed also control the generation of both the water and sediments present in channelized flow (Walling, 1983). Part of the suspended sediment load is detached from soil surfaces through the delivery of precipitation itself by direct impingement of rainfall, particularly on bare ground (Hairsine and Rose, 1991; Gabet and Dunne, 2003). The generation of runoff and its conveyance to the channel through sheet wash (shallow overland flow), rill and gully transport, etc. also entrain sediment particles (Tucker and Bras, 1998; Valentin et al., 2005). Secondary control of Q on SSC arises from the entrainment of deposited sediments in channel beds (particularly those at the coarser end of the suspended particle size range for a given flow) and the erosive action of channelized flow on channel banks (Collins et al., 1998; Walling et al., 1998), which can liberate large quantities of mud and sand. Thus, the exercise of producing a SSC-Q rating curve is primarily the use of Q as a proxy to describe the integrated signal of shared basin scale forcing factors that ultimately control much of the delivery of sediment to the channelized system (Gray et al., 2014).

There often remains a large amount of variance in observed SSC values around a SSC-Q rating curve fitted for a given station on a given river (Walling, 1977). Increased standard errors and lower coefficients of determination are generally associated with larger disparities between the processes controlling the delivery of sediment and water to the channel, as well as changes in these processes over the period of observation and shorter time scales (Asselman, 2000). Watersheds that are very episodic in terms of precipitation, runoff and sediment fluxes often produce SSC-Q relationships with high residual variance (Sadeghi et al., 2008). Such systems, particularly small, mountainous watersheds with a highly variable precipitation and temperature regimes highlight the importance of antecedent conditions (Gray et al., 2014). Short and long term effects of highly variable external factors lead to a wider range of internal watershed conditions, which then interact with precipitation events to produce highly variable runoff and sediment supply responses.

The residual variability in SSC not explained by its relationship with Q provides the basis for further inquiry into changes in the controls of sediment and water production and transport over time (Warrick and Rubin, 2007). Computation of SSC-Q residuals simply involves the subtraction of SSC values predicted by the rating curve from the observed values (Helsel and Hirsch, 2002). These residual values can then be examined for patterns in their fluctuations at different time scales. For example, a suspended sediment record can be examined for monotonic increases or decreases in SSC independent of instantaneous discharge fluctuations, which can be conceptualized as departures from the normal sediment and water supply regime (Warrick and Rubin, 2007; Warrick et al., 2013). Furthermore, SSC-Q residuals can also be tested for correlation with the state of other factors in the watershed that may exert control on suspended sediment production over time, including episodic and legacy disturbances such as wildfire and earthquakes, changes in vegetation, climatic cycles and climate change, and changes in human land use operations such as agriculture, forestry, urbanization and hydrologic modifications (Gray et al., 2014; 2015a).

It should be noted that examination of SSC-Q residuals is an analytical approach to investigating net change in the production of sediment and water supply to the channel and the routing of these constituents through the channelized system. Indeed, if sediment and water supply characteristics change in magnitude and direction (decreasing or increasing) the net effect on the SSC-Q relationship can be null (Warrick, 2015). For this reason, independent analysis of changes in the relationship between precipitation and Q generation should also be examined over time to investigate the role of hydrologic changes on SSC dynamics. For example, large increases in impervious land surface area due to widespread urbanization have been found to increase the proportion of effective precipitation that becomes runoff (Warrick and Rubin, 2007). After the initial wave of sediment generation through construction processes, these urban surfaces often generate less erosion (Wolman, 1967). Therefore the net effect of urbanized land surface area increase can be a dilution of the existing sediment supply, which may be compounded by decreases in sediment supply as well.

As sediment supply and its relationship to water supply exert the dominant control of SSC dynamics, the relative sources of suspended sediments are a topic of great interest. Many analytical approaches have been employed to encounter the origins of suspended sediment at the watershed scale, including subbasin monitoring (Tanji et al., 1978), and natural and artificial tracer studies (Ritchie and McHenry, 1990; Sommerfield et al., 1999). This problem can also be approached through simulation models, whereby the interaction of internal and external factors that affect water and sediment generation are described and related through mathematical functions to generate predictions of sediment and water flux (e.g. Jones et al., 2001, Zhu et al., 2007). Both analytical and simulation modeling approaches generally suffer from a lack of data, both for more detailed analytical inquiry, and for proper validation and calibration of the hydrologic model. However, technological advances in the use of natural tracers, including stable isotope and cosmogenic radio-nuclides have led to recent advances in sediment provenance analysis, while increases in computing power and the sophistication of distributed watershed scale models continue to advance the ability of modeling to incorporate sediment dynamics.

2.4 Estimating Suspended Sediment Flux (Q_{SS})

Estimation of suspended sediment flux (Q_{SS}) is central to the study of fluvial sediments and their role in the environment. Sediments in suspension play a large role in the biological and geophysical processes operating in terrestrial, aquatic and coastal ecosystems, and represent the majority of solid material flux from the terrestrial to oceanic spheres (see Section 2.1). Monitoring ambient SSC is useful for initial water quality characterization, which can be used to evaluate suspended sediment impacts on aquatic ecosystems and the beneficial uses of surface waters. Investigation of suspended sediment dynamics through the consideration of SSC in terms of time, Q, and the temporal patterns of internal and external forcing factors can provide valuable insights into the processes controlling suspended sediment production (see Section 2.3). Understanding controls on suspended sediment dynamics can then be leveraged to better characterize the environmental impacts of fluvial sediments and develop plans for sediment impact abatement. The association of SSC and Q data from a given station on a river or stream also allows for the estimation of Q_{SS}. Characterizing the geographic and temporal distribution of fluvial sediment fluxes is perhaps the most comprehensive approach to determining the processes controlling sediment production and transport. Estimation of sediment flux from a given subbasin also provides the basis for estimating the mass flux of sediment associated fluvial constituents, including pollutants, and characterizing their impacts on receiving water bodies downstream.

Approaches to estimating suspended sediment flux mirror the scale of complexity incorporated into analyses of suspended sediment dynamics. The simplest analytical method for estimating suspended sediment flux is to monitor both SSC and Q, which are then multiplied to obtain Q_{SS}. The most accurate method of monitoring Q_{SS} would be one where measurements are distributed through the channel cross section (see Section 2.1), with SSC and Q measurement frequencies equal to or higher than the temporal scale change for either parameter. The term for this is ‘near-census’ suspended sediment sampling, which is a very intensive approach, but still leaves some amount of meaningful variation unsampled. As the USGS monitors stage and estimates Q on a 15-minute interval at stream gauge stations throughout the US – this establishes what would typically constitute ‘high-resolution’ sampling, even though turbidity usually fluctuates more frequently than that interval. Fifteen-minute suspended sediment monitoring is also possible, but also usually relies on turbidity meters, which are used to estimate SSC through a SSC-turbidity rating relationship (see Section 2.2), and generally not employed with explicit acknowledgment of SSC depth stratification.

In many early studies SSC was measured, or averaged from a set of measurements collected over a period of time, and then multiplied by the entire volume of water discharged over that time period, despite variation in Q and SSC. There are many drawbacks to this approach. Employing a convolution of averaged SSC and summed Q values requires either invariance in Q over time, or the assumption that the relationship between SSC and Q is linear. Widespread analyses of suspended sediment dynamics have generally found that the SSC-Q relationship is not linear in most rivers and streams (Walling, 1977), which renders the approach of applying averaged parameters applied over longer time scales relative to the scale of parameter change as fundamentally flawed. Furthermore, even in the rare cases where the SSC-Q relationship is found to be linear, in a scenario of variable Q over the summation period, the distribution of samples would have to be equally representative across the Q domain. For these reasons, lumped estimates of Q_{SS} on the basis of averaged SSC and summed Q_{SS} over long periods relative to the variability of these two parameters is no longer generally practiced in the field of hydrology.

More common is the use of a smaller pool of SSC measurements to develop empirical models of the SSC-Q relationship (see Section 2.3), which are then applied to a Q time series to compute suspended sediment flux. The simplest empirical models are those that fit a single rating curve to an entire {Q, SSC} data set using a single mathematical formula, such as a log-linear/power law, or a polynomial equation (Cohn et al., 1989). Rating-curve-based estimates of suspended sediment load must modify rating curve estimations of SSC to account for systematic biases through bias correction factors (BCF), which are then multiplied by water yield values of a resolution determined by that of the Q time series. For the common scenario of instantaneous

Q data used to construct a log-linear SSC-Q rating curve, and daily Q (Q_d) data used for load estimation, Q_{SS} is estimated as per Warrick and Mertes (2009):

$$SSC = BCF_d \cdot BCF_l \cdot SSC_{rating\ curve(Q)} \tag{2.2}$$

$$Q_{SS} = Q_d \cdot SSC \tag{2.3}$$

where BCF_d corrects for bias introduced by using daily rather than instantaneous Q, BCF_l corrects for the logarithmic transformation consequence of calculating regression parameters using geometric rather than arithmetic mean, and $SSC_{rating\ curve(Q)}$ is the suspended sediment concentration value estimated from the rating curve applied to the discharge record.

The parameter BCF_d can be estimated by comparing sediment loads estimated from Q_d values to sediment loads estimated with higher resolution data, if available (Warrick and Mertes, 2009). The calculation of BCF_l can use the parametric methods of Ferguson (1986), or the nonparametric 'smearing' method of Duan (1983). The Ferguson correction for log-transform bias (BCF_{lf}) is calculated as:

$$BCF_{lf} = 10^{\frac{s^2}{2}} \tag{2.4}$$

where s^2 is the mean squared error of the residuals. Use of BCF_{lf} is contingent upon the assumption of normality in the distribution of rating curve residuals. However, if the distributions of residuals for the given rating curves are found to differ significantly from normal, then a nonparametric log-correction factor should be investigated (Cohn et al., 1989; Hicks et al., 2000). Testing for normality can be pursued through the Shapiro-Wilk test, where the null hypothesis is that a distribution is normal, and p-values below 0.05 are considered to indicate significant departures from normal (Helsel and Hirsch, 2002). The Duan smearing correction factor (BCF_{ld}) does not require residual distribution normality as is calculated as:

$$BCF_{ld} = \frac{\sum_{i=1}^{n} 10^{e_i}}{n} \tag{2.5}$$

where e_i is each residual value generated by subtracting the log of the observed SSC values from the log of the $SSC_{rating\ curve(Q)}$ estimates and n is the number of samples (Rasmussen et al., 2009). The suitability of these factors in correcting log transformation bias can be further examined by computing the arithmetic mean SSC for each sample set using uncorrected rating curve estimations of SSC, and those corrected by either BCF_{lf}, BCF_{ld} or the arithmetic mean of the two ($BCF_{l(f+d)/2}$), and then comparing these values to the observed sample arithmetic mean SSC (Gray et al., 2015b). The *BCF* (or lack thereof) that resulted in a mean SSC closest to the observed may then be chosen for inclusion in the estimation of Q_{SS}.

One must also bear in mind that as the calculation of any BCF_l is based on the variance of residuals about the rating curve, it should only be applied uniformly across the entire Q domain under conditions of homoscedasticity. Thus, residuals for all rating curves should be tested for homoscedasticity before BCF_l application. This can be done using the nonparametric Filgner-Killeen test of homogeneity of variances (Helsel and Hirsch, 2002). If the rating curves are found to be heteroscedastic, then efforts should be taken to apply localized BCFl's, or another method should be used to fit the rating curves in the first place, such as LOESS (Warrick and Mertes, 2009).

Five principle assumptions are implied with the use of parametric SSC-Q rating curves: (i) that the modeled bivariate relationship fits sampled relationship, (ii) normality, (iii) homoscedasticity, (iv) no autocorrelation, and (v) stationarity (Helsel and Hirsch, 2002). Although these assumptions are fundamental to statistical regression, they bear repeating here as they are commonly ignored in practice, with the result of poorly chosen models and misrepresentation of model error. Most importantly, the relationship between the dependent and independent variables (in this case SSC and Q, respectively) of the sample data must follow that of the parametric formula over the independent variable (Q) domain. If this is not the case, non-parametric methods are available, such as localized regression techniques including LOESS, which do not impose a single formula but curves on a localized or weighted proximity basis. When parametric rating curves are fit to data that do not display the modeled relationship, it commonly leads to the violation of the following two assumptions: that sample SSC values must be normally distribute around the fitted curve with residual variance that does not systematically fluctuate with Q (i.e. homoscedasticity). Often both Q and SSC must be log-transformed in order to achieve normality, which has further ramifications for Q_{SS} estimation that were detailed above. No autocorrelation (aka serial correlation) should be present in the SSC and Q data sets, which by extension implies that the relationship between SSC and Q should be stationary (i.e. time independent) within the period of sampled data.

Application of a single rating curve to a Q record outside of the base period of suspended sediment sampling to estimate Q_{SS} also carries the assumption that the SSC-Q relationship is stationary (i.e. remains the same) over the non-sampled period (Gray et al., 2014). However, it is readily apparent that Q in a stream at any given time is always dependent to some degree on previous Q states and transient depletions of upstream sediment sources. The amount of water flowing through a channel rises and falls over time periods that are determined in part by the lasting effects of internal and external drivers of surface water flow. Similarly, SSC also displays serial correlation patterns, with SSC at a given time often closely related to previous values at event (storm-discharge) and even seasonal time scales. This can be driven by the sudden unlocking of a new sediment source, which eventually depletes (e.g., bank collapse, stripping of riverbed armor layer, or upland mass movement). Annual to interdecadal trends or patterns can also be present in SSC and Q values, particularly with long term changes in internal and external factors influencing sediment and water delivery to, and routing through, the channelized system (e.g. Hestir et al., 2013; Warrick et al., 2013; Gray et al., 2015a).

The issues of autocorrelation and non-stationarity in SSC and Q are tacitly ignored when using a single rating curve, but the explicit incorporation of such dynamics is a step toward more thorough methods of estimating Q_{SS}. For example, suspended sediment hysteresis (i.e., path dependence) is an event scale non-stationary behavior that manifests as different SSC-Q relationships on the rising vs. falling limb of the hydrograph (Hudson, 2003). Consistent hysteretic behavior results in higher variance about a single SSC-Q rating curve fitted to both rising and falling limb sample data.

More complex empirical models include factors that influence SSC beyond instantaneous Q, such as the aforementioned hysteretic behavior, as well as antecedent watershed conditions, seasonality, and time (e.g. Warrick and Mertes, 2009; Gray et al., 2015b). Such additional components can be applied to the estimation of suspended sediment flux through a variety of techniques including multiple regression rating curves and stratified or nested simple regression rating curves. The multiple regression approach uses Q in concert with additional independent variables to estimate SSC values. Multiple regression rating curves require the same assumptions as simple SSC-Q rating curves, with the additional assumption that there is little or no collinearity between independent variables. Stratified simple regression approaches utilize different SSC-Q rating curves depending on the value or state of a given factor or time period (Gray et al., 2015b). For example, if consistent event scale suspended sediment hysteresis is found, two separate rating curves may be employed: one for discharges on the rising limb of the hydrograph, and another for falling limb discharges. Similarly, nested rating curve approaches employ multiple decision tree structures that use the state or value of multiple factors to arrive at a given SSC-Q rating curve (Syvitski et al., 2000).

The purpose of going beyond single SSC-Q rating curves is to produce better estimates of Q_{SS}, whether the proximal motivation is to increase the amount of observed variability that is accounted for by the model or to merely construct a model were the basic assumptions inherent to statistical regression are met. However, the price for increased model complexity is two-fold: (i) increased data demands and (ii) the potential for increased error estimates, which will be discussed at the end of this section. Higher resolution and longer sampling periods are required to elucidate SSC-Q dynamics to inform more complex empirical models for Q_{SS} estimation. Returning to the hysteresis example, if SSC has been measured 20 times at a station on a river over the course of a year, a single rating curve approach will have 20 points with which to fit the regression. However, if about half of the samples were collected on the rising and half on the falling limb of various hydrographs, and one chose to use a stratified rating curve approach, there would only be 10 points for each stratified (i.e. rising and falling) rating curve. The lower number of samples per stratified curve may preclude the ability to determine if suspended sediment hysteresis occurs through statistical techniques such as analysis of covariance (ANCOVA). The ability to determine if a given dynamic is at play is more difficult in systems with high variance in SSC around a simple SSC-Q rating curve, which is typical of rivers draining smaller, steeper and more arid watersheds (Gray et al., 2014). Anthropogenic disturbances can also increase SSC variance (Warrick and Rubin, 2007). Although multiple regression techniques do not result in multiple rating curves fitted to lower populations of data, this technique does require data for each of the additional variables.

Error estimation is often ignored when computing environmental fluxes, and fluvial sediments are no exception. In the modern age of estimating Q_{SS}, attempting to calculate honest and thorough estimates of error is essential to subsequent considerations and analyses that may rely on interpreting these numbers. Sediment load uncertainty is estimated on the basis of measurement errors, rating curve uncertainty, and additional uncertainty associated with extrapolation beyond rating curve Q domains (Helsel and Hirsch, 2002; Harmel et al., 2006; Farnsworth and Warrick, 2007). The original SSC and Q measurements used to construct a rating curve have associated error, which is often approximated on the order of 10% (Guy and Norman, 1970; Wass and Leeks, 1999; Yu, 2000; Farnsworth and Warrick, 2007). Rating curve uncertainty for log-linear and multiple linear regressions can be calculated as per Helsel and Hirsch (2002). Error associated with LOESS rating curve uncertainties are generally calculated using the standard error of estimate for discreet Q domains due to the localized regression techniques associated with this method (Farnsworth and Warrick, 2007; Gray et al., 2015b). The application of any rating curve to estimate SSC beyond sampled Q domain incurs additional error as per Helsel and Hirsch (2002). To arrive at total error for a given Q_{SS} estimate, error terms should be propagated through each component of the load estimation formula to arrive at a 1 or 2 sigma error interval.

Moving from single bivariate rating curves to both multiple regression and stratified rating curve techniques has implications for error estimation. Although rating curve uncertainty is generally lowered by these techniques, additional error penalties may outstrip these gains (Gray et al., 2015b). For example, uncertainty can be introduced by additional variables in multiple regression. Stratified rating curves may reduce the Q domain of each individual curve and entail additional error. However, it should be noted that more complex rating curve approaches are often employed to remedy the fact that a single rating curve approach would violate fundamental assumptions such as no autocorrelation and stationarity. As traditional methods of error estimation are predicated on these assumptions having been met, methods that entail their violation produce error estimates that are artificially low. The way forward for reduced Q_{SS} error is to employ estimation approaches that explicitly acknowledge the complexity of sediment production dynamics and the presence of autocorrelation/non-stationarity in SSC-Q relationships, on the basis of data obtained from intensive monitoring over longer periods of time (Downing-Kunz and Schoellhamer, 2013).

2.5 Sediment Impacts on the Aquatic Environment and Human Beneficial Uses

Watershed sediments are a key component of terrestrial and aquatic systems along the entire continuum of sediment production to burial (Syvitski, 2003). All natural channelized flows (e.g., rills, gullies, streams, creeks, and rivers) transport sediments (Ryan, 1991). Therefore the presence of fluvial sediment in and of itself is not an indication of an impaired or adversely impacted waterbody (Bilotta and Brazier, 2008). Definition of adverse sediment impacts (referred to hereafter as sediment impacts) is dependent on location of the landscape of interest, and the ecosystem services and/or human beneficial uses derived from the system. Sediment impacts may include: (i) erosional effects on uplands and channels, (ii) effects of sediments in suspension, (iii) effects of deposited sediment, and (iv) effects of sediment mediated pollutants (US EPA, 2003a; 2006). These groups of impacts can be broadly divided into terrestrial and aquatic spheres, i.e. impacts of hillslope erosion and fluvial sediments, respectively.

Although the focus of this report is on fluvial sediments and their effects, production of these sediments from the landscape can also have significant effects on local stakeholders and the environment, hence the basis for the major landscape-oriented GIS analysis presented in Section 7. Degradation of land surfaces through erosion can cause loss of productive soils, disruption of transportation networks, destruction of homes, and alteration of channel habitats. Upland erosion generally occurs through interaction of surface sediments, soils and bedrock with water, waterborne chemicals, air and temperature regimes over time. In temperate to subtropical dry summer Mediterranean climates, most sediments in low gradient terrains are generally eroded from the land surface through diffuse interactions with precipitation and shallow, precipitation driven surface flow such as sheet flow and rilling, and through channel erosion associated with channel meandering or avulsion (Walling, 2005). Even in terrain with moderate to high relief, sheet flow and rilling can be the dominant erosion mechanism. For example, Hadley and Schumm (1961) made a sediment budget for the Upper Cheyenne River basin and found that sheet wash yielded two orders of magnitude more volume of sediment per unit area per year than observable channel processes. Higher relief landscapes can also produce sediment through more discrete ‘point-source’ processes including gullying and mass wasting (i.e. land-slides) (Gomez et al., 2004; Booth and Roering, 2011). Gullying can also impact generally low relief landscapes in localized areas of high slope, such as the transition between farm fields and drainage ditches, and drainage ditches to higher order streams (Wells et al., 2013). Channel beds and banks can also be significant sources of sediment when net channel erosion occurs, which from a watershed scale perspective means that more bed and bank material are eroding throughout the channelized system then being deposited within it.

Sediments eroded from hillslopes and the channelized network become fluvial sediments. The amount of sediment carried in suspension, and transported along the bed (i.e. bedload) and the qualities of these sediments play important roles in the physical and biotic functioning of aquatic systems (Bilotta and Brazier, 2008; Naden, 2010). Increased SSC has been found to be associated with increased detrimental impacts on aquatic organisms (i.e. fish, benthic invertebrates and vegetation) (e.g. Reynolds et al. 1988; Newcombe and MacDonald, 1991), although this is not universally the case. In some systems aquatic biota rely on suspended and deposited sediments for nutrient and energy inputs, and elevation maintenance (Brown, 1987; Bronmark, 2005, Nittrouer and Viparelli, 2014).

The manner in which increasing SSC has been found to have adverse impacts on aquatic biota is species specific and also dependent on sediment characteristics and the duration of exposure (Birtwell, 1999; Bilotta and Brazier, 2008). Sediment qualities that are known to be important components of the impact of suspended sediments on the aquatic environment include particle size distribution, mineralogy, angularity, organic content and character, and the load of chemicals associated with the sediment surface (Lake and Hinch, 1999; Bilotta and Brazier, 2008). Each of the characteristics and functions of suspended sediment can be described as a continuum of values, certain ranges of which are beneficial, detrimental or even completely prohibitive for the needs of any given beneficial use, aquatic organism, ecosystem component, or human beneficial use of interest.

The most important roles of suspended sediment in terms of aquatic habitat and human beneficial uses of surface water can be broadly subdivided into the effects of sediments that are in suspension or after deposition. For an in-depth description of the sediment transported in suspension, see Section 2.1. Sediments in suspension can impose direct impacts through interactions between the sediments and aquatic organisms and human beneficial uses, as well as indirect impacts through the mediation of other characteristics of the water body in question.

Many studies have been conducted on the direct physiological and behavioral effects of suspended sediment on salmonids (see Cook-Tabor, 1995 for a list of publications). Direct impacts on aquatic organisms include mechanical abrasion of periphyton and macrophytes (Francoeur and Biggs, 2006), the clogging of the gills (Alabaster and Lloyd, 1982; Lake and Hinch, 1999), increased mortality of invertebrates and fishes (Robertson, 1957; Alabaster, 1972; Gray and Ward, 1982; Wagener and LaPerriere, 1985; Reynolds et al., 1988), and avoidance behavior and feeding habit changes in fishes (Boubée et al., 1997; Robertson et al., 2006). Direct impacts on human beneficial uses include sedimentation and clogging of water entrainment and distribution facilities, particularly for irrigated agriculture, and increased pretreatment demands if used for drinking water sources (US EPA 2003a,b) or as a water source for fish hatcheries. Indirect impacts on aquatic ecosystems include increasing light attenuation (turbidity) and chemical changes imposed by the dynamics of surface associated chemicals – discussed in detail below (Newcomb and McDonald, 1991; Koch, 2001; Bilotta and Brazier, 2008). Increasing turbidity in turn can decrease primary productivity (Lloyd et al., 1987) and increase the amount of effort required for visual feeders to forage successfully (Redding et al., 1987). Increases in turbidity can also have adverse impacts human valuations of water bodies, including decreasing aesthetic qualities and posing an impediment to visualization of underwater hazards for bathers and navigation purposes (US EPA, 2003a).

Alteration of channel beds through suspended sediment deposition can impose physical habitat effects such as clogging of interstitial spaces between larger bed materials, changing the particle size distribution of bed surface sediments, and presenting a physical barrier to points of attachment or grazing resources for invertebrates (Ryder, 1989; Graham, 1990). These changes to the structure of the channel bed can result in direct impacts on organisms that live on or within the channel bed (Yamada and Nakamura, 2002; Rabeni et al., 2005; Matthaei et al., 2006; Heywood and Walling, 2007; Niyogi et al., 2006). Fining of surficial channel bed sediment and filling of pore spaces can reduce the amount of habitat used by benthic invertebrates and fish as refugia and egg-laying sites (Sedell et al., 1990; Heppell et al., 2009). Changes to the particle size distribution and porosity of the channel bed in turn influence the dynamics of water movement through the bed (i.e. the hyporheic flow regime), which can reduce channel bed oxygen saturation profiles (Chapman, 1988; Beschta and Jackson, 1979; Acornley and Sear, 1999; Soulsby et al., 2001; Greig et al., 2005). Furthermore, deposition of labile organic compounds and subsequent decomposition can decrease oxygen levels in the channel bed and water column, which can impair or kill aquatic biota (Ryan, 1991).

An additional dimension of both suspended and deposited sediment impacts involves the conveyance of surface bound/associated chemicals and micro-organisms. Fine sediment (i.e., mud, which is composed of clay and silt, $D < 63$ μm) represents the largest proportion of solid surface area moving through fluvial systems, which along with the high surface charges of clays results in most surface associated materials transported through rivers and streams in association with suspended fine sediments (see Section 2.1) (Naden, 2010). Surface-mediated materials transported with fine sediments include organic carbon, nutrients (particularly P), hydrophobic organic chemicals, heavy metals, and microbia (Meybeck, 1982; Weston et al., 2004; Smalling 2005; Springborn et al., 2011; Pandey and Soupir, 2014). These materials can have a wide range of effects, including mediation of oxygen availability in stagnant waters and bed sediments through the delivery of labile (consumable) carbon, eutrophication, and toxic effects on aquatic organisms and humans, and impacts on human beneficial uses (Bilotta and Brazier, 2008).

2.6 Review of Sediment Impact Assessment Methodologies

A wide range of aquatic responses to sediments have been observed due to the specific characteristics of biota, sediment composition, and sediment associated constituents (Section 2.5). For these reasons, an ideal sediment impact assessment methodology would employ an approach based on site-specific information in term of both sediment characteristics and the demands of the aquatic habitat/human beneficial uses in question. In practice such specificity is rarely employed (Bilotta and Brazier, 2008). Sediment is generally only considered in terms of turbidity or SSC levels, without any handling of the timing or duration of these conditions, much less further characterization of the sediments themselves (Bilotta and Brazier, 2008). Impairment is generally assessed in terms of (i) specific qualities required of the water body for given components of the aquatic system (i.e. the needs of aquatic biota) and/or human beneficial uses, (ii) general guidelines in terms of absolute values of sediment metrics, or (iii) guidelines relative to some condition considered to be natural or 'undisturbed' by humans (US EPA, 2006; Bilotta and Brazier, 2008). The latter two assessment methods are the most prevalent, and tend to be employed in a highly general manner, with rote guidelines that vary little, if at all, with site characteristics (Bilotta and Brazier, 2008). None of these methodologies address all of the modalities of fluvial sediment impact detailed in Section 2.1. Thus, development of a sediment impact methodology for the Battle Creek Watershed necessitates the employment of a combination of methodologies to fully consider the impacts of human impacts, climate change, and natural disturbances on fluvial sediments.

As discussed in Sections 2.1 and 2.5, unlike many human-generated pollutants, sediment is a naturally occurring and important component of aquatic ecosystems (US EPA, 2003a; Naden, 2010). This natural or 'background' sediment production presents a need for characterizing not only sources of sediment, but also the role of human activity in determining sediment qualities and production. The highly altered nature of many watersheds throughout the USA, including California, in combination with limited interdecadal monitoring and historical data from time periods of lesser human impacts presents a significant challenge to the characterization of human impacts on watershed-scale sediment regimes (Napolitano et al., 2007). Methodologies that seek to discriminate between 'natural' baselines and human-elevated levels of fluvial sediment are often hampered by this paucity of data. As a result, water quality mangers often use simple generalizations, speculation or monitoring data within the time period of human impacts to develop baseline fluvial sediment condition estimates (Bilotta and Brazier, 2008). Reference reaches of similar unaltered systems are also sought when possible, or more sophisticated empirical methods may be applied to estimate a 'natural' state of a given water body (see Section 2.6.1.3)

The following subsections detail sediment impact assessment methodologies/frameworks recommended and/or employed by federal agencies in the USA and Canada, and US state and regional agencies. The legacy and ongoing guidance from the US EPA for water quality criteria and sediment impact assessment methodology development is a major factor in steering state and local applications. Thus, recent US EPA framing of the aquatic sediment issue was drawn upon heavily to outline the generic approaches to developing sediment impact assessment methods (Section 2.6.1). This is followed by discussion of state and regional examples of sediment impact methodologies employed for given projects (generally related to sediment TMDL development) in terms of the generic approaches defined by the US EPA (Section 2.6.2)

2.6.1 US EPA Defined Sediment Impact Assessment Methods

A great deal of guidance on the development of methods to address the direct impacts of suspended and deposited sediments has been produced by the US EPA (US EPA, 2003a). A critical US EPA (2003a) draft on 'Developing water quality criteria for suspended and bedload sediments (SABS)' presented the basis for much of this section. The US EPA recognized that developing regional/site specific methodologies to produce new and improved water quality criteria for aquatic sediment was one of the highest priorities of water quality standard and criteria development for the first decade of the 21st century (US EPA, 2003a,b).

The US EPA defines water quality standards as a three component system consisting of (i) designating beneficial use(s) for a water body, (ii) developing water quality criteria to protect designated use(s), and (iii) developing and implementing policies to maintain or return to said water quality (US EPA, 2003a). In the 21st century, the US EPA has chosen to focus mainly on the protection of aquatic life (US EPA, 2003a). Aquatic life is nearly ubiquitous and generally requires the most stringent water quality criteria of any of the mixed uses commonly required of a given water body, with the occasional exception of drinking water requirements (US EPA, 2003a). However, there is also a long legacy of considering sediment impacts on a wide range of beneficial uses of water bodies.

Sediment oriented water quality criteria recommendations from the US EPA have evolved over the past 40 years. Early criteria in the 1960s and 1970s focused on turbidity before transitioning to more explicit incorporation of the major suspended and depositional impacts of sediments on aquatic biota and human beneficial uses over the last 20 years. A 1976 report introduced a focus on light reduction as summarized in the US EPA Quality Criteria for Water (US EPA, 1986). This report recommended that all solids in the water column "should not reduce the depth of the compensation point for photosynthetic activity by more than 10% from the seasonally established norm for aquatic life."

While the photosynthetic criterion has not been subject to widespread adoption in the US, other aesthetic standards proposed by the US EPA have seen significant incorporation into water quality standards of the states (US EPA, 2003a; Pflüger et al., 2010). The US EPA aesthetic standard is that, "all waters shall be free from substances attributable to wastewater or other discharges that: settle to form objectionable deposits; float as debris, scum, oil, or other matter to form nuisances; produce objectionable color, odor, taste or turbidity; injure or are toxic or produce adverse physiological response in humans, animals, or plants; produce undesirable or nuisance aquatic life," (US EPA, 1986).

Two early reports utilized by the US EPA Quality Criteria for Water (1986) in formulating recommendations for sediment were from the National Technical Advisory Committee (NTAC, 1968) and the National Academy of Science, National Academy of Engineering (NAS/NAE, 1972). These reports included the following recommended criteria for sediment in terms of drinking water and aquatic biota: (i) "Raw drinking water with treatment: turbidity in water should be readily removable by coagulation, sedimentation and filtration; it should not be present in any extent that will overload the water treatment plant facilities, and should not cause unreasonable treatment costs. In addition, turbidity should not frequently change or vary in characteristics to the extent that such changes cause upsets in water treatment processes (NAS/NAE, 1972)." (ii) "Freshwater aquatic life: combined effect of color and turbidity should not change the compensation point more than 10 percent from its seasonally established norm, nor should such a change take place in more than 10 percent of the biomass of photosynthetic organisms below the compensation point (NTAC, 1968)."

Consideration of recreational uses also imposes aesthetic and risk mitigating criteria on sediment levels in surface waters (USEPA, 2003a; Parametrix, 2003). Visual qualities of water (i.e. color and clarity) are important aesthetic components for recreational activities such as swimming, boating, hunting, fishing, and sightseeing (Smith et al., 1995). Mitigation of risk for humans entering surface waters for swimming and bathing includes sufficient clarity to visualize submerged hazards (NAS/NAE, 1973), which was quantified as a minimum secchi disk visibility of four feet (NTAC, 1968).

An operational flow chart for application of the general US EPA guidelines to developing fluvial sediment criteria would begin with (i) the water quality parameters of interest and potential environmental indicators of their impacts, and then progression through (ii) establishing expectations for water bodies, (iii) linking water quality parameters with indicator responses, and (iv) defining and interpreting impacts (Figure 5.2.1 (US EPA 2003a,b; 2006). The US EPA (2003a) report also outlined five potential approaches that were under consideration for the development of water quality criteria in terms of SABS, the first four of which focus on aquatic life: the toxicological dose-response approach (Section 2.6.1.1, the conditional probability approach to establishing thresholds (Section 2.6.1.2), the reference condition approach (Section 2.6.1.3), the fluvial geomorphic approach (Section 2.6.1.4), and the water body use functional approach (Section 2.6.1.5). These approaches are outlined below.

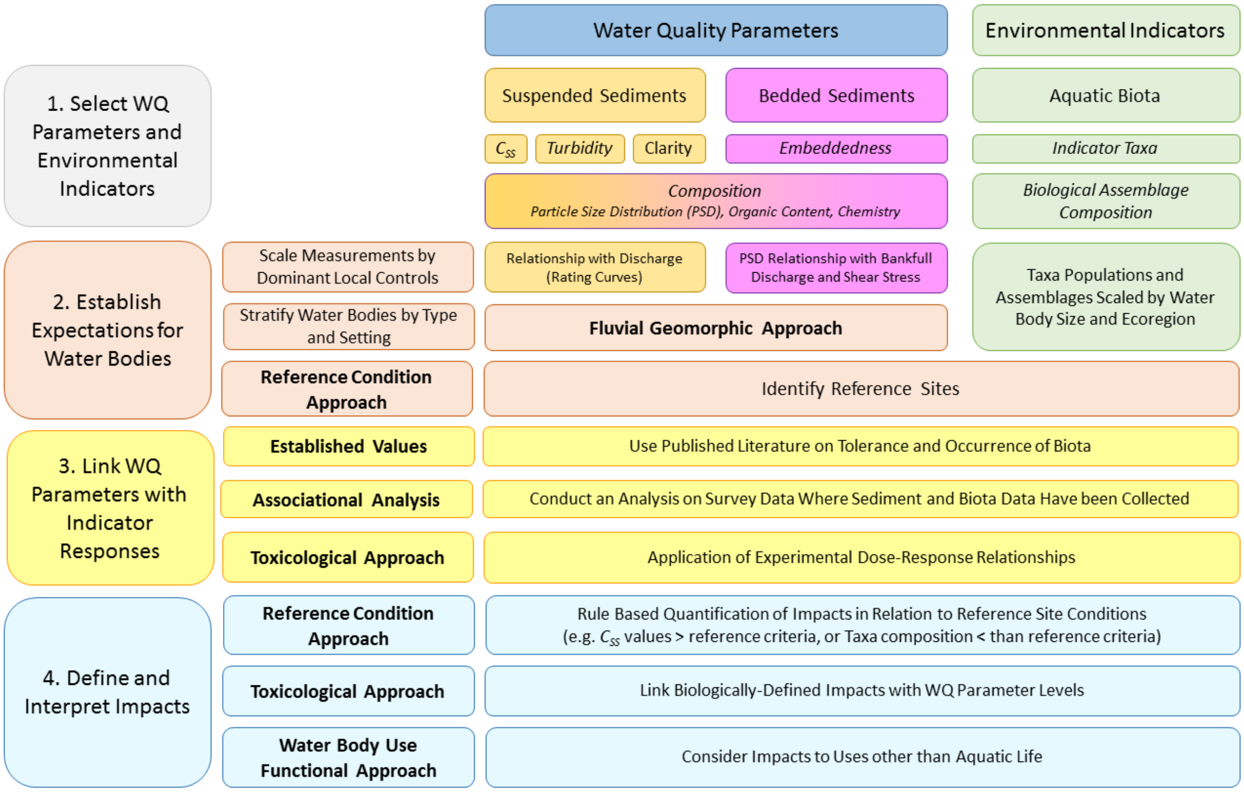


Figure 2. Synthesis of US EPA guidelines for developing water quality criteria and environmental impact assessment in terms of fluvial sediments (see US EPA 2003a,b; 2006).

2.6.1.1 Toxicological Dose-Response Approach

The toxicological dose-response approach stems from water quality criteria development to address the requirements under Section 304(a) of the Clean Water Act, and is primarily based on methodologies presented in US EPA (1985) 'Guidelines for Deriving Numerical National Aquatic Life Criteria for Protection of Aquatic Organisms and Their Uses'. This approach requires acute toxicity data from at least 8 families of organisms with an additional requirement of minimum taxonomic diversity, and chronic toxicity test data from at least three families. These test data are then analyzed to compose a number of acute and chronic toxicological metrics. The Final Acute Value (FAV) and Final Chronic Value (FCV) are estimates of the 5th percentile of a sensitivity distribution of the average LC50/EC50s of the tested organisms for short term and long term exposure, respectively. The Criterion Maximum Concentration (CMC) is calculated as 0.5 x FAV, and the Criterion Continuous Concentration (CCC) is similarly 0.5 x FCV. However, it is only advisable to estimate CCC if chronic toxicological data are available from at least 8 families of organisms. Thus, CCC is usually computed using a simple ratio relationship to CMC. The CCC and CMC metrics then serve as targets that should not be exceeded for certain durations related to base of their test periods, with certain return intervals.

Some examples of suspended and bedload sediment dose-response models include recommendations from Newcombe and Macdonald (1991), the British Columbia Guidelines in Caux et al. (1997) and the Chesapeake Bay Water Clarity Guidelines in US EPA (2003c). Despite such applications, the US EPA has decided that this approach is not generally applicable to SABS due to the lack of species-specific data and generally acceptable methods for determining sediment effects on biota, as well as the fact that suspended sediments are diverse in composition. However, simplification to fewer (i.e. single) indicator organisms could render this approach more tenable. Even further simplification is possible if general dosage rates and durations are simply culled from the small body of experimental literature and applied to a given system.

2.6.1.2 Conditional probability approach to establishing thresholds

The development of a conditional probability approach to establishing water quality thresholds is based on the probability of a give impact occurring if a given water quality threshold is exceeded (Long and Morgan, 1991; MacDonald et al., 2000; US EPA, 2003b). The fundamental concept behind this approach is 'conditional probability', which is the probability of an event occurring given the occurrence of another event. The common notation for conditional probability is $P(Y|X^*)$, where X^* is the other event that is known to have occurred, and Y is the impact in question. When applied to a threshold based water quality framework, X^* indicates a given $X > Xc$ scenario, where Xc is the water quality criterion or threshold (Long and Morgan, 1991). This approach is subject to the following requirements: (i) a metric (X) quantifying the water quality parameter, (ii) X must be a strong stressor on Y that is not obscured by other factors/stressors, (iii) a biologic impact metric must be available, and (iv) the data/results from a probabilistically designed study must be available in order to extrapolate impact probability estimations to larger spatial scales. Problems with (ii) are particularly important due to the correlative nature of this approach.

The conditional probability approach has been used specifically in the context of channel bed sedimentation in a US EPA assessment of streams in the Mid-Atlantic Highlands (US EPA, 2000). This study employed a channel sedimentation index (CSI) quantifying the deviation of channel fines content from expected conditions, which was then used to find the probability of benthic community impairment, defined as EPT taxa < 9. Benthic invertebrate survey data was sourced from the Environmental Monitoring and Assessment Program (EMAP) - a USEPA monitoring program for the environmental characterization of water bodies and assessment of environmental impacts of water quality impairments. Sub-setting of stream reach segments by CSI value was used in conjunction with benthic community data to develop an empirical curve for benthic community impact probability in relation to CSI.

2.6.1.3 Reference condition criteria derivation approach

The reference condition criteria derivation approach is derived from the regional reference approach for developing biocriteria (Barbour et al., 1999; US EPA, 2003a,c). This approach is based on the theory that empirical models can use known relationships between environmental parameters, channel morphology and sediment dynamics in order to establish reference conditions that can then be used as the basis for establishing levels of impairment and impact (Knighton, 1984, Gordon et al., 1992). A caveat is that relationships should be derived from non-disturbed or minimally disturbed streams, which are often unavailable in many regions. Reference site selection is further complicated by the interdecadal to centennial effects of historic land use/disturbances, the elucidation of which can require considerable research/paleo-environmental reconstruction (see Trimble, 1974; Schumm, 1977; Brundsden and Thornes, 1979, Trimble, 1999). Direct modification to the channelized system, including straightening, reinforcement and impoundment can also effect stream response over longer (interdecadal to centennial) time scales (Gregory and Madew, 1982; Walker, 1985; Reiser et al., 1989; Simon and Hupp, 1992; Gordon et al., 1992; Kondolf and Wilcock, 1996).

Hughes (1995) advanced the following criteria or optimal conditions for reference watershed selection: (i) approximately 95% under undisturbed/natural cover, (ii) historic land use disturbances ≤ 10% in the last 50 years, 25% in the last 100 years, (iii) human land use activities are not known sediment generators, such as mining, timber harvesting or steep slope agriculture, (iv) the spatial distribution of stream crossings by roads ≤ 1/mile, (v) no hydrologic modification of the stream ≤ 10 miles upstream of the sampling region, and (vi) no alteration of the stream in the last 50 years (US EPA, 2003a). In general five reference streams per 'type' are considered the minimum, while up to thirty are desirable (Elliot, 1977). Many reference sites have been identified and sampled as part of state biocriteria programs, EMAP, and the National Water Quality Assessment Program (NAWQA). The NAWQA is the USGS program to systematically collect chemical, biological, and physical water quality data from 51 study watersheds in the US (USGS, 2015). Note that many watersheds and subbasins in the US (including the Battle Creek Watershed) do not have corresponding reference watersheds that meet these criteria. However, this issue is generally dealt with by relaxing criteria.

Empirical models are developed on the basis of suspended and bed sediment characteristics found in reference streams, and the environmental characteristics of their watersheds. This requires P, Q, SSC and bed sediment data sets, along with historic and current land use, geology, soil, vegetation, and topography survey data from reference watersheds. Continuous empirical models use the reference reach data to develop relationships between 'independent' variables and sediment response variables. In a site-specific application, the relevant independent variable data for a study site are then used to predict study site conditions of interest (in this case suspended and bed sediment characteristics). In contrast, a discrete predictive approach is used to estimate the sediment characteristics of types or classes of streams, under which the stream reaches of interest are classified. An example of the site-specific approach applied directly to aquatic communities is the River Invertebrate Prediction and Classification System (RIVPACS) (Wright et al., 1984; Hawkins et al., 2000; Wright, 2000). Examples of the discrete predictive approach include biological assessment models such as the fluvial geomorphic approach, notably the David L. Rosgen/US EPA WARSSS approach to sediment impact assessment and management (Section 2.6.1.4).

The USEPA has reported it to be ‘highly likely’ that EMAP and NAWQA datasets would “have sufficient data, including extensive sediment, physical and hydrologic data, to develop good predictive models of reference sediment conditions” (US EPA, 2003a). The authors find this assertion to be highly unlikely for most Californian watersheds experiencing high variability in rainfall/runoff event and sediment loads over time.

2.6.1.4 Fluvial geomorphic approach

The US EPA funded an extensive study to develop a sediment assessment framework named Watershed Assessment of River Stability and Sediment Supply (WARSSS) (US EPA, 2015). The project was conducted by private practitioner David L. Rosgen, who previously developed a river classification system using secret data he won’t allow scientists to evaluate. The sediment assessment approach is based on geomorphic analysis of watersheds and channels with a focus on directing sediment management through the elucidation of hillslope and channel processes controlling sediment production and deposition, rather than developing water quality criteria. However, the US EPA also considers this particular approach to be potentially useful in developing suspended and bed sediment criteria.

The WARSSS approach to assessing hillslope and channel processes begins with a simple ‘screening level’ assessment and proceeds through a more complex, process-based assessment of sediment sources and hydrologic responses in the context of land use. Much of the WARSSS approach hinges on the relationships between channel type and stability, which by extension implicates sediment production, as found by Rosgen and many others (Meyers and Swanson, 1992; Simon, 1992; Montgomery and Buffington, 1993; Rosgen, 1994; Buffington and Montgomery, 1999). An extension of these river classification schemes proposed by Rosgen through the WARSSS framework is the development of reference SSC-Q rating curves. The US EPA has expressed interest in extrapolating SSC-Q rating curve coefficients to entire regions (i.e. Hawkins, 2002) and to detect unstable streams (Troendle et al., 2001). Development of reference SSC-Q rating curves has primarily occurred in the Rocky Mountain states.

2.6.1.5 Water body use functional approach

This approach focuses on the human uses of a given water body rather than aquatic life. Thus the water body use functional approach is generally constrained to those systems that do not contain aquatic organisms, or where the human use is paramount. This is sometimes the case for waterbodies that are used as drinking water sources (US EPA, 2003b). In terms of Battle Creek waterways, the main human uses of the water are hydropower (see Section 3.2.1), water intake for the Coleman Fish Hatchery (see Section 3.7.1), local landowner drinking water, and recreational angling.

2.6.2 Examples of Sediment Impact Studies

While the previous Section provided an overview of the wide array of methods recognized by the US EPA to assess sediment impacts on aquatic systems, there is also a wide range of sediment-oriented water quality criteria imposed by state governments. These criteria are formed on the basis of quantitative, qualitative, or narrative criteria, or in some cases from no criteria at all (US EPA, 2003a). Most qualitative approaches rely on turbidity measurements for water quality criteria, which may be fixed, related to a predetermined background value, and may also vary seasonally with the needs of aquatic organisms, such as migrating Salmon (Bilotta and Brazier, 2008). Most states use the US EPA method 180.1 to measure turbidity and method 160.2 to measure TSS (USEPA, 2003a). There is very little effort by states to correlate turbidity with TSS or biological impacts. A few states measure SSC, and very few measure particle size distributions. No states measure bedload. Criteria for TSS range from 30–150 mg/L. Some states use deposition depths for a given time period or on an event basis – typically on the order of 5–10 mm for streams.

2.6.2.1 Regional Water Quality Control Board Studies

The California Legislature created the State Water Resources Control Board (SWB) in 1967 for the regulation of state water resources. As an extension of, and in collaboration with the SWB, nine Regional Water Quality Control Boards were tasked with the regulation of water pollution as mandated by the Federal Clean Water Act and the California Porter-Cologne Act. The Regional Water Boards develop, adopt and implemented water quality control plans, which include (i) identifying beneficial uses of water, (ii) developing water quality objectives, and (iii) developing and implementing plans and policies to meet or exceed water quality objectives. Section 303(d) of the Clean Water Act requires biennial assessments to determine if water quality standards are being met.

Regional Water Boards have developed sediment related TMDLs for several rivers in California, four of which are discussed below. Three of these sediment TMDL cases, those of the Alamo River, the New River, and Imperial Valley drains are examples of flux-based sediment source investigations applied to ambient SSC-based TMDLs, with sediment budgets developed in relation to both adverse and target ambient sediment conditions. The Alamo and New Rivers, and the Imperial Valley drains have watersheds that are primarily impacted by irrigated agriculture, which has resulted in sediment and contaminant loading issues. The third case of the Napa River sediment TMDL employed a geomorphic approach that sidestepped the construction of sediment budgets.

The Colorado River Basin Regional Water Quality Control Board (CRBRWQCB) identified fluvial sediment issues in the Alamo and New Rivers and a series of agricultural drains in the Imperial Valley, all of which discharge directly into the Salton Sea. The influx of surface water to each of these watersheds is dominated by irrigation supply from the Colorado River (CRBRWQCB, 2002a,b; 2005). For example, the Alamo River drains 340,000 acres, greater than 90% of which is used for irrigated agriculture, which receives an average of 3 in. of rain and 650,000 ac-ft (i.e. 23 inches of water distributed over the watershed area) of irrigation supply waters annually (CRBDWQCB, 2002a). Agricultural products are mostly field crops and sugar beets, which are irrigated through furrow and border methods that can produce considerable off-field transport of sediments.

Ambient SSC levels were found to violate the water quality standards set by the CRBRWQCB for these waterways, particularly in terms of parameters established for warm water fish and migratory bird habitats (CRBRWQCB, 2002a,b; 2005). At the time of these studies (i.e. the late 1990s to early 2000s) the average ambient conditions in these water ways was nearly 400 mg/L. High levels of sediment mediated contaminants such as DDT and DDT metabolites (e.g. DDE) were found in bottom sediments in these systems (Setmire et al., 1990; Setmire et al., 1993; CRBRWQCB, 2002a). Some of the highest levels of DDE on record in California have been found in tissues of birds and fishes in the Alamo River (Mora et al., 1987; CRBRWQCB, 2002a). Fluvial sediments were also known to be the primary contributor of the nutrient P to the Salton Sea, which is the major cause of its eutrophication, a condition that has resulted in numerous algal blooms, followed by die-offs and low DO conditions in the lake (Cagle, 1998). These observations led to further investigations into the processes affecting sediment production in these watersheds, and eventually to the development of TMDLs and sediment management frameworks.

Development of sediment TMDLs for the Salton Sea tributaries was based on proscribed maximum average ambient SSC conditions, from which target sediment loads for each system and sediment source area were estimated (CRBRWQCB, 2002a,b; 2005). The targeted maximum annual SSC for each system was set at 200 mg/L on the basis of generic guidance for adverse impacts of fine sediment on warm water fishes obtained from NAS/NAE (1972), US EPA (1986) and the European Inland Fisheries Advisory Council (1964). The NAS/NAE (1972) and US EPA (1986) guidelines list annual average SSC levels of 80 mg/L and 400 mg/L as providing a moderate and low level of protection, respectively, for warm water fish. The European Inland Fisheries Advisory Council (1964) notes that death rates are significantly higher for warm water fishes living under chronic SSC conditions in excess of 200 mg/L.

Flux-based approaches were used to investigate the sediment sources of the Salton Sea tributaries (CRBRWQCB, 2002a,b; 2005). In each of the Salton Seas tributary systems sediment loads from each source and the tributary outlet to the Salton Sea were calculated as monthly average Q multiplied by monthly average SSC. Nonpoint sources from agriculture, routed through minor and then major agricultural drainage ditches were found to be the primary source of sediment in all systems. Sediment load reduction to reach the targeted reduction in ambient SSC levels were then prescribed for each watershed, and source area.

The San Francisco Bay Regional Water Quality Control Board (SFBRWQCB) listed the Napa River watershed and its tributaries as impaired by sediment in 1990 on the basis of reports of widespread erosion (USDA/NRCS, 1985; White, 1985), which were thought to threaten fish habitat (Cordone and Kelly, 1961), as evidenced by declines in abundance and distribution of steelhead trout in the region since the 1940s (Leidy et al., 2005). In 1990 the Napa River and its tributaries were listed by the SFBRWQCB under Section 303(d) of the federal Clean Water Act as impaired by too much sediment. This required that the Regional Board determine if aquatic habitat was indeed impaired by sediments, and then develop a plan for the protection of aquatic habitat and biota. This resulted in funding of a two-year study by Stillwater Sciences and the University of California, Berkeley to investigate the factors limiting populations of steelhead, Chinook salmon and California freshwater shrimp – all native species that are considered to be at risk (Stillwater Sciences and Dietrich, 2002) and a further study to determine a sediment TMDL (Napolitano et al., 2007) .

The main goals of the Stillwater Sciences and Dietrich (2002) study were to determine (i) the primary factors limiting populations of the aforementioned aquatic biota, (ii) the importance of sediment relative to the field of forcing factors, (iii) the actions needed to conserve and restore self-sustaining populations of the biota in question. This study involved the collection of new data sets to characterize factors affecting limiting populations of the aquatic biota of interest, including (i) documentation of channel pools filling with fine sediment, (ii) measurements of channel bed gravel permeability, (iii) duration of elevated turbidity following storms (surface grab samples, 18 sites in 16 tributaries after 4 to 5 storm events, and 6 mainstem sites after 5 storm events), (iv) stream temperature, (v) late dry-season surface flow throughout the watershed.

Only about 10% of measured pools were found to fill with fine sediment. Storm monitoring showed that turbidity values fell below the 10 NTU threshold of chronic impairment in 1–2 days after peak Q. Fine sediment impacts on the biota of interest appeared to primarily occur through fine sediment deposition in the channel bed – resulting in decreases in interstitial spaces, porosity and permeability. The authors compared the permeability values for Napa River and tributary stream beds with literature results to predict up to 50% or greater mortality rates of fish eggs and larvae before emergence. However, an aerial-imagery-based analysis of the mainstem of the Napa River found that much of its habitat loss for the fish of interest was related to incision of the channel by 4 to 6 ft. (1 to 2 m), which simplified the channel and reduced the quality and quantity of spawning grounds (gravel bars).

Despite the fact that fine sediments were not found to be the largest impact on the persistence of the aquatic biota, the results were sufficient to support a continuation of listing the Napa River and tributaries as sediment impaired by the SFBRWQCB, and a mandate for additional research to determine if fine sediment impairment was due to human influenced sediment sources. This study recommended that such research include a “detailed sediment budget to quantify relationships between land use and delivery of fine sediment to channels, and additional vigilance to prevent increased delivery, or preferably to reduce the delivery, of sediment to channels.” The recommended sediment source analyses are reported in Chapter 3 of Napolitano et al. (2007).

Napolitano et al. (2007) presented the development of a sediment TMDL for the Napa River watershed as well as plans to regulate and mitigate sediment supply to the channelized system and begin habitat enhancement/restoration. The primary foci of the sediment TMDL in the Napa River watershed were those defined by the study of Stillwater Sciences and Dietrich (2002), namely fine sediment deposited in channel bed gravels and channel incision. A novel aspect of this study is the presentation of channel incision as a ‘controllable water quality factor.’ Magnitude and spatial distribution of sediment supply to the channelized system was estimated as mandated by the TMDL development protocol (US EPA, 1991; 1999). They employed a ‘rapid sediment budget approach’ based on professional opinion, established empirical values, and limited field analysis to identify important processes of sediment production and estimate rates of sediment delivery to channels from 1994 – 2004.

This sediment supply assessment approach was founded on a spatial classification of the watershed area through the development of sediment supply terrain types that shared attributes related to operative sediment supply processes. Professional assessment of the region led to the identification of four major sediment supply processes. Sediment supply terrain types (derived from Ellen and Wentworth (1995) hillside material units) were based on the physical properties, spatial distribution and topography of regional geologic formations. The result was five terrain types: (i) hard rocks, (ii) sedimentary rocks, (iii) ash-flow tuffs, (iv) intensively deformed Franciscan mélange, and (v) a lowland terrain type. The first four types are listed in order of increasing erosion potential. Sediment supply was then linked to gravel permeability (the main environmental impact of interest), by testing the relationship between permeability, sediment supply and stream power. The results showed that higher sediment supply and lower stream power resulted in lower channel bed permeability. In this way the authors were able to quantitatively link sediment load with an in-channel habitat characteristic target.

2.6.2.2 UC Davis and US EPA Colusa Basin Study

Besides the previously describes studies driven by state regulators, there is another example of a sediment impact assessment study in California that is highly relevant to understanding what is possible to achieve with a relatively short-lived effort of a few years, but an appropriately substantial financial budget. In the late 1970s there was a UC Davis and US EPA study on nonpoint sediment production in the Colusa Basin drainage area (see Tanji *et al.*, 1978, 1980, 1981, 1983; Mirbagheri, 1981; Mirbagheri and Tanji, 1988a,b). This study explicitly focused on the processes controlling non-point source sediment production, composition and transport dynamics over the entire Colusa Basin drainage area. A major component of this study was the delivery of sediment best management practice suggestions for rangelands, cultivated lands and unpaved roads aimed at lowering the amount of sediment discharged from the CBD. The reports produced by this study are of particular interest as they present the most complete examination to date of the Colusa Basin watershed in terms of fluvial sediment production and transport dynamics and the identification of plausible controls on sediment erosion, transportation, deposition and resuspension.

Although the Colusa Basin includes a large, agricultural lowland unlike in Battle Creek, the uplands draining to those lowlands include the same kinds of land covers and land uses as present in Battle Creek for the same elevational range. Therefore the types of studies performed in that upper watershed are informative for what could be done for Battle Creek, not only for those land types, but also for the higher elevation forested mountains in Battle Creek Watershed. Sediment sources were approached through an assessment of the spatial distribution of erosion across the landscape and channelized system. This was conducted through a combination of field observations, plot-scale tests, rain simulations, and a watershed-scale sediment production model based on the modified Wischmeier and Smith Universal Soil Loss Equation (USLE). Geographic information was gathered to inform this model, which included the spatial distribution of soil types and characteristics, topographic relief, vegetation cover and land use. Elucidation of watershed-scale suspended sediment dynamics was approached through the (i) examination of SSC–Q relationships in terms of seasonality and location, (ii) computation of spatially and temporally explicit sediment budgets, and (iii) development of a 1-D sediment transport model. The spatial pattern of sediment fluxes was then used to assess the accuracy of the watershed-scale erosion model.

The Colusa Drain Basin example shows an effective approach to obtaining a short-term snapshot of sediment conditions, but it is important to understand that such an approach really needs to be done at least periodically as land use and climate conditions change, with some automated monitoring and supplemental sediment sampling performed continuously in perpetuity.

2.6.2.3 Deep Creek, Montana Sediment Assessment and Criteria Development

Endicott and McMahon (1996) produced a study of Deep Creek, Montana with goals to (i) identify non-point sources of fine sediment, (ii) develop TMDL targets for fine sediment, (iii) define remedial actions for achieving TMDLs, and (iv) develop a monitoring framework or assessing the efficacy for remediation. All of this work was motivated by trout fisheries in Deep Creek and water bodies that benefitted from trout spawning in its reaches. This study utilized comparison between water quality values and those of less impacted streams in Montana. Sediment source determination was achieved through analysis of suspended sediment data collected from stations on Deep Water Creek and tributaries, including rudimentary sediment load estimations. Channel banks were determined to be major sources of sediment on the basis of low estimations of sediment load from the tributaries, and professional assessment of the geomorphic trajectory of the Deep Water Creek Channel and banks. The development of a fine-sediment TMDL was based on suspended sediment concentrations and a very small data set on the particle size characteristics of trout spawning habitats (riffles).

3 EXISTING INFORMATION REVIEW

Battle Creek has been historically recognized as an important watershed for the recovery of diverse life histories and abundant populations of Chinook salmon (especially the spring-run) and steelhead trout (Terraqua, 2004). Many individual projects, reports, and documents have been completed in relation to processes affecting water quality. Previously published literature and other reports within the Battle Creek Watershed have addressed multiple factors affecting streamflow and sediment, and their implications for water quality.

All publicly available information related to water quality in Battle Creek were located, compiled, and summarized. A database of existing information was developed to centralize important documents. A literature review of 59 sources including peer-reviewed journal articles, publications, reports from state and federal agencies, reports from local and private entities, books, and abstracts provides a synopsis of geomorphic processes. An existing information review of all previous geomorphic information and data pertinent to processes that affect water quality and the subsequent effects on habitat, the biological community, and salmonid restoration efforts is presented. Electronic copies of all literature and reports are provided in DVD format as supplemental material for the watershed assessment.

This section of the report is organized into eight subsections that address the different topics of watershed science relevant for sediment and its impact on water quality. The first two sub-sections address the landscape itself (Section 3.1) and how humans have altered it (Section 3.2). The next two sub-sections address climate as a driver for landscape processes in terms of natural disturbances (Section 3.3) and watershed hydrology (Section 3.4). Then the known facts about sediment conditions are laid out along with a description of local fluvial geomorphology (Section 3.5). The topic of aquatic biology comes next, as the effects of sediment on water quality are often evident in biotic metrics (Section 3.6). Finally, information about river management (Section 3.7) is provided along with internet links to key data sources (Section 3.8).

3.1 Landscape

Battle Creek is a mountainous catchment with volcanic bedrock and highly porous soils. The permeability of parent rock and overlying soil produces many snowmelt fed springs within the basin ensuring perennially flowing streams. The cold-water summer baseflows are prime habitat for anadromous fish species and support fall and spring runs for Salmon and Steelhead species. Battle Creek has unique geology and soil characteristics that have been geospatially mapped to provide comprehensive resources for evaluating landscape properties.

3.1.1 Geology

Battle Creek is located at the southern end of the Cascade Range in the northern Central Valley and flows into the Sacramento River at RM 272 (Ward and Kier, 1999). Approximately 368 square miles (953 km^2) of watershed include the Latour Buttes, the western slope of Mt. Lassen, and surrounding mountains. The headwaters begin in Lassen Volcanic National Park at 10,400 ft and carve through basalt canyons and foothills where its joins the Sacramento River at 335 ft elevation (Terraqua, 2004). The United States Geological Survey (USGS) published a detailed geologic map and report of Lassen Volcanic National Park (USGS,2010). Lassen Peak is a volcanic dome that produced basaltic and andesitic volcanic flows forming the parent rock for the Battle Creek watershed. The volcanic rocks underlain in Battle Creek are highly porous and have created a network of subterranean flow paths that emerge as cold water springs supplying year-round sustained base flows.

3.1.2 Soils

The United States Department of Agriculture (USDA) completed soil surveys for Shasta (1974) and Tehama (1967) Counties. Two main soil associations are present in the Greater Battle Creek Watershed: (1) the Cohasset-Windy-McCarthy association and (2) the Jiggs-Lyonsville-Forward association (USDA/NRCS, 1967; USDA/NRCS, 1974). The Cohasset-Windy-McCarthy association has dark brown to dark reddish brown soils derived from andesitic to basaltic volcanic rock forming thin to moderately thick layers that cover gentle sloping to rolling ridges capped by lava flows and very steep slopes of volcanic mountains. The Jiggs-Lyonsville-Forward soil association covers broad gentle slopes and ridges and steep slopes that flank incised stream channels. They are mostly light gray and are derived from rhyolitic to dacitic volcanic rock. The Jiggs soil is identified as being derived from rhyolitic parent material and is described as being sensitive to ground disturbance resulting from timber harvest. Rhyolitic soils are well known to be highly erodible sources of sediment.

3.1.3 Geospatial Data

The USGS National Geospatial Program, The National Map (TNM), is a collaborative effort among the USGS and its Federal, State, and local partners to improve and deliver topographic information for the Nation. Elevation, orthoimagery (i.e., georeferenced aerial photographs), geographic names, hydrography, boundaries, transportation, structures, land cover and more are provided in 30 m and 10 m resolution for use in Geographical Information Systems (GIS). Data are publicly available for download through the USGS website (http://nationalmap.gov/index.html).

The USDA National Resource Conservation Service (NRCS) provides spatially explicit soils information for the Nation. Web Soil Survey (WSS) is an Internet tool providing soil data and information produced by the National Cooperative Soil Survey. Soil maps and data are available online (http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm) and cover more than 95% of the Nation’s counties including Battle Creek.

The California Department of Forestry and Fire Protection’s Fire and Resource Assessment Program assesses the amount and extent of California’s forests and rangelands, analyzes their conditions, and identifies alternative management policy guidelines. They offer publicly available GIS data for the historical extent of wildfire in California through the CALFIRE portal (http://frap.cdf.ca.gov/index.php).

The U.S. Fish and Wildlife Service (USFWS) contracted Watershed Sciences, Inc. to acquire airborne near-infrared (i.e., terrestrial) Light Detection and Ranging (LiDAR) and true-color orthophotographs for Battle Creek on August 19th, 2011. The study covered Mainstem Battle Creek, North Fork Battle Creek, and South Fork Battle Creek resulting in 6,528 acres of coverage including a 100 m buffer on river corridors. It reports on the technical details of data acquisition, processing, accuracy assessment, and study results. The resolution is 9.13 points/m^2 with a project average accuracy of 0.06 m and vertical accuracy of 2.1 cm. A full report containing descriptions of the study area, methodology, and accuracy of measurement was delivered with point, vector, and raster data, and orthophotos (USFWS, 2011).

3.2 Anthropogenic Changes

Battle Creek has a long history of development dating back to the early 19th century. It has long been recognized as a key watershed for mitigating the effects of development to fish species in the Sacramento River Basin. Hydropower and timber harvest are the two main activities occurring in Battle Creek.

3.2.1 Hydropower

To put the impacts of hydropower into ane environmental context, approximately 250 miles of stream are fish bearing and 87 miles were historically accessible to anadromous fish species (Terraqua, 2004). The valley reach of Battle Creek is not significantly diverted allowing for year-round sustained flows to support anadromous fish species. Extensive hydropower development above the valley reach consists of many continuous small run-of-the-river facilities, which are those that store little water.

Hydroelectric development of Battle Creek dates back to the beginning of the 20th century with the construction of Volta Powerhouse by Keswick Electric Power Company in 1901 (Ward and Kier, 1999). The South and Inskip Powerhouses were constructed in 1910 followed by Coleman Powerhouse in 1911. Pacific Gas & Electric (PG&E) acquired the lot in 1919 and was licensed by the Federal Power Commission in 1932. PG&E secured a 50-year license in 1976. Volta II Powerhouse was constructed in 1980.

Currently, PG&E's Battle Creek Hydroelectric Project (FERC No. 1121) consists of five powerhouses (Volta, Volta II, South, Inskip, Coleman), two reservoirs (North Battle Creek and Macumber) three forebays (Grace, Nora, and Coleman), five diversions on North Fork Battle Creek (Al Smith, Keswick, North Battle Creek Feeder, Eagle Canyon, and Wildcat), three diversions on South Fork Battle Creek (South, Inskip, and Coleman), and a systemic network of tributary and spring diversions, canals, ditches, flumes, and pipelines (Ward and Kier, 1999) (Figure 3).

The Lassen Lodge Hydroelectric Project (FERC No. 12496) is located on upper South Fork Battle Creek near Mineral, Ca. The project proposed to divert water from 2.4 miles of stream reach before returning powerhouse discharge to the creek. The FERC licensing process required an assessment of potential impacts for the bypass reach on hydrology, biology, sediment transport, and geomorphology under a range of conditions. Other small hydroelectric projects exist in the greater Battle Creek watershed located outside of the Restoration Project boundaries. These projects include FERC No: 3948, 8357, 5697, 4714, 8476, and 8550. All PG&E FERC related documents can be found filed chronologically at the FERC Online eLibrary (http://elibrary.ferc.gov/IDMWS/search/fercgensearch.asp).

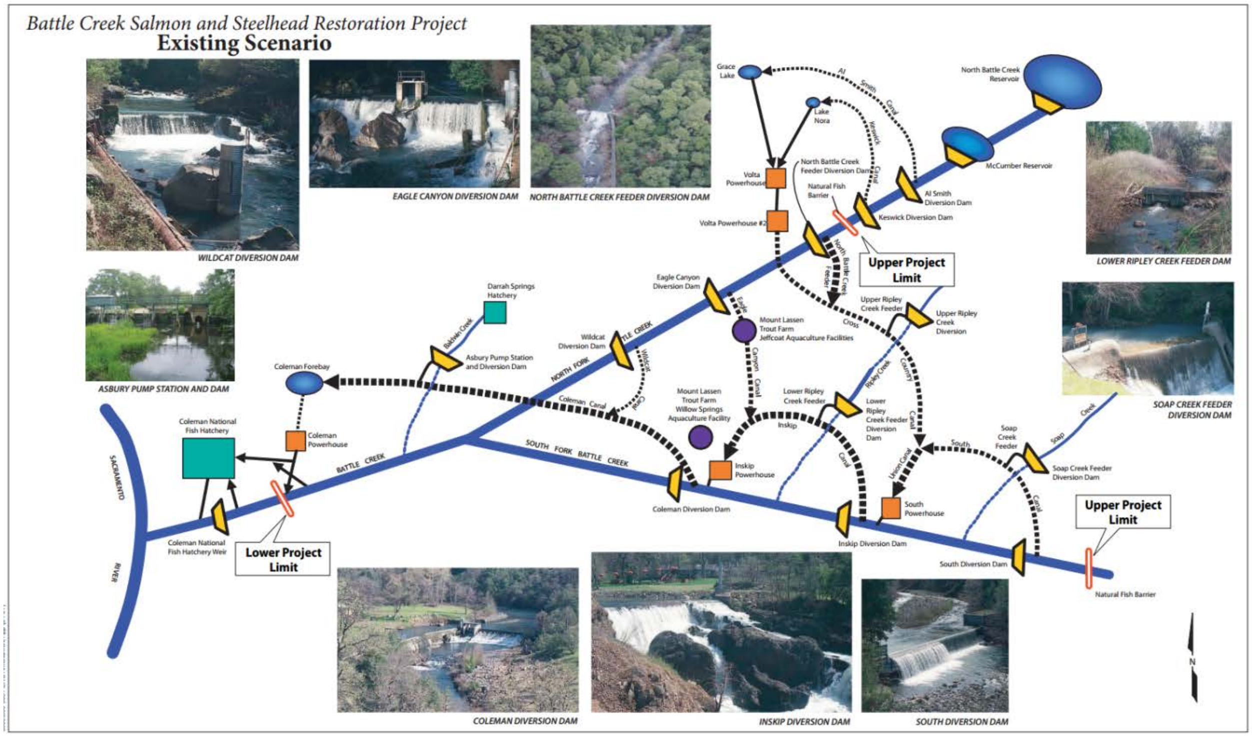


Figure 3: Existing hydro facilities in Battle Creek (from Battle Creek Restoration Plan, 2004).

3.2.2 Land-Use

A blend of private and public (Federal and State) landowners exist in Battle Creek. The headwaters of Battle Creek residing in Lassen Volcanic National Park operated by the National Park Service. The surrounding forest is maintained by the U.S. Forest Service (USFS) at elevations above ~ 6,000 feet. Sierra Pacific Industries (SPI) is a private timberlands company owning a substantial portion of the watershed encompassing both NFBC and SFBC from elevations ranging ~ 3,000 – 6,000 ft. For the lower watershed (below ~ 3,000 ft), cattle grazing is the predominant land use. Cultivated crops in the bottom land of the valley is < 0.1% of total land area.

3.2.3 Historical Logging

Aerial photos show that recent timber harvesting and clear-cutting operations are the dominant land use activities in the region. The California Sportfishing Protection Alliance (CSPA) evaluated historical aerial imagery in 2011 and reported in a letter to Marily Woodhouse of the Battle Creek Alliance (BCA) that 35% of the 85 mi^2 they investigated were clearcut within the past 9-12 years (CSPA, 2011). Google Earth imagery shows the absence of observable clearcuts in July 1999 (Figure 4) followed by a substantial area of clearcuts and its spatial pattern in April 2015 (Figure 5).

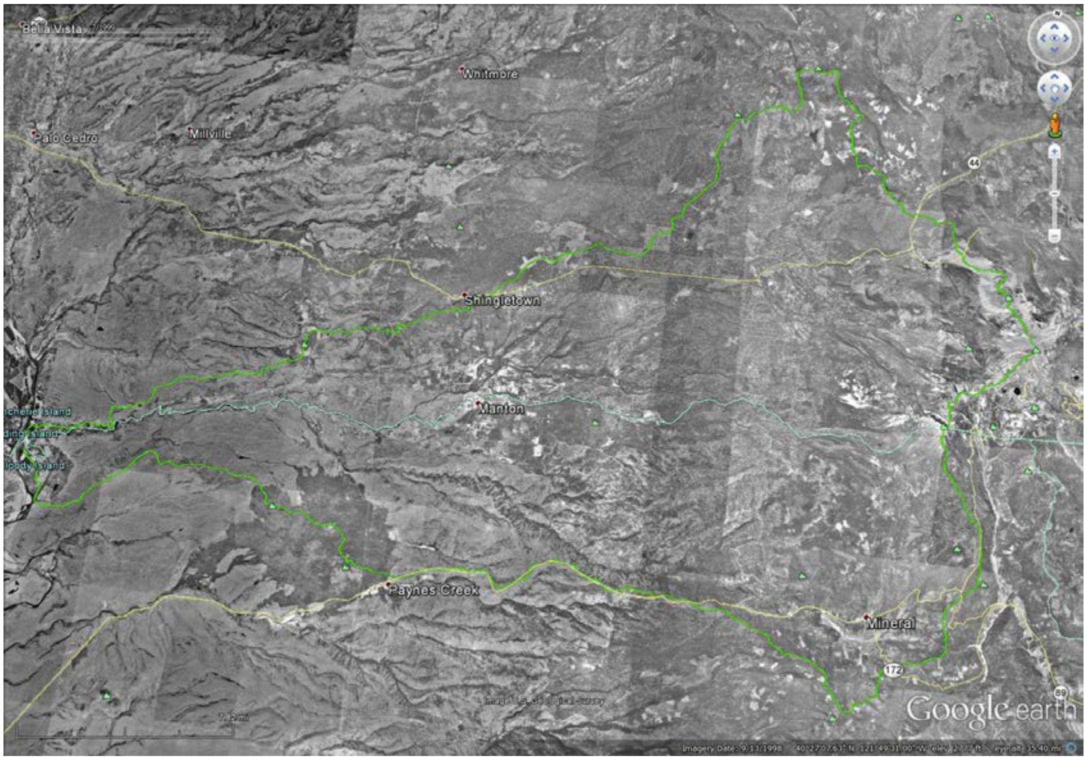


Figure 4: Google Earth image from July 1999.

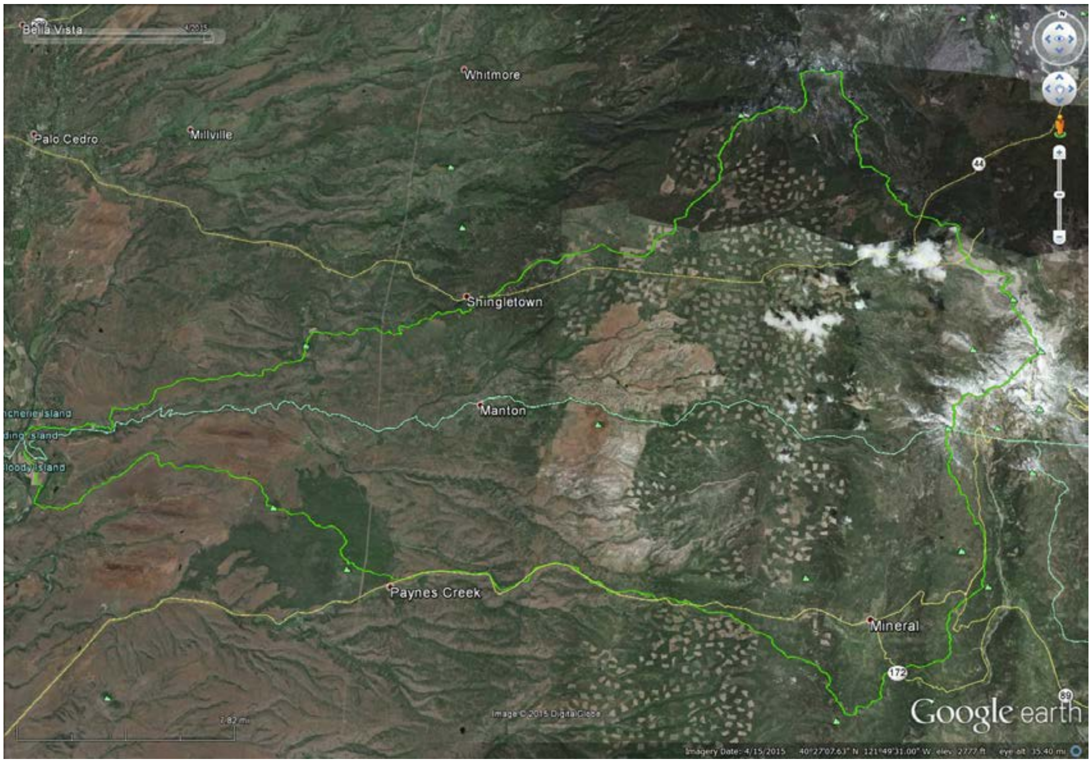


Figure 5: Google Earth image from April 2015.

3.2.4 Roads

Kier (2003) analyzed public versus private roads in Battle Creek. Road density for all sub-basins in Battle Creek was found to range from 1.06-6.26 mi/mi^2. This may be compared against the target value of 2.5 mi/mi^2 for anadromous fish habitat defined by USFS for all anadromous watersheds on Lassen National Forest (Armentrout et al., 1998). Higher road densities were observed on private timberlands. Road-stream crossing data ranged from 0.81-2.89 crossings per mile with a target goal of ≤ 2 stream crossings per mile. Roads near streams were evaluated and data illustrate the same trend of higher values on private vs. public lands. These values are interpreted as conservative due to lack of comprehensive data and errors associated with hydrography and road layers in the analyses. Roads on slopes ≥ 35% were recognized to have greater erosion potential.

3.3 Natural Disturbances

Flooding and wildfire are the largest natural disturbances affecting Battle Creek, though these are often exacerbated by historic and modern anthropogenic impacts. Sediment spends the majority of time in storage in a watershed. Floods are the primary movers of sediment in the fluvial system (Pizzuto et al., 2014). Wildfire alters the hydrologic response by reducing infiltration, evapotranspiration, and interception (Coombs and Melack, 2013) thereby increasing the potential for surface erosion and delivery to streams. Paleoenvironmental reconstruction of environmental history by coring and analyzing deposited sediment can reveal sequences of rapid sedimentation in response to logging and/or wildfire followed by period of sediment supply exhaustion and recovery (Constantine et al., 2005).

3.3.1 Floods

The largest discharge ever recorded for Mainstem Battle Creek was ~ 35,000 cubic feet per seoncd (cfs) in 1937 (Waananen and Crippen, 1977). Five major floods have been recorded with a magnitude over 15,000 cfs (Figure 6). In January 1997 a large flood struck Battle Creek. The USGS streamgage at Coleman National Fish Hatchery (CNFH) was temporarily rendered inoperable and did not record this event. A special Task Force documented significant road-related sediment delivery in 2011. Historical evidence of cutbank failures, fillslope failures, crossing failures, and inside-ditch incisions was observed and attributed to this event (Task Force 2011).

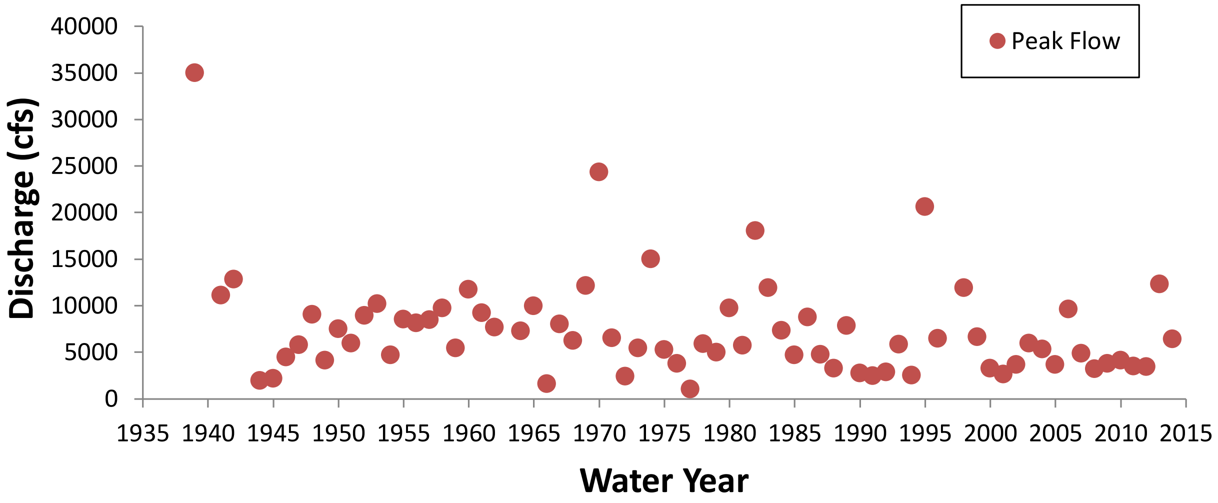


Figure 6: Annual peak flow for USGS streamgage at CNFH.

3.3.2 Wildfire

Battle Creek has a recorded history of wildfire dating back to 1911 (Table 2). The Ponderosa fire occurred in 2012 burning an area of 27,676 acres (Figure 7) of mixed confer forest encompassing ~ 9% of the watershed in both SFBC and NFBC (James, 2014). The Ponderosa fire was a natural disturbance severely impacting the watershed by removing vegetation cover, increasing the hydrophobicity of soils, and increasing the susceptibility of the landscape to surface erosion.

Sierra Pacific Industries (SPI) performed a field experiment evaluating hillslope response for delivery of sediment to streams from various post-salvage logging techniques. They employed ground treatments to select headwater sites and compared erosion results for WY 2013 by comparing average total pounds per acre for treated and non-treated sites. James (2014) report benefits from forest management on increasing infiltration rates and reducing hillslope length thereby limiting hillslope erosion and sediment delivery.

Table 2: Historic wildfire information for Battle Creek.

Year	Name	Acres
1911	n/a	1458
1911	n/a	584
1917	n/a	248
1917	n/a	2194
1917	n/a	322
1917	n/a	1681
1917	n/a	319
1917	n/a	1974
1917	n/a	309
1917	n/a	478
1917	n/a	585
1918	n/a	16112
1919	n/a	510
1920	n/a	296
1920	n/a	202
1924	n/a	255
1926	n/a	4641
1926	n/a	2391
1926	n/a	907
1926	n/a	483
1926	n/a	637
1928	n/a	657
1928	n/a	339
1929	n/a	200
1929	n/a	111
1931	MANZANITA CHUTE	4391
1931	n/a	295
1931	n/a	1384
1931	n/a	1476
1931	n/a	673
1931	n/a	286
1932	n/a	193
1939	n/a	205
1939	PAYNES CREEK	10529
1939	n/a	13
1941	SUPAN	4951
1943	BATTLE CREEK	1080
1943	BAILY THICKET	263
1943	n/a	316
1944	WRIGHT	646
1946	JEFFCOAT	388
1946	n/a	1371
1946	n/a	292
1948	MANTON	8605
1950	MANTON	972
1952	COLEMAN FORBAY	538
1955	HIGHWAY 36 #1	351
1955	HIGHWAY 36 #1	890
1961	SOAP BUTTE	10633
1962	DUNCAN R.I. ESCAPE	736
1963	COLEMAN FOREBAY	664
1963	DEADHORSE	692
1963	n/a	709
1969	MANZANITA	631
1969	MANZANITA	517
1973	INSKIP GRADE	19561
1974	BATTLE CREEK BOTTOM	1700
1981	MANTON ROAD SERIES	44
1990	BLACK #481	281
1990	FINLEY	35862
1998	POWERHOUSE	1996
1998	MANTON #3	1060
1999	SPRING	6456
1999	ROCK #4	517
2001	MANTON	54
2002	AMMEN	43
2003	RIDGE	49
2004	HAZEN	197
2004	COLEMAN	27
2005	MANTON	1822
2007	PONDEROSA	15
2007	SPRING	49
2008	SHU LIGHTNING	388
2012	PONDEROSA	27670

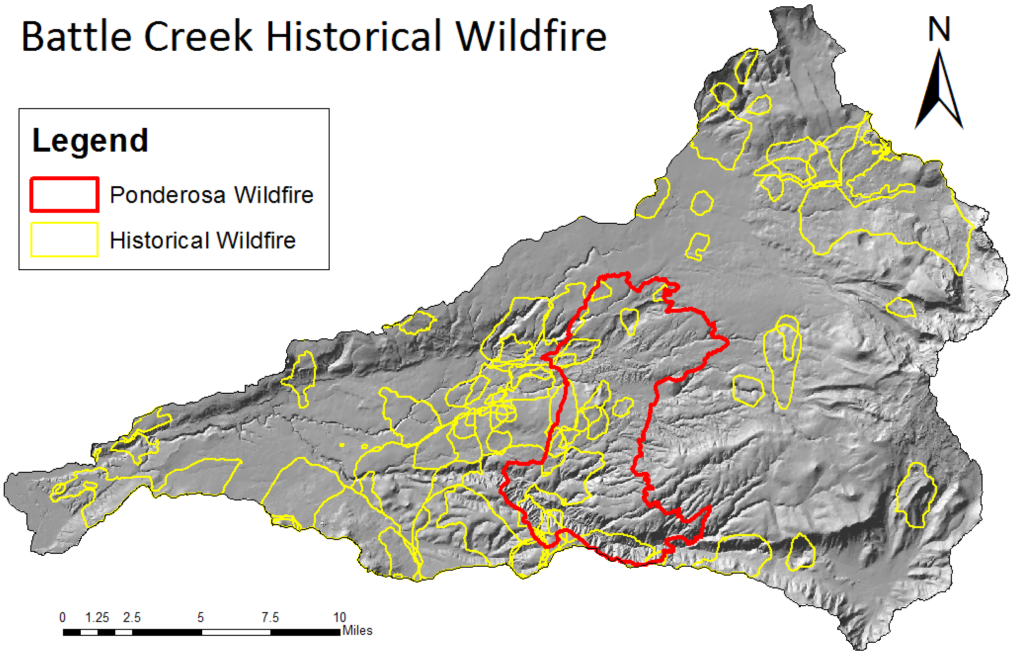


Figure 7: Locations of historical wildfires (yellow) and Ponderosa Wildfire (red).

3.4 Hydrology

Hydrology is the study of water storage and flux in the natural or disturbed environment (Viessman and Lewis, 2003). Hydrology integrates the basic principles of meteorology, biology, and soils, as well as physical, chemical, and biological characteristics of water itself. A watershed, also known as a catchment, is an area of land in which water flowing across the land surface drains into a particular stream or river and ultimately flows through a single point on that water course. The watershed is defined relative to a specific location along a water course and the associated area draining to the specified location (Hornberger et al., 2014). A watershed is a scale of measurement corresponding to any location along the river. Watershed hydrology is the application of hydrology encompassing all the hydrological processes occurring across the watershed, or at the watershed scale. Here hydrology is analyzed for Battle Creek at the watershed scale.

Among California’s watersheds of a similar size, Battle Creek experiences a distinct hydrology due to the volcanic nature of the drainage basin, which is not common in the state. Seasonal precipitation that falls as snowmelt high atop Lassen Peak percolates through the volcanic strata and emerges as cold springs ensuring a relatively high and stable baseflow (SRWP, 2010). The spring-fed nature of Battle Creek ensures that average September cold-water flows of 255 cfs reach the Sacramento River (Ward and Kier, 1999). Hydrology is explored though analyses of peak, seasonal, and synthetic streamflow data collected from existing streamgage infrastructure.

3.4.1 Streamgages

Battle Creek has three current streamgages measuring streamflow and temperature located on Mainstem Battle Creek (MSBC), South Fork Battle Creek (SFBC), and North Fork Battle Creek (NFBC) (Figure 8). Eleven additional streamgages measuring flow at diversions and reservoir levels are distributed throughout the basin at regulatory infrastructures (Figure 3).

Streamflow is the amount of water flowing in streams commonly measured in units of discharge and units of volume. Discharge, or rate of flow, is the volume of water passing through a particular reference point per unit of time (Veissman and Lewis, 2003). Discharge is commonly measured in the United States in units of cubic feet per second (cfs).

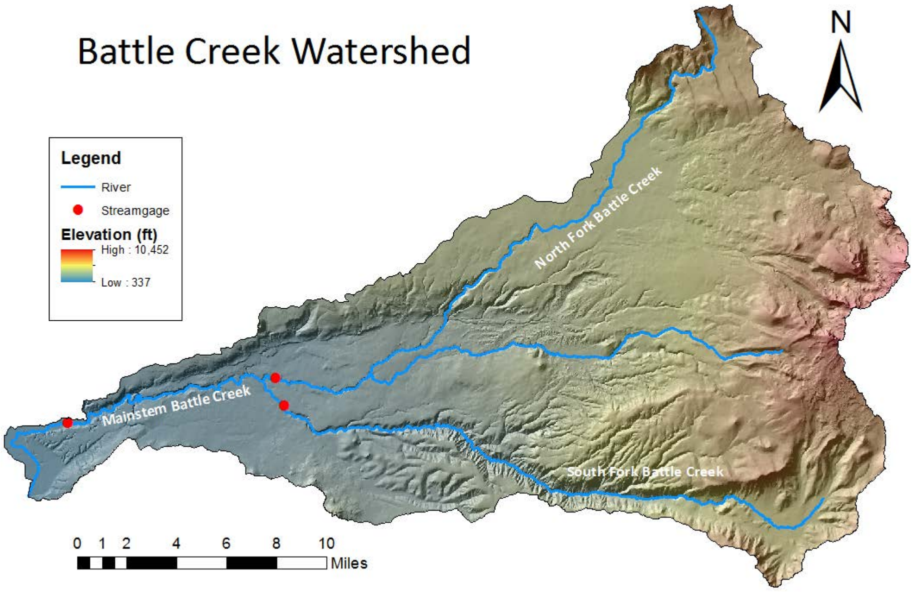


Figure 8: Streamgage locations in Battle Creek.

The USGS owned and operated a streamgage on MSBC located at Coleman National Fish Hatchery (CNFH) from water year (WY) 1941 – 1961 (11376500) and currently operates a streamgage from WY 1962 – present (11376550). The original gage was historically located ~0.6 miles upstream of the current site, which is immediately downstream of CNFH. Streamgages recorded water surface elevation (i.e., stage) at 15-minute intervals. USGS personnel measured discharge over a range of flows to develop discharge-rating curves. The rating curve was applied to stage records to calculate daily, monthly, and annual statistics for average and peak values of streamflow.

A streamgage on NFBC located approximately 0.9 mi upstream from the confluence with SFBC recording stage and temperature data was installed in 1999 by the California Department of Water Resources (CDWR) and began operation on October 21, 1999. Due to funding constraints, the NFBC streamgage was discontinued in WY 2012 - 2013. Funding resumed in 2014 and reactivated hydrologic monitoring at this site. DWR continued to record data unofficially during the deactivation period although no discharge measurements were recorded. DWR processed available streamflow data for WY 2012 – 2013 and applied a quality code of 70 (estimated data) to provide a continuous record in absence of sufficient funding for certified information (Personal Communication, CDWR). These data are included in the analysis.

A streamgage on SFBC approximately 1.4 mi upstream from the confluence with NFBC recording stage and temperate data was installed in 2000 by CDWR and began operation on June 26, 2000. Similarly to NFBC, funding constraints halted data collection during WY 2012 - 2013. Funding resumed in 2014 and reactivated hydrologic monitoring at this site. DWR continued to record data unofficially during the deactivation period although no discharge measurements were recorded. Data was not logged from this site from August 2012 through September 2013. DWR processed available streamflow data for WY 2012 – 2013 and applied a quality code of 70 (estimated data) to provide a continuous record in absence of sufficient funding for certified information (Personal Communication, CDWR). Unofficial data are included in the analysis, although no data exists for 8/20/12 – 9/30/13.

Streamflow data are publicly available on the USGS website (http://nwis.waterdata.usgs.gov/nwis) and the California Data Exchange Center (CDEC) website (http://cdec.water.ca.gov/). These data have been utilized for instream flow and hydrologic analyses previously completed. Historical operation for each gage is summarized in Table 3.

Table 3: Battle Creek streamgage operation.

River	Site ID	Operator	Duration
Mainstem Battle Creek	11376500	USGS	Oct 1940 - Sept 1961
Mainstem Battle Creek	11376550	USGS	Oct 1961 - Nov 1996 May 1997 - present
North Fork Battle Creek	A47190	DWR	Oct 1999 - present
South Fork Battle Creek	A47115	DWR	Jun 2000 - present

The USGS currently owns and operates streamgages on diversions and reservoirs distributed throughout the basin. These gages record the magnitude for regulated flows (Table 4). Data are publicly available on the USGS website and have been downloaded and plotted in Excel. See appendix 12.1 for plots of historical data through water year 2014. NFBC contains five diversions (Al Smith, Keswick, North Battle Creek Feeder, Eagle Canyon, and Wildcat) and three reservoirs (North Fork, McCumber) and one lake (Manzanita). SFBC contains three diversions (South, Inskip, and Coleman). All eight diversions are monitored for streamflow. The Battle

Creek Restoration Project incorporates the removal of specific diversion dams to increase access to spawning grounds for anadromous fish.

Table 4: USGS streamgage information for water regulation on North Fork Battle Creek (NFBC) and South Fork Battle Creek (SFBC).

River	Site Number	Site Name
North Fork Battle Creek	11376010	N BATTLE C RES NR MANZANITA LAKE CA
North Fork Battle Creek	11376015	NF BATTLE C BL N BATTLE C DAM NR MANZANITA LAKE CA
North Fork Battle Creek	11376025	NF BATTLE C BL MCCUMBER DAM NR MANZANITA LAKE CA
North Fork Battle Creek	11376040	NF BATTLE C BL DIV TO AL SMITH CN NR MANTON CA
North Fork Battle Creek	11376050	NF BATTLE C BL DIV TO KESWICK CN NR MANTON CA
North Fork Battle Creek	11376140	NF BATTLE C BL DIV TO XCOUNTRY CN NR MANTON CA
North Fork Battle Creek	11376150	NF BATTLE C BL DIV TO EAGLE CY CN NR MANTON CA
North Fork Battle Creek	11376160	NF BATTLE C BL DIV TO WILDCAT CN NR MANTON CA
South Fork Battle Creek	11376420	SF BATTLE C BL DIV TO S CN NR MANTON CA
South Fork Battle Creek	11376440	SF BATTLE C BL DIV TO INSKIP CN NR MANTON CA
South Fork Battle Creek	11376460	SF BATTLE C BL DIV TO COLEMAN CN NR MANTON CA

3.4.2 Flood Frequency Analysis

The US Bureau of Reclamation (USBR) evaluated the hydrology of Mainstem, North Fork, and South Fork Battle Creek using historical records of streamflow data from the USGS (Greimann, 2001). Historical records of streamflow from the CNFH streamgage were used to evaluate average flows over the period of record. They performed a log-Pearson Type III flood frequency analysis and calculated the 100-year flood event on MSBC as a peak discharge of 26,900 cfs. Streamflow at the USGS gage on Mainstem Battle Creek was extrapolated to North and South Fork and corrected for instream diversions using rating curves produced in HEC-RAS to derive unimpaired flows. South Fork Battle Creek was shown to have higher peak flows although it has a smaller drainage area then North Fork Battle Creek while North Fork Battle Creek contributes a greater proportion of total flow with higher mean annual flows.

More recently, the 2011 Battle Creek Rapid Assessment included a flood frequency analysis with combined peak-flow data from USGS streamgages (#11376550, #11376500). It estimated the 100-year recurrence interval peak flow to be 27,350 cfs using USGS PeakFQ software (Task

Force, 2011), so a little higher than the USBR estimate. The streamgage at CNFH became inoperable for a few months in January 1997 due to a high magnitude flood. The Taskforce (2011) reports the January 1997 event reaching a peak flow of 17,376 cfs, although these data are not available on the USGS website. This flood event is reported as the 5th largest flow recorded on Battle Creek since 1937 with an exceedance probability of 5.5% and return interval of 18 years.

Northwest Hydraulic Consultants (NHS) (2014) derived synthetic flows with separate wet/dry year spring high flow regressions that were selected to be the most representative for SFBC. The synthetic record was used for flood frequency analysis and to develop flow exceedance probabilities. These probabilities are for use in sediment transport analyses that will use a hydraulic model to identify flow thresholds needed to initiate transport and deposition. The synthetic raw data are provided in supplemental material in DVD format.

3.4.3 Seasonal Flows

The BCA hired Dr. Tom Myers to perform a study analyzing the cumulative watershed effects in Battle Creek in an attempt to identify target areas most affected by timber harvest activities (Myers 2012). Myers (2012) analyzed streamflow data from the USGS streamgage at CNFH (#11376550) from 1961 – 2012. He obtained precipitation data from PRISM (see Section 5.1.1 for description) and evaluated climatic trends in relation to runoff processes. He reported average monthly flow range from a maximum of ~ 700 cfs in March to a minimum of ~ 252 cfs in September with peak flows occurring in January through March. Myers (2012) found that rainfall is the primary driver of runoff with rain on snow events producing the largests floods when antecedent moisture conditions are elevated. Precipitation data displayed more variability then runoff data suggesting that flow may be dependent on previous year’s precipitation. Although this is generally observed in all watersheds, the degree of it in this data reflects the long flow paths for base and groundwater flow through the highly porous volcanic bedrock. January is the wettest month recording the highest average values for both precipitation and streamflow. Hydrologic history at Mainstem Battle Creek is discussed further in Section 5.2.1.

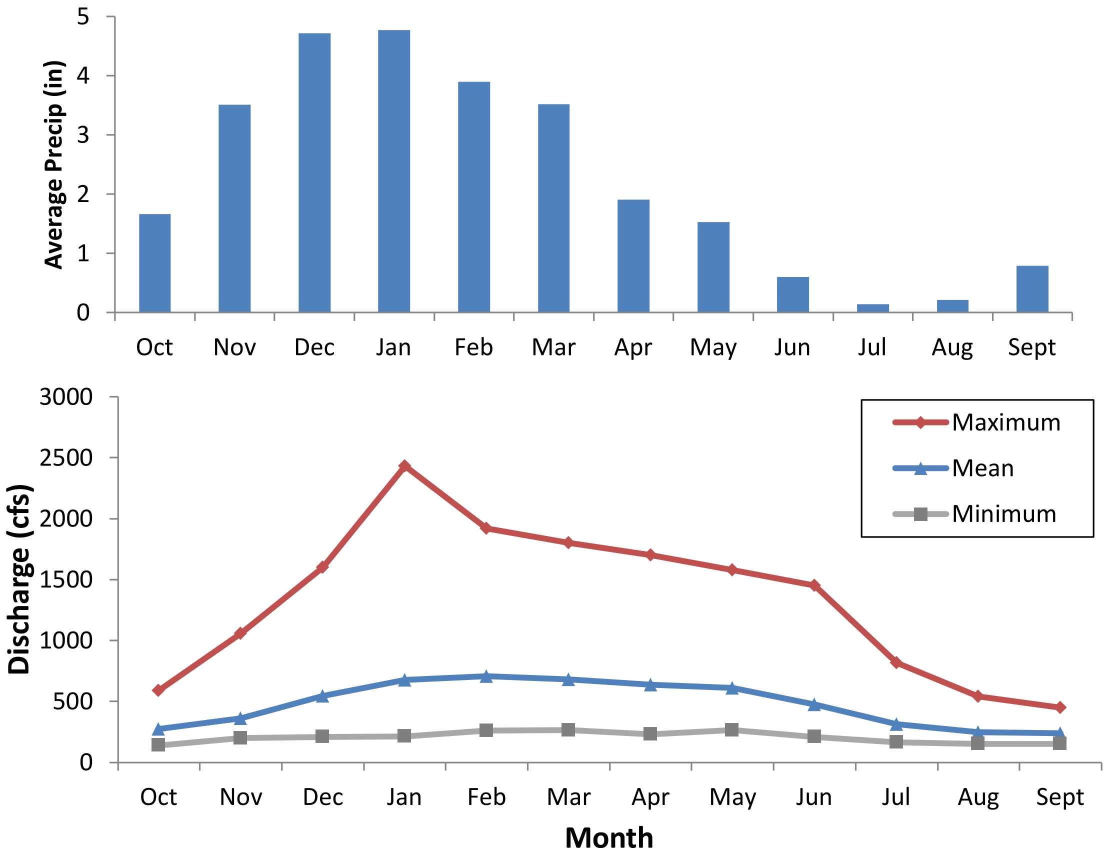


Figure 9: Monthly average precipitation (top) and average streamflow (bottom) for USGS streamgage at Coleman National Fish Hatchery.

3.4.4 Synthetic Flows

No extensive streamflow records existed at the proposed hydroelectric facility on SFBC near Lassen Lodge. Rugraw, LLC hired NHC to develop streamflow data for project operations and impact assessments (NHC, 2014). They used the nearby Mill Creek watershed to create a synthetic record by regressing the long-term daily flow record from Mill Creek on a daily streamflow dataset on SFBC from 1960-1967. Normalized daily flows were created with weighted drainage area and separate regressions were applied by water year classification.

A base streamflow study was conducted by Doug Parkinson to record the baseflow and accretion for the proposed Lassen Lodge Hydroelectric bypass on Upper South Fork Battle Creek over 5 days in September 2014 (Parkinson, 2014). Flow entering the bypass reach was measured at 0.5 cfs (RM 22.50) and exited the bypass reach at 28.3 cfs. A 1.6-mile stretch including Angel Falls within the bypass reach experienced no flow during the period of measurement. Multiple spring and tributary inputs between the upper and lower end show a 70-fold increase in base streamflow. The observed no flow stretch of river is located within the project reach. Further downstream, a significant increase in streamflow occurs from Panther

Grade to Ponderosa Way. A thorough photo-documentation of sampling sites displays stream conditions was provided. No interpretations were associated with the summarized results of the study.

3.5 Sediment and Geomorphology

Watershed managers often expect sediment abundance and distribution to reflect current watershed landscape conditions, including land cover, land use, topography, soils, and geology. In part, this expectation derives from the philosophy of Hack (1960), which traces back to G.K. Gilbert at the outset of the 20th century. As explained in Carley et al. (2012), in considering river adjustments and sediment flux in the context of landscape evolution, Hack (1960) summarized the concept of dynamic equilibrium in which all sections of a river network (and beyond) adjust to each other. For alluvial rivers, Hack (1960) relied on contemporary observations that indicated the presence of so many mechanisms of fluvial adjustment that equilibrium ought to be restored “very quickly, almost immediately” after a disturbance. Certainly Hack understood that change takes some time, but the question as to how and how fast a system adjusts under different settings is of central importance in geomorphology and river management and largely remains unanswered. Scatena (1995) reported time durations of centuries to millennia for turnover and recovery for sediments and landscapes in the highly responsive, dynamic tropical montane rain forest of Puerto Rico, but otherwise few such comprehensive analyses exist.

Multiple studies have addressed fine sediment in Battle Creek with conflicting results. Industry reported turbidity values indicate land-use does not have significant effects on water quality, while environmental and scientific reports interpret land use and cumulative watershed effects as inputs causing erosion and sedimentation. Although there are methodological problems with some of these studies as discussed below, a common conclusion has been that the large event in January 1997 overwhelmed the geomorphology of Battle Creek, with its disturbance sedimentation processes masking the long-term normative effects of upland sources contributing sediment through the system. In the case of Battle Creek, the salient question is whether Hack’s (1960) “very quickly, almost immediate” adjustment to the 1997 flood should be conceived of as occurring in years, decades, centuries, or millennia. Insufficient monitoring has occurred to answer this question. It should be expected based on Scatena (1995) that corresponding time durations for disturbance recovery in Battle Creek’s dry summer subtropical climate would be even longer than for the tropical montane rain forest of Puerto Rico, because normative rainfall, runoff, and fluvial processes are required for recovery, but these can be highly intermittent given the region’s climate.

3.5.1 Suspended Sediment Concentration

The USGS collected sediment data at the CNFH streamgage from 1957 – 1961 (#11367500) and 1962 – 1970 (#11376550). They measured total suspended sediment concentration (SSC), mineral content, particle size distribution, and specific conductivity (SC). Myers (2012) evaluated historical records of sediment data from 1962 – 1970 during a period of relatively average streamflow. Data were interpreted as representative of sediment relations without the influence of substantial management or extreme flood or drought events. He created sediment-rating curves relating SSC to streamflow and SC to streamflow. Myers (2012) reported that a threshold value of ~ 600 cfs is needed to initiate a significant increase in sediment concentrations. Grain-size analysis indicated variable sand fractions in SSC showing watershed scale dependency of runoff process such as overland flow, interflow, and groundwater flow. SC displayed two distinct trends reflecting the mixture of surface and groundwater at less than 700 cfs and of surface runoff at higher flow rates. These findings indicated the complex interaction of surface and subsurface water on runoff over a range of flows.

3.5.2 Fine Sediment

Sources of fine sediment including roads, timber harvest clearcut units, and logging infrastructure are reported as delivering sediment to streams (Ward and Moberg, 2004; Kier Associates (KA), 2009; Myers, 2012) although these results are in direct conflict with a 2011 rapid assessment performed by Task Force (2011).

The 2001-2002 Battle Creek Watershed Assessment (BCWA) measured fine sediment in scour pool tailouts at 50 sites in the Battle Creek watershed and attempted to relate the differences to watershed-scale factors. Surface fine sediment ≤2 mm was measured at 35 of 50 sites as a result of algae at seven sites and lack of scour pools at eight sites. Ward and Moberg (2004) reported mean percent fine sediment of 31%. Fine sediment conditions at 8 of 35 sites were fully or likely favorable using Ecosystem Management Decision Support (EMDS) models. EMDS models quantify overall biological conditions. EMDS modeling assigns “truth” values returning a measure of certainty that a premise is true or false (Figure 10). Conditions at 22 sites were designated as fully or likely unfavorable using the EMDS criteria. They found no statistically significant relationship linking surface fine sediment to watershed-scale factors, including elevation, watershed area, roads, precipitation, soils, and land cover. Lack of a positive relationship was interpreted to be due to the overwhelming effect of a large storm in January 1997 that delivered a lot of sediment to the river, purportedly masking the long-term balance of sediment sources and sinks of fine sediment that might be reflected in pool tail outs. Alternately, pool tailouts could be poor locations to look for the watershed-scale signal, because local fluvial processes that were not investigated in this study primarily control pool scour and deposition processes in those locations (MacWilliams et al., 2006; Brown and Pasternack, 2014).

Kier (2009) analyzed spatial data for the 2001-2002 BCWA and reported levels of fine sediment and median particle diameter (D50) outside the optimal range according to EMDS criteria. They reported results that were consistent with high sediment supply and increased peak discharge measured from the previous study. Battle Creek GIS data showed patterns of upland disturbance that likely drove mechanisms generating sediment production (KA, 2009).

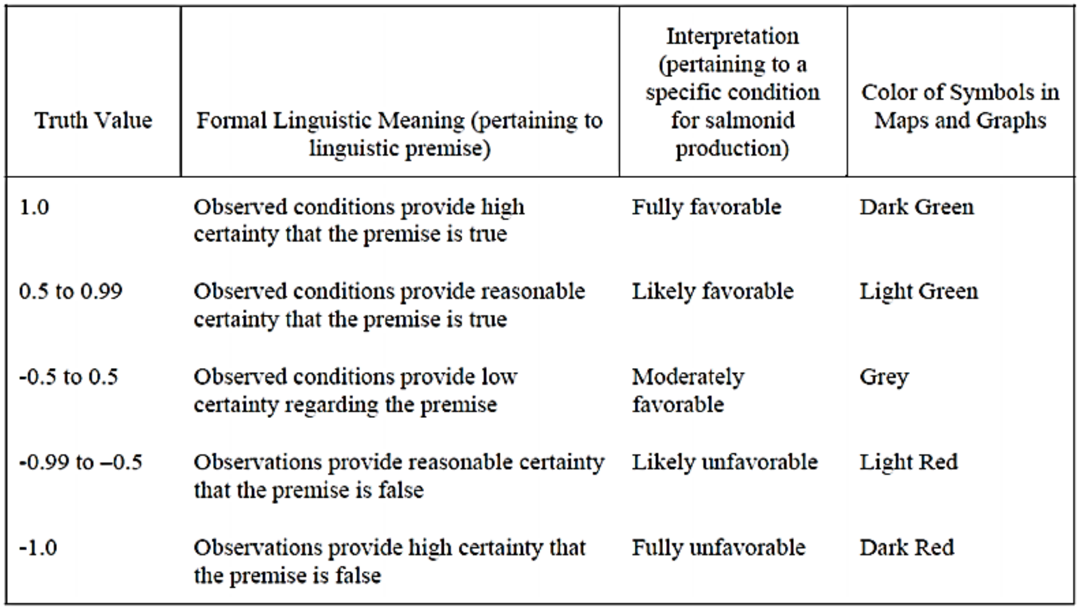
In 2011, a multiagency special task force was assigned to perform a rapid assessment on sediment delivery from timber harvest activities in the Battle Creek watershed. Over five days, a detailed survey of potential sources and pathways impacting water quality at 135 sites associated with logging operations were evaluated. Sites included 58 clearcut harvest units, 39 road-stream crossings, 6 vehicle and equipment landings, 5 tractor-stream crossings, 24 stream-adjacent road segments, and 3 other sediment sources. Out of 132 sediment source sites associated with streams and swales, they observed:

1) 39% of these sites delivered sediment
2) Only one out of 55 clearcut harvest units delivered sediment
3) 69% of road crossings delivered sediment
4) 67% of stream adjacent road segments delivered sediment
5) 100% of tractor crossings delivered sediment
6) 17% (1/6) of landings delivered sediment

Results displayed that road crossings and road segments have a higher number of sites contributing sediment than clearcut units, although the volume of sediment was not reported. Lack of sediment production from clearcuts is explained as high surface cover and contour ripping post-harvest. They also credit riparian buffer strips with halting the transport of sediment from harvest units to streams. The impact to downstream fish and aquatic habitat given the relatively low inputs of sediment from clearcut activities was uncertain. Sediment delivery from roads and crossings was found to be a chronic problem that may result in impacts to anadromous fish and their habitats. More extensive monitoring and data collection was recommended to determine the impact of timber harvest activities on fisheries in Battle Creek.

Myers (2012) reported observing clearcuts with substantial debris and soil erosion. Watershed sediment production to downstream gaging stations is a long-term process and clearcuts with no cover generate sediment that may have travel periods of years to decades before delivering to streams.

Myers (2012) compared sediment data collected in the 2001-2002 BCWA (Ward and Moberg, 2004) to the resampling data collected in 2006 (Tussing and Ward, 2008). The amount of fine sediment was found to decrease over this time period in the watershed. No positive correlations between fine sediment and sediment-source variables were present in the 2001-2002 study. Myers (2012) interpreted the lack of correlation as possibly due to sampling techniques that focused on observations of fine sediment abundance at pool tailouts. Pools are natural scour features which also contain the signatures of local effects on sediment characteristics. At some relatively low flows, pool tailouts may receive fine sediment deposition, but at higher flows they predominantly scour. Whether they then deposit sediment on the falling limb of a hydrograph is highly variable, largely controlled by local hydraulic controls and processes associated with local sediment sources. Variables affecting fine sediment deposition may also be influenced by cumulative variables upstream of measurement sites that are not independent of each other. Note that twelve of 49 study sites have multiple channels and this channel pattern was interpreted by KA (2009) to reflect an increase in sediment load from logging, but it could also be related to geomorphic factors. The 2001-2002 study speculated that a large storm event in January 1997 overwhelmed the system causing a significant sediment wave, but did not substantiate the claim.



Truth Value	Formal Linguistic Meaning (pertaining to linguistic premise)	Interpretation (pertaining to a specific condition for salmonid production)	Color of Symbols in Maps and Graphs
1.0	Observed conditions provide high certainty that the premise is true	Fully favorable	Dark Green
0.5 to 0.99	Observed conditions provide reasonable certainty that the premise is true	Likely favorable	Light Green
-0.5 to 0.5	Observed conditions provide low certainty regarding the premise	Moderately favorable	Grey
-0.99 to –0.5	Observations provide reasonable certainty that the premise is false	Likely unfavorable	Light Red
-1.0	Observations provide high certainty that the premise is false	Fully unfavorable	Dark Red

Figure 10: EMDS truth values taken from Ward and Moberg (2008).

3.5.3 Turbidity

Turbidity has been monitored by SPI and the BCA in recent history. SPI has reported no elevated levels of turbidity due to best management practices, while the BCA has reported extreme effects in turbidity levels. Turbidity is an optical characteristic of water measuring the cloudiness of liquid used as a surrogate for suspended sediment transport. The presentation of results can often be construed to provide evidence for interpretations and should always be viewed with a cautious and inquisitive eye.

SPI owns and operates six water quality monitoring stations on private timberlands acquired in 1992. Extensive logging occurred on SPI's ownership from 1998 – 2012. Turbidity was measured at 15-minute intervals with turbidity sensors and water levels were measured at five sites with

Design Analysis H355 gas bubblers and at South Fork Digger Creek with a pressure transducer (James and MacDonald, 2012). Sites were visited weekly for maintenance. Discharge was manually measured. SPI maintained two weather stations in Baily Creek installed in 2002 and one station in South Fork Digger Creek since 2011. Turbidity data was evaluated to assess the impacts of timber harvest practices and their effects on water quality (James, 2011; James and Macdonald, 2012). Three stations located in the Bailey Creek watershed, a tributary to NFBC, were thoroughly analyzed for continuous turbidity. James and Macdonald (2012) presented turbidity results binned in classes from 0-5, 6-25, 26-50, and 51-100 Nephelometric Turbidity Units (NTUs). They compared the frequency distribution of mean daily turbidities by turbidity class for each site. They also grouped all three sites in Bailey Creek and analyzed the cumulative frequency distribution of mean daily and mean hourly turbidity. No significant differences between daily and hourly data were observed. Turbidity values ≥ 25 NTU were only observed 0.5% of the time in Bailey Creek. Analyzing the number of hours per day with mean hourly turbidities ≥25 NTUs from all three sites indicates that high turbidity events were short lived. For all sites, only 3 of 8013 days of streamflow with valid records had 20 or more hours with mean turbidity values ≥ 25 NTUs. The duration of high turbidity events were much shorter than that shown to adversely affect salmonids in laboratory studies. James and MacDonald (2012) reported for all valid records for each of the six water quality monitoring sites, mean daily turbidity values ≤ 5 NTU occurred 82% of the time. Less than 1% of values were above 25 NTU. The trend in high turbidity values lasted 6-8 hours and there were no continuous days of elevated turbidity values above 25 NTU. Results displayed a low frequency and duration for turbidity values were interpreted as indicating a lack of turbidity as a threat to native salmonid species. The presentation of results is weighted by the effects of more dry days occurring then wet days. Turbidity occurs when it rains and since rain is short-lived the results that turbidity is short-lived are to be expected. An analysis of what percent of time during storm runoff with turbidity values ≥ 25 NTU would be more representative of sediment transport then comparing with the entire duration of flow records.

The BCA is a nonprofit organization that began measuring turbidity at 13 locations in the Battle Creek watershed in 2009 (Woodhouse, 2011). Turbidity was measured using a portable turbidimeter in the field at irregular intervals roughly every 7-12 days and after storm events. The CSPA compared turbidity data collected by the USFWS from 1999 – 2001 at CNFH to BCA turbidity data from 2009-2011 (CSPA, 2011). The USFWS data represent pre-clearcut conditions and the BCA data represent post-clearcut conditions. CSPA (2011) found timber harvest activities to be the dominant land use in Battle Creek, including harvesting 35% of forested land from 2001 – 2011. Post-clearcut data had higher turbidity values then pre-clearcut data indicating an effect of harvesting. The BCA monitoring program data registered at least 100 occurrences of exceedances of the Basin Plan Water Quality Standards for turbidity.

Myers (2012) discussed turbidity data collected by the BCA and evaluated correlation between turbidity and runoff. Correlation between North Fork and South Fork Sites with substantially different management and soils demonstrated further need for assessing watershed scale management impacts. Myers rigorously criticized industry-reported turbidity data from SPI as misleading based on data presentation methods, stating that large effects on turbidity may occur 10 – 15 years after harvest and results should be presented by year to make comparison amongst sites.

The BCA hired Jack Lewis, a statistical hydrologist, to analyze the proportion of watershed harvested vs. turbidity values to evaluate the effects of harvest intensity on turbidity values at study sites. Lewis (2014) used Google Earth to estimate the harvested proportion of clearcut units based on an average size clearing of 20-25 acres and counting the number of cutblocks within each drainage. The Ponderosa Fire occurred in 2012 burning approximately 27,000 acres that was subsequently salvage logged (James, 2014). Turbidity data were collected at sites and analyzed for prefire, postfire, and post salvage logging. The proportion harvested was estimated for each drainage at the time of BCA sample collection. Turbidity and proportion harvest metrics were analyzed with simple linear regression on individual sites and multiple regression on all sites combined.

Lewis (2014) reported that the findings clearly state turbidity is positively correlated with variations in harvesting among all sites. Statistically significant elevated turbidity values were reported with greater proportion harvested for all sites. Predicted change varied from 46% for harvesting 10% of a watershed to 4300% for harvesting 100% of a watershed. Post-fire trends indicated significantly increased values of turbidity. Lewis (2014) found a correlation between turbidity and discharge. After removing the variability due to discharge, the remaining variability was interpreted as related to the proportion of watershed harvested. Regression techniques showed positive trends in turbidity values at most sites. Sites that were not burned and hadn't been harvested since 2010 showed decreasing turbidity in 2014 and were interpreted as recovering from legacy effects of harvesting. No results on a storm event basis were presented. Alternative sources of variability such as geology, topography, precipitation, and other land-use were not expected to have a systematic component present in multi-year trends and were dismissed as not influencing turbidity values. The effects of these alternative sources are explored using GIS in Section 7.

3.5.4 Gravel

Thomas R. Payne & Associates (TRPA) was hired by the Department of Fish and Game to investigate gravel resources associated with the impacts of the Battle Creek Hydroelectric Project on aquatic habitat and fisheries. This study was commissioned with the recognition that understanding the distribution of spawning gravel related to physical factors is vital for quantifying the availability for salmon spawning in Battle Creek and evaluating the need for gravel augmentation. For this reason, the mobility, quality, and effects of sediment management practices were examined in detail.

A large total gravel area was found in the Battle Creek watershed, with 57,275 ft^2 of gravels estimated in MSBC, 101,422 ft^2 estimated in NFBC, and 28,042 ft^2 in SFBC (TRPA, 1994). Gravels were commonly distributed at concentrations ≤ 2 ft^2/ft^2. Larger concentrations were found upstream of Coleman Powerhouse and downstream of Macumber Reservoir. Lower stream gradients were related to higher gravel concentrations, although this relationship did not hold for certain restricting local factors.

Five types of gravel formations including general, riffle, and bar type formations were categorized at study sites. Deposit types were analyzed with local gradients and found to be associated with slopes ≤ 1.5%. Higher gradient reaches had spawning gravels associated with large boulders creating local controls for sediment deposition. Mean gravel particle diameter was within the range used by salmon and trout species. Fine sediment concentrations were observed within accepted standards from various lab and field studies. TRPA (1994) also assessed gravel mobility by comparing channel cross-sections before and after high flows in 1989. Little net change was observed at five cross-sections for high flows in 1989, although both aggradation and degradation occurred. Analysis of flow records indicated the mobility of bed material tends to occur every 2-3 years.

Although there was a lack of recorded evidence of sediment management practices , TRPA (1994) recommended operational management techniques in relation to sluicing protocols, actions, and monitoring for PG&E to augment potential impediments to sediment transport for watershed infrastructure. They found no significant effects on sediment posing threats in Battle Creek that demanded immediate remediation.

3.5.5 Sediment Transport

Greimann (2001) assessed stream hydraulics at Inskip Powerhouse and South Powerhouse using HEC-RAS to develop water surface elevations for flows derived from a flood frequency analysis. HEC-RAS is the U.S. Army Corps of Engineers one-dimensional computer model for simulating water surface elevation and cross-sectionally averaged velocity at measured cross-sections along a river given topographic, hydrological, and river roughness inputs. Cross-sections near Inskip Powerhouse gave data for pre- and post-removal of Coleman Dam. Local scour at South Powerhouse was analyzed using sediment transport models and empirical equations. The channel was observed to be stable in the vicinity of South Powerhouse. Maximum scour occurring during floods was not expected to cause long-term degradation. A peninsula existed downstream of South Powerhouse and channel design recommendations for the installation of instream riprap were presented. The 100 -year flood and potential scour from sediment transport modeling were integrated into the recommended design for riprap bank protection.

3.5.6 Fluvial Geomorphology

Terraqua Inc. conducted a watershed assessment in Battle Creek collecting field data on various metrics in 2001-2002 to characterize the health of the watershed for anadromous fish species and to identify sources of sediment potentially impacting aquatic habitat (Ward and Moberg, 2004). Field data were analyzed to evaluate whether stream conditions were favorable for salmonid production at 50 sites within the study area. Stream conditions were documented for use as a baseline in further studies. Field variables including fine sediment in pool tails, median substrate particle size, pool frequency, residual pool depth, and instream wood were quantified. GIS analysis characterized potential controls from land-use including; road density, near-stream road density, road-stream crossing frequency, susceptibility to “rain on snow” events, presence of erosive rhyolitic soils, forest cover, near-stream meadow areas (KA, 2003). Watershed scale controls included watershed area, elevation, and stream gradient.

Terraqua (2004) followed the Aquatic and Riparian Effectiveness Monitoring Program (AREMP) protocol guidelines for data collection for the 2001-2002 BCWA. The AREMP is a data quality control protocol for the implementation of effective management of monitoring programs (Gallo et. al., 2003). Ward and Moberg (2004) randomly selected 50 sites in the Battle Creek watershed. At each site topographic surveys were conducted by collecting longitudinal profiles and cross-sectional profiles at 6 or 11 cross-sections per site dependent on whether the site was constrained or unconstrained. Streambed particle size was measured at 11 transects per site. The quantity of fine sediment was defined at pool tailouts. Large woody debris meeting size criteria were counted at logjams. Physical stream channel conditions were assessed using the EMDS model. This model ranks the favorability of productive habitat for salmonids based on empirical relationships. All physical and quantitative field variables measured in this study were assigned watershed averaged EMDS values for interpretation of the health of aquatic habitat (Figure 10). Ward and Moberg (2004) measured fine sediment in pool tailouts, median substrate grain size, and residual pool depths. Physical metrics were analyzed as dependent variables in a statistical analysis attempting to define watershed scale controls from land-use and basin characteristics. The analysis did not prove land-use and basin characteristics were statistically significant controlling factors on any of the three key stream condition indices. No specific conclusions on geomorphology were presented.

KA (2003) analyzed spatial data in relation to the 2001-2002 BCWC to assess upland watershed conditions. They evaluated potential risk from rain-on-snow events for elevations ranging from 3500 - 5000 ft. Fire history ranging from 1900 - 1997 was also analyzed with the assumptions that increased erosion occurs on land disturbed by fire and watershed effects are greater for more recent fires. Combined public and private land GIS coverage for date, size, location, and other relevant information were assimilated into the analysis.

KA further analyzed the 2001-2002 BCWA data in relation to upland management (KA, 2009). They noted many of the braided channels at sample sites were below areas with intensive timber harvest and high road densities, both potential sediment sources and mechanisms for increased peak flows to deliver the sediment. KA (2009) summarizes existing data from 2001-2002 BCWA and places the physical stream condition variables in a scientific context in regards to upland effects. KA (2003) perfomed a change-scene-detection analysis, and this suggested that changes in tree size and canopy cover were more extensive on private lands then on public lands. This trend extended to riparian corridors displaying larger, older trees on public lands.

Tussing and Ward (2008) characterized physical stream conditions by measuring fine sediment, particle size, pool frequency, and large woody debris. Mean particle size (D50) was quantified and compared for all 10 sites sampled in 2006. The mean particle size diameter in 2001-2002 averaged 77 mm and in 2006 averaged 111 mm. Scour pool frequency for the 10 sites in 2006 averaged 0.86 pools per 100 m and in 2001-2002 average 1.14 pools per 100 m of stream reach. For four sites, residual scour pool depths in 2001-2002 and 2006 averaged 0.71 m and 0.62 m respectively. Large woody material frequency was characterized at 10 sites from 2001-2002 as an average of 40 pieces per 1000 m of stream reach, while in 2006 the average was 25 pieces per 1000 m.

Tussing and Ward (2008) computed EMDS values for the unweighted averages of substrate, pool frequency, and wood frequency for comparison of overall physical stream conditions for the same 10 sites between the two time periods detailed above. An increase in physical stream conditions between 2002 and 2006 was observed and interpreted as watershed recovery from the January 1997 storm event. EMDS values of -0.31 and -0.24 were reported in 2001 - 2002 and 2006 respectively. Physical conditions were consistent with recovery since 2001 – 2002, although due to the small sample size statistical significance could not be assigned to variables. Physical conditions favorable for salmonid production remained low from EMDS truth values but increased since 2001 - 2002. The watershed scale EMDS truth value for biological stream conditions in 2006 was 0.76 indicating with reasonable certainty that conditions are “likely favorable” for salmonid habitat in Battle Creek and presenting a higher level of certainty over the 2001 - 2002 value of 0.59.

3.5.7 Cumulative Watershed Effects

The presence and absence of cumulative watershed effects in Battle Creek have been documented. Of six studies addressing the effects of land use on sediment, three reported a direct relationship while three indicated no directly observed correlations.

Most rivers are constantly adjusting to the input of water and sediment into the fluvial system yielding an approximate dynamic equilibrium over centuries (Bull, 1991). Cumulative watershed effects (CWEs) are defined as “all the effects on beneficial uses of water that occur away from the location of actual land use which are transmitted through the fluvial system” (Napper, 2001). CWEs may be either beneficial or adverse, depending on your point of view, and can result from land management activities in a watershed. Land use can alter the flow regime and sediment delivered to upset the streamflow/sediment transport balance that aquatic and riparian species are adapted to. CWEs in a watershed may present themselves as changes in runoff and sediment observable in streamflow and turbidity (Dunne et al., 2001).

Soil is a major source of sediment and is susceptible to compaction, displacement, erosion, nutrient cycling, and mass failure. Responses to CWEs include changes in hillslope and stream channel hydrology, chronic sedimentation, pulse sedimentation, and changes in woody debris. Napper (2001) evaluated the susceptibility to CWEs for nine subwatersheds in Battle Creek totaling 39,659 acres, by analyzing soil instability related to road density and timber harvest activities. She reported the likelihood of adverse CWEs to be low within all subwatersheds evaluated. Field observations indicated sources of non-point sediment exist associated with roads, landings, and skid trails. Napper (2001) presents alternatives to current harvesting practices that could reduce the potential impacts of non-point source pollution in Battle Creek.

The BCA hired Dr. Tom Myers to perform a study analyzing the CWEs in Battle Creek in an attempt to identify target areas most affected by timber harvest activities. Myers synthesized previous work on hydrology, turbidity, morphology, and suspended sediment to develop a conceptual flow and sediment transport model (Myers, 2012). He critiqued prior data collection methods and analyses from studies within the preceding decade and recommended the development of a numerical model to supplement the conceptual model he presented to simulate current and future flows and turbidity. Meyers (2012) also recommended that additional sediment, habitat, and morphology data should be collected and used to track and compare change over time. Recommended data collection methods included sediment sampling at the USGS streamgage, repeat sampling from the 2001-2002 BCWA with increased transects, and continued turbidity measurements from the BCA.

To predict future changes and make better management decisions, Myers (2012) presented a conceptual flow and sediment model detailing an academic review for governing hydrologic processes. Precipitation was the primary input. The conceptual model followed the path of water into, from, and through the watershed and included considerations of the interactions of vegetation, soils, and geology that control the development of streamflow with sediment transport capacity. Soils provided the sediment load and the stream network carried sediment through the basin.

Myers (2012) identified CWEs in Battle Creek as primarily arising from timber harvesting, road building, and water regulation resulting in changes in runoff, sediment transport, and turbidity. Removing canopy cover from clearcutting can have effects that alter hydrology, which compound as water moves downstream. Myers posited that Battle Creek may be reaching a threshold at which both runoff and sediment transport could substantially increase. He concluded with the statement that previous work was inconclusive on the status of the watershed to make informed decisions on future management.

KA (2009) addressed the CWEs risk for increased sediment yields and peak discharges for non-vegetated patches in areas receiving rain-on-snow events. The effects were expected to extend to lower elevations where intensive land use is widespread. System recovery from the 1997 storm was undocumented due to no basin-wide post storm study being conducted.

KA (2003) complimented the 2001-2002 BCWA using spatial data to further analyze potential sediment sources from land-use and management activities. They assessed multiple variables contributing to CWEs, which pose risks for elevated sediment yield. Landsat images were interpreted for upland and riparian areas as a surrogate for timber harvest activities in absence of harvest data. The effect of roads was analyzed using road density, road-stream crossings, and roads near streams on steep slopes. Rain-on-snow events, steep slopes, and wildfire were identified as important sediment sources in this study. KA (2003) posited that timber harvest on private lands where canopy cover was reduced over 25% for a sub-basin were of concern for increased delivery of sediment, particularly in the rain-on-snow elevation band where rhyolitic soils are present. Roads on steep slopes and adjacent to streams were noted as having high erosion potential in Battle Creek. The study suggested that roads and timber harvest might have combined to increase sediment risk, especially given geology and precipitation patterns. Areas covered with rhyolitic soils were the most sensitive to increased erosion where timber harvest occurs and steep slopes are present. Rain-on-snow events were found to have increased erosion potential on timberlands, areas of high road density, and steep slopes. Timber harvest in the region mainly avoided steep slopes and did not seem to combine together as a cumulative effect to exacerbate erosion, although roads on steep slopes can yield cumulative effects.

The condition and factors described above likely do not work independently yet contribute to CWEs. Whereas Ward and Moberg (2004) could not statistically link upland effects with sediment deposited in pool tailouts that are also heavily influenced by local fluvial processes, risk associated with cumulative effects as analyzed by KA (2003) is consistent with compromised aquatic habitat values, given that sediment eroded from uplands move into and through the river system over years to decades. The Task Force (2011) also failed to link timber harvest practices to CWE in the form of sediment delivery to stream channels.

3.6 Aquatic Biology

3.6.1 Benthic Macroinvertebrates

The Surface Water Ambient Monitoring Program (SWAMP) is a statewide monitoring effort designed to assess the conditions of surface waters through the State of California. Benthic macroinvertebrates are indicators of ecosystem health and are commonly used for stream assessments in California. SWAMP protocols describe methods for evaluating biological stream conditions and have been applied in Battle Creek.

The diversity of macroinvertebrates was characterized in the 2001-2002 BCWA to provide data for use in future habitat monitoring programs. Terraqua Inc. And Kvam Associates (2003) used the 2001-2002 BCWA data to produce a report on site-specific conditions and data exclusive to Battle Creek to assess biological conditions within the basin. Impairment scoring and multimetric indices produced in Oregon and Washington were applied in Battle Creek due to the lack of existing California standards and methodology.

Macroinvertebrates were sampled from 44 sites in Battle Creek over fall 2001 and summer and fall 2002 (Ward and Moberg, 2004). Sites were randomly selected and randomly subsampled for macroinvertebrate identification. The data were analyzed as abundance by taxa by site. Seven metrics and two multimetric indices were evaluated for each site. The metrics and indices were scored and then used to interpret stream conditions. Sites were classified as poor, fair, or good.

The Oregon Department of Environmental Quality Biotic Index (ODEC-BI) and Benthic Index of Biotic Integrity (B-IBI) were the primary metrics used to interpret stream health in Battle Creek. For both indices, 0% of sampled sites were in poor condition. Certain sites were identified as poor condition in specific metrics. Ward and Moberg (2004) present results for all metrics and indices by season of data collection. Graphical comparison of selected sites for metrics and indices displays thresholds for poor and good conditions providing a representative sample for sites within Battle Creek.

Tussing and Ward (2008) characterized biological stream condition with four biological metrics and indices measuring population abundance of macroinvertebrate communities. The Biological metrics were Sediment Sensitive Taxa Richness (SSTR) and Percent Sediment Tolerant Taxa (PSTT). Multimetric indices were believed to better detect habitat community disturbances in comparison to single metrics as they integrate biological attributes at ecosystem, community, population, and individual levels. The indices employed in this study included the Benthic-Index Biotic Integrity (B-IBI) and the Oregon Department of Environmental Quality- Benthic Index (ODEQ-BI).

Graphical comparisons and statistical testing were used to assess change in stream conditions from the original 2001-2002 study to 2006. Tussing and Ward (2008) reported an increase in favorable biological conditions from 2001-2002 to 2006. The average of all four biological metric EMDS truth values was 0.76 in 2006 and 0.59 in 2001-2002 and was statistically significant ($p < 0.005$). A Wilcoxon paired signed rank test for 43 paired sites displayed EMDS condition increases ($p < 0.005$) and supported the overall EMDS truth value results. Increased EMDS truth values indicated more favorable stream conditions for aquatic species.

KA (2009) interpreted the lack of positive scores reported in the lower Mainstem and South Fork Battle Creek for almost any macroinvertebrate index to be consistent with the pattern of upland disturbance and cumulative watershed effects.

Terraqua Inc. prepared an official stream condition monitoring plan (Ward et al., 2008) in Battle Creek to continue focused efforts for establishing trends through time in the basin, but it has not been funded or fully implemented yet. Monitoring within four subject areas was proposed:

1) Macroinvertebrate sampling annually during low-flow at the 50 sites from the 2001-2002 BCWA and analyze for acute and chronic trends
2) Physical stream condition and riparian monitoring at the original 2001-2002 BCWA 50 sites. Data was to be collected at 20 sites each year on a rotating panel with 10 fixed sites and 10 rotating sites to complete all sites each four years. Data was to be analyzed for long-term and multi-year trends.
3) Water temperature monitoring conducted at six locations in addition to USFWS sampling as part of ongoing adaptive management.
4) Land cover change performed using the California Land Cover Mapping and Monitoring Program (LCMMP). Data was proposed to be reanalyzed every 4 years coordinated with the duration for completion of physical stream and riparian condition monitoring.

A total annual cost for the SCMP of $85,663 was estimated in 2006. The proposed data collected was to be publicly available through the KRIS web-based database already housing many data and reports associated with the Restoration Project. BCWC submitted an ERP proposal for a Battle Creek Stream Condition Monitoring for Adaptive Management (Ward and Tussing, 2008) project requesting $445,225 from 2011 – 2012 that was not funded. The BCWC continues its efforts to gain funding to support monitoring continuing monitoring efforts in Battle Creek.

3.6.2 Salmonid Monitoring

The USFWS monitored juvenile and adult salmonids in Battle Creek in support of Adaptive Management for the Restoration Project. Studies include salmonid escapement estimates at CNFH and stream surveys documenting spawning distributions upstream of the barrier weir.

Annual reports from 2001- 2010 for adult and juvenile salmonid populations and habitat are available in the existing information report database.

3.6.3 Aquatic Habitat

The CDFWS, formerly the California Department of Fish and Game, contracted Thomas R Payne and Associates (TRPA) to conduct an instream flow aquatic habitat analysis of the Battle Creek watershed (TRPA 1995, TRPA 1998). Using the software Physical Habitat Simulation (PHABSIM), which is a component of the Instream Flow Incremental Methodology for assessing streams, TRPA developed statistical relationships between discharge and habitat availability for 52 river miles of Battle Creek. The objective of this study was to evaluate the impact of hydropower operation on aquatic habitat and fisheries in the watershed.

TRPA (1998) identified seven study reaches. Five reaches were selected as impaired by regulation and diversions. For the five selected study reaches, habitat mapping was used in the model to produce weighted usable areas (WUA). WUA is a habitat index, which varies by discharge in PHABSIM. Study reaches were categorized by macrohabitat and entered into a database creating a sequential map of habitat units. Some 149 transects were selected to model fish habitat availability as a function of discharge and were weighted in proportion to the abundance of each habitat unit type in the study reach. Hydraulic data including flow velocity and depth were collected for model calibration. Substrate and cover data and coding were integrated into the analysis. TRPA (1998) developed WUA vs. discharge relationships for each study reach for known resident fish species. WUAs in each study site were calculated over a range of flows. Fish habitat was modeled from developed rating curves over various life stages of target species. Payne (1998) presented habitat mapping, transect weight, hydraulic, substrate, and cover data, hydraulic calibration, and WUA vs discharge relationship results. The WUA curves for native fish were interpreted to illustrate the statistical variability of aquatic habitat availability with discharge. A more thorough understanding of results requires integration with stream hydrology, water quality, and fish species life stage periodicity.

Regulating instream flows was a key component of the Restoration Project (Ward and Kier, 1999) and was managed under the Battle Creek Hydroelectric Project (FERC No. 1121). Minimum instream flow proposals under the Restoration Project were to provide approximately 95% of estimated habitat for the most limiting life stage to fish production for a specific stream reach (PG&E, 2008). Increased minimum flow releases would have significantly affected wetted habitat (Jones and Stokes, 2005). Instream flows were heavily managed in Battle Creek and monitored through USGS streamgages located at water diversions.

Jones and Stokes performed site assessments for the California Red-Legged Frog (Jones and Stokes, 2001) and the California Spotted Owl (Jones and Stokes, 2002) as supplemental work to the Battle Creek Restoration Project. In both studies, they targeted the 11 sites on NFBC and

SFBC proposed in the Restoration Project. Only 1 mile within 1 project area evaluated would provide suitable habitat for red-legged frogs. In 2001-2002 spotted owl surveys, no owls were detected.

Surface water sampling spatially distributed on SPI private lands found no reportable detections of herbicide materials in watercourses over 11 years of surface water sampling, although the lack of detecting presence does not prove absence.

3.7 Management

Battle Creek has experienced a long history of management in relation to water regulation infrastructure (Section 3.2.1) and fish hatcheries (Section 3.7.1). In recent years, stream restoration has been a major topic as an approach to facilitate recovery of sustainability of salmonids (Section 3.7.2). Restoration planning requires a collaborative effort, including adaptive management (Section 3.7.3). Many restoration plans and management strategies have been completed to define and guide the objectives towards restoring Battle Creek to a sustainable watershed providing viable aquatic habitat.

3.7.1 Fish Hatchery

In 1895 the first fish hatchery was constructed on Battle Creek and remained in operation until 1945 when a new set of threats to native fisheries was created from the Shasta-Keswick Dam complex. The Coleman National Fish Hatchery was erected in 1943 in response to threatened native salmon and steelhead species cutoff from their spawning grounds from the construction of the Shasta-Keswick dam complex (Black, 2001). The Central Valley Project included a Battle Creek Salvage Plan to mitigate the effects of Shasta Dam by augmenting spring and fall run Chinook fisheries.

Black (2001) presents a comprehensive history for the operations, management, and problems facing CNFH from its inception to 2001. The Shasta-Keswick salvage effort received false praise as a successful venture during its operation, but was recognized as a failed effort when reevaluated for primary objectives in the 1950’s. CNFH was unable to propagate one half of the threatened spring run of Chinook salmon. Multiple alternative projects also failed. CNFH persisted as one of two surviving pieces of the original Shasta Salmon Salvage Plan.

In the 1950’s, production of fertilized Chinook salmon and steelhead trout eggs ramped up at the hatchery while aquatic habitat and natural fisheries continued to decline. Production persisted in the 1960’s and integrated in a series of experiments for feeding, ponds, and fish species. Several limiting factors were identified including the availability of fresh water to sustain such high levels of production, excess crowding in rearing ponds, and disease. Large production continued into the 1970’s while operations at the hatchery faced challenges including insufficient funding, decaying infrastructure, high power demands, and falling numbers of salmon.

A notable improvement occurred in the 1980's with the development of an "Operational Plan" specifying strategies to halt and reverse declines in anadromous fisheries. The hatchery's mission was redefined as a restoration effort to rehabilitate stream conditions and recover natural fish species. Whirling disease affected steelhead populations in 1985 and caused the destruction of over 2 million eggs. The 80's saw a series of reports and plans to upgrade or develop sound and practical station development plans for future funding requests. The Richardson reports commissioned by the FWS and USBR argued the USBR had an outstanding unmet mitigation obligation for native fisheries that were cut off from spawning habitats by the Shasta Dam.

In 1992 the Central Valley Project Improvement Act was passed assuring natural fish and wildlife resources would have legitimate standing for beneficial uses. The act targeted the protection, restoration, and enhancement in the Central Valley river basin. Recognizing fish as a legitimate interest favors natural spawning over artificial propagation as a reproductive strategy, restoring critical habitats for spawning, and removing barriers that halt the passage of returning migratory fish.

Black (2001) delivered a comprehensive summary from 1895 – 2001 covering the developmental, operational, and legislative history for fish hatchery installations in Battle Creek presented in chronologic order. He identified the need for balance in attempting to mitigate the loss in natural fish populations with the loss incurred from the Shasta-Keswick complex, and articulated the need for sufficient instream flows as a beneficial use for fish species is critical to the restoration effort for anadromous fish species. Black (2001) argued that salmon biodiversity in the Sacramento River basin is a national treasure that requires a concerted effort for mitigating the effects of reduced aquatic and spawning habitat for native fish species.

3.7.2 Restoration Project

The Battle Creek Working Group (BCWG) is a multi-stakeholder group of local, State, and Federal agencies responsible for fish conservation in the Battle Creek watershed. It formed in 1997 in response to low fish populations and degraded habitat in order to institutionalize restoration activities in Battle Creek. The BCWG seeks to identify and accelerate salmon and steelhead restoration opportunities. KA was contracted by the BCWG to develop a restoration plan to guide future watershed restoration and management decisions (Ward and Kier, 1999). The Restoration Plan described the Battle Creek watershed and the historical roles it served in regards to hydropower and fish habitat. A total of 42.4 river miles on MSBC, NFBC, and SFBC, plus an additional six miles in tributaries above CNFH were targeted for restoration (USBR, 2001) and may require reallocating streamflow away from current hydroelectric operations.

Determining priorities for successful production of target species in specific study reaches is of greatest concern reported. The Restoration Plan spells out management actions, monitoring, and evaluation measures necessary for a successful restoration project with long-term sustainability.

The Central Valley Action Plan addressed restoration opportunities for Battle Creek and recognized the significant opportunities for natural spawning of salmon and steelhead (USDFG, 1993). The plan reported that restoration in Battle Creek would require physical and operational changes at CNFH that will conflict with PG&Es Battle Creek Project and hatchery operations. They recommended improving fish passage, screening hydropower diversions, and restoring spawning gravel in North Fork Battle Creek.

Ward and Kier (1999) presented a technical report discussing the potential restoration opportunity for fish species using an ecosystem level approach to restoration. They looked at water temperature, flow, fish passage, and gravel augmentation. They provided recommendations for increasing salmonid habitat and proposed methods for monitoring the effects of proposed restoration.

Ward and Kier (1999) produced a supplementary document to the Battle Creek Salmon and Steelhead Restoration Plan dealing with the creek's lower reaches. The necessity of CNFH operations to be compatible with the upstream restoration program is important to ensure success in the upper reaches. The Compatibility Plan addressed the need for compatibility, a technical plan for management action, and recommendations for the operation of CNFH and the habitat of lower Battle Creek. The Compatibility Plan presented a decision matrix to be used as a template in collaborative efforts to identify alternative management scenarios optimizing restoration of fish populations. The Restoration Plan (Ward and Kier, 1999a) and Compatibility Plan (Ward and Kier, 1999b) provided a succinct set of management actions to ensure the successful implementation for restoration activities in the Battle Creek watershed.

The Bureau of Reclamation addressed public interest by hosting a public meeting on January 31st, 2000 in Manton, CA and developed a Restoration Plan Scoping Report (USBR, 2001). The intent was to evaluate public issues, concerns, and information to utilize for the development of an environmental impact statement/ environmental impact report (EIS/EIR). Key concerns from the scoping process included viewing the Restoration Project in Battle Creek holistically incorporating not just the targeted project reach, but CNFH, wetlands, the Greater Battle Creek watershed, and even extending efforts to the Sacramento River basin. A main goal was to reduce the costs and impacts associated with CNFH to allow fish free passage, and reduce water diversions for instream flows.

A special panel of fisheries and ecosystem experts was assembled to examine the potential effects of CNFH on the Restoration Project (Brown and Kimmerer, 2004). A workshop was held in October 2003 addressing issues and concerns raised from the Battle Creek Salmon and Steelhead Restoration Plan (Ward and Kier, 1999). Brown and Kimmerer (2004) summarized the workshop and appended the presentations from keynote speakers into a comprehensive report specifically focused on the restoration of anadromous fisheries.

The Restoration Project proposed to restore native salmon and steelhead populations through the modification of the Battle Creek Hydroelectric Project (FERC No. 1121) facilities and operations including instream flows. These modifications would require state and federal actions and require compliance with both the National Environmental Protection Act (NEPA) and the California Environmental Quality Act (CEQA). To fulfill the requirements under both environmental regulation measures, a joint EIS/EIR was completed in 2005 (Jones and Stokes, 2005). They reported on the impacts associated with the Restoration Project and potential alternatives to proposed restoration. The Final EIS/EIR was delivered in June 2005 and is publicly available on the Bureau of Reclamation website (http://www.usbr.gov/mp/nepa/nepa_projdetails.cfm?Project_ID=99).

The Battle Creek Watershed Conservancy (BCWC) created the Battle Creek Watershed Community Strategy in response to restoration efforts from agency and local watershed working groups (Paquin-Gilmore, 2007). This document laid out a framework for future watershed restoration and education in the Battle Creek watershed. Information gathered at numerous community meetings was synthesized to develop a targeted approach for community involvement towards restoring habitat and fisheries in Battle Creek. Paquin-Gilmore (2007) presented a background of watershed, land-use, and people involved in Battle Creek including public, private, and recreational uses. Five distinct communities exist of variable size and interests in Battle Creek. Community members concerns, interests, and suggestions at local meetings were summarized and expressed. The goal of the community strategy was to “to preserve the environmental and economic resources of the Battle Creek watershed through responsible stewardship, liaison, cooperation and education”. The BCWC developed 12 strategies based on the community values observed at local meetings and created action items specifically stating how to achieve each strategy. The strategies addressed conservation, fire, stewardship, best management practices, water quality, ecosystem health, planning, restoration, recreation, and monitoring. The BCWC recognized the importance of Battle Creek as becoming one of the state’s most important streams for salmon and steelhead recovery. The BCWC responded to the voice of the community to integrate them within the context of management, restoration, and land-use activities. The community strategy was a key step towards preserving environmental and economic resources that will benefit the entire watershed and those parties involved.

3.7.3 Adaptive Management

Adaptive Management is a process that uses monitoring research to identify and define problems, examine various alternative strategies and actions for meeting measurable biological objectives, and make timely adjustments to strategies and actions based on current scientific and commercial information as needed (KA, 2001). Adaptive Management is a technique applied to the Restoration Project in Battle Creek.

Adaptive Management is an important component of the Battle Creek Restoration Project as it employs extensive monitoring to identify problems and explore possible solutions for meeting biological objectives of restoration. The Adaptive Management concept requires collaboration from invested stakeholders in the Battle Creek watershed. Kier Associates developed an Adaptive Management Plan (AMP) to describe policy regarding the management of restoration project related fisheries and habitat (KA, 2001). Adaptive Management objectives described in the AMP focus on the management of hydroelectric operations within the Restoration Project increasing beneficial habitat changes for salmon and steelhead. Limiting factors and unanticipated circumstances were addressed in the AMP, but the plan acknowledged the unpredictable nature of events. The AMP responds to new circumstances using the scientific method with hypothesis testing of objectives through monitoring and analysis. The AMP outlined objectives for successful restoration of salmon and steelhead focusing on improving population dynamics, aquatic habitat, and safe fish passage for variable life stages of target species. Terraqua Inc. updated the KA (2001) AMP in 2004. This revised document included focused studies to address uncertainties and learning opportunities that may not be directly addressed by adaptive management objectives (Terraqua, 2004).

KA (2001) presented a technical chapter describing the linkages between the Adaptive Management of the Battle Creek Restoration Project and other planning or restoration programs. The AMP suggested that monitoring tasks be coordinated by the BCWC. Local participation from schools and private landowners could aid in sediment and water quality observations. The BCWC was recommended to partner with local schools initiating sediment quality monitoring thus providing an opportunity for connecting with unique fish populations while providing an early warning system for stream health. Sediment quality monitoring identified erosional problems a posteriori but a long-term watershed assessment program could prevent erosion problems before they occur. The BCWC was suggested to work with private landowners in the upper watershed to implement appropriate land-use practices protecting against adverse ecological impacts and preventing further regulatory action.

Stillwater Sciences developed a sediment monitoring plan for the restoration project. The plan recommended increased monitoring in Battle Creek to identify deficiencies or critical actions for adaptive management, document the degree of success for the project, and identify key responses or relationships for the planning and implementation of similar projects. KA (2009) suggested an upland sediment budget might be necessary to better quantify disturbance and understand the linkages between upland processes and downstream channel metrics measured from the SCMP

3.8 Internet Links

A plethora of resources with information pertaining to Battle Creek exist on the worldwide web. Table 5 provides website names and hyperlinks.

Table 5: Internet links to Battle Creek resources.

Site	Web Address
Wikipedia	http://en.wikipedia.org/wiki/Battle_Creek
Battle Creek Watershed Conservancy	http://www.battle-creek.net/
Battle Creek Alliance	http://www.thebattlecreekalliance.org/
Bureau of Rec Restoration	http://www.usbr.gov/mp/battlecreek/index.html
Site Map	http://www.usSabr.gov/mp/battlecreek/pdf/main/Fig_x_Facilities-Limits.pdf
Sacramento River Watershed Program – Battle Creek	http://www.sacriver.org/aboutwatershed/roadmap/watersheds/eastside/battle-creek-watershed
Geology of the Lassen volcanic area	http://en.wikipedia.org/wiki/Geology_of_the_Lassen_volcanic_area
Klamath Resource Information System (KRIS)	http://www.krisweb.com/krisbattle/krisdb/html/krisweb/index.htm
USDA Web Soil Survey	http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm
USGS Streamgage	http://waterdata.usgs.gov/usa/nwis/uv?11376550 http://waterdata.usgs.gov/usa/nwis/uv?11376500
USGS The National Map	http://nationalmap.gov/index.html
DWR Streamgage	http://www.water.ca.gov/waterdatalibrary/
KRIS web restoration	http://www.krisweb.com/battleck_bg/ver1_bg/restore.htm
Lassen Geology	http://pubs.usgs.gov/sim/2899/
Coleman National Fish Hatchery	http://www.fws.gov/coleman/

4 EXISTING DATA GAPS

Through a comparison of the range of sediment impact assessment methodologies presented in Section 2.6 and the existing information presented in Section 3 it is evident that very little is known about the physical conditions in Battle Creek and the potential of sediment and geomorphic processes to create impacts on biota and on beneficial human uses. This is especially true in terms of understanding the watershed through time. Although a variety of environmental studies have been done that provide a useful snapshot of conditions, it will be necessary to track conditions over many years in order to get into a position to make firm interpretations and conclusions at some point in the future.

Before describing specific data gaps, one thing that is clear from the existing information review of Battle Creek is that the situation that exists now is not just one of a lack of data, but far more importantly, a lack of a consensus-based conceptualization of the linked physical-biotic system as a whole as well as a framework for monitoring and assessing that system. This is true not just for sediment impacts, but for the broader issues of environmental management within which the topic of sediment comes into play. Further, there has been a lot of anecdotal reporting and *ad hoc* sampling that can be highly influential to individual stakeholders, but without a transparent and objective framework for analysis, there is no way to know whether concerns are founded or not. Therefore, the most glaring and immediate problem is to develop the conceptualization of the system and a framework for monitoring and assessment.

For example, sections 3.6.2 and 3.6.3 summarized past studies monitoring salmonids and characterizing their aquatic habitat, but there has not yet been an effort to implement one of the major assessment frameworks for salmonid status, such as the Viable Salmonid Populations approach (McElhaney et al., 2000; Lindley et al., 2007) or approaches for assessing “good condition” per California Fish & Game Code § 5937 (e.g., Moyle et al., 1998; Börk et al., 2012). Recently, the Yuba Accord River Management Team (YARMT) (2010) developed and implemented a plan for applying both of these frameworks to the lower Yuba River, and it not only produced many new findings, but it did yield specific conclusions about the status of salmonids in the system and point toward opportunities for further improving the river (YARMT, 2013). Much more geospatial data and biological monitoring would be required for Battle Creek in order to implement a plan like that, as well as resources and technical expertise for analysis and interpretation. These constitute major data gaps in the broadest sense of what might be of interest to characterize the status of salmonids with respect to physical and biological factors.

With regard to sediment specifically, none of the approaches described in Section 2.6 have been implemented yet, nor have any other comprehensive approaches been done. The closest effort thus far to assessing the status of the river in terms of water quality impacts, including those of sediment, relates to benthic invertebrate studies. Much more of that work is necessary, especially tracking conditions through time in light of the strong spatial and temporal variability of California’s climate and environmental disturbance regimes. Beyond that, the US EPA framework and major components illustrated in Figure 2 have not been implemented.

Although not part of the US EPA approach, a sediment budget framework, such as illustrated by the Colorado River Basin Regional Water Quality Control Board (CRBRWQCB) (2002a,b; 2005) for TMDL development, or demonstrated by Tanji et al. (1978, 1980, 1981, 1983) for mitigating sediment impacts, is extremely important for assessing sediment sources and planning solutions to mitigate sediment flux and sediment impacts. Considering this type of approach, there are major data gaps in terms of the lack of a network of automated water and sediment monitoring stations throughout the watershed as well as supplemental regular (i.e., weekly and/or event-based) suspended sediment sampling for quantifying mass fluxes, sediment characteristics, and checking for sediment-associated contaminants. In addition there is a lack of characterization of fluxes associated with individual landscape physical processes, such as streambank erosion and landsliding. There is no single element of a sediment budget for which there is adequate data from Battle Creek, whether a budget is considered on a process-by-process basis, on a subcatchment-by-subcatchment sediment yield basis, or on a watershed-scale sediment export basis.

Apart from the short-term efforts from the existing literature and presented later in this report, there is no systematic sediment monitoring in the watershed. Various stakeholders are performing *ad hoc* grab sampling and turbidity measurement, which has little to no value when done this way. Very little information is available on recent suspended sediment composition, including the magnitude and composition of sediment associated contaminants. There are no efforts to monitor and understand potential sediment impacts on downstream water bodies, and this would be especially difficult given the lack of an automated sediment monitoring station co-located with the discharge gaging station near the Coleman Fish Hatchery.

Overall, the situation for Battle Creek is not so much one of data gaps, but of a near complete absence of sediment data and sediment analyses, especially within the context of one or more assessment frameworks.

5 HYDROLOGICAL HISTORY ANALYSIS

Beginning with this section and continuing in sections 6 and 7, the report now switches focus from a consideration of past analyses to the development of new ones that can contribute to an improved understanding of sediment in the Battle Creek Watershed. These new analyses address hydrology, sediment, and landscape physical processes, in that order. As a starting point for new developments, it was necessary to look into the climatic data and hydrological gages in the watershed at this time and update common hydrological analyses with the latest data. That is the primary information presented in this section. The extent of hydrological analyses possible is limited given the relatively short duration of gage data, especially for the two major subbasins.

All publicly available climatic and hydrologic data for Battle Creek were downloaded, compiled, and processed. Climate data and analyses herein focused on precipitation rates and patterns with an emphasis on GIS data (Section 5.1).. Streamflow distributions were reanalyzed and compared between subbasins (Section 5.2). Finally, an updated flood frequency analysis (Section 5.3) for streamgages at MSBC, NFBC, and SFBC was completed for later use in comparing hydrological effects on sediment processes associated with hydrologic history. Water diversions are prominent in Battle Creek and are summarized for their effects on the hydrologic regime.

5.1 Climate

The Battle Creek watershed experiences a dry-summer subtropical climate (per the Köppen climate classification system) foundin the Sierra Nevada and southern Cascade Ranges of California. Wet winters and dry summers characterize this climate andproduce distinct seasonality in runoff and streamflow. Winters are dominated by convective rainfall at low elevations and snowfall at high elevations with an elevation band experiencing rain-on-snow between 3,600 and 5,000 feet (Armentrout et al., 1998). Summers experience occasional high intensity short duration thunderstorms. However, soil moisture conditions are low in summer months, which results in the infiltration of precipitation before ponding and surface runoff are large enough to influence stream levels summer storms. Snow fields persist on Lassen Peak during the dry season providing a constant inflow of groundwater to support perennial baseflow in Battle Creek.

5.1.1 Precipitation Maps

Anecdotally, there are reports from stakeholders that Battle Creek experiences unusual spatial precipitation patterns, especially during large storms that likely produce the most fluvial sediment. Thus it is important to consider the available geospatial precipitation data in order to further understand sediment dynamics in the region.

The PRISM Climate Group located at Oregon State University compiles climate observations from a multitude of monitoring networks to develop spatial climate datasets revealing short- and long-term climate patterns for the contiguous United States (Figure 11). The datasets incorporate a variety of modeling techniques and are publicly available at multiple spatial and temporal resolutions (http://www.prism.oregonstate.edu/). At the end of each decade, average temperature and precipitation values are computed for the preceding 30 years to produce 30-year normal estimations. The current PRISM 30-year normal dataset spans the period 1981 – 2010. Data were downloaded for mean annual precipitation and mean January precipitation at 4 km resolution for use in GIS analyses.

For the 30-year normal, mean annual precipitation ranges from approximately 26” at the confluence with the Sacramento River to 125” in the headwaters at Lassen Peak (Figure 12).

The majority of the basin receives 79” annually. The dominant rain-on-snow elevation band for nearby Deer, Mill, and Antelope creeks is 3,600 – 5,000 ft (Armentrout et al., 1998). Although snow can fall at any elevation, high elevations above 5,000 feet may receive the dominant amount of precipitation as snowfall, and receive increased precipitation due to orographic lifting.

The spatio-temporal resolution (4-km, 30 year average) of the monthly precipitation maps is very good, but still insufficient to observe the kinds of spatial patterns in precipitation that are common features of montane watersheds. Such patterns include differences in precipitation between along the river level to hilltop gradient as a function of elevation and topographic aspect (i.e., the compass direction that a slope faces). It remains an open question as to the potential importance of the details of event-scale spatial patterns in governing landscape physical process, but this could be a major control on spatial distribution of precipitation volume and intensity, and in turn the surface paths of runoff and sediment transport that have yet to be considered. As a first step in this direction the spatial pattern of mean annual and monthly precipitation as available from PRISM was investigated for how it might impact landscape physical process (see Section 7.3.2).

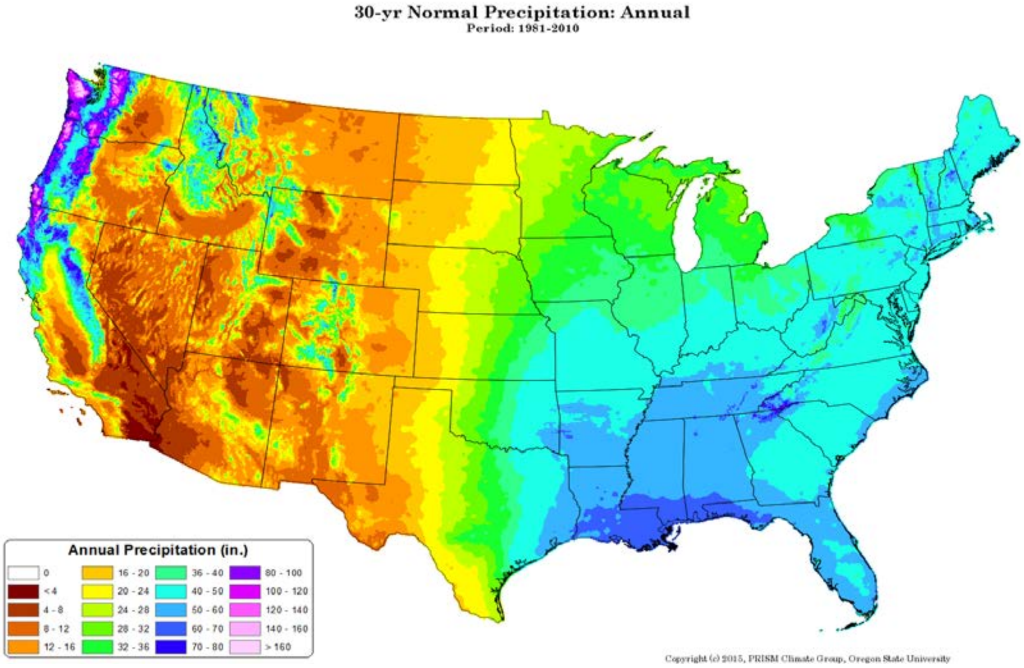


Figure 11: PRISM Climate Group 30-year normal for mean annual precipitation. Image taken from OSU website.

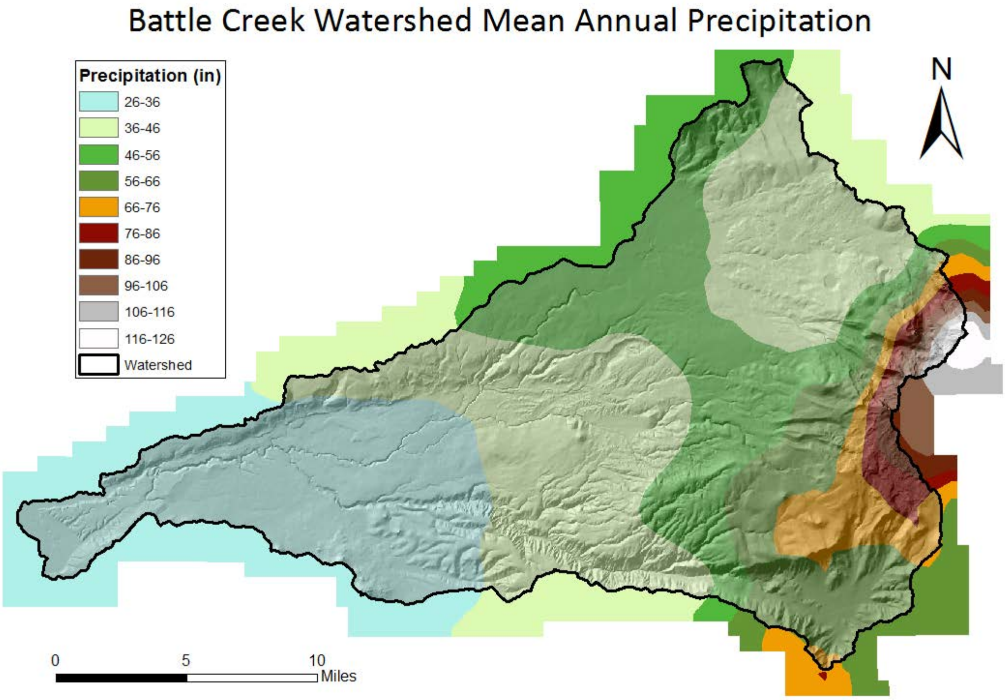


Figure 12: Mean annual precipitation pattern for the 30-year normal overlying terrain imagery. Climate data are from the PRISM Climate Group at Oregon State University.

5.1.2 Precipitation Gages

Continuous precipitation data is available online through the NOAA National Centers for Environmental Information (NCEI) formerly known as the National Climatic Data Center (NCDC) (https://www.ncdc.noaa.gov/). CDEC also records precipitation and snowfall data for snow sensors in the basin. Many precipitation gages have been collecting rainfall and temperature data in Battle Creek for variable lengths of time (Figure 13). All available data were downloaded from the NCEI website and compiled into a database attached in supplemental material.

Four long-standing weather stations have been collecting precipitation over different intervals. A weather station at CNFH has operated since January 1944 and indicates that the highest monthly average precipitation occurs in January with 4.8” and lowest monthly average in July with 0.14” (Figure 14). The Volta Powerhouse has been collecting precipitation records since November 1926. Peak monthly average precipitation occurs in January with 5.3” and low value is July with 0.12” (Figure 14). Precipitation data has been recorded near Mineral, CA continuously beginning in July 1914 with one month recorded previously in December 1909. Monthly average high is December with 8.9” and monthly low in July with 0.16” (Figure 14). Lake Manzanita weather station has operated since January 1949 and monthly averages are highest in January with 5.8” and lowest in July with 0.35” (Figure 14).

Additional weather stations exist with shorter periods of record. Hourly data are recorded at Manton, CA at from 2/29/2008. Lassen Lodge began collecting weather information on 1/1/2013 Shingletown has three gages within 7 miles of town proper collecting monthly data from 11/1/2008 for one and 11/1/2012 2012 for the other two. Snow depths have been recorded on Lassen Peak (CDEC snow sensor 47) intermittently from February 1930 – present and Lake Manzanita (CDEC snow sensor 343) from 1950 – present. The average April snowpack for Lassen Peak at 8,250 ft elevation and Lake Manzanita at 5,900 ft elevation is 80.2” and 8.0”, respectively.

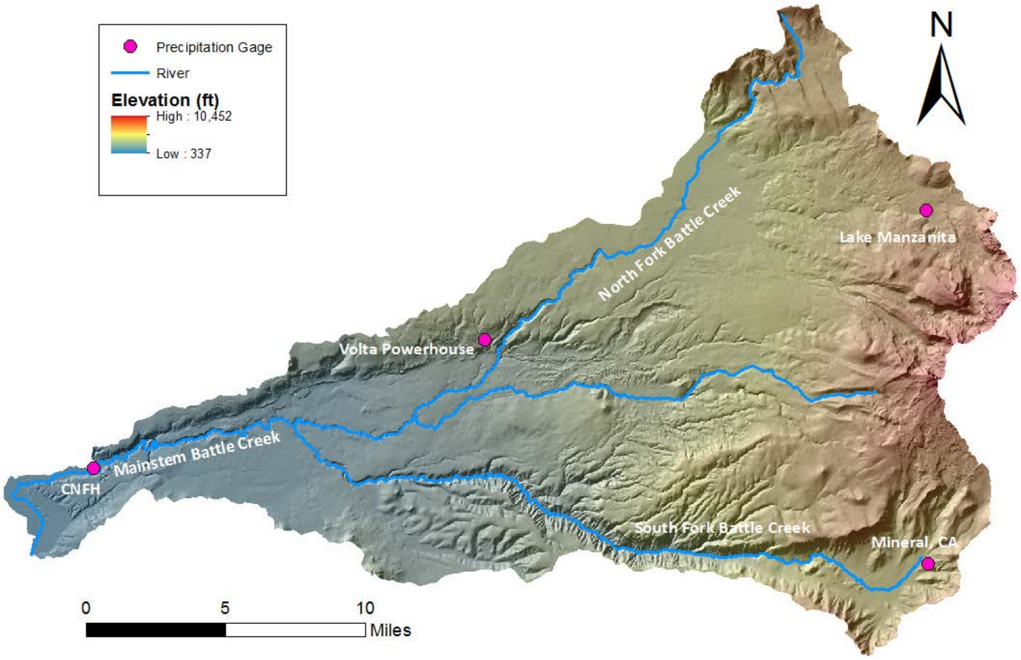


Figure 13: Locations of long-term precipitation gages in Battle Creek.

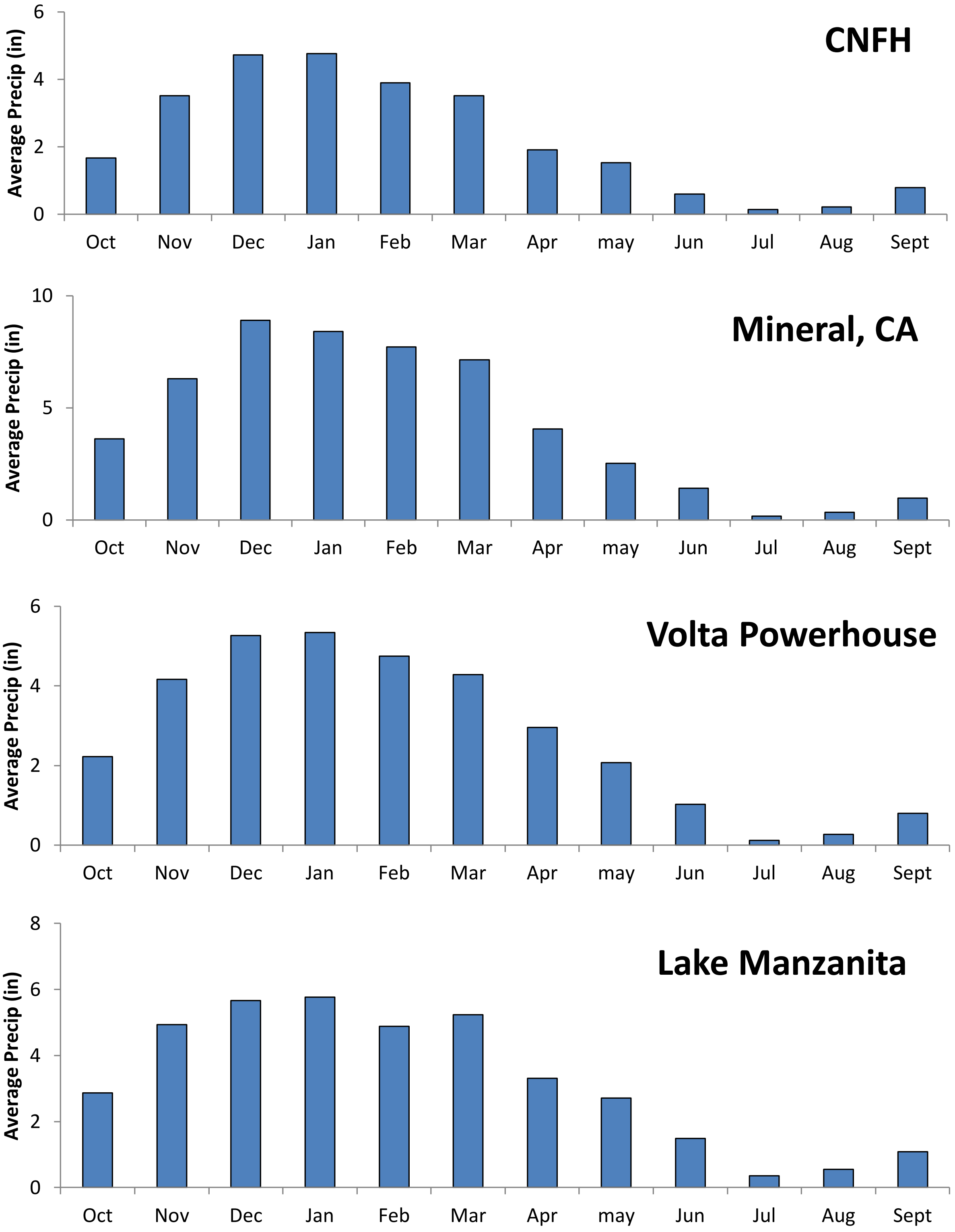


Figure 14: Monthly average precipitation for precipitation gages in Battle Creek.

5.1.3 2015 Climate Year

California has been subject to extended droughts for thousands of years as evidenced in tree rings, pollen deposits, and sedimentary, fossil, and geologic records (CDWR 2014). Last year (2014) marked the driest calendar year and WY 2014 was the 3rd driest on historical record. WY 2015 yielded another drought year with precipitation far below statewide averages. CDWR reported on April 1, 2015 that California set a new “low water” mark for early –April snowpack measurements thus elevating WY 2015 to the driest winter in California’s written history. Suspended sediment transport has been shown to respond to hydrologic preconditions of antecedent moisture annually (Gray et al. 2014). During WY 2015 the majority of California’s precipitation occurred in December 2014 from atmospheric river type storms bringing pulses of high water vapor content from mid-latitude offshore regions. These atmospheric rivers resulted in Battle Creek experiencing two floods in the midst of a drought year.

5.2 Streamflow Distributions

The unique hydrology of Battle Creek produces distinct responses in streamflow that can be analyzed to understand governing processes in the watershed. Streamflow was evaluated for time series, boxplots, and histograms at MSBC, NFBC, and SFBC indicating log distributions and reflecting regional climate. Comparisons also revealed strong correlations between streamgaging sites.

5.2.1 Mainstem Battle Creek

A streamgage on MSBC was relocated in 1961 from its former location ~0.6 miles upstream of where it currently resides. No documentation explaining the relocation of this streamgage was found, though personal communication with USGS staff indicated possible reasons due to the location of the Coleman Power Plant upstream, the Hatchery downstream, channel morphology, or additional entities in the watershed (Personal Communication, USGS). A composite dataset of both streamgages would provide a longer period of record allowing a more thorough analysis of hydrological characteristics in Battle Creek. Given that MSBC was relocated at the end of the WY 1961, it was necessary to assess whether data from the two locations are equivalent, or if the relocation precludes using data from both periods for hydrological analyses. Water is diverted into CNFH below the historic upstream gage and returned to the channel above the current downstream gage, so apart from a small amount of consumptive use the values might be indistinguishable, especially in light of inherent error in streamgaging, which is on the scale of 10% for measured discharge reported as “good” on the USGS website station description.

The effects of water diversion from CNFH were tested by comparing minimum, mean, and maximum daily average streamflow values for the two gages (Table 6) and using a paired t-test. No statistically significant difference ($p<0.01$) for the means of the two streamgages existed, which was confirmed with a one-way Anova over all three sets of daily flows. Analysis of boxplots (Figure 15) indicated that the diversion poses insubstantial effects over the range of average flows. No statistical or graphical differences were observed at minimum, mean, and maximum daily average values. Based on the results of the statistical analysis comparing streamflow values for the two gages, historical records were combined into a single dataset for hydrologic analyses and reported as the MSBC streamgage.

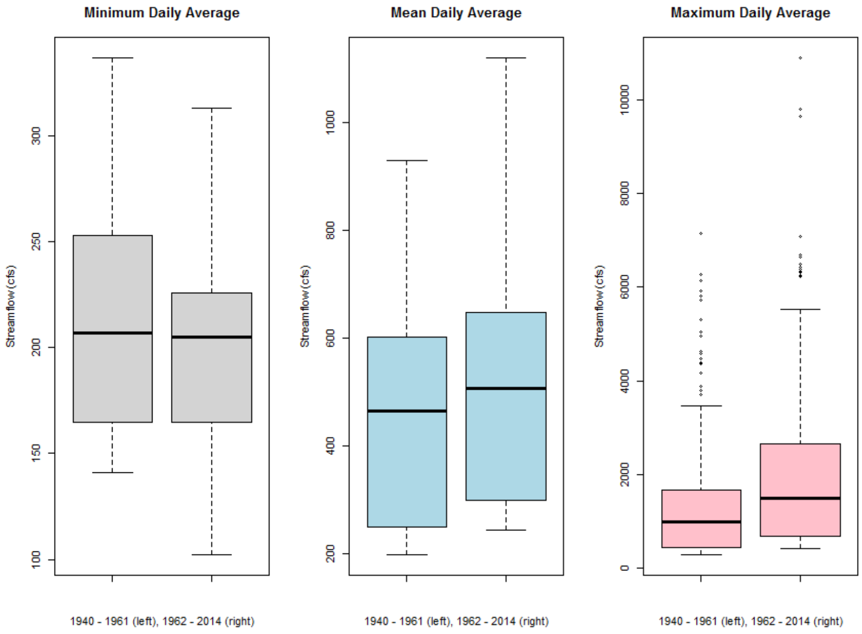


Figure 15: Boxplots of minimum (left), mean (middle), and maximum (right) daily average flows for comparing streamgages on MSBC at CNFH.

Table 6: Comparison of daily average streamflow (cfs) at USGS streamgages.

	Streamgage 11376500			Streamgage 11376550		
Daily Average	Mean	Median	CI (1.5 sd)	Mean	Median	CI (1.5 sd)
Minimum	213	205	200 - 210	199	207	200 - 214
Mean	448	466	436 – 494	492	507	478 – 535
Maximum	1292	990	888 - 1092	1970	1490	1327 – 1652

Daily average streamflow data at MSBC were evaluated for minimum, mean, and maximum values from WY 1940 - 2014. Boxplots (Figure 16) and histograms (Figure 17) were created to graphically display mean values and probability distribution functions. Minimum daily average flows ranged from 102 - 292 cfs with a mean of 194 cfs and displayed a bimodal distribution with peaks around 150 and 210 cfs. Mean daily average flows ranged from 221 - 877 cfs with a mean of 470 and displayed a bimodal distribution with a heavy right skew and peak at 600 - 650 cfs. Maximum daily average flows ranged from 418 - 10,900 cfs with a mean of 2097 cfs, were heavily right-skewed, and exhibited a log-normal distribution. A log-normal distribution is a continuous probability distribution of a random variable (streamflow) whose logarithm is normally distributed.

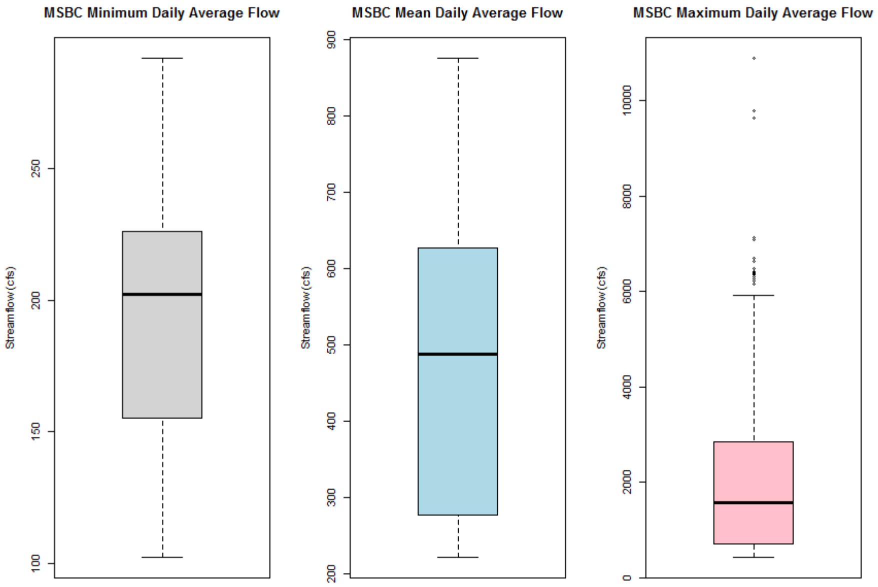
Minimum, mean, and maximum daily average flows were plotted by Julien day for a graphical representation of flows for WY 1940–2014 (Figure 18). Variability existed in all three curves beginning mid-September and ending mid-June. The June–September dry season indicated that no significant precipitation events occurred during this time. The data reflected the dry-summer subtropical climate Battle Creek experiences with wet winters and dry summers. The hydrograph showed an upward trend in mean and maximum values through autumn and early winter until January–February before the apex and resumed a downward trend returning back to baseflow. The largest maximum daily average flow for a single day occurred on January 16 with a magnitude of 10,900 cfs. The lowest mean daily average flow occurred on September 8th with a magnitude of 502 cfs.

Streamflow values for minimum, mean, and maximum flows were plotted by month (Figure 19). January experienced the largest maximum flow with 2,353 cfs and February experienced largest mean flow at 708 cfs. Minimum flows ranged from a low in September at 152 cfs to a high in March at 266 cfs indicating any month is susceptible to low magnitudes of streamflow.

The continuous record of daily average streamflow, monthly average streamflow, and peak annual streamflow at MSBC were plotted as a time series (Figure 20) and show distinct seasonality in the historical record. Boxplots for all three time series (Figure 21) and associated histograms (Figure 22) were plotted and indicated the range of variability of streamflow at MSBC across multiple scales. The histogram for daily average values displayed heavy right skew indicating higher frequencies of low flows and lower frequencies of high flows. Flows ranging 200 – 300 cfs are the most frequent and occurred approximately 30% of the time. A log-normal distribution fit the heavy right-skewness of all three time-series.

The peak annual flow represents the largest flood within a given water year. The largest peak annual flow ever recorded is approximately 35,000 cfs in 1937 (Figure 23). Peak annual flows have a mean discharge of 7,378 cfs with a standard deviation of 5,429 cfs. Five flood events larger than the mean plus one standard deviation have been recorded at MSBC occurring from largest to smallest in 1939, 1970, 1995, 1982, and 1974. MSBC experienced intense flooding in 1997 that rendered the streamgage inoperable. Task Force (2011) estimated the flood at 17, 376 cfs although these records are not published by USGS or CDEC. Battle Creek experienced heavy flooding in December 2014 and provisional data subject to revision from the USGS quantify a peak flow at 15,300 cfs. Gathering all reported data and statistics for peak flow events, seven years have experienced high flows greater than the mean + one standard deviation. Flood flow frequency and recurrence intervals are discussed further in Section 5.3.

Mean annual streamflow for MSBC ranged from 238 – 925 cfs (Figure 24). The proportion of low flow days was much greater then days with precipitation moderating the range of mean flows recorded on an annual basis.


MSBC Minimum Daily Average Flow

MSBC Mean Daily Average Flow

MSBC Maximum Daily Average Flow

Figure 16: MSBC boxplots for minimum (left), mean (middle), and maximum (right) daily average flows.

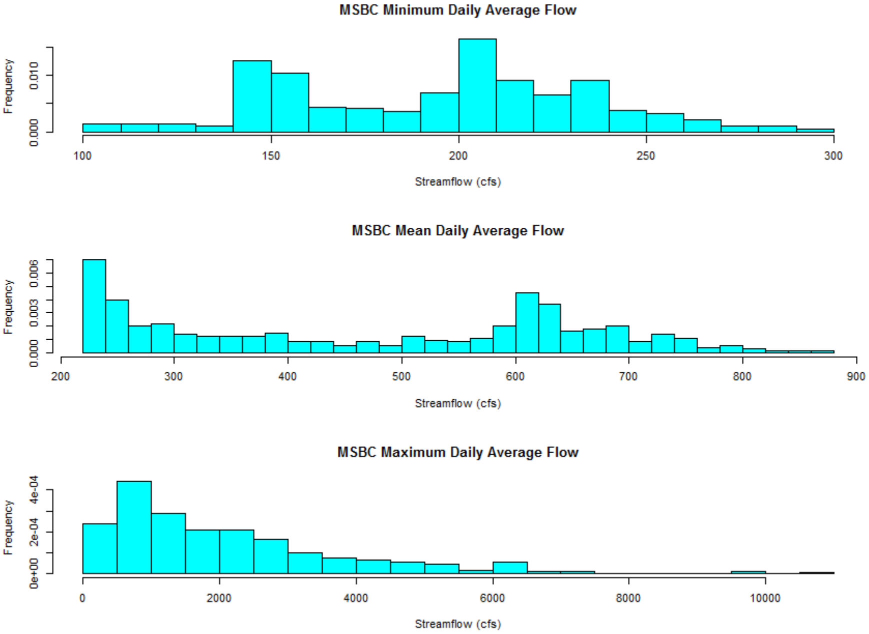


Figure 17: MSBC histograms for minimum (top) mean (middle) and maximum (bottom) daily average flows.

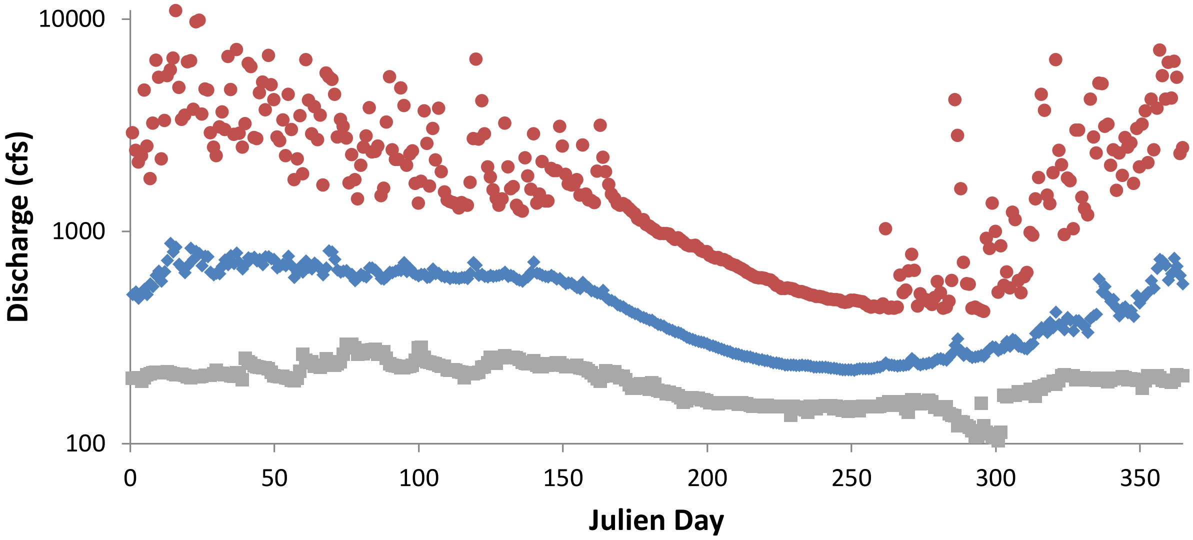


Figure 18: MSBC discharge by Julien day for minimum (gray square), mean (blue diamond), and maximum (red circle) daily average streamflow.

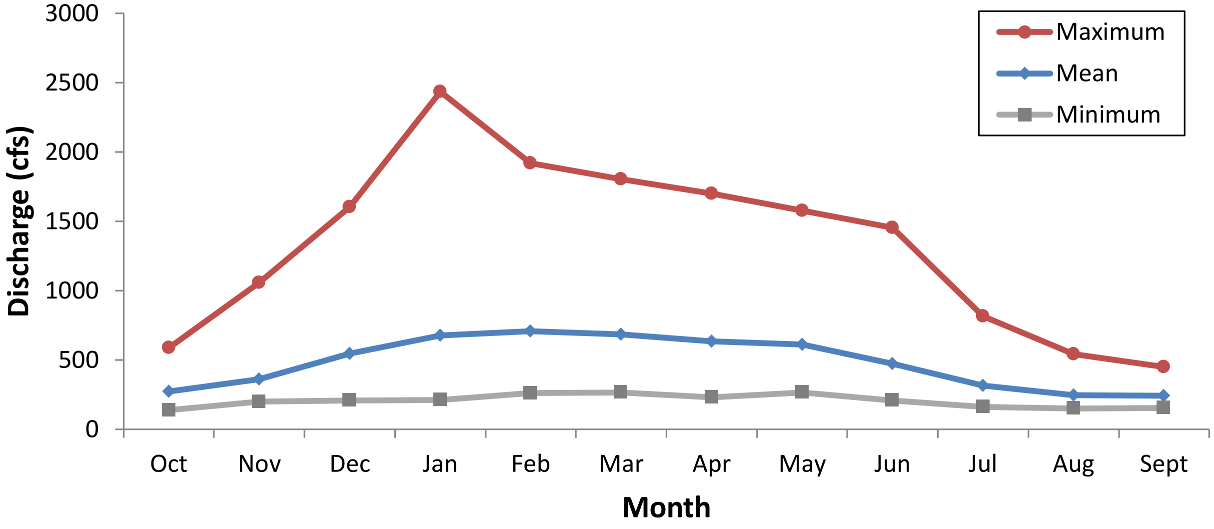


Figure 19: MSBC discharge for minimum (gray square), mean (blue diamond) and maximum (red circle) streamflow by month.

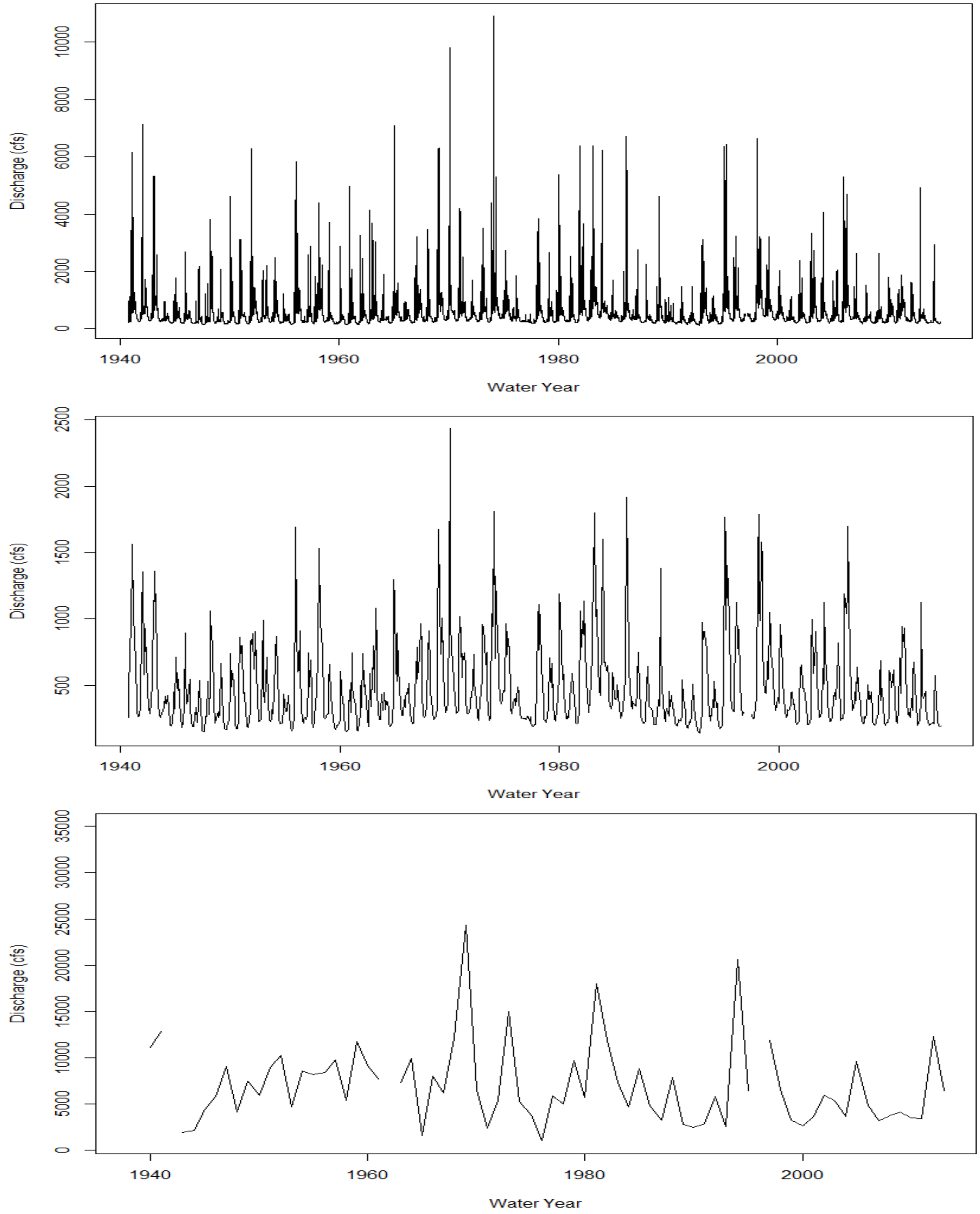


Figure 20: Time series for daily average (top), monthly average (middle) and peak annual (bottom) streamflow at MSBC.

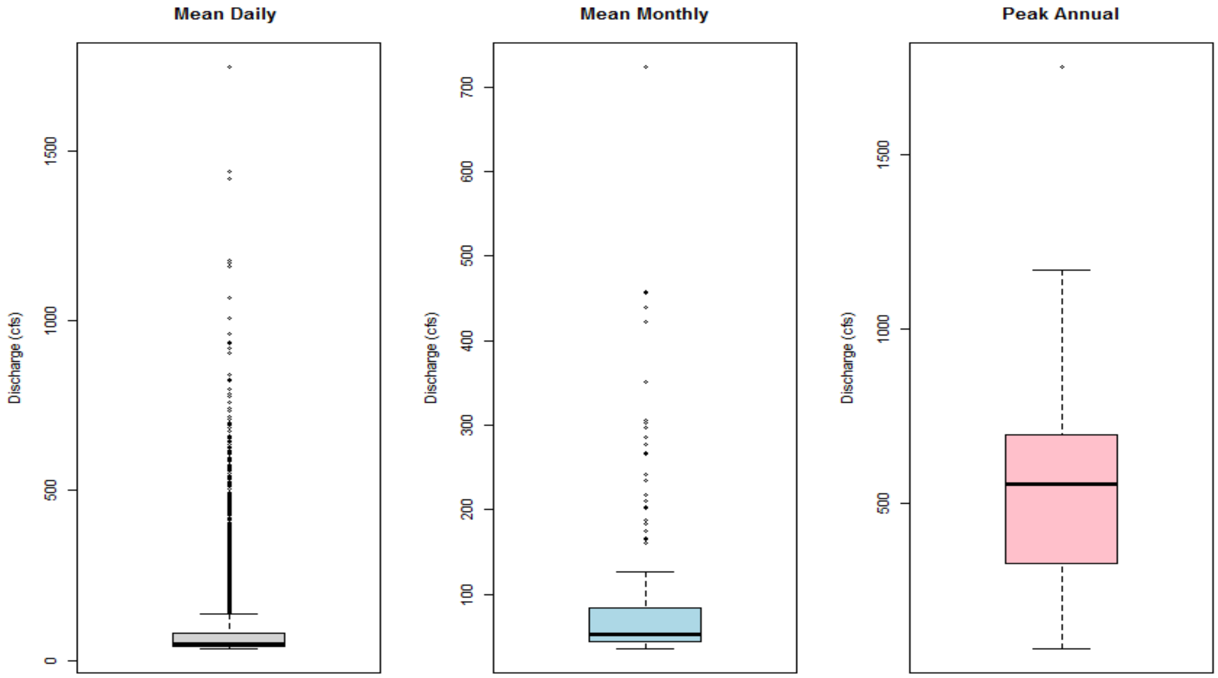


Figure 21: Boxplots for daily average (left), monthly average (middle) and peak annual (right) streamflow at MSBC.

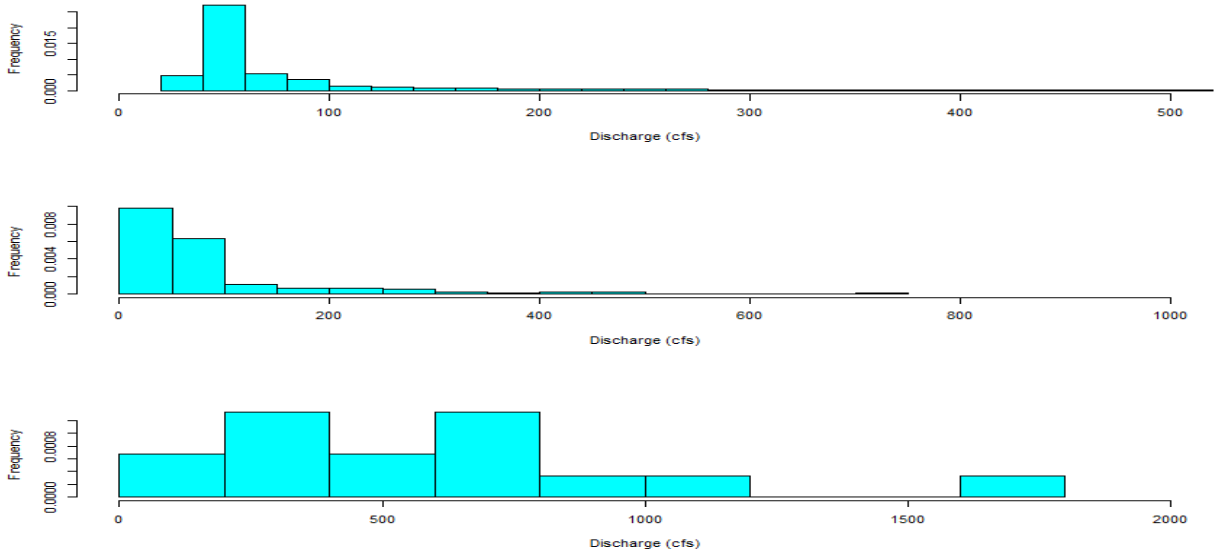


Figure 22: Histograms for daily average (top), monthly average (middle) and peak annual (bottom) streamflow at MSBC.

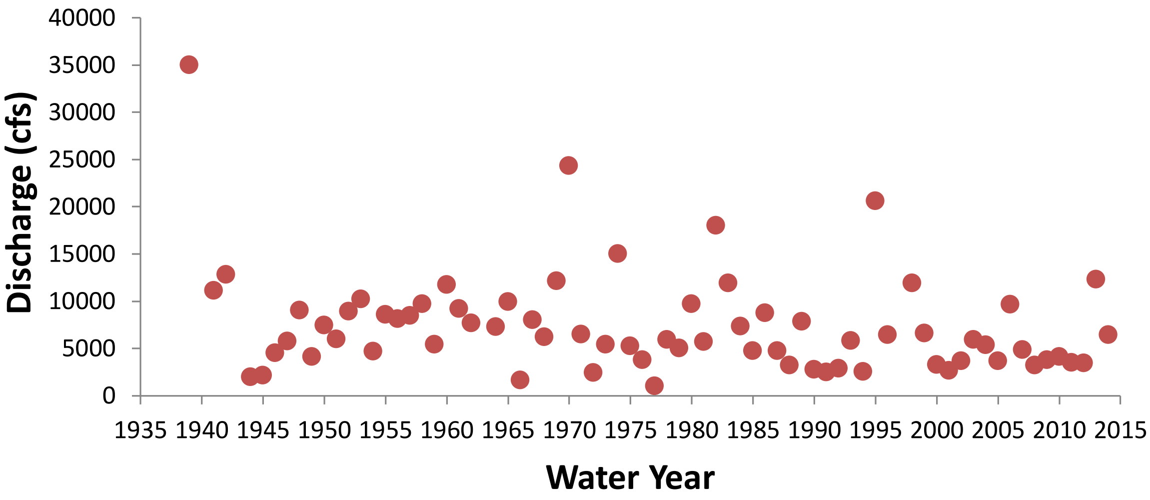


Figure 23: MSBC peak annual streamflow.

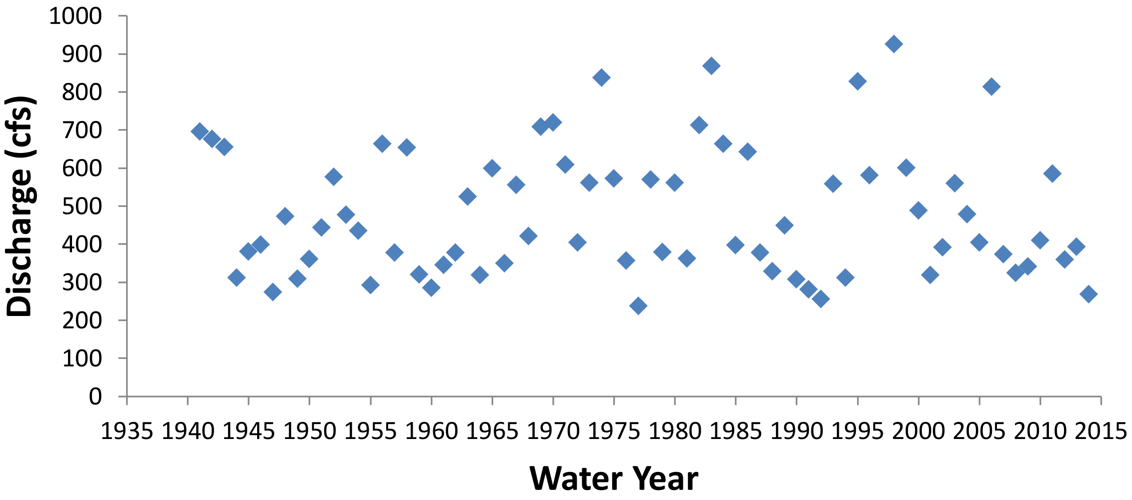


Figure 24: MSBC mean annual streamflow.

5.2.2 North Fork Battle Creek

Streamflow data for minimum, mean, and maximum daily average flows are not provided by CDEC for NFBC. Streamflow values for minimum, mean, and maximum discharge were plotted by month (Figure 25). December experienced the largest maximum flow with 1,750 cfs and April experienced largest mean flow at 146 cfs. Minimum flows range from a low in May at 32 cfs to a high in April at 40 cfs indicating a low variability in minimum flows occurring any month in the year.

Time series were created for mean daily, mean monthly, and peak annual flows (Figure 26) and their associated boxplots (Figure 27) and histograms (Figure 28). Daily time series display distinct seasonality with wet winters and dry summers. Monthly average time series convey exceptionally wet vs. dry years. The average flow over the period of record is 89.5 cfs. Mean daily flows exhibited a heavy right-skew and fitted a log-normal probability distribution function. Mean monthly streamflow values also displayed a heavy right-skew and log-normal distribution. Data were sparse for peak annual streamflow (n=15) and a characteristic distribution for fifteen years of record was not sufficiently represented, although daily and monthly data, as well as the limited annual data indicated a similar distribution would fit with larger sample size. The largest flow on record occurred in 2006 with a peak discharge of 1,750 cfs (Figure 29). 2006 was a relatively wet year with a high magnitude of precipitation occurring in April and May resulting in an annual mean discharge of 276 cfs (Figure 30).

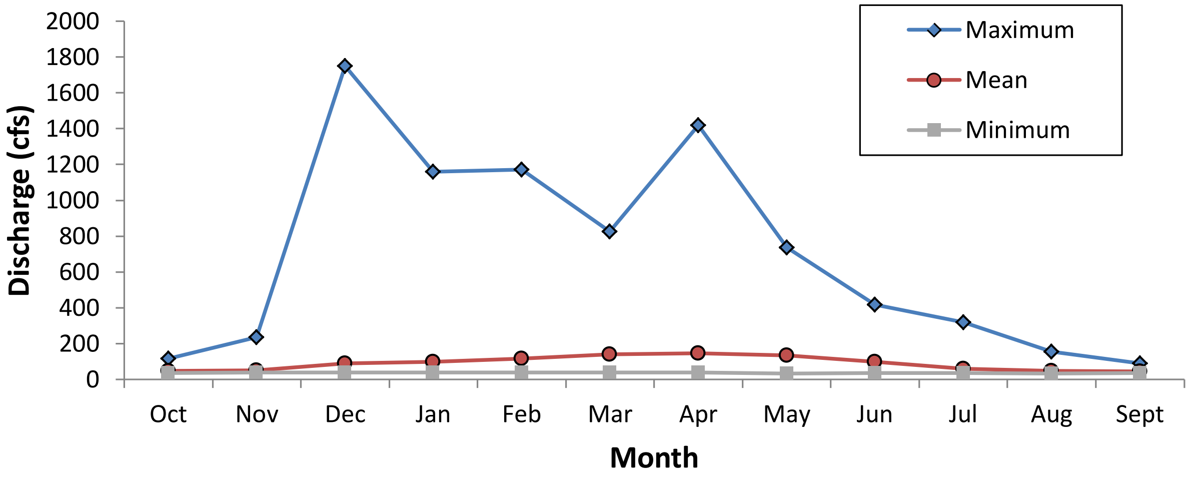


Figure 25: NFBC discharge for minimum (gray square), mean (blue diamond) and maximum (red circle) streamflow by month.

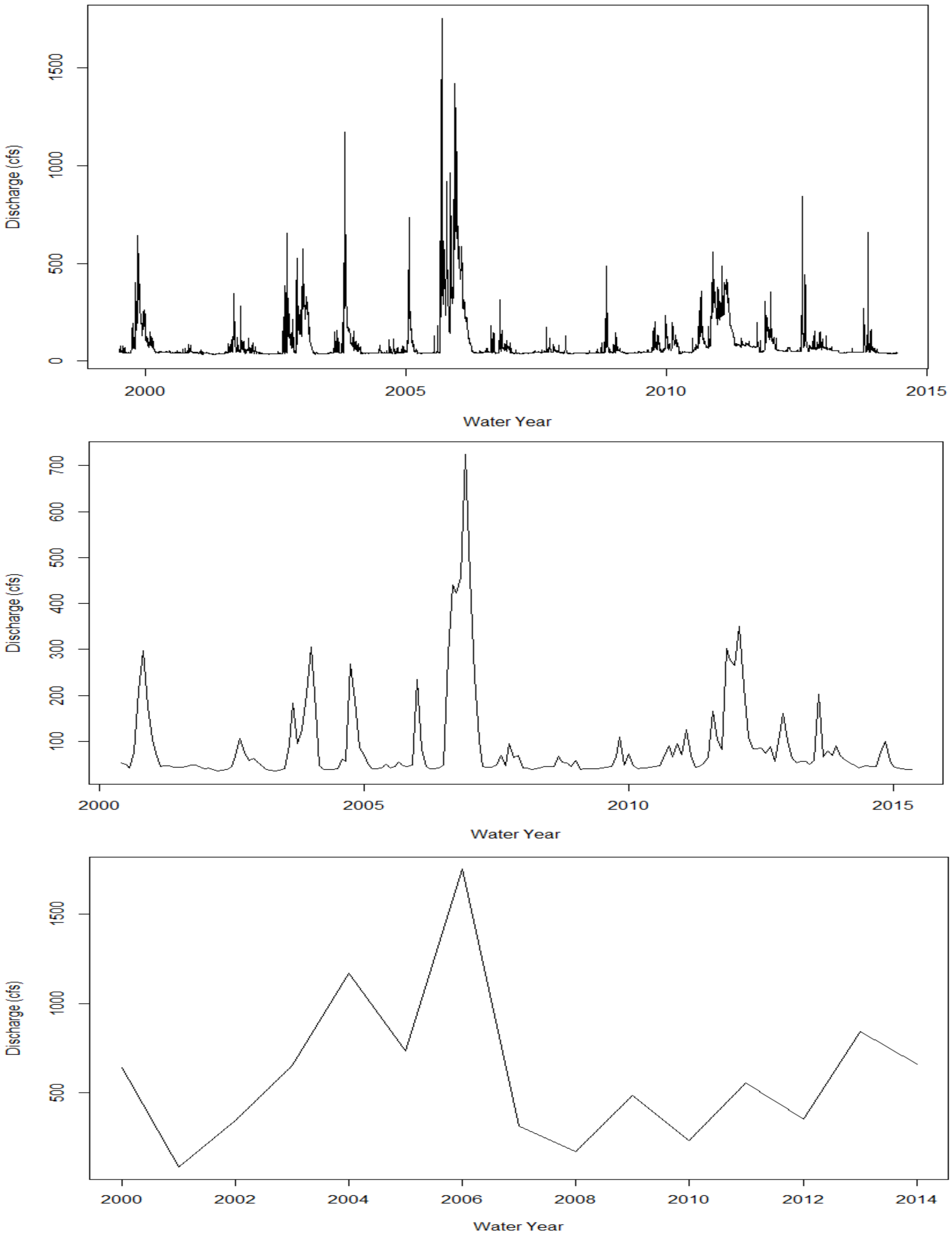


Figure 26: Time series for daily average (top), monthly average (middle) and peak annual (bottom) streamflow at NFBC.

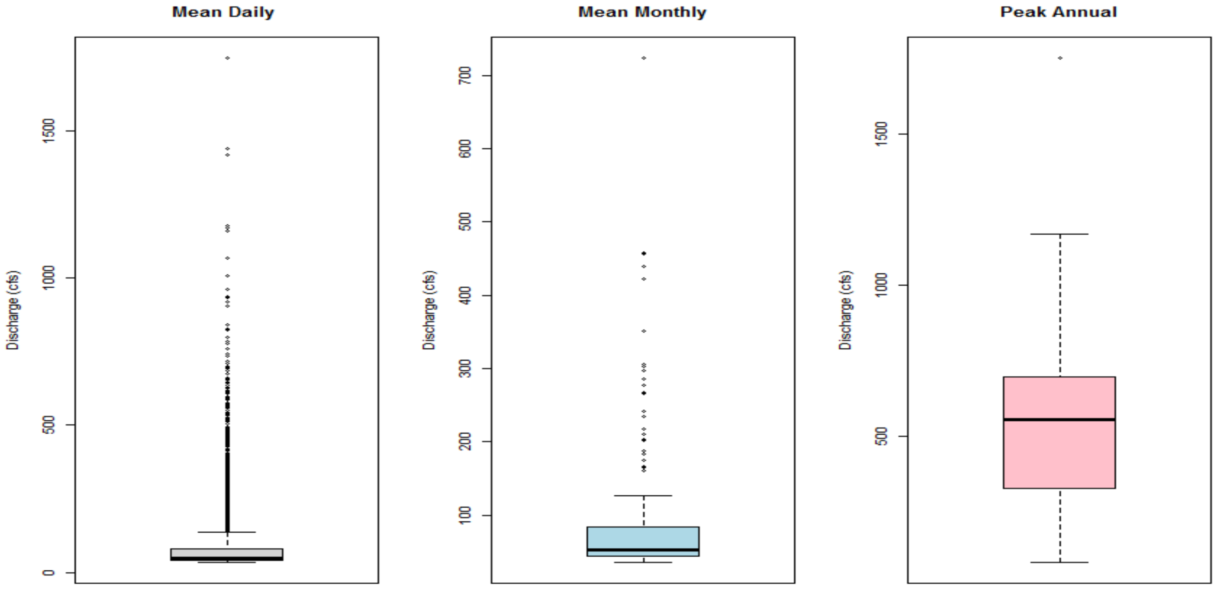


Figure 27: Boxplots for daily average (left), monthly average (middle) and peak annual (right) streamflow at NFBC.

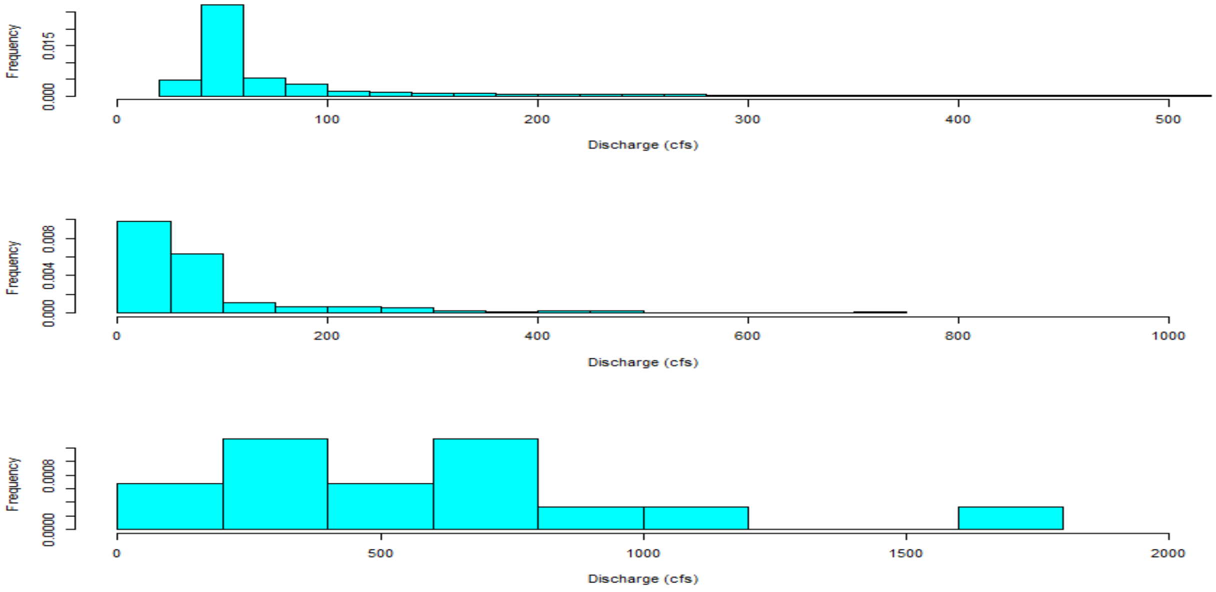


Figure 28: Histograms for daily average (top), monthly average (middle) and peak annual (bottom) streamflow at NFBC.

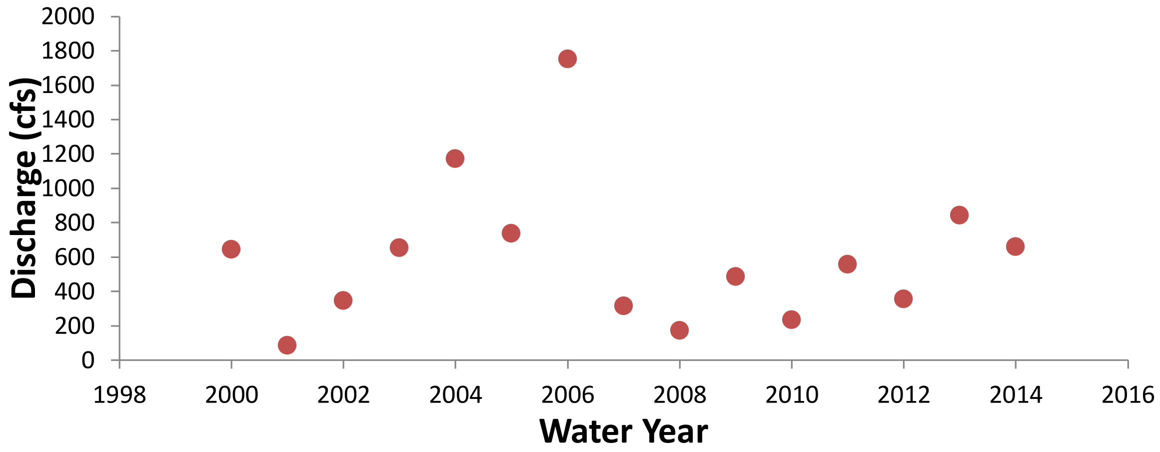


Figure 29: NFBC peak annual streamflow.

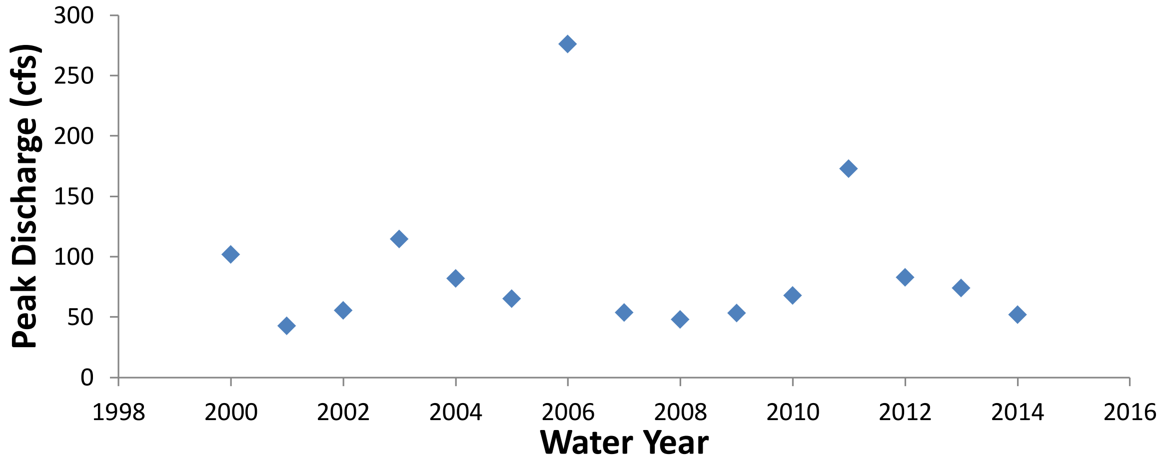


Figure 30: NFBC mean annual streamflow.

5.2.3 South Fork Battle Creek

Streamflow data for minimum, mean, and maximum daily average flows are not provided by CDEC for SFBC. Streamflow values for mean, minimum, and maximum flow plotted by month (Figure 31). December experienced the largest maximum flow with 3,590 cfs and May experienced the largest mean flow at 171 cfs. Minimum flows range from a low in July at 5.6 cfs to a high in April at 21 cfs indicating a low variability in minimum flows occurring any month in the year.

Time series were created for mean daily, mean monthly, and peak annual streamflow (Figure 32) and their associated boxplots (Figure 33) and histograms (Figure 34). Daily time series display distinct seasonality with wet winters and dry summers. Monthly time series convey wet vs. dry years. The average flow over the period of record is 92.2 cfs. Mean daily flows exhibited a heavy right-skew and fit a log-normal probability distribution function. Mean monthly streamflow values also displayed a heavy right-skew and log-normal distribution. Peak annual streamflow data was insufficient to characterize the distribution as there were only fourteen years of record (n=14). However, daily, monthly, and annual data indicated a similar distribution would fit with larger sample size. The largest flow on record occurred in 2006 with a peak discharge of 3,590 cfs (Figure 35). 2006 was a relatively wet year with a high magnitude of precipitation occurring in April and May resulting in an annual mean discharge of 409 cfs (Figure 36). Mean, minimum, and maximum monthly average flows indicate that maximum flows occur in December while mean values are highest during May. These values reflect dominant hillslope and runoff processes occurring in the basin.

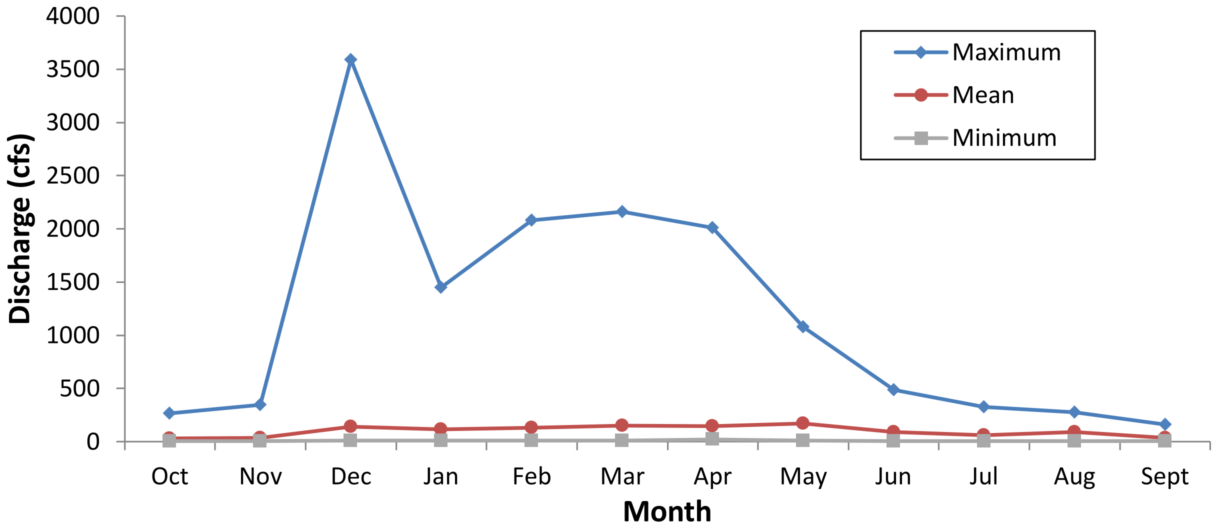


Figure 31: SFBC discharge for minimum (gray square), mean (blue diamond) and maximum (red circle) streamflow by month.

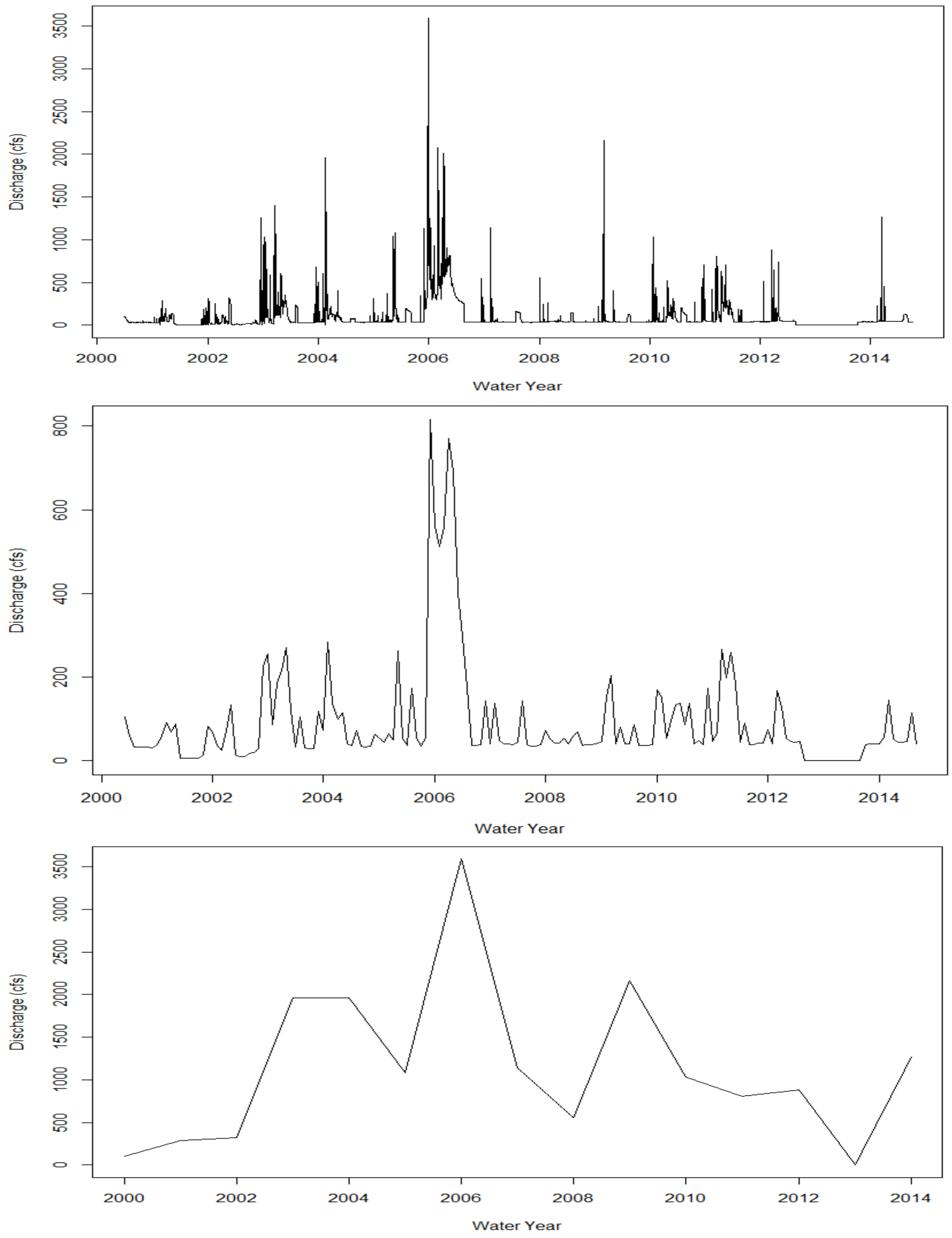


Figure 32: Time series for daily average (top), monthly average (middle) and peak annual (bottom) streamflow at SFBC.

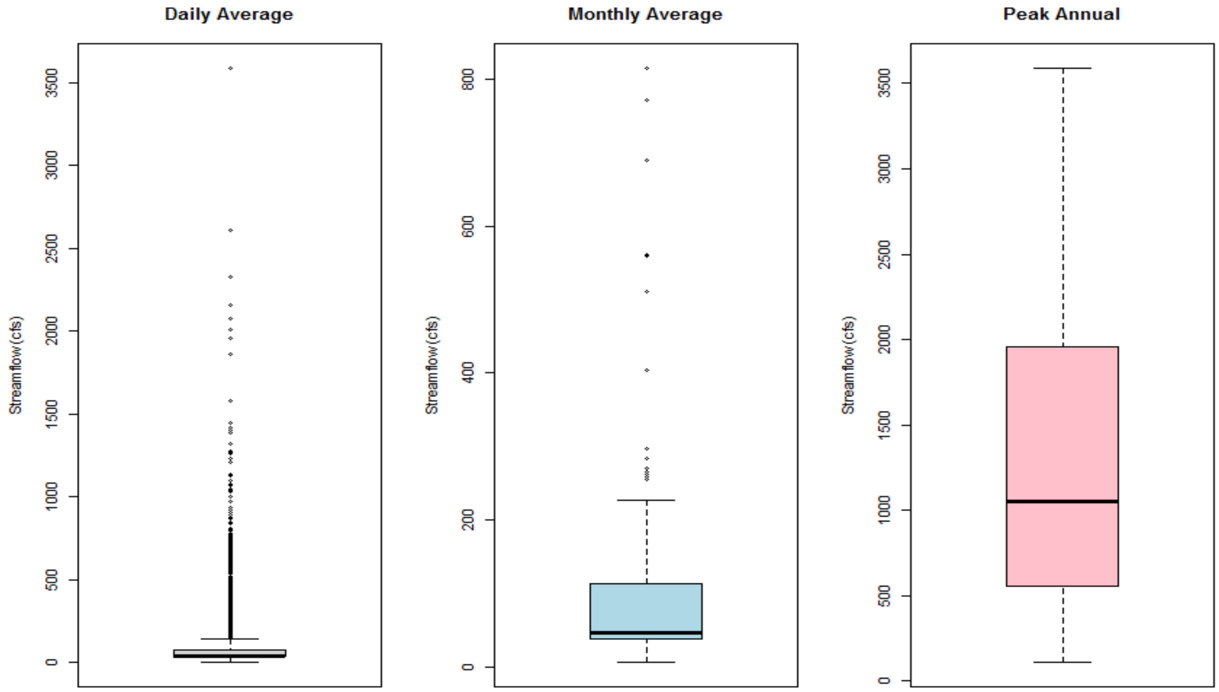


Figure 33: Boxplots for daily average (left), monthly average (middle) and peak annual (right) streamflow at SFBC.

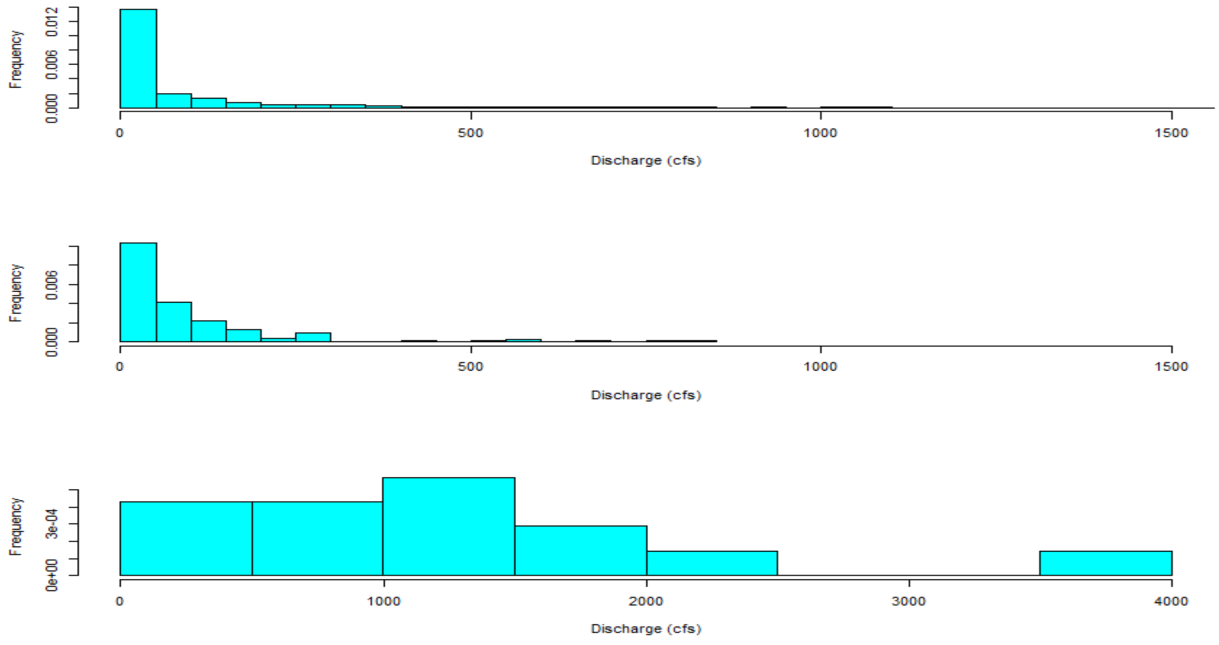


Figure 34: Histograms for daily average (top), monthly average (middle) and peak annual (bottom) streamflow at SFBC.

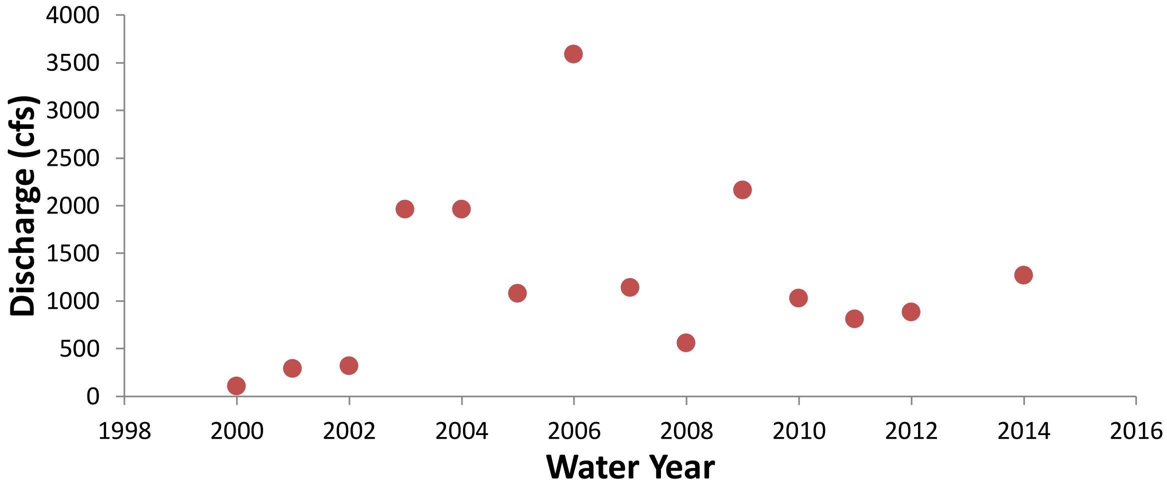


Figure 35: SFBC peak annual flows

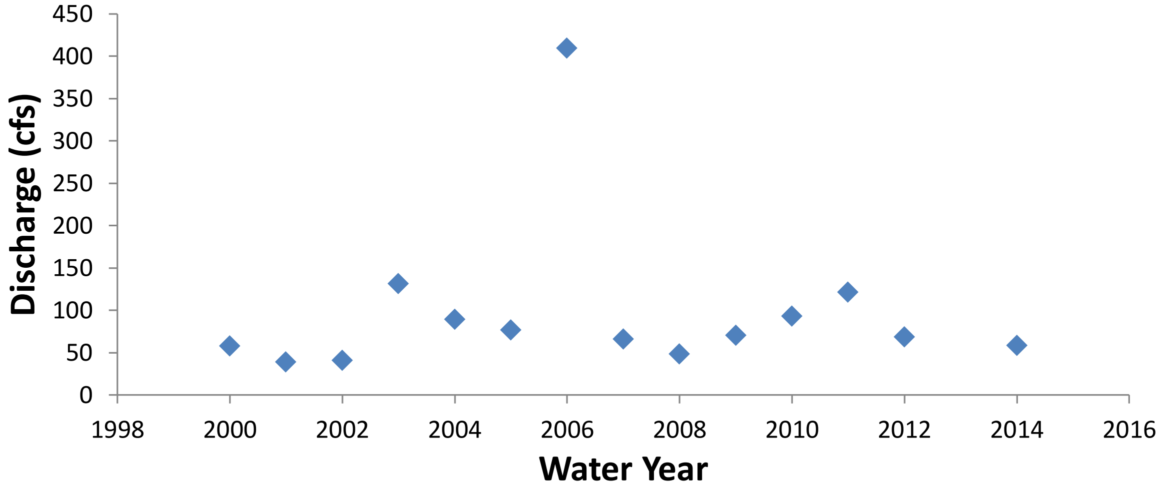


Figure 36: SFBC mean annual flows.

5.2.4 Streamflow Comparison

Streamgages in Battle Creek on MSBC, SFBC, and NFBC were highly correlated when comparing peak and mean annual discharge. MSBC and SFBC had the greatest correlation for peak annual discharge while MSBC and NFBC had the greatest correlation between mean annual discharge.

Streamflow values for peak and mean annual discharge (Figure 37) were compared for streamgages at MSBC, NFBC, and SFBC for overlapping years of data collection from WY 2000 – 2014. MSBC, NFBC, and SFBC have a drainage area of approximately 359 mi^2, 194 mi^2, 118 mi^2, respectively. MSBC has the largest contributing area and thus recieved the largest magnitudes of both mean and peak discharge accordingly. NFBC and SFBC exhibited similar mean annual discharges although this varied from year to year. SFBC experienced a greater magnitude of mean discharge in 2006 while NFBC was greater in 2011. Although SFBC had a smaller drainage area then NFBC, for all years but two it experienced higher peak discharge. This reflected drainage basin characteristics. SFBC has a steeper longitudinal profile at lower elevations and also receives the bulk of convective rainfall precipitation. NFBC is a larger basin, but has milder slopes at higher elevations and recieves more precipitation as snowfall. Snowfall melts more gradually, thereby producing smaller peak discharges than those of rainfall driven events of a given volume.

The relationships of peak and mean annual discharge values between streamgages were evaluated to observe how well the response in streamflow was correlated (Figure 37). Examination of overlapping 15-minute streamflow data for all three sites from WY 2008 - 2012 revealed a time lag between MSBC and SFBC that ranged from 15 minutes to 3 hours.A variable relationship was found between NFBC and SFBC peak flow timing, with NFBC occuring both before and after SFBC with lag times from 30 minutes to 9 hours (Table 7). Linear trends were used to compare MSBC to both SFBC and NFBC, and SFBC to NFBC in terms of mean discharge and peak discharge (Table 8). Mean discharges correlated more closely than peak discharge for all site comparisons, with R^2 values ranging from 0.8 - 0.91 and 0.42 - 0.73, respectively. These correlations reflect dominant runoff processess for subbasins NFBC and SFBC and how they transport and deliver streamflow to MSBC.

Table 7: Date and time of peak flow for streamgage sites.

Water Year	MSBC	NFBC	SFBC
2007	n/a	2/10/07 8:30	2/10/07 17:45
2008	1/4/08 15:00	1/4/08 15:00	1/4/08 14:30
2009	3/2/09 14:00	3/2/09 14:30	3/2/09 11:00
2010	1/19/10 14:45	1/19/10 12:15	1/19/10 14:30
2011	3/20/11 4:45	3/20/11 2:00	3/20/11 3:15
2012	1/21/12 1:00	1/20/12 23:00	1/21/12 00:15

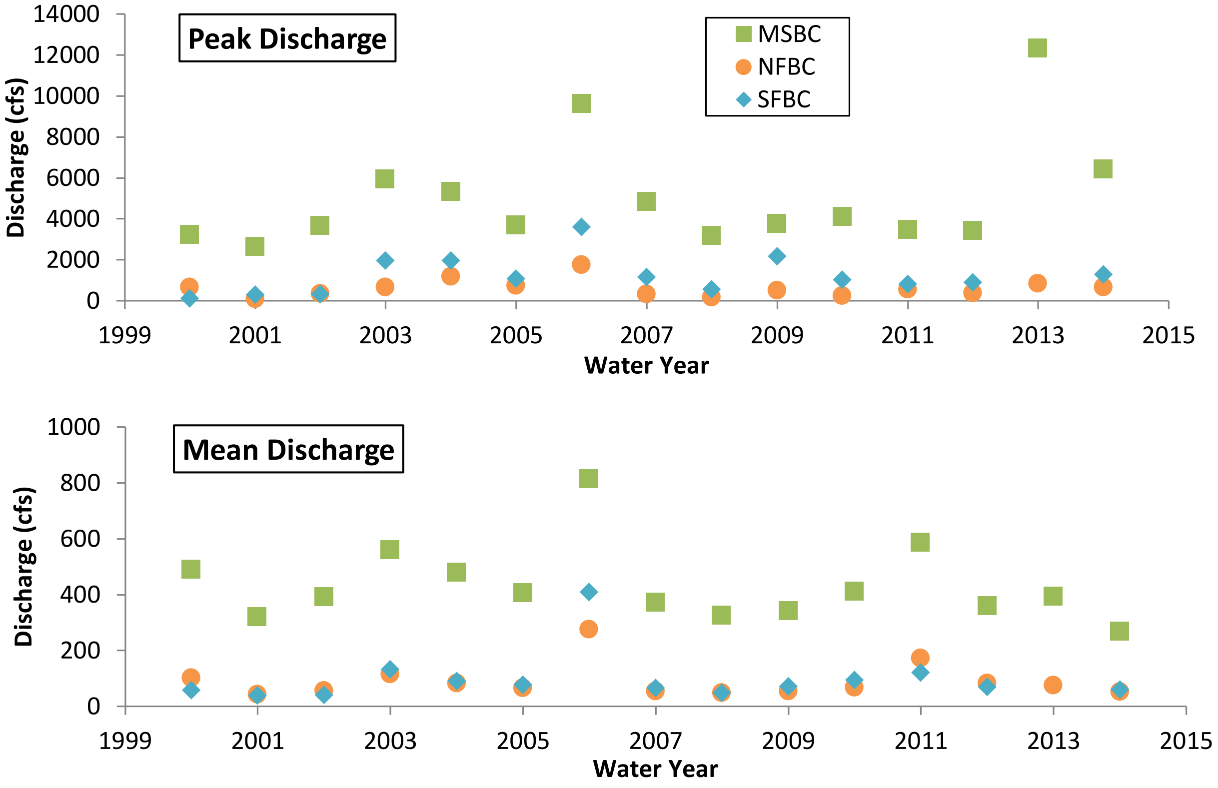


Figure 37: Comparison of mean and peak annual flows at MSBC, NFBC, and SFBC.

Table 8: Relationships of mean and peak discharge between MSBC, NFBC, and SFBC.

Site	Peak Discharge	Mean Discharge
SFBC = f(MSBC)	y= 0.4322x - 726.05, R^2 = 0.72	y= 0.6287x - 182.43, R^2 = 0.81
NFBC = f(MSBC)	y= 0.1041x + 75.864, R^2 = 0.43	y= 0.427x - 96.01 , R^2 = 0.91
SFBC = f(NFBC)	y = 1.6991x + 234.99, R^2 = 0.63	y= 1.3571x - 24.811, R^2 = 0.85

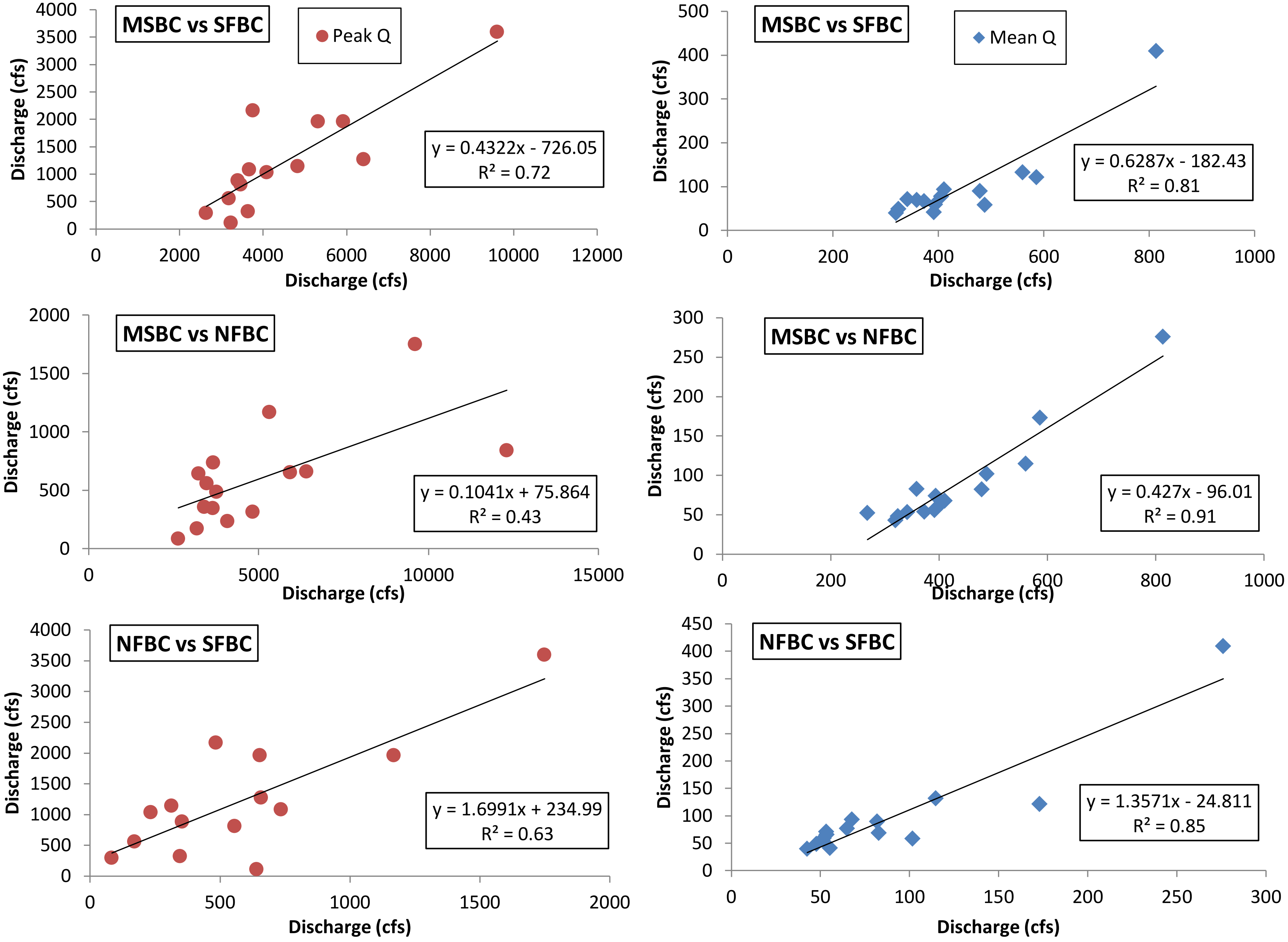


Figure 38: Relationship of peak annual (left) and mean annual (right) streamflow between streamgages.

5.3 Flood Frequency Analysis

The annual maximum series for MSBC, NFBC, and SFBC were evaluated for flood flow frequency. Histograms indicated data are of a log-normal distribution and data were log-transformed to perform a log-Pearson Type III flood frequency analysis to observed annual peaks (USGS Bulletin 17B). This is the standard method for flood forecasting in the United States, providing a uniform flood-frequency analysis method for large-scale planning and water-resource development. The logarithms of discharge at selected exceedance probability, P, were computed by equation (5.1).

$$Log(Q) = \bar{X} + KS \tag{5.1}$$

Where $\bar{X}$ and S are the log-transformed average discharge over the entire data set and standard deviation respectively. K is a factor that is a function of the skew coefficient and P. The mean, standard deviation, and skew coefficient were computed from log-transformed values of peak discharge. K-values are provided from Haan (1977) from empirical based studies computing frequency factors K for log-Pearson Type III distributions at recurrence intervals of 2, 5,10,25,50,100, and 200 years.

5.3.1 Mainstem Battle Creek

MSBC historical streamflow annual maximum from 1939 – 2014 were used in the log-Pearson Type III flood frequency analysis. No data exists for water years 1940, 1943, and 1997 and these years were excluded from the analysis giving 72 annual maximum points (n=72). Peak streamflow values were log-transformed for use in the analysis creating a normal distribution of the data (Figure 39). Following methods in USGS Bulletin 17b (1982), a standard deviation (S) and Skew Coefficient (C) were calculated at S = 0.28 and C = -0.02. K values are presented by Hahn (1977) in intervals of 0.1 and selected by skew coefficient. A linear interpolation of K values between 0.0 and -0.1 to exactly match C for MSBC was computed and applied to equation (5.1). Estimated peak discharge was plotted vs recurrence interval in log-log space (Figure 42) for recurrence intervals to corresponding K values.

A peak flow with 2 year recurrence interval is estimated to be 6,019 cfs. Utilizing the existing dataset of annual maxima, this event has an exceedance probability of 49% (Figure 43). The 50-year flood event was estimated at 22,382 cfs and is larger than any flood on record except for water year 1939. 1939 was estimated at 35,000 cfs and registers larger than the estimated 200-year flood at 31,145 cfs. All estimated values of peak flood flow for recurrence intervals 2, 5, 10, 50, 100, and 200 years are presented in Table 9 and Figure 42.

The peak event for water year 2015 occurred on 12/3/14 with a value of 15,300 cfs. This event registers as a 19 year flood from the log-Pearson Type III flood frequency analysis. This event is analyzed further in regards to sediment load estimations in Section 6.2.5.

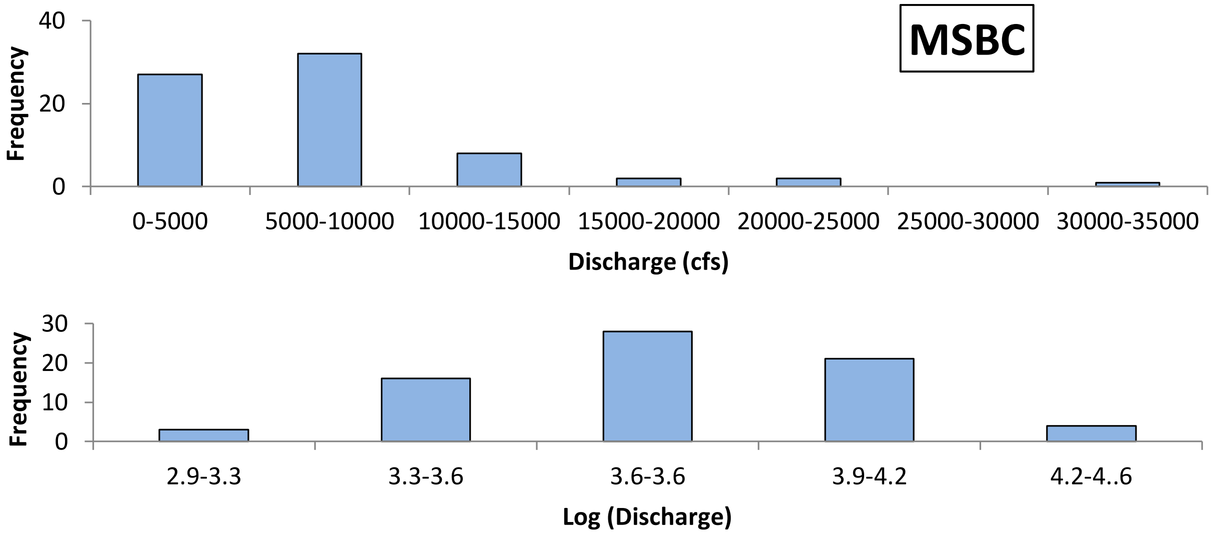


Figure 39: Histograms of peak and log-transformed peak discharge at MSBC.

5.3.2 North Fork Battle Creek

NFBC historical streamflow annual maximum from 2000 – 2014 were used in the log-Pearson Type III flood frequency analysis totaling 15 years of data (n=15). Peak streamflow values were log-transformed for use in the analysis creating a normal distribution of the data (Figure 40). Following methods in USGS Bulletin 17b (1982), a standard deviation (S) and Skew Coefficient (C) were calculated at S = 0.33 and C = -0.58. K values are presented by Hahn (1977) in intervals of 0.1 and selected by skew coefficient. A linear interpolation of K values between -0.5 and -0.6 to exactly match C for NFBC was computed and applied to equation (5.1). Estimated peak discharge was plotted vs recurrence interval in log-log space (Figure 42) for recurrence intervals to corresponding K values.

The peak event for water year 2015 occurred on 12/3/14 with an estimated value of 3,994 cfs (see Section 6.2.5 for calculation). This event registers well beyond the log-Pearson Type III 200 year flood estimated flow of 2,239 cfs. The longer duration record of MSBC (n=72) indicates this was a 15 year event although a low correlation between peak discharge at MSBC and NFBC exists (R^2 = 0.4289). Flood frequency results should be viewed with caution due to the short record and limited amount of high magnitude events occurring from 2000 – 2014. All estimated values of peak flood flow for recurrence intervals 2, 5, 10, 50, 100, and 200 years are presented in Table 9 and Figure 42. Exceedance probabilities for the short record (Figure 43) should also be viewed with great caution. Both flood frequency estimates and exceedance probabilities can give a quantitative view of streamflow trends within the last 15 years, although trends on longer timescales are not captured over the short record. Streamflow and precipitation are also stochastic processes with extreme events that occur irregularly. A sufficient number of extreme events would be necessary to accurately estimate the probability of rare, high discharge floods.

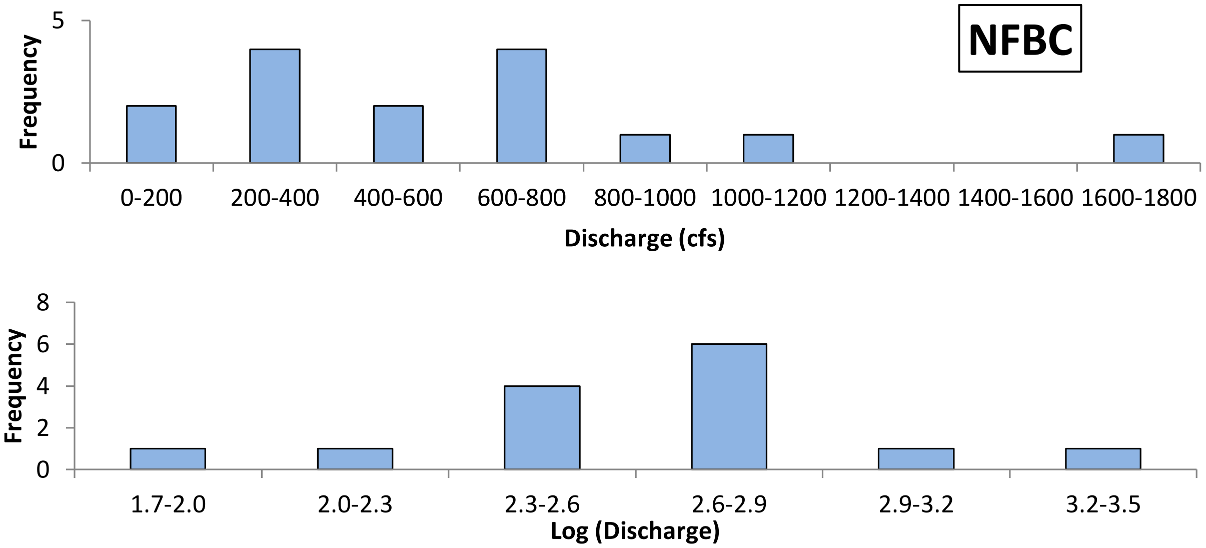


Figure 40: Histograms of peak and log-transformed peak discharge at NFBC.

5.3.3 South Fork Battle Creek

SFBC historical streamflow annual maxima from 2000 – 2014 were used in a log-Pearson Type III flood frequency analysis. A total of 14 years of data (n=14) were available as water year 2013 was excluded due to missing data. Peak streamflow values were log-transformed for use in the analysis creating a normal distribution of the data (Figure 41). Following methods in USGS Bulletin 17b (1982), a standard deviation (S) and Skew Coefficient (C) were calculated at S = 0.35 and C = -0.55. K values are presented by Hahn (1977) in intervals of 0.1 and selected by skew coefficient. A linear interpolation of K values between -0.5 and -0.6 to exactly match C for SFBC was computed and applied to equation (5.1). Estimated peak discharge was plotted vs recurrence interval in log-log space (Figure 42) for recurrence intervals to corresponding K values.

The peak event for water year 2015 occurred on 12/3/14 with an estimated value of 9,287 cfs (see Section 6.2.5 for calculation). This event registers over twice as large as the log-Pearson Type III 200 year flood estimated flow of 4,452 cfs. The longer duration record of MSBC (n=72) indicates this was a 15 year event although a relatively high correlation between peak discharge at MSBC and SFBC exists ($R^2 = 0.7232$). Flood frequency data should be viewed with caution due to the short record and limited amount of high magnitude events occurring from 2000 – 2014.

All estimated values of peak flood flow for recurrence intervals 2, 5, 10, 50, 100, and 200 years are presented in Table 9and Figure 42. Exceedance probabilities for the short record (Figure 43) should also be viewed with caution. Both flood frequency estimates and exceedance probabilities can give a quantitative view of streamflow trends within the last 15 years, although discharge patterns over longer timescales are not captured during the short record. Streamflow and precipitation are also stochastic processes with extreme events that occur irregularly. A sufficient number of extreme events would be necessary to accurately estimate the probability of rare, high discharge floods.

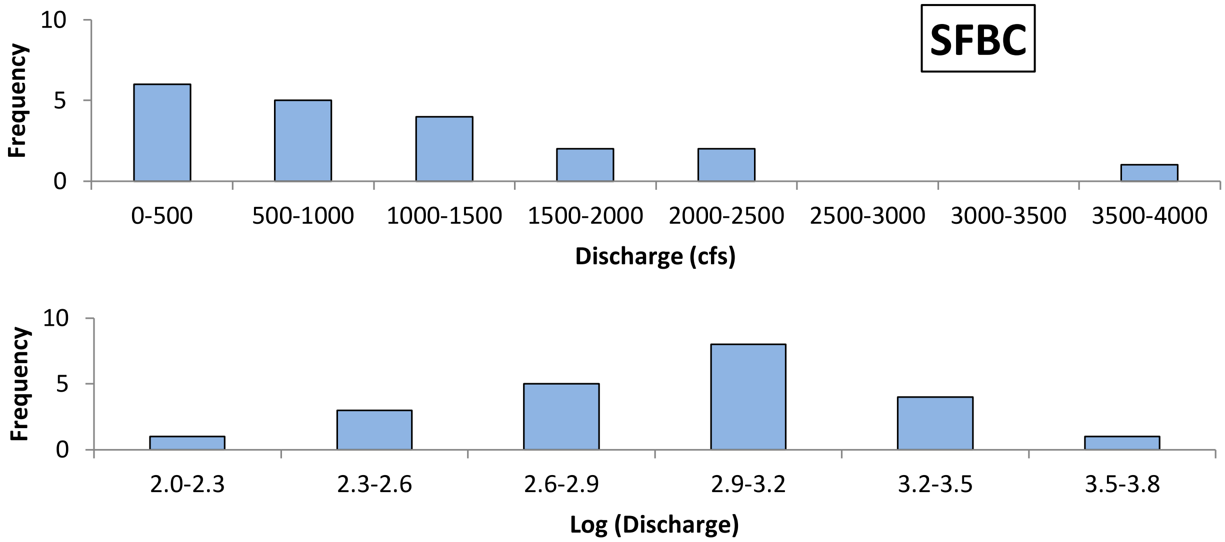


Figure 41: Histograms of peak and log-transformed peak discharge at SFBC.

5.3.4 Peak Flow Comparison

Flood frequency analysis for MSBC, NFBC, and SFBC displayed similar patterns when evaluated for log-Pearson Type III flood frequency (Figure 42) and exceedance probabilities (Figure 43). A comprehensive record that dates back to 1938 allowed for a robust analysis of MSBC floods, while short records for NFBC (n=15) and SFBC (n=14) were not representative of the range of peak discharge conditions that occur at these sites over interdecadal to centennial time scales (Table 9). The 100-yr recurrence interval value for MSBC found in this report (26,590 cfs) is slightly lower than those from past reports cited in Section 3.4.2 (26,900 and 27,350 cfs). The addition of recent years of observations has slightly reduced the estimate due to the relatively low hydrologic activity during this time period. However the difference between each estimate areonly a few percent, suggesting that flood frequency estimates up to the 100 year scale have remained robust since the original USBR analysis of MSBC.

Table 9: Estimated streamflow values (cfs) for flood flow frequency.

RI (years)	MSBC	NFBC	SFBC
2	6019	507	899
5	10337	909	1674
10	13694	1185	2227
25	18464	1529	2933
50	22382	1776	3453
100	26590	2012	3960
200	31145	2239	4452

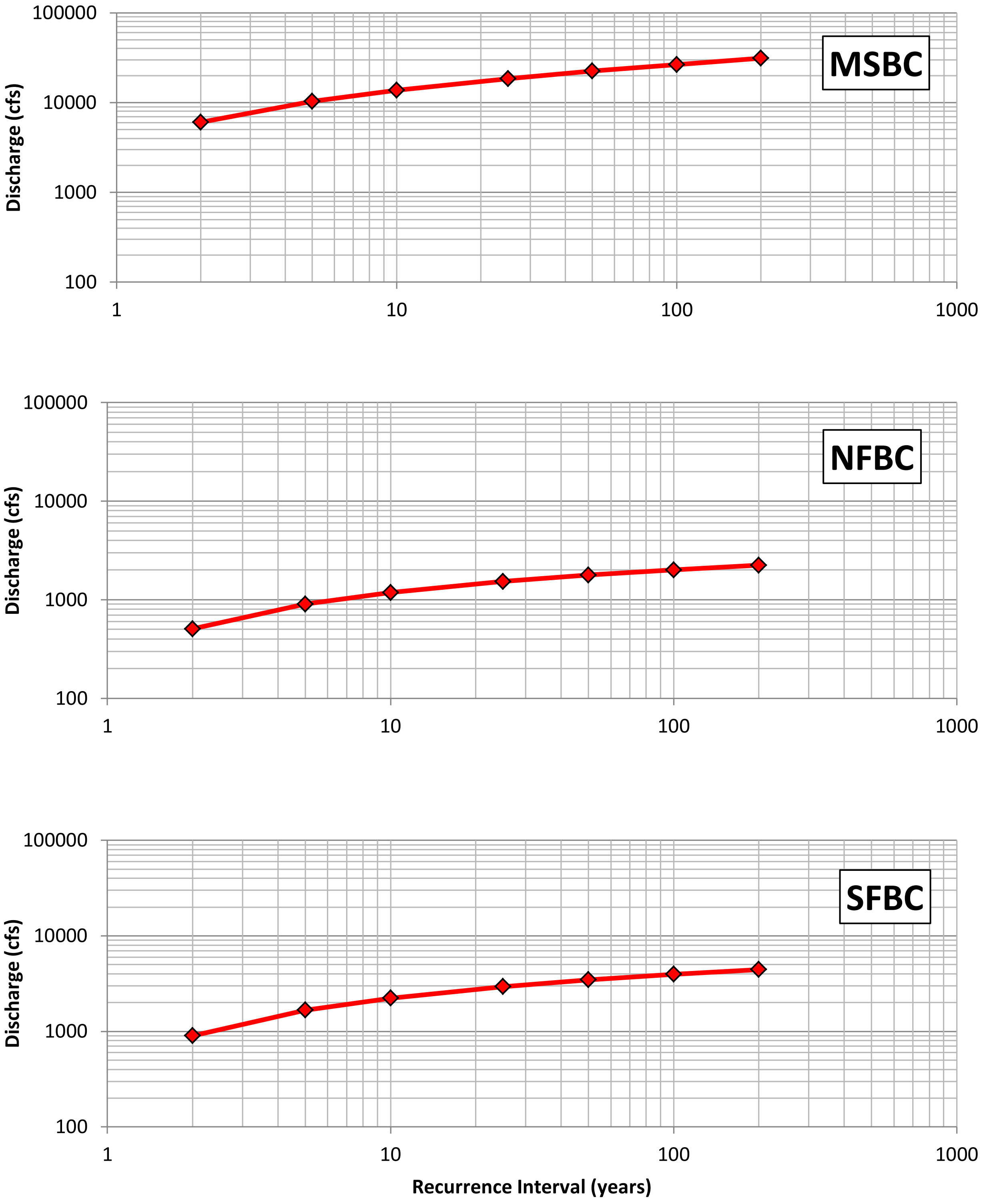


Figure 42: Estimated flood flows using log-Pearson Type III distribution.

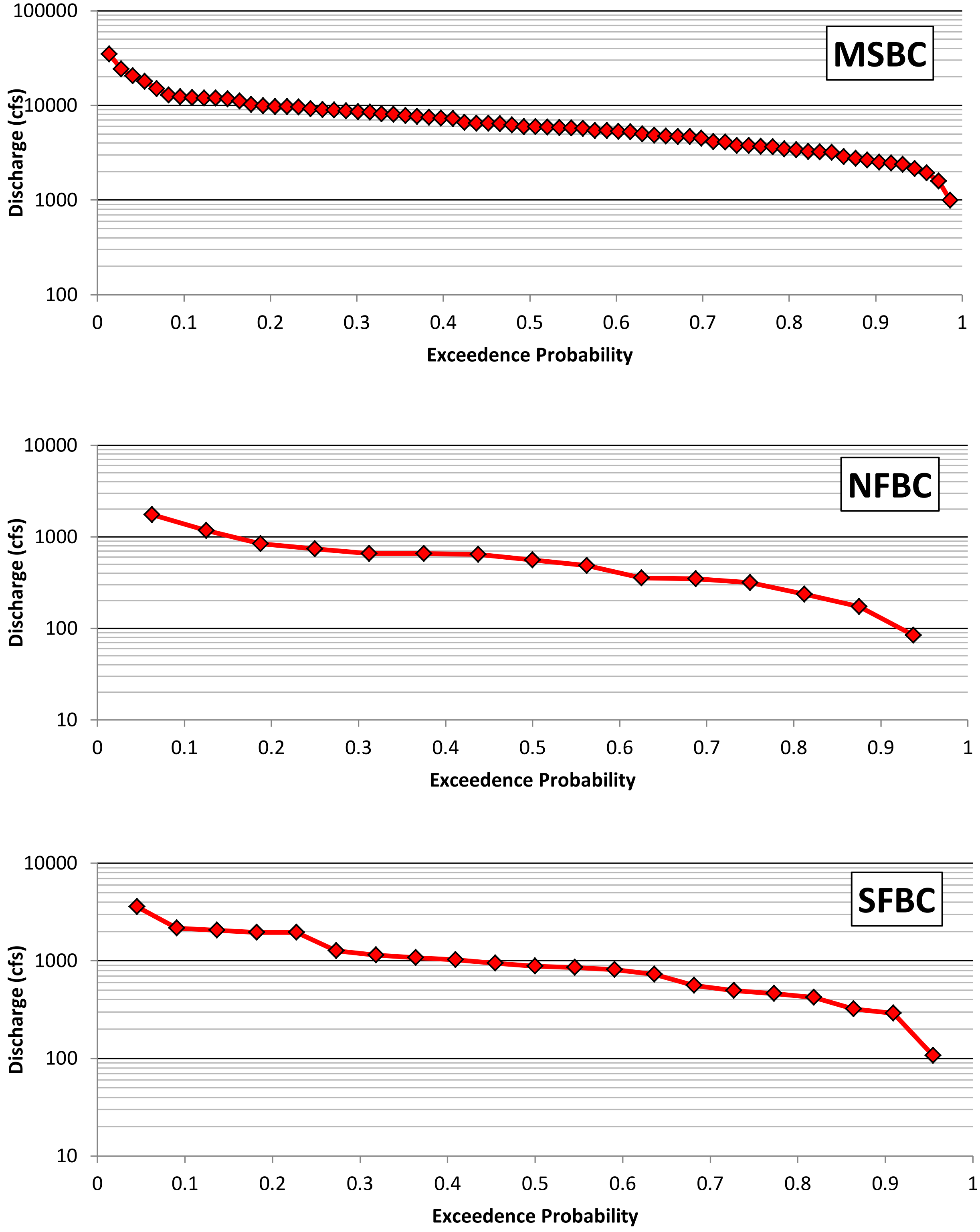


Figure 43: Exceedance probability for annual maximum flows.

6 SEDIMENT AND WATER QUALITY ANALYSIS

Sediment is a critical component in river systems supporting physical and ecological functions such as providing aquatic habitat (Ryan, 1991), transporting nutrients (Walling et al., 2001), and degrading benthic health when in excess (Henley et al., 2000). Historical water quality data relevant to sediment was downloaded, processed, and summarized graphically using Excel and is provided on a supplemental DVD. Results are reported in Section 6.1. In addition, a pilot sediment monitoring program was performed for WY 2015 as reported in Section 6.2. This effort involved automated turbidity monitoring as well as water and sediment sampling for laboratory analysis of SSC. For suitable samples, additional analyses were performed for grain size distributions and/or organic content. Despite our efforts to get as much out of these data and analyses, they primarily serve to stimulate future monitoring of the watershed, because in and of themselves they could not be sufficient to sufficiently inform the sediment impact methodologies described in Section 2.6.

6.1 USGS Historical Load Data Analysis

Water quality data from WY 1957 – 1970 was evaluated to create sediment-rating curves and estimate suspended sediment flux (Section 6.1.1). For Battle Creek, SSC is strongly correlated with both peak discharge (R^2 = 0.76) and mean discharge (R^2 = 0.74). Nevertheless, there remains significant scatter in the unexplained residuals that could be analyzed in the future using the methods of Gray et al. (2014, 2015a,b), though at this time the length of record is too short for the North Fork and South Fork Battle Creek datasets. Historical records indicate disproportionate sediment loads during large floods. Although not typical thought of as sediment, as it is not particulate, dissolved load affects water quality, so it was measured and analyzed by the USGS (6.1.2).

6.1.1 Suspended Load

From 1957 – 1970, USGS staff collected 173 water-sediment samples and processed them for SSC. Historically, the USGS collected water-sediment samples using a depth-integrated sampler, necessitating suitable infrastructure to enable the safe lowering and raising of the sampler through the water column to obtain water from all depths. Because the exact vertical velocity profile is unknown during sample collection, there would have been no way to know how much of the integrated sample came from each depth. Also, there is a region near the bed that is not sampled. As a result, even though these are high-quality samples, there is uncertainty in any such data.

Water-sediment samples were processed for SSC by the USGS by filtering the mass of sediment from the volume of water yielding a concentration in mg/L. Values of SSC were downloaded from the USGS streamflow website and used to develop sediment-rating curves for a historical SSC analysis, and included an analysis of the control of flow on sediment load. This enables a determination of an annual sediment flux. SSC was measured at USGS streamgage 11376500 from WY 1957 – 1961 and USGS streamgage 1176550 from WY 1962 – 1970. This analysis produced rating curves for each location and evaluated the applicability of compiling the two stations to create a single rating curve. A composite rating curve encompasses a longer temporal scale providing higher resolution from increased sample size. Similar to the streamflow comparative analysis, no significant differences between the two datasets were found. This analysis was similar to that of Myers (2012) although he only used gaging data from WY 1962 – 1970.

Many natural phenomena exhibit power law ($y = ax^b$) relationships (Malamud and Turcotte, 2006) including flooding and sediment transport. SSC (mg/L) was plotted vs. Q (cfs) to in log-log space (Figure 44) and fitted with a rating curve in the form of a power law equation (6.1), where *y* is SCC and *x* is Q.

$$y = 0.0028x^{1.3545}, R^2 = 0.69 \tag{6.1}$$

The rating curve was applied to daily average streamflow for water years 1957 - 1970 corresponding to the duration of sample collection.

Before an SSC - Q rating curve can be applied to a discharge record to estimate Q_{SS}, sources of systematic bias, including log-transform bias, must be investigated. Log-transformation bias occurs due to the fitting of the rating curve to log-transformed data, which systematically under-estimates non-transformed values (Ferguson, 1986). A log-bias correction factor as reported by Ferguson (1986) was applied to load estimates using equations (6.2) and (6.3).

$$exp(2.65s^2) \tag{6.2}$$

$$s^2 = \sum_{i=1}^{n}\left(logC_i - log\widehat{C_\iota}\right)^2/(n-2) \tag{6.3}$$

where C_i is the measured SSC, $\widehat{C_\iota}$ is the estimated SSC, and *n* is the sample size.

Daily sediment loads were summed producing annual sediment loads (Table 10). Sediment loads are presented in short tons vs. peak discharge (Figure 45) and mean discharge (Figure 46) in cfs. Suspended sediment varies with discharge exhibiting larger annual sediment loads with higher magnitude peak (Figure 47) and mean annual (Figure 48) streamflow. The largest flows on record occurred in 1970 and that year also had the highest estimated sediment load at 88, 257 short tons with a peak and mean streamflow of 24,300 and 720 cfs respectively.

The USGS processed very few of the water-sediment samples for particle size distribution (approximately 7 out of 173), and thus it is not possible to estimate the proportions of clay, silt and sand size classes within the suspended load.

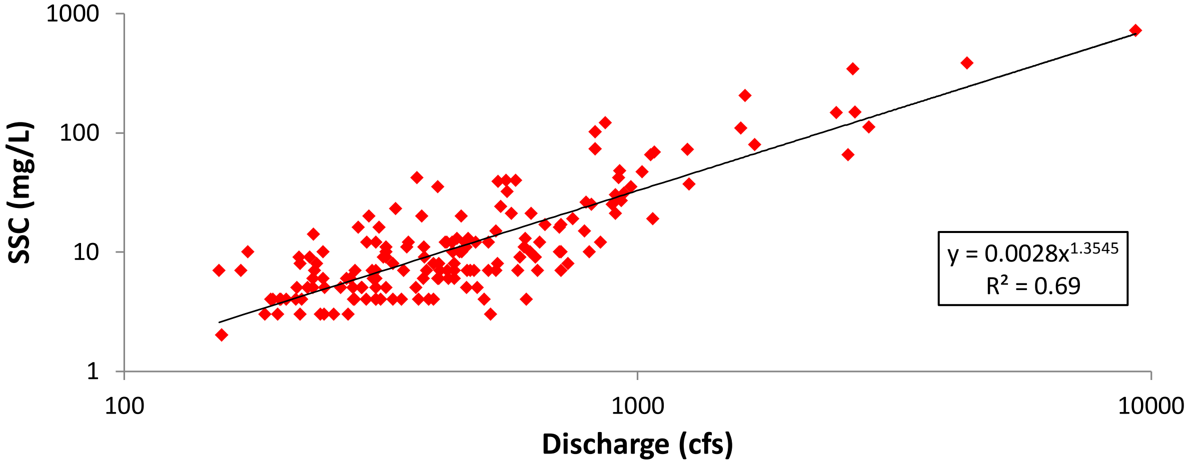


Figure 44: Sediment rating curve at Mainstem Battle Creek from WY 1957-1970 (n=173).

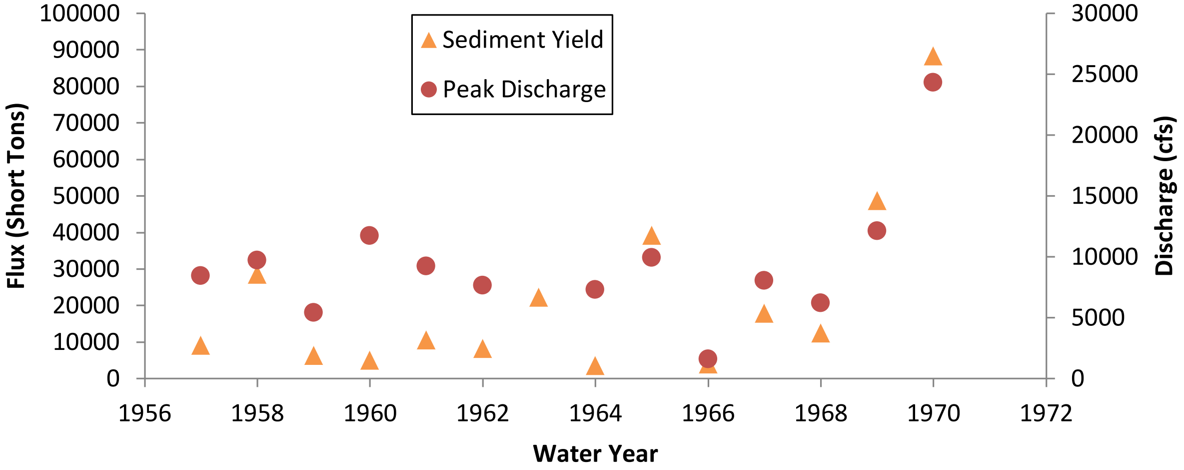


Figure 45: Annual sediment load and peak annual discharge.

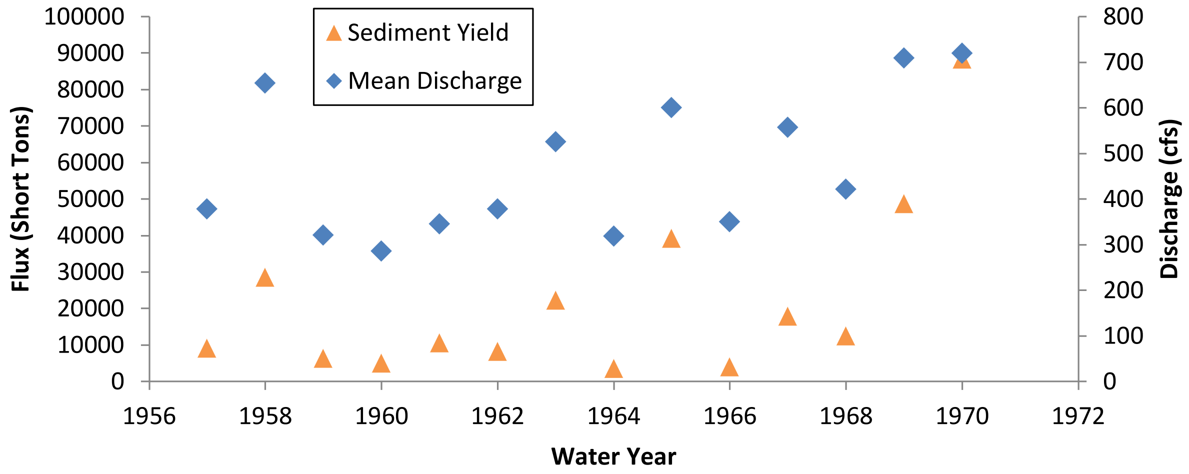


Figure 46: Annual sediment yield and mean annual discharge.

Table 10: Historical suspended sediment flux estimates.

Estimate	**1957**	**1958**	**1959**	**1960**	**1961**	**1962**	**1963**
short tons	9127	28499	6364	4952	10562	8168	22276
tons/hectare	0.098	0.306	0.068	0.053	0.113	0.088	0.239
Estimate	**1964**	**1965**	**1966**	**1967**	**1968**	**1969**	**1970**
short tons	3495	39248	3939	17911	12436	48728	88257
tons/hectare	0.038	0.422	0.042	0.192	0.134	0.524	0.948

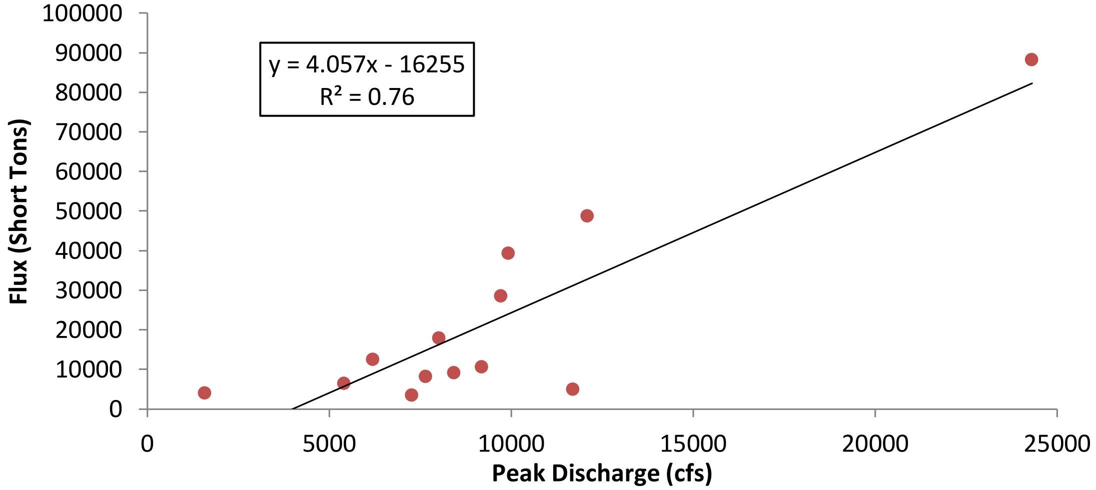


Figure 47: Linear regression for peak discharge on sediment flux.

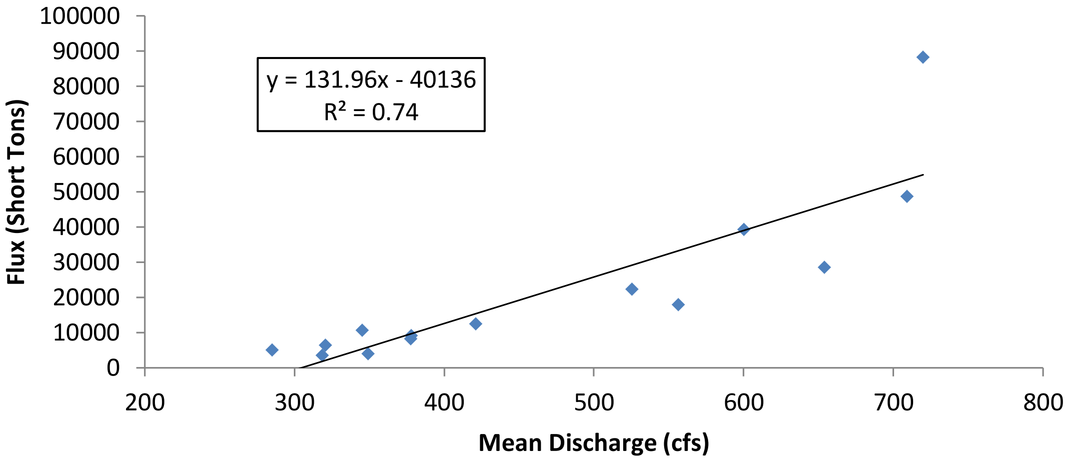


Figure 48: Linear regression for mean discharge on sediment flux.

6.1.2 Dissolved Load

Specific conductance is a measure of the ability of water to conduct an electrical current and is highly dependent on the amount of dissolved solids in the water (USGS website). The USGS processed 71 water-sediment samples collected WY 1961 – 1966 for specific conductivity (SC). SC displays higher values at low discharges with a linear decreasing trend until around 1200 cfs (Figure 49). The two samples collected at discharges larger than 1200 cfs had higher SC values, but many more would be needed to ascertain what is occurring. Myers (2012) claimed the rate of delivery of surface runoff is likely to be faster than the dissolution of solids in suspension, causing higher magnitude flows to be less conductive than base streamflow. On the other hand, discharge increases on the rising limb of a hydrograph, because more areas of land become saturated and thus contribute saturation excess overland flow (i.e., the “variable source area concept”). As a result, it is possible that these newly contributing areas could bring fresh dissolved load to the river. At this point, there is insufficient data and understanding of the watershed to evaluate these concepts locally.

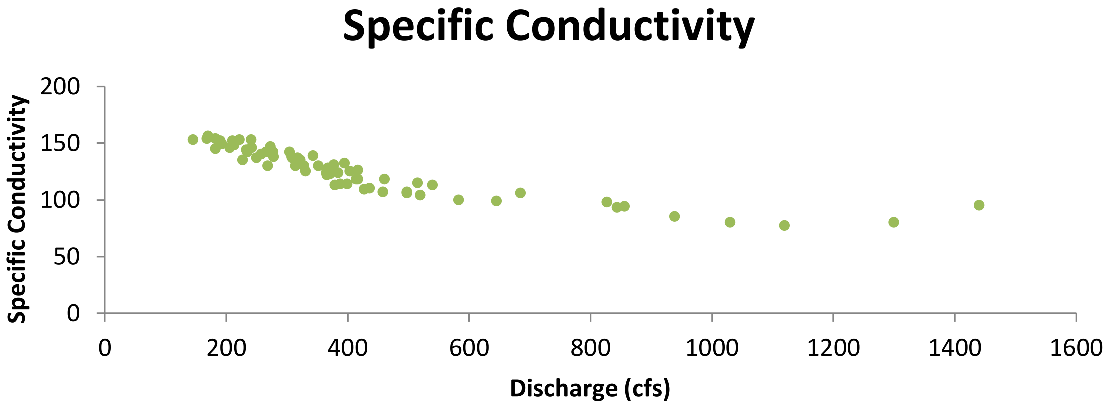


Figure 49: Specific Conductivity (microsiemens per cm) of water-sediment samples at MSBC.

6.2 2015 Sediment Monitoring

A collaborative field monitoring campaign was executed working with local stakeholders and the Central Valley Regional Water Quality Control Board staff to monitor and record watershed sediment flux in Battle Creek for WY 2015. Four field monitoring sites were identified as ideal locations to track sediment over a range of spatial scales. Three sites were co-located with existing streamgages to utilize continuous discharge records on MSBC, NFBC, and SFBC. An additional site was located on Digger Creek (DCK), a tributary to NFBC. Water-sediment samples were collected at all four sites during WY 2015.

6.2.1 Grab Sampling Concepts

Whereas USGS sediment sampling involves substantial infrastructural development at each site and regular use of heavy equipment, funding for this study did not allow for such a level of monitoring capability. A best effort was made under the constraints of available resources with additional contributions from UC Davis and the researchers themselves to establish a field campaign sufficient for obtaining meaningful samples. In support of this study, a sampling protocol was developed for collecting what are termed “grab samples” (see Section 12.2 for the full protocol). A grab sample is a single sample taken at a specific time by submerging a sample bottle affixed to a telescoping pole into the flow until it is completely full and then transferring completely to a labeled bottle. Because grab samples are taken close to the water’s surface, they capture only a portion of the larger grain sizes in transport, so it is necessary to explain this effect and its consequences further before proceeding with data analyses. Note that Gray (2014, 2015a,b,) and many other suspended sediment studies have employed this kind of sampling approach, which is a well-establish and standard method.

Recall from Section 2.1.1 that the depth distribution of each sediment size is largely controlled by the balance between the particle's fall velocity (which is a function of particle diameter) and the turbulent intensity of the flow. Figure 50 illustrates the effect of grain size on the depth distribution of sediment concentration based on the fall velocity relation of Dietrich (1982) and the Rouse-Vanoni equilibrium suspended sediment profile (Rouse, 1939). This analysis assumes the standard value for the submerged specific gravity of sediment (1.65), a near-bed entrainment boundary at 5% of full depth, and a shear velocity of 0.2 m/s (equivalent to a shear stress of 40 Pa). Of course, the actual shear velocity at any point in a river depends on discharge, topography, and channel roughness, so this theoretical demonstration has to be for illustrative purposes only. Still, 40 Pa is more than reasonable for the flood events observed and reported on in this study, which were very large events that easily moved large trees down the river and were observed to yield channel changes.

In the example presented, the sediment concentration at the water's surface is 95% that at mid-depth for sediment diameters up to 40 μm (0.04 mm), indicating virtually no effect and no consequence as to whether a sample is taken using a grab sampler or a depth-integrated sampler. At the threshold size delineating silt and sand (63 μm), the sediment concentration at the water's surface is 88% that at mid-depth, still showing that the vast majority of sizes are represented. Thus, grab sampling for a flood that produces a shear velocity of 0.2 m/s is an excellent and suitable methodology for capturing the suspended sediment concentration and sediment load for fine sediment, defined as the full range of clay and silt sized particles (0-63 μm). Once particle sizes gets well into the sand-size range, the sediment concentration at the surface becomes a smaller fraction of that at mid-depth (Figure 51). Thus, grab sampling is not going to represent the concentration and load of sand particles, especially if they are larger than 100 μm (the size at which surface concentration is 76% of that at mid-depth).

To provide a contrast using the case of a low-magnitude flow, consider that if the shear velocity is only 0.04472 (equivalent to a shear stress of 2 Pa, which is double the typical value needed to begin to entrain non-cohesive submerged sand), then the particle size for which the surface concentration is 95% of that at mid-depth is 19 μm. This makes sense, because if shear velocities are near the threshold of entrainment when particles are just beginning to move along the bed, one would expect great disparity between the amount of particle entrained along the bottom and those transported all the way to the surface. The result of this analysis is that the effect of grab sampling on sediment estimation is the worst for the lowest flows, but then of course these flows are also moving the least sediment, so they are not particularly important from both mass flux and water quality perspectives. Meanwhile, in the large events that accomplish the vast majority of sediment transport, grab sampling not only captures the vast majority of fine sediment, but also samples much of the fine sand as well.

Recall also from Section 2.1.1 that suspended sediments that display invariant concentration profiles with depth are often labeled as ‘washload.’ Washload sediment is generally considered to be supply rather than transport limited, as its abundance is not related to the flow field, but rather to sediment erosion and delivery mechanisms (Gabet and Dunne, 2003). Washload has been found to account for the majority of suspended sediment in most rivers of a scale large enough to develop floodplains (Naden, 2010). As suspended sediment is also the major component of total fluvial load, it becomes apparent that most, or at least a very significant proportion, of fluvial sediment flux is controlled by the delivery of sediment to the channel rather than the ability of channelized flow to transport the load.

An additional consideration is that the majority of concerns related to sediment and water quality have to do with fine sediment, not sand. As a result, a quantification of the SSC weighted towards fine sediment would not harm the ability to evaluate fine sediment impacts. The one major concern related to sand would be if the sand was filling in salmonid spawning substrate, which is predominantly composed of gravel and cobble. Because the sediment analyses in this section focused on sediment flux, not channel change or sediment deposition, this is not at issue here.

Given that the vast majority of clay- and silt-sized sediment is captured by grab sampling during a flood, the floods monitored in this study were large, and washload often accounts for the majority of suspended sediment, then the methods used in this monitoring campaign should be viewed as effective at estimating SSC and suspended sediment load during the study period. If stakeholders are interested in a more complete representation of the suspended sediment load, then they will have to be prepared to invest the level of resources necessary to fund a USGS-type sediment monitoring methodology. Such a monitoring program would cost approximately an order of magnitude more than invested in the monitoring program of this study, and even such a rigorous approach will produce data with significant uncertainty as explained in section 2.2 and 6.1.1. Nevertheless, the effects of sampling approach should be remembered when considering the study’s findings, especially when comparisons are made with historical data.

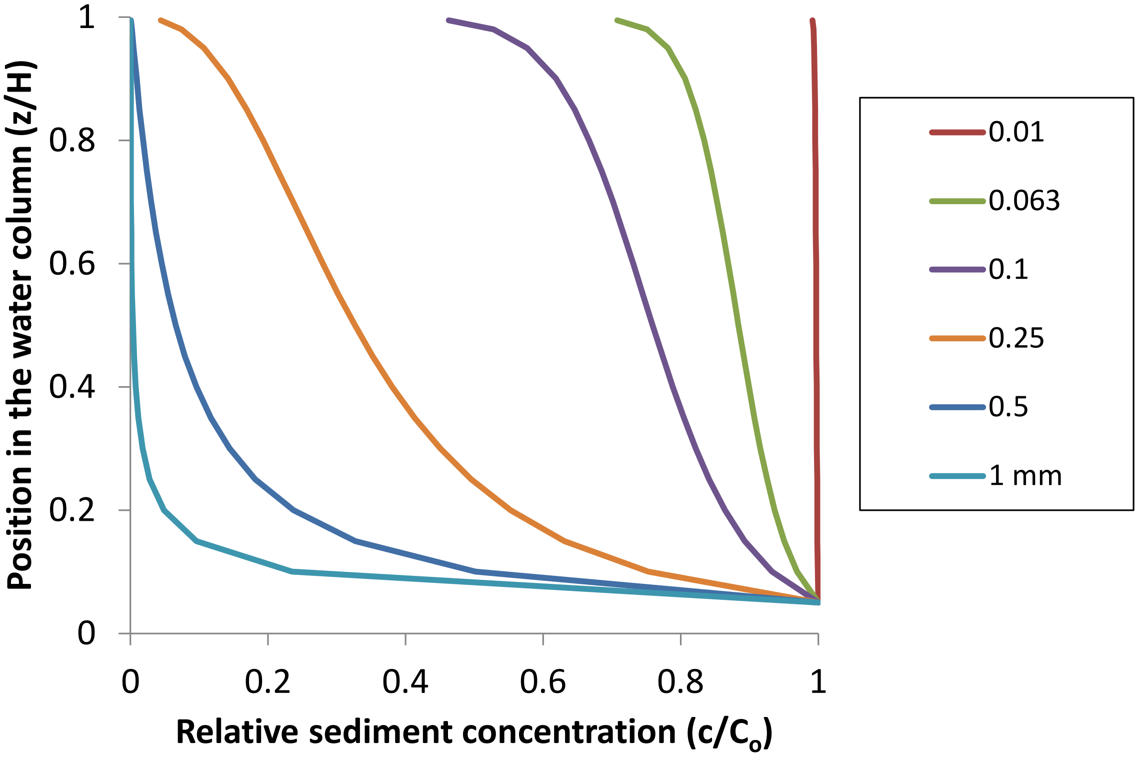


Figure 50: Theoretical depth distribution of sediment for each grain size. Each curve is for a different grain size (mm), as shown in the legend.

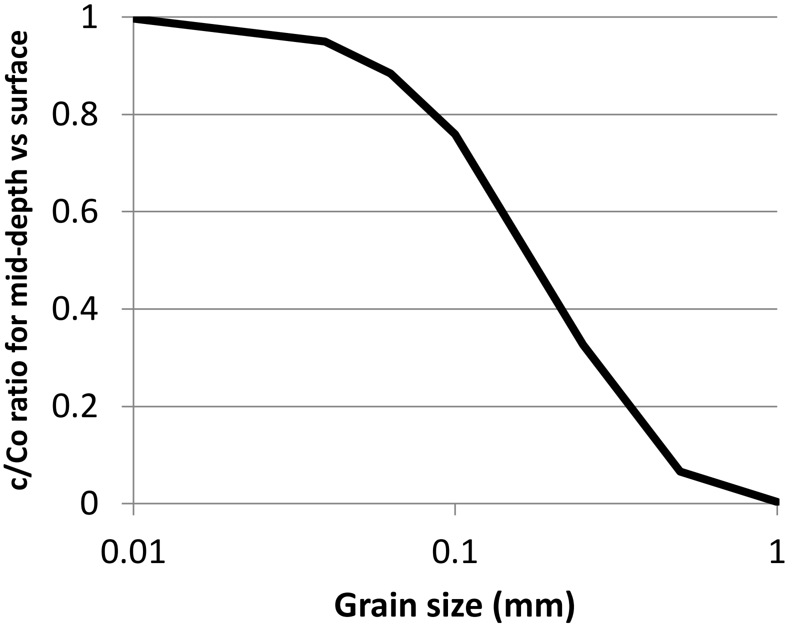


Figure 51: Ratio of relative sediment concentration at mid-depth to that at the surface. A higher value means that a surface sample is more representative.

6.2.2 Water-Sediment Sampling

Water-sediment samples were collected at all four sites by Jameson Henkle every field visit. Jameson coordinated with Water Board staff for additional sample collection. Jameson met with Guy Chetelet and Whitney Brown to demonstrate grab sampling at the SFBC site on November 20th, 2015. Jameson also met with Shane Edmunds and Griffin Perea on January 21st, 2015 in Manton, Ca. Both field meetings involved a short demonstration for proper sample collection techniques and visiting the SFBC, NFBC, and DCK sediment monitoring sites. Jameson delivered paper copies of grab sampling and safety protocol to Water Board staff.

Whereas sample collection on SFBC and NFBC always occurred at the same locations, that on MSBC had to change during floods due to access and safety concerns. On MSBC sample collection occurred upstream of CNFH at the diversion dam, at CNFH, and downstream of CNFH at the Jelly's Ferry Bridge. Lab turbidity and SSC analysis indicate that suspended sediment does not vary significantly in the short reach between sample locations, and all data are compiled as representative of MSBC at CNFH.

Grab samples were collected over a range of flows for the 12/11/14 storm event and intermittently at low flows during the sampling period from 11/11/14 to 5/13/15 during water year 2015. The 12/11/14 storm produced significant streamflow. Jameson Henkle monitored the storm and collected water-sediment samples on both rising and falling limbs of the hydrograph at MSBC, NFBC, SFBC, and DCK monitoring sites (Figure 52). Samples cover a range of discharges and are evaluated as representative of the sediment transport regime in Battle Creek for the entire water year. For the lower flows observed, sand was not in transport and thus the effect of using grab sampling over depth-integrated sampling is not affected by missing sand-sized particles. There could be some missing silt-sized particles, but these events moved so little material that it is not a significant factor in the outcome.

Manual sample collection through a hydrograph at multiple locations is complicated by the speed of the rising limb of the flow relative to the time it takes to drive around the sampling network. One solution for collecting samples on the rapid rising limb of the hydrograph is to use single stage sediment samplers (USGS, 1961). Jameson Henkle constructed a set of these samplers and attached them to a 2x6 pressure treated board in a vertical array at SFBC with the aim of capturing the rising limb of floods beginning February 2015. Samples were correlated to stage elevations and water-sediment samples were evaluated with discharge.

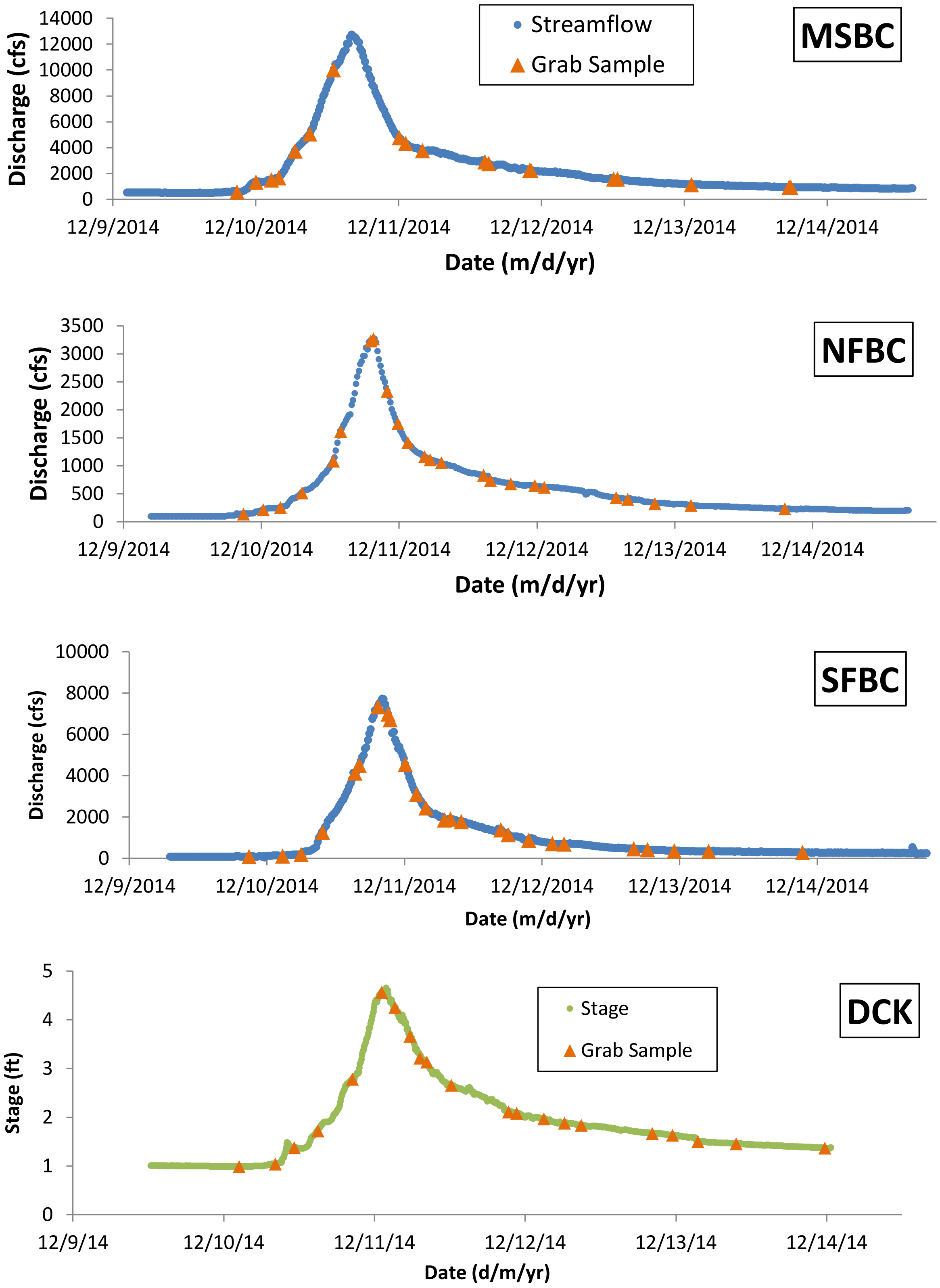


Figure 52: Grab samples for December 3, 2014 storm.

6.2.3 Suspended Sediment Lab Processing

All samples for WY 2015 were processed in the laboratory at UC Davis. Water-sediment samples were processed for SSC, turbidity, and percent organic matter (POM). For samples with a lab turbidity value ≥ 20 NTU, grain size analysis of fine- vs. coarse-fraction was completed. The coarse fraction was assumed negligible at low flow samples with turbidity values ≤ 20 NTUs. Particle size diameter ≥ 65 µm are considered coarse-fraction and diameter ≤ 65 µm fine-fraction (Wentworth, 1922). Samples were filtered through a 65-µm sieve before processed through a 0.15-µm glass-fiber filter following ASTM (2002) standards for wet-sieving and filtration. Samples were dried at 105° for 2 hours then weighed for dry mass in milligrams (mg). The volume of water collected was measured in liters (L) and the concentration of suspended sediments in mg/L (i.e., ppm) was calculated. SSC concentrations were converted to mg/L for use in analyses. Grab samples collected at site visits were processed in the laboratory for turbidity using a HACH 2100p turbidimeter. The Hach 2100P measures nephelometric signal (90°) scatter light ratio to transmitted light in NTUs over a range of 0-1000 NTU. Water-sediment samples with turbidity values ≥ 1000 NTU were diluted with deionized water and reprocessed for turbidity with a dilution factor calculation. Lab turbidity values were regressed on corresponding field turbidity values to generate a rating curve for use in further analyses. Water-sediment samples processed for SSC and turbidity with lab turbidity values ≥ 20 NTU were analyzed for particulate organic matter (POM). Samples were burned in a muffle furnace for 1 hour at 550° F and reweighed to calculate the amount of organic material removed.

6.2.4 Suspended Sediment Analyses

Sediment-rating curves were developed and applied to continuous discharge data to develop sediment flux estimates for WY 2015. Rating curves were analyzed for individual relationships amongst total SSC, fine-fraction SSC, and coarse-fraction. SSC values were evaluated for hysteresis during the 12/11/15 storm event. No graphically significant trends were observed between rising and falling limbs of the hydrograph at MSBC, NFBC, and SFBC, so it was not necessary to create separate rating curves for each limb. A single total SSC vs. Q rating curve was used for computation of sediment loads at each gage.

The total SSC sediment-rating curve was then applied to continuous records of discharge to estimate sediment load for each streamflow measurement at 15-minute intervals. Q was used as the independent variable to calculate the response in suspended sediment concentration, for each interval of discharge measurement. The total load was summed from 10/1/14 through 5/20/15 at time of computation yielding annual estimates of sediment load in short tons at each gaged monitoring site. Log-transformation bias occurs when unmeasured concentrations are estimated from discharge using a rating curve for the logarithm of concentration (Ferguson, 1986). A log-bias correction factor as reported by Ferguson (1986) was applied to load estimates using equations (6.2) and (6.3). Streamflow data were preliminary at the time of this analysis and thus do not extend through the entire water year, but the data capture all of the significant runoff events given the dry conditions ever since December 2012 storms. The contribution of sediment at low summer base flows during a drought is properly assumed to be negligible compared to the effect of large storms, as commonly known for suspended sediment and exemplified in analyses below.

CDWR streamgages at both NFBC and SFBC recorded erroneous discharge data for peak discharge values during the 12/3/14 event. As a result, peak flows were estimated using MSBC discharge data. The peak magnitude of the 12/11/14 event was 78% of peak magnitude for the 12/3/14 event. This percent was applied to peak magnitudes for the 12/11/14 event at NFBC and SFBC to estimate peak streamflow for the 12/3/14 event at both sites on a linear basis. Values were interpolated between the last known reliable data and estimated peak flow to resolve the hydrograph for erroneous data. Estimated streamflow values from this calculation are presented in red circles on the graphs for December streamflow for SFBC and NFBC (Figure 53).

Annual and event-based sediment loads were calculated for water year 2015 at MSBC, NFBC, and SFBC. Battle Creek experienced two major storm events both occurring in December 2014. To evaluate the significance of individual storm events, discharge data were divided by event in December 2014 (Figure 53, Table 11) and sediment loads calculated for each. The total annual loads are compared to loads from individual events within each site and are used to interpret the significance of large storm events and their effects on watershed scale sediment flux.

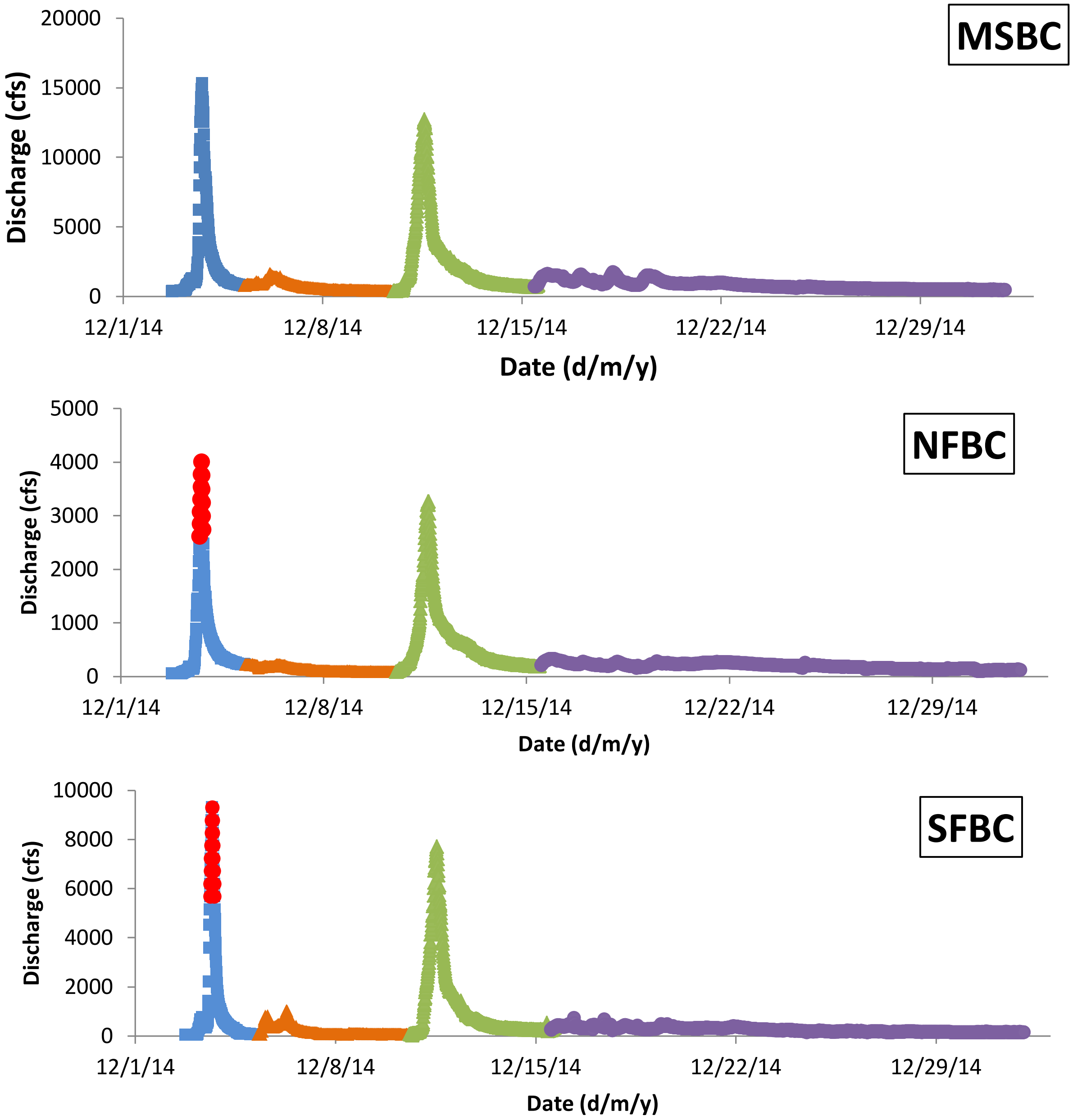


Figure 53: December streamflow by event used for sediment load analysis. Red circles are estimated streamflows for when recorders were erroneous.

Table 11: Durations of December storm events.

Event	Begin	End	Plot Color
1	12/2/14 17:00	12/5/14 5:30	Blue
2	12/5/14 5:45	12/10/14 12:00	Orange
3	12/10/14 12:15	12/15/14 14:00	Green
4	12/15/14 14:15	12/31/14 23:45	Purple

6.2.5 Suspended Sediment Results

Suspended sediment monitoring via collection of grab samples from the four monitoring sites allowed for processing of samples into SSC, development of rating curves, analysis of hysteresis and grain size, computation of annual loads, evaluation of SSC-turbidity relationships, and evaluation of particulate organic matter. Grain size varies with discharge, although separate sediment-rating curves were not warranted. SSC did not display any significant hysteresis trends. Annual load estimates show the importance of SFBC delivering and transporting sediment to the system. The relative contribution of organics may have influenced some variables.

6.2.5.1 SSC

Twenty-six water-sediment samples were collected at MSBC during WY 2015, of which 19 were collected during the 12/11/14 storm event (Figure 54). Peak streamflow for this event was approximately 12,200 cfs and stormflow duration about five days. Due to access restrictions from flooding along Coleman Hatchery Road and Jelly’s Ferry Road, no samples were collected at the peak of the storm. SSC values ranged from approximately 3 mg/L at low flow to approximately 1140 mg/L collected at 4,770 cfs.

Thirty-four water-sediment samples were collected at NFBC in WY 2015, including 24 during the 12/11/14 storm (Figure 54). Peak streamflow for this event was estimated as 3,263 cfs and the duration was about five days. Sampling occurred on the rising and falling limbs. A water-sediment sample was obtained at the peak. SSC at NFBC was approximately 1 mg/L collected at low flow and 2,315 mg/L at a peak discharge of 3,263 cfs.

Forty-five water-sediment samples were collected at SFBC in WY 2015, of which 26 were collected during the 12/11/14 storm event (Figure 54). Peak streamflow for this event was approximately 7,700 cfs and stormflow duration about five days. Sampling occurred on the rising and falling limbs and water-sediment samples were collected near peak discharge on both limbs. SSC ranged from a low of 1.5 mg/L to 4,404 mg/L at 7,334 cfs.

Forty water-sediment samples were collected at DCK in water year 2015, of which 18 were collected during the 12/11/14 storm event. No discharge information exists at DCK. SSC values ranged from a low of ≤ 1 mg/L to a maximum observed value of 3,405 mg/L.

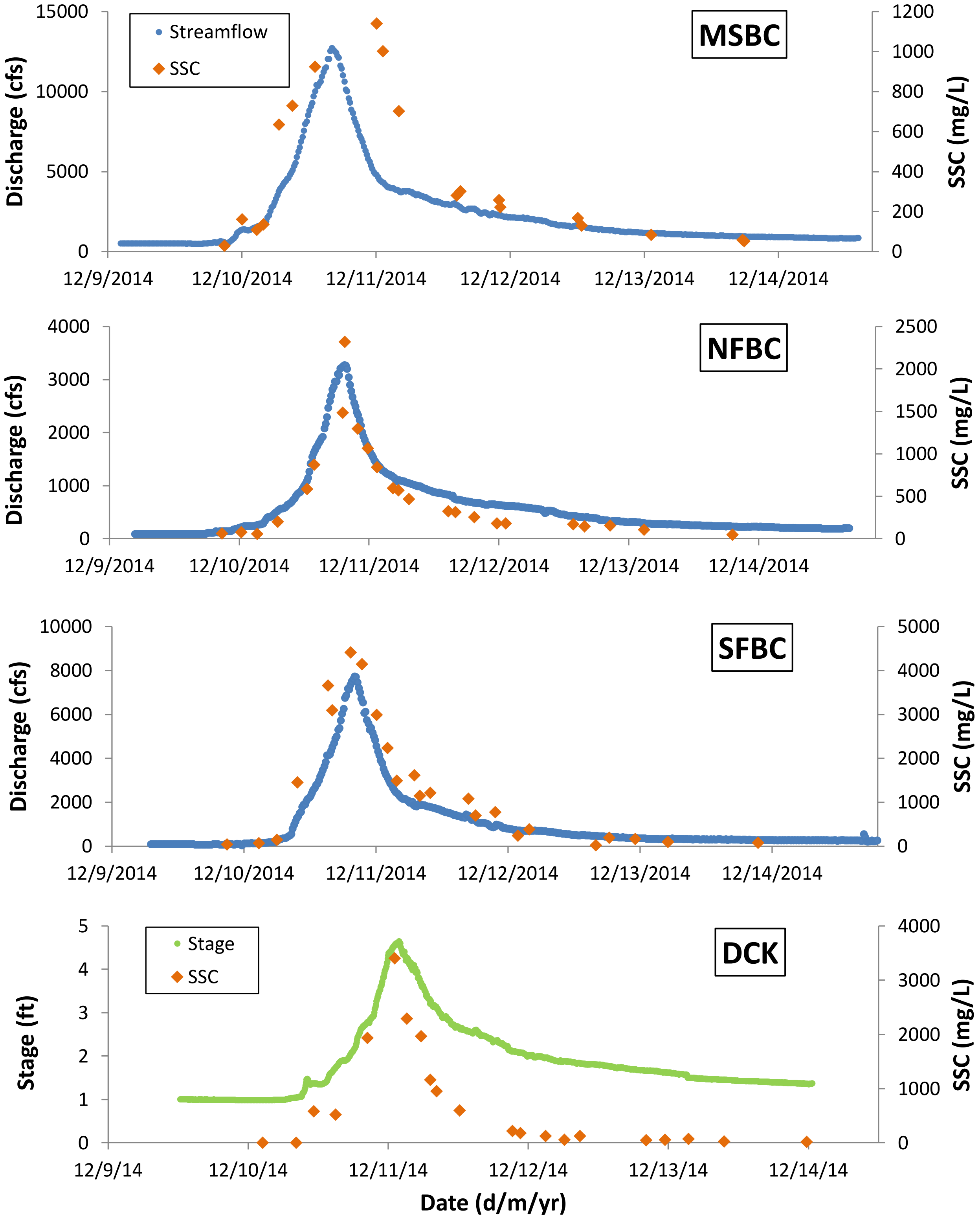


Figure 54: SSC for 12/11/14 storm event.

6.2.5.2 *Hysteresis*

Hysteresis is a time-based dependence of changing conditions with incomplete reversibility in a system. In fluvial systems, sediment may or may not increase and decrease linearly with discharge, yet has been shown to exhibit a clockwise or counterclockwise hysteretic function (Figure 55). Causes of hysteresis include channel entrainment, delivery time of surface runoff relative to groundwater discharge, wave celerity, routing effects, and event scale components. SSC vs. Q was evaluated for hysteresis on rising and falling limbs of the hydrograph for all four sediment monitoring sites (Figure 56). At MSBC, no hysteresis is evident below 3,720 cfs. Above this magnitude, a possible counter-clockwise hysteresis may be present, although limited samples exist at high discharge. NFBC and SFBC did not indicate any hysteresis function displaying linear trends in rising and falling limbs. DCK indicates a potential clockwise hysteresis although the sample collected at a stage of 2.76 ft may be an outlier and more data are necessary for validation.

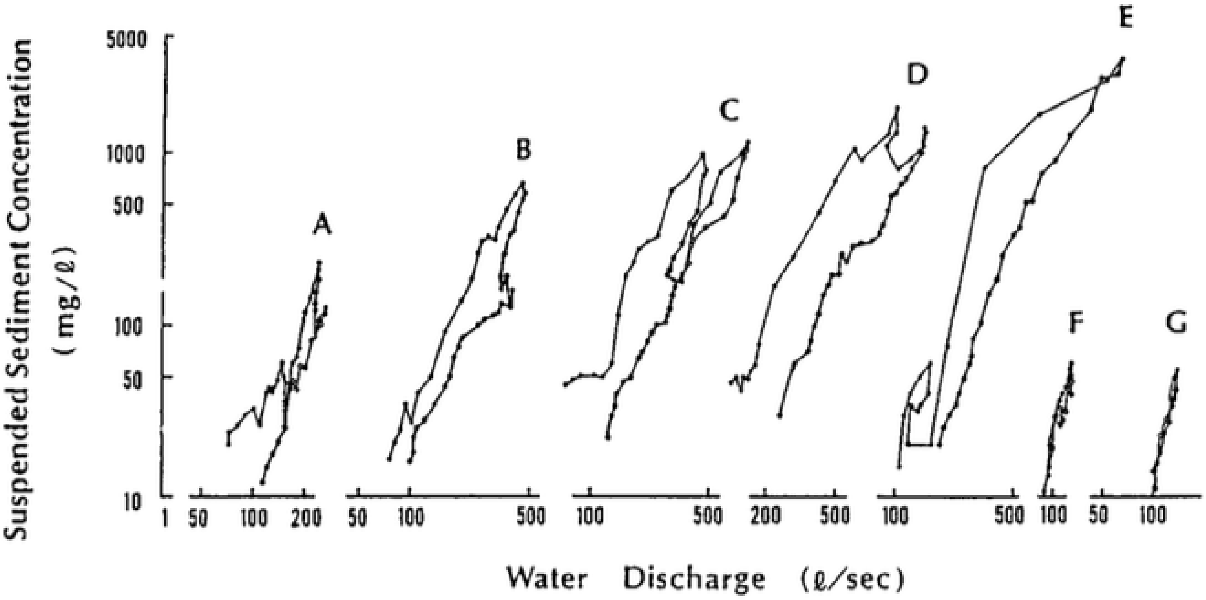


Figure 55: Examples of hysteresis loops for storm events (Park, 1992)

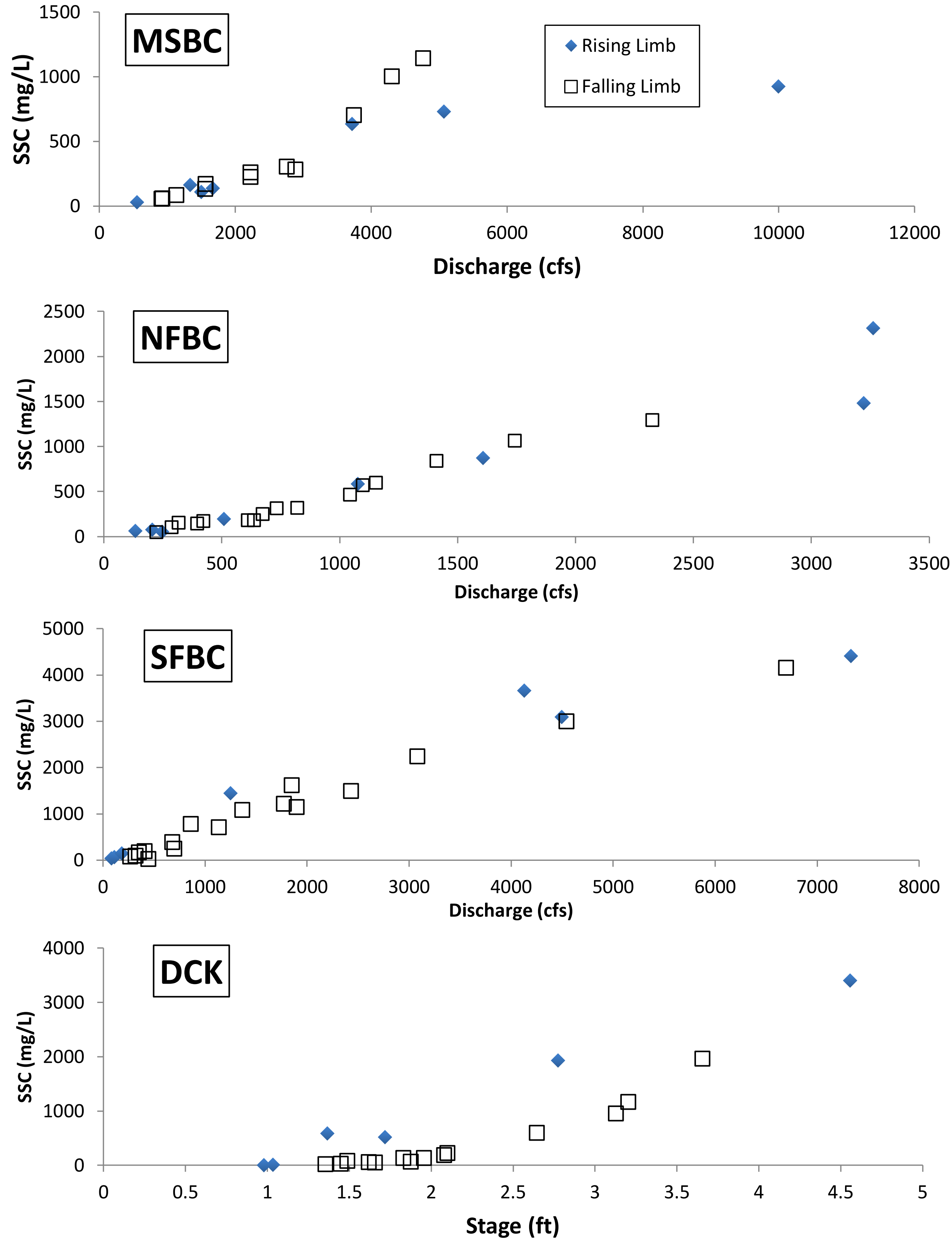


Figure 56: Hysteresis for December 3, 2014 storm.

6.2.5.3 Grain Size

Analysis of grain size separating fine- vs. coarse-fraction conveyed observable trends in suspended sediment transport (Figure 57). MSBC transported more fine material then coarse material in all but 2 samples (1340 and 3720 cfs). The average percent of fine-fraction for all samples was 61.9 % covering a range of flows for the storm event. Grain size distribution at NFBC was roughly equal between fine- and coarse-fraction until approximately 1,000 cfs, above which there was a higher total percent fine-fraction. SFBC exhibited a greater proportion of total SSC as coarse-fraction for flows above approximately 681 cfs with the exception of one sample collected at 2,073 cfs. Samples between 224 and 381 cfs indicated almost equal proportions of fine- and coarse-fraction and below 225 cfs a greater proportion of fine-fraction was observed. A general coarsening in total SSC occurs rapidly from baseflow to approximately 681 cfs and coarse-fraction dominates total SSC with an average 59.9% coarse-fraction at higher flows. DCK displayed almost no coarse-sediment at low flows below stages of 1.5’ transitioning quickly to an equal proportion of fine- and coarse-sediment at stage levels > 2.0’. Approximately 50% fine- and coarse-fraction was observed for all samples collected during the 12/11/14 storm event.

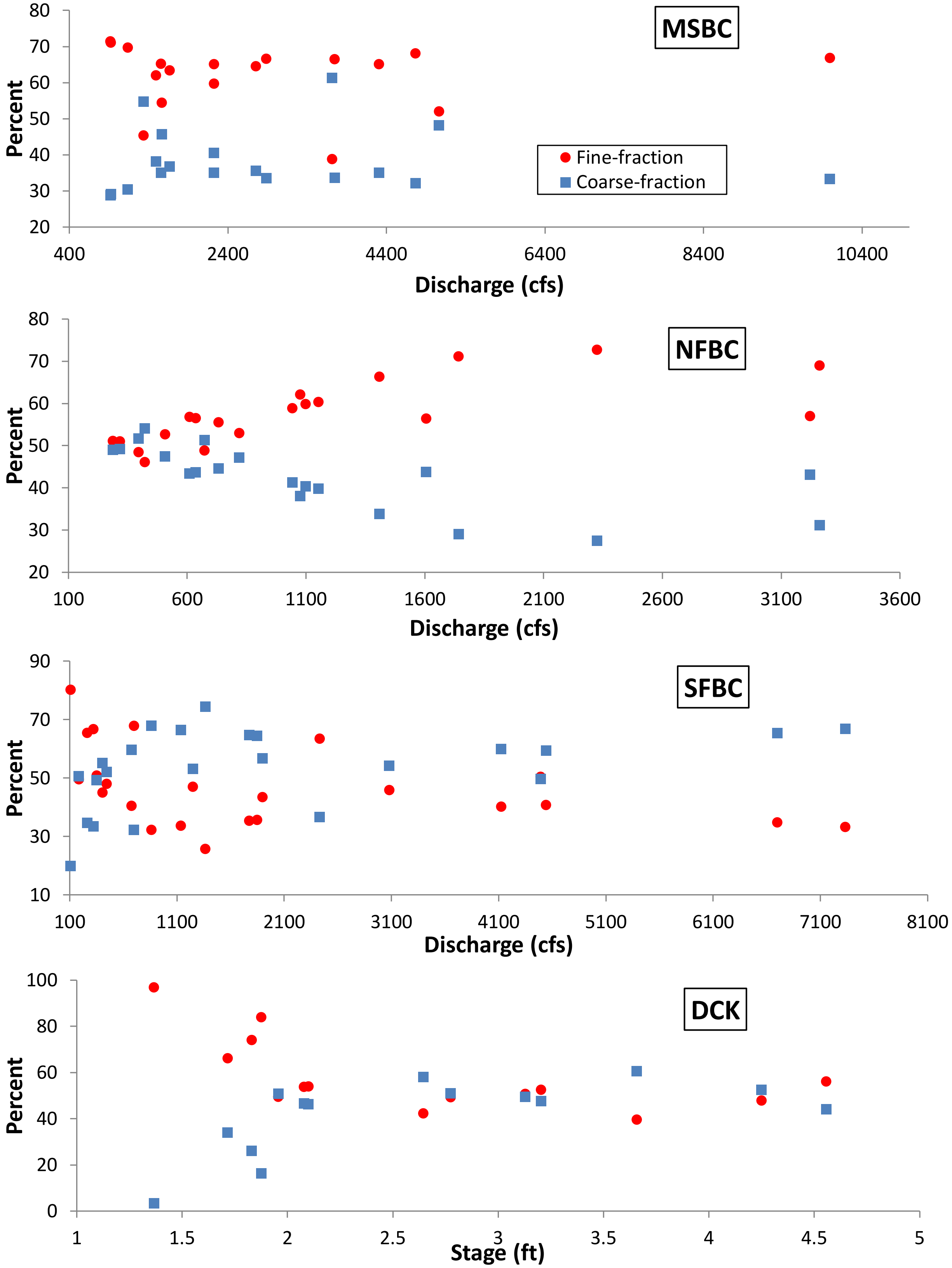


Figure 57: Fine- vs. coarse-fraction for water sediment samples.

6.2.5.4 SSC-flow Rating Curves

SSC rating curves were developed for MSBC, NFBC, and SFBC using Q and for DCK using stage (Figure 58). Rating curves were evaluated for individual relationships between fine-fraction and coarse-fraction (Figure 59). No significant differences in the slopes of the lines ($p \leq 0.01$) were observed for all sites. SSC is highly correlated with discharge with coefficient of determination all above 0.86 (Table 12).

Table 12: Regression equations for sediment-rating curves.

Site	Regression
MSBC	$y = 0.0003x^{1.7595}, R^2 = 0.95$
NFBC	$y = 0.0066x^{1.6186}, R^2 = 0.95$
SFBC	$y = 0.0389x^{1.3673}, R^2 = 0.88$
DCK	$y = 0.6484x^{0.2337}, R^2 = 0.86$

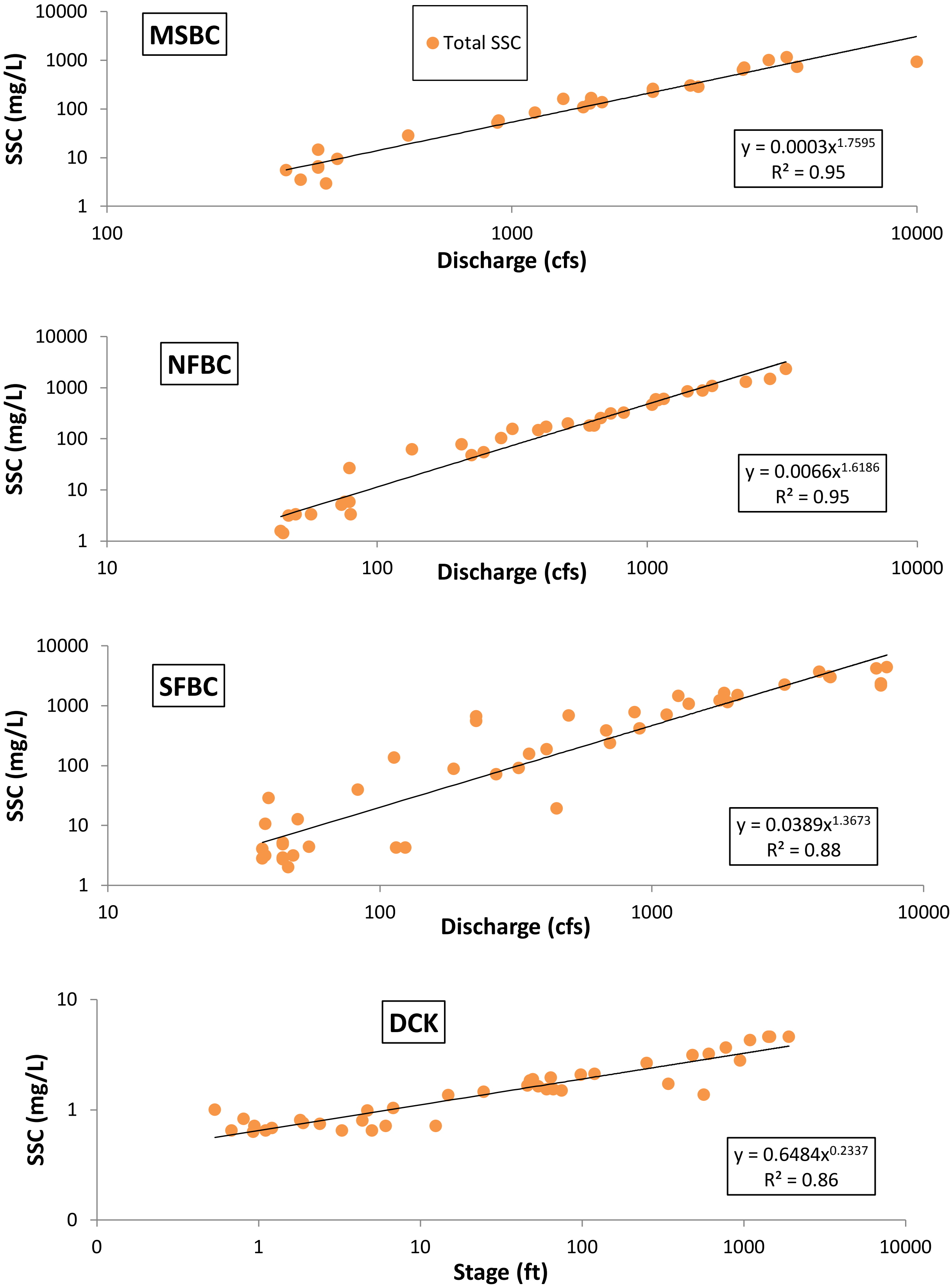


Figure 58: Sediment-rating curves for total SSC at monitoring sites.

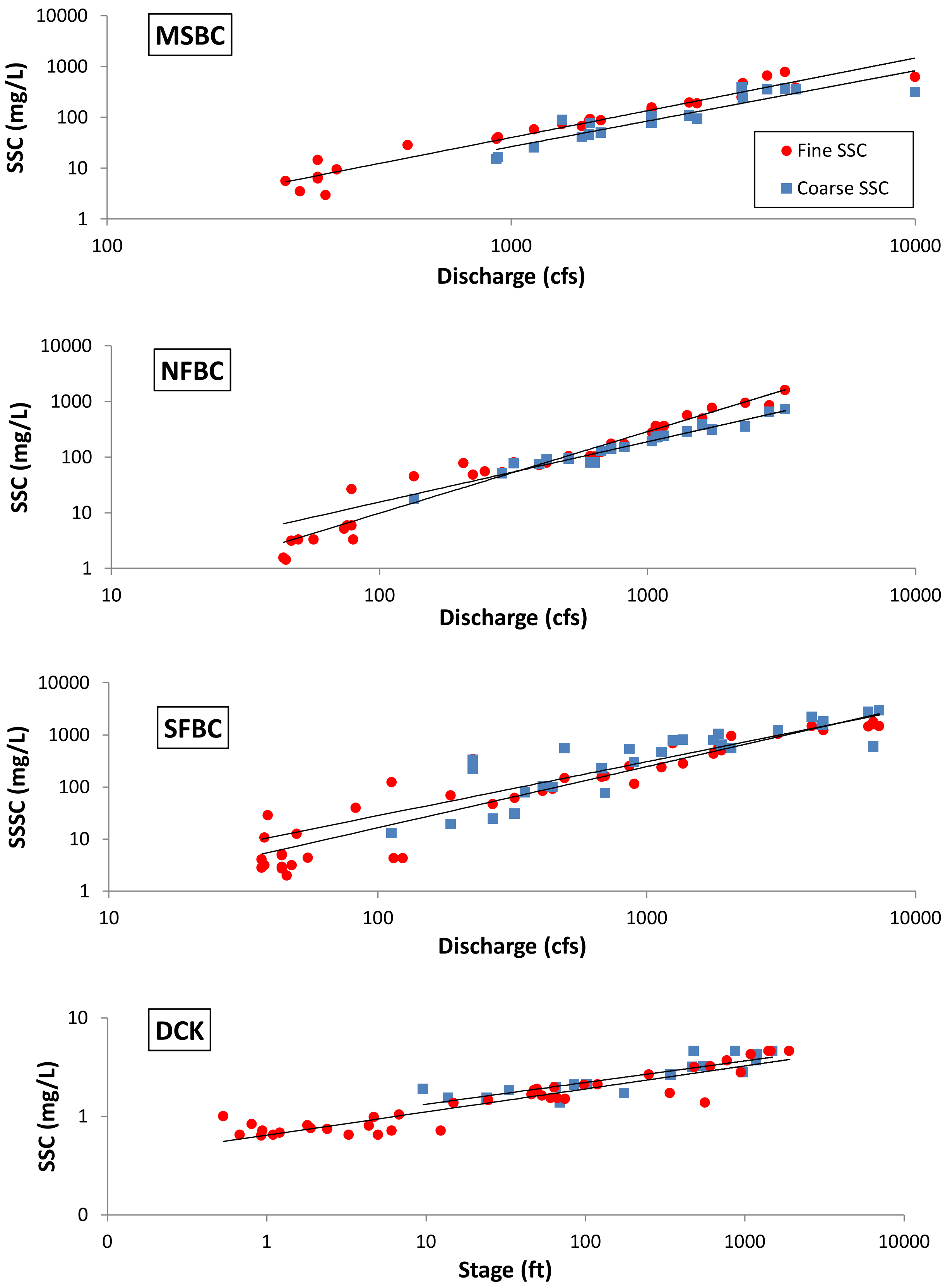


Figure 59: Sediment-rating curves for fine and coarse fraction.

6.2.5.5 *Annual Load*

Annual suspended sediment flux was estimated for MSBC, SFBC, and DCK for WY 2015 and on a storm event basis (see Table 11 for dates). Results for sediment flux in short tons and sediment yield in short tons/hectare are presented in Table 13.

WY 2015 sediment flux for MSBC was estimated to be 99,911 short tons. Of that, 97,944 short tons were transported in December. The two significant events 1 and 3 transported 43,087 and 52,437 short tons, respectively, constituting 95.6 % of the total volume of sediment transported at the MSBC monitoring site. Suspended flux for NFBC in water year 2015 was estimated to be 15,588 short tons. Of that, 15,355 short tons were transported in December alone. The two significant events 1 and 3 transported 5,908 and 9,052 short tons respectively constituting 96.0% of the total volume of sediment transported at the NFBC monitoring site. Sediment flux for SFBC was estimated to be 118,771 short tons. Of that, 116,602 short tons were transported in December. The two significant events 1 and 3 transported 44,364 and 70,193 short tons respectively constituting 96.0% of the total volume of sediment transported.

The majority of suspended sediment transport through each station occurred in December. Combined, NFBC and SFBC transported 131, 957 short tons but only 97,944 short tons were estimated at MSBC. A loss of 34,013 short tons indicated that deposition occurred between sites. The stretch between the main channel and its two main arteries is a low gradient alluvial reach. A significant amount of deposition was observed and photo-documented at the South Fork Battle Creek bridge on Manton Road. Photos are supplied on the data disk that accompanies this report and are discussed in Section 8.3. Of the combined 131,957 short tons at NFBC and SFBC, SFBC transported 88% of the total load moving through these sites. SFBC produces more sediment delivered to the mainstem and has a much higher transport capacity than NFBC.

Table 13: Sediment load calculations for monitoring sites in Battle Creek.

Site	Estimate	WY 2015	December	Event 1	Event 2	Event 3	Event 4
MSBC	short tons	99911	97944	43087	480	52437	1909
MSBC	short tons/hectare	1.073	1.052	0.463	0.005	0.563	0.021
NFBC	short tons	15588	15355	5908	47	9052	348
NFBC	short tons/hectare	0.311	0.306	0.118	0.001	0.180	0.007
SFBC	short tons	118771	116602	44364	639	70193	1402
SFBC	short tons/hectare	3.864	3.794	1.443	0.021	2.284	0.046

6.2.5.6 SSC-Turbidity Rating Curves

Lab turbidity was highly correlated with SSC across all sites (Figure 60) and indicates the benefits of applying turbidity measurements as a surrogate for SSC. Battle Creek is a well-behaved system ideal for suspended sediment monitoring. Turbidity values for grab samples are attached in Appendix 3 (Section 12.3) and data are provided on the supplemental data disk.

6.2.5.7 Organic Content

The organic component of suspended sediment was explored to observe the relative flux of organic matter for sediment transport, which has potential negative water quality impacts, but can also be important for beneficial and harmful ecosystem functions. Particulate organic matter (POM) may affect estimates of inorganic total load. General trends across all four monitoring sites indicated higher POM at low flows reaching a threshold discharge before settling at a constant value. MSBC and SFBC both exhibited two samples that have POM ≥ 60%. Although no documented field or lab errors were recorded, the values are suspiciously high and should be viewed with caution. The average percent POM for all samples processed at MSBC, NFBC, SFBC, and DCK was 22, 13.8, 19.7, and 13, respectively. These are relatively high values. For example, Goñi et al. (2013) collected 15-16 water samples from different flows in the coastal Eel and Umpqua Rivers to west and north of Battle Creek to ascertain SSC and POM. These are larger, wetter, and more vegetated watersheds. The average percent POM values were 1.0 and 4.9 for the Eel and Umpqua, respectively. The highest percent POM for the Eel was 2.4. The Umpqua samples included a range from 2.3 to 11.8%.

Trends in Battle Creek POM were similar to findings from Madej (2005) and Goñi et al. (2013) in that they displayed higher percent POM and higher variability in percent POM at low flows. Percent POM decreased with discharge. Moderately high POM in Battle Creek water may be of importance for further studies if linked to specific water quality issues and ecological functions.

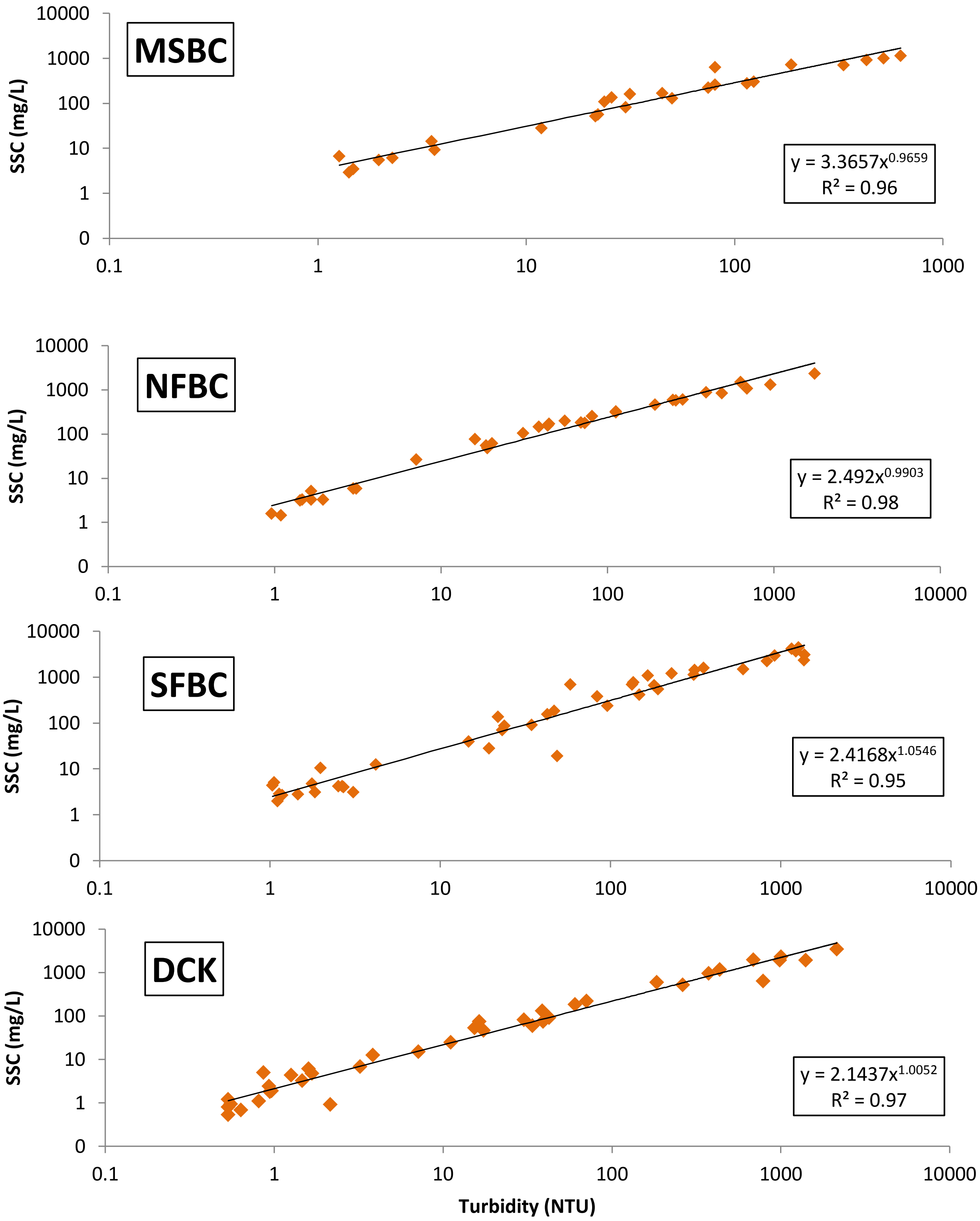


Figure 60: SSC-turbidity rating curves.

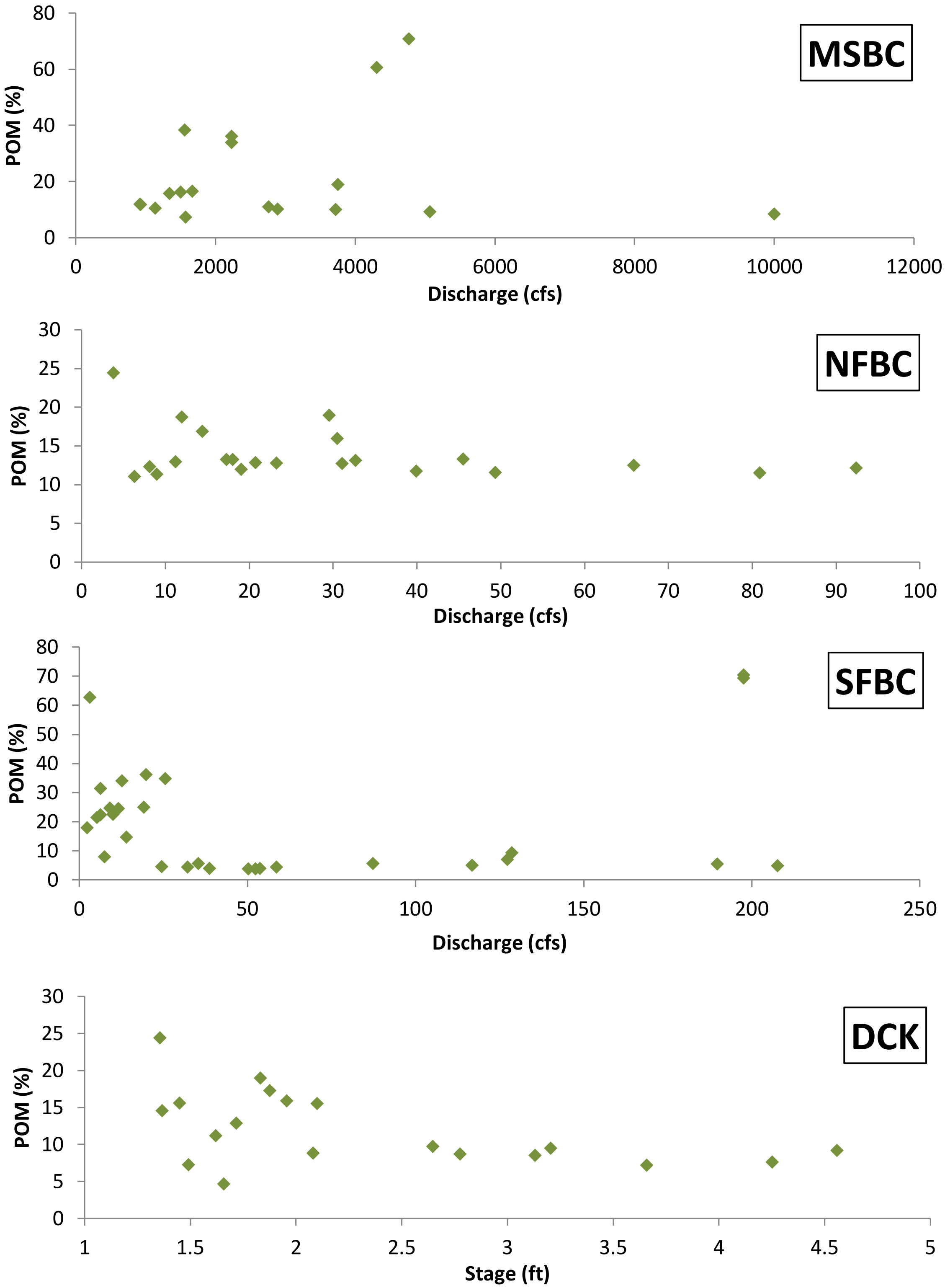


Figure 61: Percent organic matter for suspended sediment concentrations.

6.2.6 Pilot Turbidity Stations

Turbidity monitoring stations were installed on NFBC, SFBC, and DCK with variable results. Discontinuous data were collected at sites due to the inherent nature of mechanical and operational problems associated with the development of new monitoring stations. Troubleshooting issues allowed for development of recommendations for future monitoring (Section 10). The methods and results of WY 2015 instream turbidity monitoring are presented below.

Turbidity is an optical characteristic of water. It is a measure of how murky or opaque water is. Suspended solids obstruct the transmittance of light causing turbidity that can be interpreted as a measure of the relative clarity of water (Sadar, 1998). Turbidity is caused by particles and colored material in suspension and can be measured directly with a digital turbidity sensor in the field or turbidity meter in the laboratory. Turbidity sensors can be useful for collecting continuous turbidity measurements (D&A, 1991). Turbidity units are a qualitative value with no standard unit of measurement and therefore are not directly intercomparable. Turbidity can be used as a surrogate for suspended sediment concentrations once turbidity - SSC relationships have been developed. In lieu of SSC, turbidity provides a qualitative understanding to the dynamics of suspended sediment flux without associated magnitudes. Continuous turbidity data can provide enormous analytical benefits both quantitatively and qualitatively for studying the specific characteristics of sediment transport at the event scale.

Turbidity was measured in Battle Creek during water year 2015 by installing in situ OBS-3 digital turbidity sensors. The OBS monitor is an optical sensor that detects infrared radiation scattered from suspended matter. It emits infrared light and records the amount of light backscattered using nepholometry and measures a range of 0-2000 NTUs. The OBS unit records turbidity in nephelometric turbidity units (NTU). Sensors were installed at NFBC, SFBC, and DCK with varied success for continuous turbidity records resulting from equipment malfunctions to natural forces such as sun spikes and biofouling. A dedicated field campaign to maintain and ensure operability of turbidity monitoring equipment is required for quality control/quality assurance. Field visits during water year 2015 encountered multiple problems that were documented for experimental design in future monitoring efforts.

6.2.6.1 Site Installation

UC Davis received landowner permission before installing equipment on private property. Steve Tussing from the BCWC was pivotal in connecting UCD with local landowners. He has worked closely with community members in the Battle Creek watershed and developed good relationships with private landowners. Laurie Early from the USFWS also aided in connecting with local landowners.

Scott Hamelberg is the project leader for the USFWS at CNFH. Jameson Henkle and Greg Pasternack met with Mr. Hamelberg on November 10th, 2014 and were granted permission to install a turbidity monitoring station pending approval and access restraints. Reconnaissance at CNFH on Mainstem Battle Creek identified potential locations to host a turbidity sensor co-located with the USGS streamgage. An ideal location was not found directly adjacent to the streamgage due to the range of peak flood flows as indicated from Mr. Hamelberg and lack of suitable infrastructure at the USGS gage. The CNFH diversion dam upstream of the hatchery was identified as the most viable option for a sustainable monitoring site to withstand flood flows. Due to timing restraints and pending coordination with USFWS staff, a turbidity sensor was not installed at MSBC for WY 2015.

Geoff Watson owns property on DCK downstream of the Rock Creek Road Bridge in Manton, CA. His land extends downstream on the right bank of Digger Creek. Jameson Henkle and Greg Pasternack met with Mr. Watson in person on November 9th, 2014 and were enthusiastically given permission to build a monitoring site. An OBS-3 digital turbidity sensor and DRUCK pressure transducer were installed instream attached to a fence post. The sensors were connected to a Campbell Scientific CR510 datalogger and 12 Volt power source. Installation was successfully completed and the DCK monitoring site began operation on November 11th, 2014.

Ron Reid gave permission to Jameson Henkle through personal communication over the phone in November 2014 to install a monitoring site at SFBC anywhere upstream or downstream of the bridge on Manton Road near Manton, Ca. Jameson and Greg met with Mr. Reid briefly while installing the SFBC monitoring site on November 10th, 2014. He relayed his support and gave caution indicating a large event that had overtopped the bridge in the 1980's.

At SFBC, an OBS-3 digital turbidity sensor was installed instream attached to a fence post. The sensor was connected to a Campbell Scientific CR510 datalogger and 12 Volt power source located on the left bank downstream from the bridge. The site was installed and operating on November 11th, 2014. A large storm event occurred on December 5th, 2014 disconnecting the turbidity sensor from the datalogger. The equipment was retrieved and brought back to the office on December 10th, 2014 to ensure the sensor was functioning properly.

A second build at SFBC occurred on January 17th, 2015. Jameson utilized existing infrastructure attaching the turbidity sensor to the staff plate securely fastened to a concrete wall downstream of the bridge. Staff at DWR indicated this was unsuitable and may affect measurements for hydrologic stream monitoring. Jameson then deconstructed the site on January 31st and removed all monitoring equipment. Permission was granted from Tehama County Public Works to drill into the concrete of the bridge itself. Greg Pasternack and CDWR staff discussed potential locations for the build and a suitable location was identified. Jameson Henkle and Andrew Gray installed a 2”x6” pressure treated wooden board using concrete anchors on the concrete wall sufficiently upstream of the DWR staff plate. The pressure treated wood served as a platform to install the turbidity sensor. The sensor was located above the current baseflow water surface elevation but was protected from a similar peak flow event possibly rendering the site inoperable.

Giovanni Coglitore owns Wildcat Ranch that encompasses the land around the NFBC streamgage. Jameson received written permission in December 2014 via email to access and install monitoring equipment at this site. An OBS-3 digital turbidity sensor was installed on January 18th, 2015 on the left bank of NFBC attached to a stable tree. The sensor was connected to a CR510 Campbell Scientific datalogger and 12 Volt power source. Jameson utilized existing DWR infrastructure to secure serial cables to metal conduit but was informed to remove and have a completely separate installation by DWR staff. He rebuilt the site on February 1st creating a completely independent monitoring site. The sensor was located above water surface elevation at baseflow.

6.2.6.2 North Fork Battle Creek Turbidity

A turbidity monitoring station was installed at North Fork Battle Creek on January 17th, 2015 upstream of the bridge on Wildcat Road near Manton, CA. An OBS-3 digital turbidity sensor located above baseflow was attached to a tree on the left bank and connected to a Campbell Scientific CR500 datalogger. The sensor was installed with the objective of capturing storm events while sacrificing low flow turbidity measurements to ensure operability during peak flow events. The datalogger did not contain a functional internal lithium battery. The 12 Volt battery powering the CR500 datalogger failed and all data were lost from 1/17/15 to 4/18/15. The site was deconstructed on 5/15/15. Streamflow was not large enough to submerge the sensor during the short period of recorded data, thus no representative turbidity data are available at North Fork Battle Creek. Turbidity measurements during the low flow period that were recorded show the effects of solar radiation causing sun spikes in turbidity data (Figure 62). These can be filtered out through careful, expert-based data processing if sites free of solar effects cannot be established.

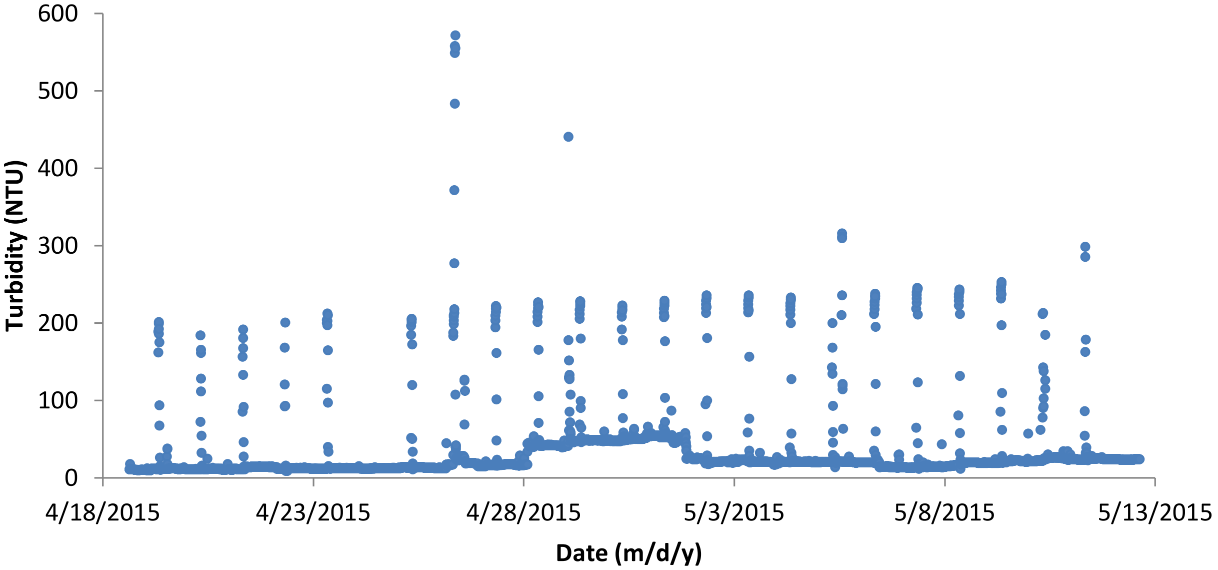


Figure 62: North Fork Battle Creek raw turbidity data for WY 2015.

6.2.6.3 South Fork Battle Creek Turbidity

A turbidity monitoring station was installed on South Fork Battle Creek on November 11th, 2014. An OBS-3 digital turbidity sensor located instream on the left bank downstream of the Manton Road bridge near Manton, CA was attached to a steel fence post. The sensor was connected to a Campbell Scientific CR-510 datalogger and recorded turbidity data (NTU) at 5-minute intervals. Low flow measurements were recorded until the 12/4/14 storm event, when the turbidity sensor serial cable was ripped from the datalogger from the high flow event.

Turbidity monitoring resumed on 1/17/15 with a new build design securing the turbidity sensor to the concrete wingwall downstream of the bridge. The sensor was located above baseflow with the objective of capturing turbidity during storm events and sacrificing low flow measurements to ensure safety and operability of equipment during peak flows. Stage and discharge necessary to submerge the sensor are approximately 7 ft and 390 cfs respectively. The station remained operable until May 13, 2015 when it was deconstructed for the water year. Dead batteries caused two periods of no data collection, although these periods were during low stage below the elevation of the sensor. Precipitation in early February 2015 was the only event that submerged the sensor producing a short record of representative turbidity for South Fork Battle Creek.

Figure 63 displays the discontinuous record of turbidity data collected in WY 2015. Preliminary discharge values were downloaded from the CDEC website and plotted with measured turbidity values in the field for the 2/7/15 storm event (Figure 64,Figure 65). A peak discharge of 1106 cfs corresponds with peak turbidity of 164 NTUs with peak sediment arriving just before peak discharge. Another wave of increased stage levels occurred on 2/8/15 although the stage oscillated above and below the sensor causing noisy data. Peak discharge and peak turbidity for this second event are approximately 500 cfs and 60 NTU.

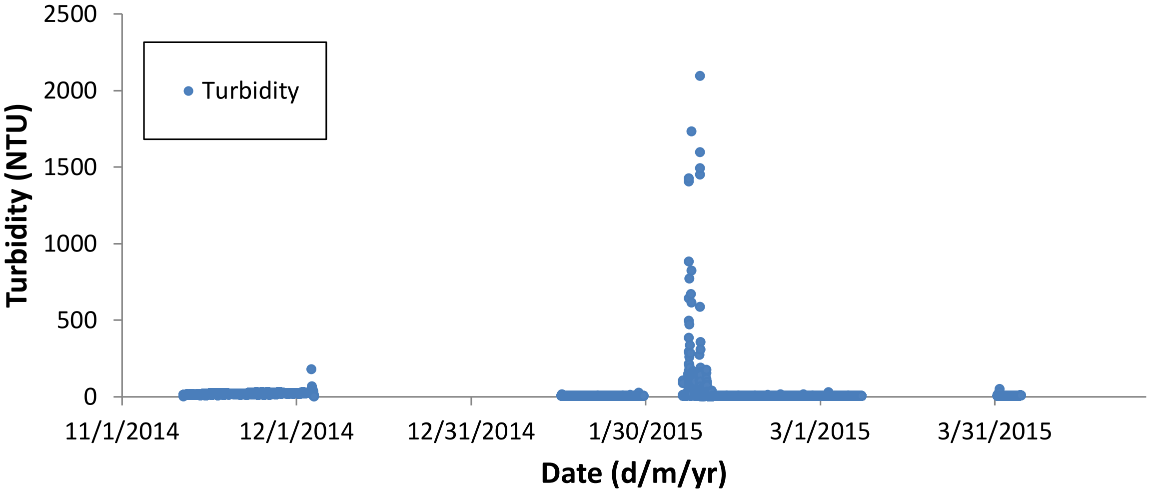


Figure 63: South Fork Battle Creek raw turbidity data for WY 2015.

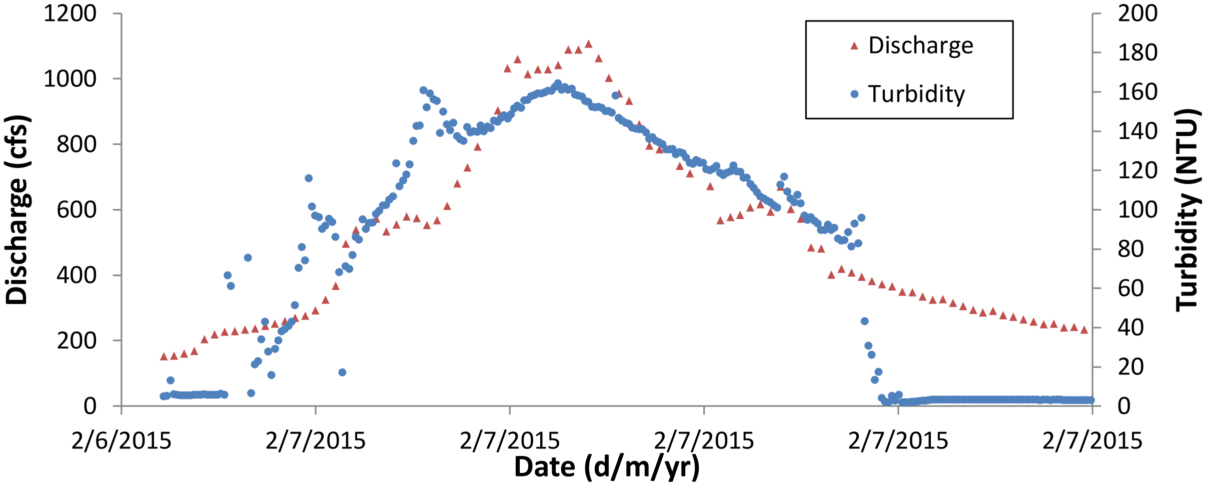


Figure 64: South Fork Battle Creek turbidity data for the 2/7/15 storm event.

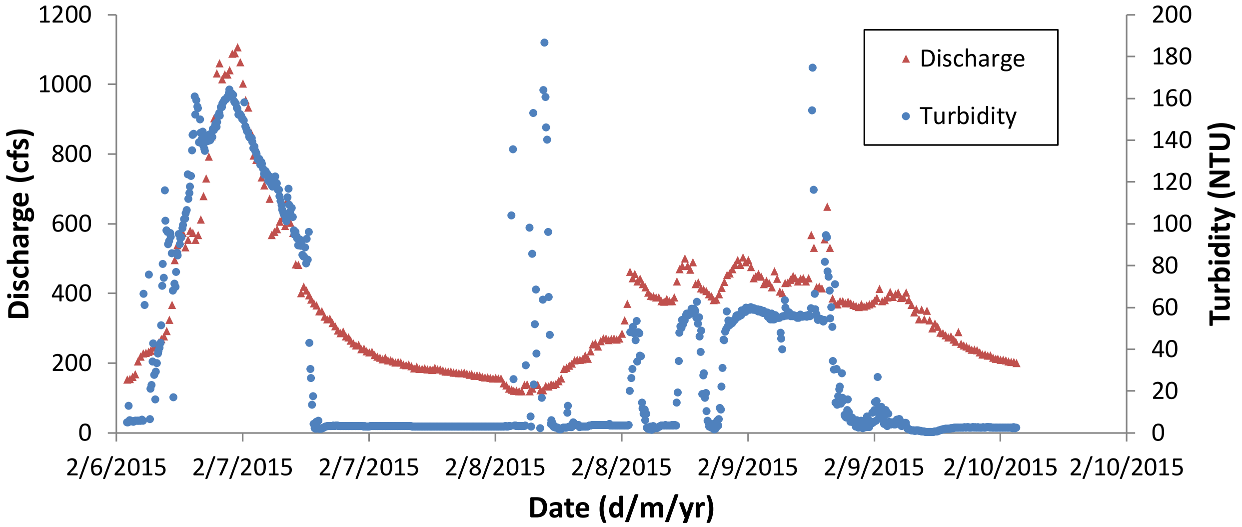


Figure 65: South Fork Battle Creek turbidity data for the 2/7/15 storm event.

6.2.6.4 *Digger Creek Turbidity*

A turbidity monitoring station was installed on DCK downstream of the Rock Creek Road Bridge in Manton, Ca. An OBS-3 digital turbidity sensor and DRUCK pressure transducer were placed instream on the right bank in a straight reach. The sensors were connected to a Campbell Scientific CR-510 datalogger. Continuous turbidity and stage data were recorded from November 9th, 2014 to May 13, 2015 at 5-minute intervals. The location of instream monitoring equipment created a trap that caught organic woody and leafy debris around both sensors affecting turbidity readings. Debris was identified and removed every site visit. Turbidity data display suspect measurements of high turbidity during periods of low flow that are not representative of channel conditions (Figure 66). Turbidity values for three specific storm events are analyzed to gain a qualitative understanding of sediment transport with the caveat that biofouling may or may not be influencing recorded values. Low flow values of turbidity are interpreted as not being reflective of actual sediment conditions due to biofouling.

Continuous stage measurements were recorded at 5-minute intervals for the duration of WY 2015 (Figure 67). Discharge measurements were not collected at DCK thus a stage-discharge rating curve could not be created to analyzing continuous discharge. Stage measurements qualitatively reveal hydrologic characteristics and help validate or refute the accuracy of turbidity data.

A large storm event occurred on 12/4/14 producing the largest flow recorded at Digger Creek. A sudden increase in discharge at 05:00 produced a response indicating 3 distinct spikes in turbidity. Turbidity data before this sudden increase in streamflow were approximately 350 NTUs, which was likely erroneously high due to biofouling. Turbidity values decreased to a value of approximately 160 NTUS until 14:20 when both streamflow and turbidity experienced a sharp rise. Heavy precipitation caused the stage to rise from 1.5 ft to 6.2 ft from 14:20 to 15:00. The flash flood caused flow to overtop the banks onto the floodplain removing vegetation. This storm event was caught on time-lapse camera and a time-lapse movie graphically illustrated this event and is provided in the supplemental DVD. Turbidity spiked from 178 NTUs to the maximum values of sensor range at ~2100 NTUs from 14:20 to 15:00 in 40 minutes. Turbidity remained above sensor measurement levels until the receding limb of the hydrograph at 19:00 (Figure 68). A smooth receding limb is observed for both stage and turbidity. Stage and turbidity records indicated the flashiness and response of the DCK sub-basin to precipitation events. In 40 minutes, a flash flood with the power to overtop bankfull and remove riparian vegetation occurred with turbidity levels above 200 NTU from 14:20 to 02:50 the next morning. The magnitude and duration of high turbidity levels can have direct consequences on aquatic and salmonid habitats.

Another large storm event occurred on 12/11/14 with a much slower rise in stage and turbidity values (Figure 69). Turbidity increased not only with the magnitude of water surface elevation but with the rate of increase in stage. Abrupt spikes in turbidity from 06:50 to 07:20 and 09:35 to 10:20 correspond with sharp rises in stage. A maximum turbidity value of 1909 NTUs occurs at 13:00 and should be viewed with a cautious eye. Peak sediment occurs before peak discharge and recedes with stage. A large log was lodged near the sensor at 16:30 that was removed at the following site visit.

A weather system produced increased levels of stage and turbidity in early February 2015 with peaks in streamflow on 2/2/15, 2/7/15, and 2/8/15 (Figure 70). Turbidity values indicate corresponding abrupt spikes although the data during this period are very noisy. Maximum stage is approximately 1.5 feet on 2/7/15 with a turbidity value of 708 NTU. On 2/6/15 at 04:15 a turbidity value of 1752.5 NTUs occurred overlapping with a sudden rise in stage, although these measurements should be viewed with caution. It is suspect that such high values of turbidity would occur during a lower flow event. Although, data may be accurate and reflect mechanisms occurring upstream that are driving turbidity and sediment transport.

Turbidity and stage monitoring at Digger Creek provide a qualitative understanding of streamflow and sediment characteristics. A full year of clean turbidity data does not exist due to the occurrence of biofouling during both high and low flows. Stage data accurately represent the magnitude and duration of storm events through the water year. The rate of increase and duration of elevated levels of stage has direct effects on the recruitment and transport of sediment yielding increased levels of turbidity.

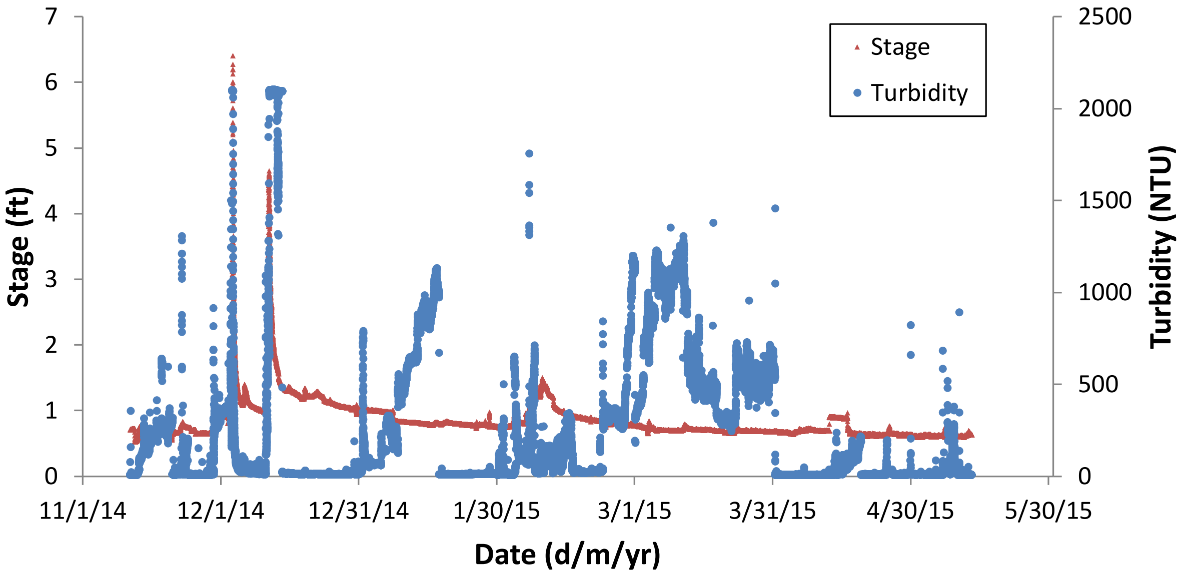


Figure 66: Digger Creek stage and raw turbidity data for WY 2015.

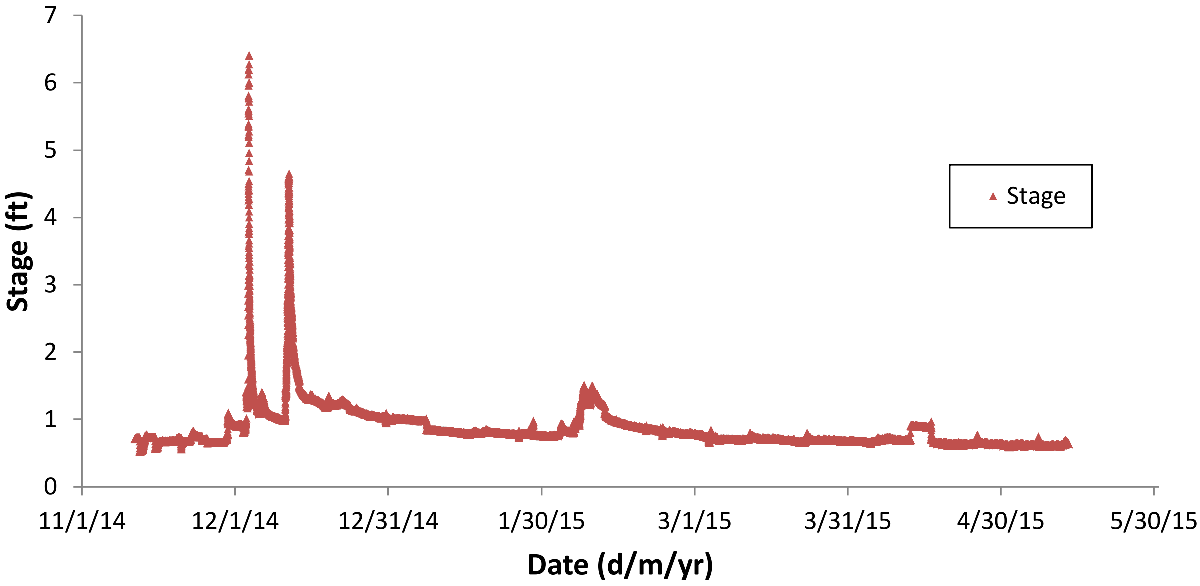


Figure 67: Digger Creek stage for WY 2015.

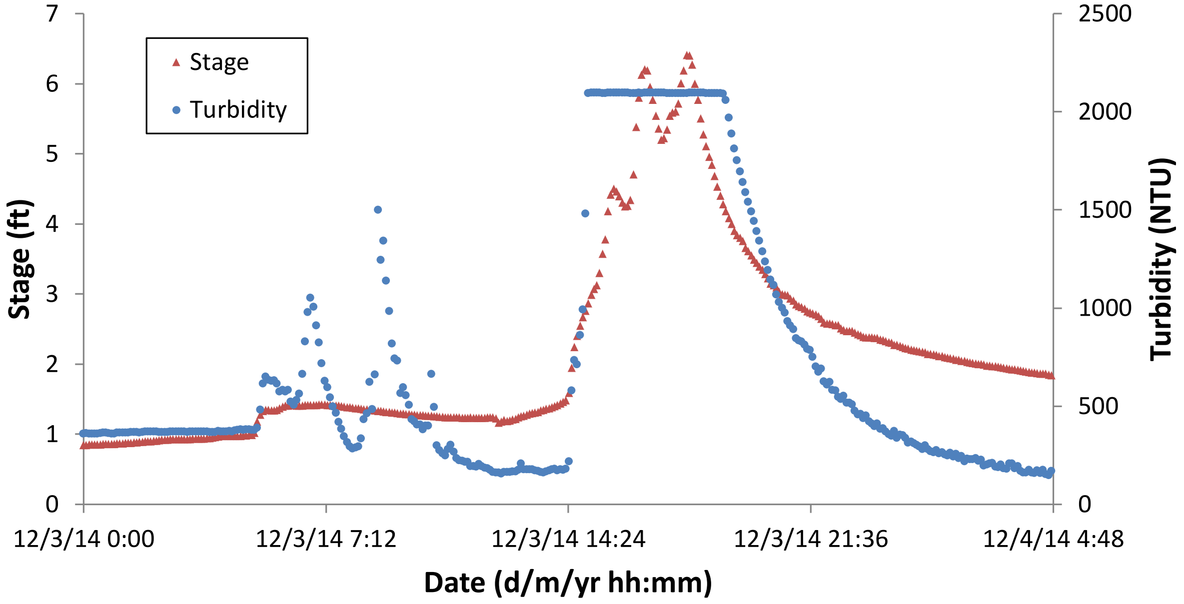


Figure 68: Digger Creek rabidity data for the 12/4/14 storm event.

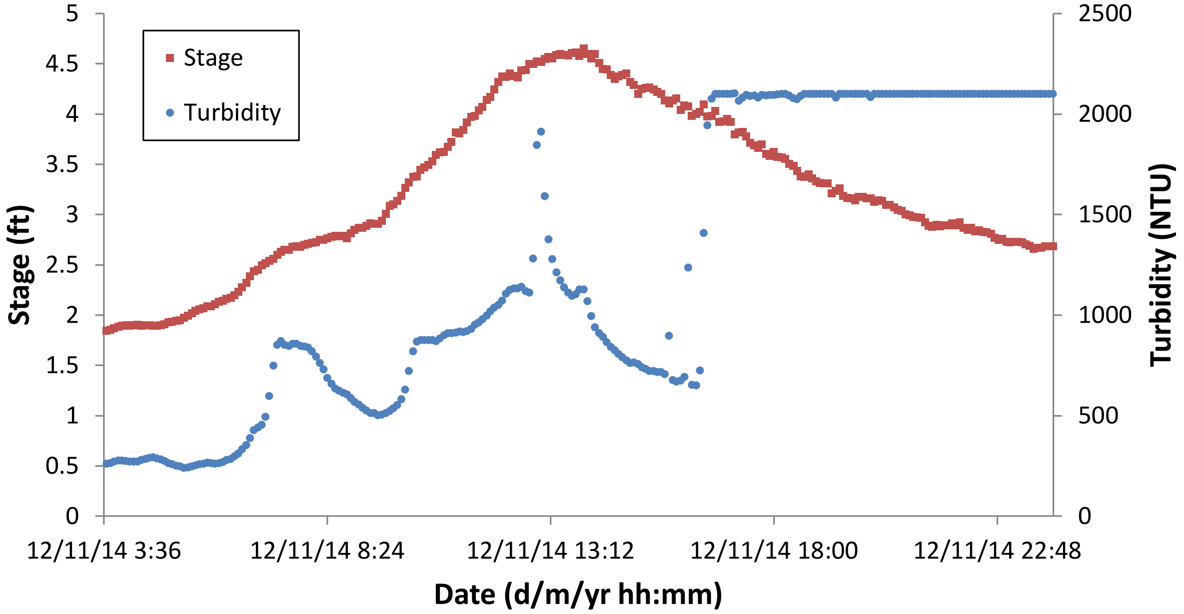


Figure 69: Digger Creek turbidity data for the 12/11/14 storm event.

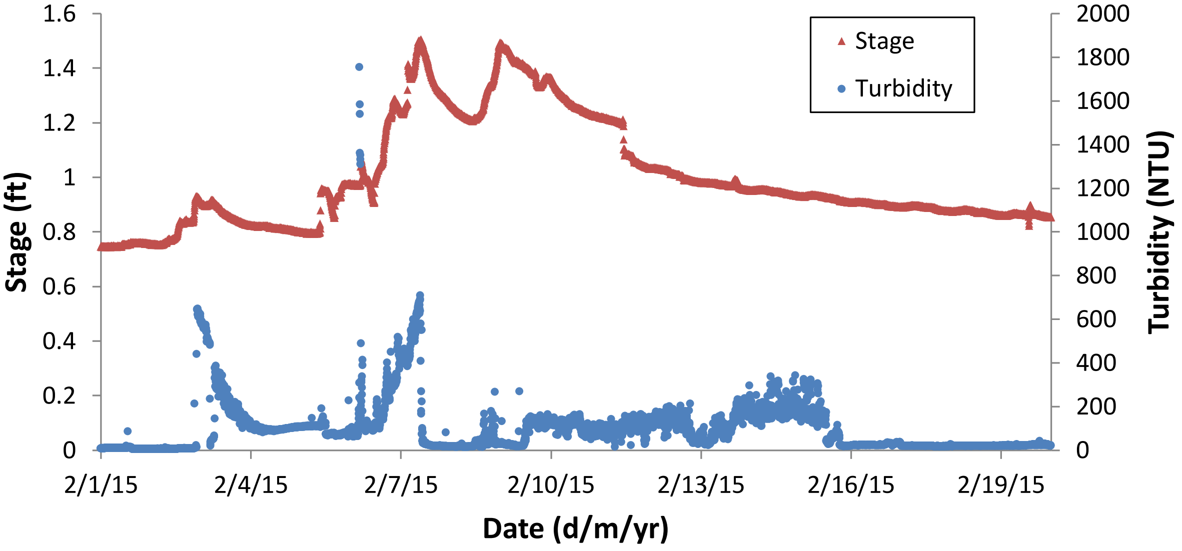


Figure 70: Digger Creek raw turbidity data for February 2015 events.

6.3 Comparing 2015 and Historical Data

As thoroughly explained in Section 6.2.1, the comparison of historic to current sediment data has inherent error from different sampling techniques, but is still commonly done and is worthwhile to consider. Historical samples were depth-integrated samples collected across the channel by USGS staff, while in WY 2015 grab samples were collected just under the water's surface and at one position close to the bank. Grab samples tend to underrepresent average SCC at a stream cross section as concentrations of larger particle size classes increase with depth, and this tends to be more of an effect at lower discharges, because silt and sand have vertical concentration distributions that become more uniform with increasing discharge. Thus, higher sediment load estimates found for WY2015 that are described in Section 6.3.2 are, if anything, underestimated in comparison to results expected if depth-integrated samplers were employed. This further supports the finding that WY 2015 sediment flux was greater than would have been expected from SSC-Q relationships developed in the 1960s and 1970s.

6.3.1 SSC Comparison

When the 2015 SSC data was compared to that from historical data, a similar magnitude was found over the full range of discharge (Figure 71), despite the fact that the sampling approaches were different and land cover conditions are different. Note that because the plot is on a log scale, the range of variability appears narrow, but this belies the actual high range of values present. Between 100 to 1,000 cfs, historical data exhibited scatter over an order of magnitude of SSC. Thus, uncertainty in the 2015 data due to sampling differences is dwarfed by the inherent variability of the historical samples. It appears that the difference in methods has little significance relative to all the other sources of variability. For flows of 1,000 to 3,000 cfs there are a similar number of 2015 and historical samples and SSC is very similar between the two. In this range sand transport is probably still limited, so the effect of sampling methods would not be a significant concern.

Tantalizing results occurred for flows > 3,000 cfs. Previously, there were only 2 samples in this range, so there is a limited ability to evaluate the difference between history and current conditions. Also, one would expect that if tens to hundreds of samples were present, they would show the same order of magnitude range of variability as the SSC values for low flows, but we cannot know where the 2 samples reside relative to that range, high or low. All we can do is report what was found and hope that in the future more samples will be collected to illuminate the situation. For a flow of 4,380 cfs, the historical sample had an SSC of 383 mg/L. Meanwhile, the four 2015 SSC values in the range of 3,720 - 5,070 cfs had SSC values of 634-1140 mg/L. Thus, current conditions showed roughly double to triple the historical value in that range.

In contrast to 3,000 – 5,000 cfs range, the values for the highest observed flows are relatively similar between the historical and latest sampling periods. Specifically, at the highest observed historical (9,340 cfs) and 2015 (10,000 cfs) flows, the respective SSC values were 722 and 923 mg/L. Given the order of magnitude variability in SCC for any given discharge, the minimal number of samples available, and the fact that the highest 2015 discharge showed a lower SSC value than for lower discharges, the observed differences in SSC between historical and modern conditions are indistinguishable. If anything, the remarkable finding is that SSC is so similar despite differences in watershed conditions, and that is even considering sampling differences, which have the least impact at these historically high flood flows. It would take much more sampling to make any quantitative conclusions about there being impacts on SSC during modern times.

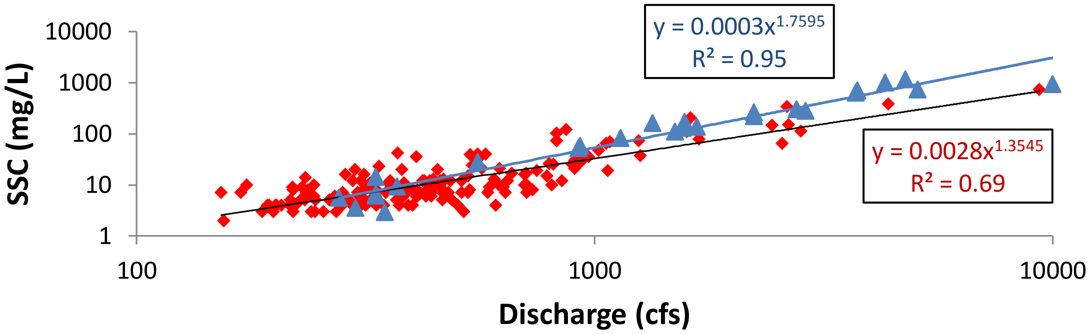


Figure 71: Sediment-rating curve for historical (red diamonds, black line) and WY 2015 (blue triangles, blue line) data with associated regression equations.

6.3.2 Sediment Load Comparison

At the MSBC streamgage, approximately 100,000 short tons of suspended sediment were transported in WY 2015 with a peak and mean discharge of 15,300 and 422 cfs respectively. In WY 1969, approximately 49,000 short tons of suspended sediment were transported with a peak and mean discharge of 12,100 cfs and 710 cfs. Over twice the volume of suspended sediment was estimated for 2015 in comparison to 1969. WY 1970 had the largest historically recorded flood with a peak discharge of 24,300 cfs transporting ~ 88,000 short tons of suspended sediment. The estimated recurrence interval for WY 1969, 1970, and 2015 are 10, 72, and 19 years respectively. Although 1970 documented a 72-year flood event, sediment flux was less than 2015. The majority of suspended sediment exported from Battle Creek is transported during high magnitude floods, a condition that has been widely observed in steep, mountainous watersheds (Pizzuto et al, 2014).

7 LANDSCAPE PROCESS PATTERNS

Mineral sediment moving through a watershed originates from bedrock soil production, but can also stem from atmospheric deposition depending on the soils and winds in the airshed contributing to the watershed. Bedrock becomes sediment through chemical and mechanical weathering (Heimsath et al., 1999). Weathering of parent rock dislodges particles that are susceptible to downslope transport as colluvium. Landscape physical processes move these particles downslope until they are delivered to a stream channel. The rate of sediment production from landscape physical processes is defined as the rate of colluvial sediment transport across a line corresponding to the streambank (Reid and Dunne, 1996).

A standard approach to evaluating landscape processes at the watershed scale involves developing a soil erosion model that translates the physical impacts of climate/weather and land cover/land use into a sediment supply characterization for streams. A number of approaches have been developed over the past 30 years (Loucks et al. 1981; Decoursey 1985; Novotny 1986; US EPA 1992a). For rural areas with relatively low slopes, field-scale models of erosion processes (in particular the Universal Soil Loss Equation (USLE)) are commonly used together with GIS to characterize soil losses (e.g., Noss and Julien 1996). Because of deposition downslope of eroded terrain, the amount of sediment actually reaching and entering the stream system is much less than USLE estimates (Shen and Julien 1993). Modelers therefore often multiply soil losses by lumped or even spatially distributed delivery ratios (Fraser 1996). More recently, process models that explicitly characterize the hydrological, erosional, and transport mechanics involved in sediment loss using first principles have begun to be tested and interfaced with GIS databases of land cover and land use (e.g., WEPP: Laflen et al. 1991; Savabi et al. 1995). Notably, these approaches do not account for gully and landslide mechanisms, which are important for mountain watershed. Several hydrological models have sediment modules in them, sometimes using algorithms based on the methods described above. Examples of widely used hydrological models for sediment modeling at the watershed scale include MIKE-SHE (Graham and Butts, 2005; Zhang et al., 2008), LISEM (De Roo et al., 1996a, b), and SWAT (Santhi et al., 2005).

At this time there are many problems with watershed-scale sediment modeling that remain to be addressed before widespread application and running such models is not part of the scope of work for this project. Before considering sediment flux, the fact remains that spatially distributed hydrological modeling remains relatively inaccurate in its ability to reproduce observed water fluxes and storage throughout a watershed. Models are highly sensitive to their numerous inputs and parameters, especially the exponents of nonlinear functions governing infiltration and groundwater processes, depending on the structure of the model. Models also often assume either Hortonian overland flow or soil saturation excess overland flow, whereas the actual runoff mechanism present in a specific watershed may differ from model assumptions and capabilities. Without accurate water fluxes, the ability to accurately estimate associated sediment fluxes is greatly limited. In addition, the mechanisms of sediment erosion, transport, and deposition are highly complex and dependent on meter-scale controls that are not accounted for in models at this time.

Without a strong understanding of hydrological and geomorphic mechanisms in Battle Creek, it is premature to attempt watershed-scale sediment modeling at this time. What is needed first is more work to understand the presence/absence, relative roles, and spatial distribution of the landscape physical processes that might be at work in the Battle Creek watershed. This would enable the development of field studies to collect the requisite geospatial data and conduct the needed monitoring about each process to get ready for systematic modeling.

The overall goal of this section of the report was to make use of available geospatial data to lay the foundation for future work in this direction. Specifically, the spatial pattern of landscape processes indicative of controls on erosion susceptibility under different watershed scenarios was explored using topographic, climatic, soils, land cover/land use, and wildfire data along with established equations and variables governing landscape processes. Inputs and parameter values were carefully established for Battle Creek. The specific purpose of this work was to provide conceptual ideas for watershed managers so that they understand the scope of what might be occurring in the Battle Creek watershed and where each process is likely to dominate in light of local and watershed-scale conditions. As with any model, the results shown are best conceived of as ***hypothesis generating*** to aid subsequent field-based observation that validates predictions and measures fluxes associated with each process where it dominates. However, it is often the case that sediment models are used for making conclusions about a watershed, especially in the absence of past or future monitoring. In that case, the methods used here are at least as robust as other common modeling methods and offers unique value by looking at the pattern of several processes based on independent equations for each one. Other common methods used often improperly compute sediment fluxes and/or yields even where the underlying processes in the model are not valid for locations within a watershed. By focusing on the pattern of dominant landscape processes instead of the magnitude of sediment generated, this study avoids the high uncertainty of such sediment flux and yield model predictions.

The results presented in this section of the report represent an essential first step to mechanistic, predictive, watershed-scale sediment erosion, transport, and deposition for Battle Creek consistent with the scope of the project. In the future it would be possible to build on this effort to (a) test the generated hypotheses evident in the results and (b) run models or analyses to estimate sediment fluxes associated with each process.

7.1 Landscape Process Concepts

Landscapes have been shown to exhibit both scale dependent and scale independent attributes, and it turns out that there is a scale dependent threshold of erosion equal to the hillslope length that is just shorter than necessary to support a channel head (Montgomery and Dietrich, 1992). Below this threshold, channelization occurs and fluvial processes transport water and sediment downstream. Above this threshold, landscape processes are dominant and sediment is transported downslope by soil creep, sheet wash erosion, rilling, gullying, and landsliding. If the rate of rainfall or snowmelting is greater than infiltration capacity, the ground becomes saturated and unabsorbed water becomes overland flow (Kirkby, 1978). Areas of saturation and overland flow are more likely to generate and deliver sediment to channels. The interaction of climate, geology, vegetation, and topography can be combined to identify a suite of geomorphic processes spatially distributed across a landscape defining the temporal pattern of disturbance.

Spatially distributed landscape processes were evaluated for the Battle Creek watershed by applying process-based equations in GIS using available data for topography, climate, land cover, soils, and wildfire area. This study focuses on four landscape processes- soil creep, sheet wash, channelization (which also represents gullying), and landsliding- with the last of those broken into two mechanisms depending on the degree of soil saturation. A brief discussion of the concepts underlying the mechanisms driving these landscape processes is provided to aid the understanding of sediment production and delivery to Battle Creek.

7.1.1 Soil Creep

Soil creep occurs irregularly in direction and rate on slopes. It may be caused by several mechanisms including wind, slope wash, sliding, soil animals, and roots (Finlayson, 1985). Field evidence in outcrop curvature, tree curvature, soil accumulations upslope of retraining structures, and cracks in soil all indicate the presence of soil creep. Hillslope erosion of soil by creep is primarily dependent on topography and soil thickness (Heimsath et al., 1999). Creep can theoretically occur at any point on a hillslope regardless of distance from drainage divide or slope length. The relative importance of soil creep depends on other hillslope processes acting on the landscape. Where conditions on the land surface are not influenced by other hillslope processes, which requires that unsaturated conditions persist during wet periods and slopes are not steep enough to cause unconditional landslides (as explained below in Section 7.1.4), then soil creep is the dominant landscape process.

7.1.2 Sheet Wash

Overland flow occurs when rainfall intensity is greater than infiltration rate or the soil becomes saturated. Raindrop impact can detach soil anywhere the soil is exposed to the shear force of drops. When overland flow occurs, sediment can become entrained and transported downslope. The quantity and size of the particles able to be transported by runoff are a function of runoff velocity and turbulence. Velocity and turbulence both increase as the slope steepens and the depth of flow increases. Once entrained, the particle will remain in suspension until a lower, depositional velocity occurs. Hydraulic conditions vary greatly over short distances and the relationship between sediment discharge, overland flow, and soil particles does not fit a simple mathematical model. Relationships are site specific based on soil characteristics, but in general sediment is transported by sheet wash erosion when the driving forces are greater than the resisting forces. Sheet wash is a process that occurs during saturated soil conditions in the absence of channelization or landsliding.

Rills are very small channels on unvegetated slopes with dimensions of a few cm to tens of cm. They are usually discontinuous and may or may not be connected to a stream channel. Parallel rills integrate into a drainage network by breaking down the divide between rills with water flowing into the deeper rill, and overtopping rills towards the lowest elevation. Given that conventional digital elevation models of landscapes typically have resolutions of 30x30 m^2 or 10x10 m^2, it is impossible to distinguish individual rills, which are much smaller than 10-m wide. Therefore, sediment generated from rilling is often lumped together with that from sheet wash erosion when developing sediment budgets. However, if the density of rills is so high as to dominate topography, then the process could be envisioned as part of the next process discussed- channelization.

7.1.3 Channelization

A master rill may widen and deepen to the point that its channel is classified as a gully. The moment that any channel or set of smaller channels is sufficiently large to dominate local topography, then the dominant process for that location is channelization. A gully may be defined as a recently extended drainage channel that transmits ephemeral flow, has steep sides, and a vertical head scarp. Thus, the process of forming a gully (i.e., gullying) is one type of channelization process. Channelization is the dominant landscape process where the contributing area per unit contour width provides sufficient overland flow for the given slope and surface roughness to initiate soil entrainment and cut a channel at the scale of the available topographic data (Montgomery and Dietrich, 1988, 1992).

7.1.4 Landsliding

Mass wasting (aka mass movements) include a large number of processes by which large amounts of Earthen materials are physically shifted downslope (Ritter, 1986). Examples include rockslide, Earthflow, deep slope failure, debris flow, and landsliding. When gravity acts on relatively thin soil overlying bedrock with over-steepened slope, then shallow landsliding occurs. Shallow landsliding is facilitated by increased soil moisture that reduces the resistance to sliding and it is impeded by additional cohesion provided by the roots of vegetation (Ritter, 1986; Selby 1987; Dietrich et al., 1993). Shallow landsliding is a common process affecting the hillslopes of California; it plays a major role in determining the location of channel heads (Dietrich and Dunne, 1993) and it increases erosion locally.

7.2 Landscape Process Spatial Domain Equations

A landscape process domain is defined as the phase-space region in which each process described in Section 7.1 is the dominant one governing sediment erosion (Figure 72). A phase-space region is defined as an area of the 2D Cartesian coordinate system with local slope (*M*) on the x-axis and contributing area (*a*) per unit contour width (*b*) on the y-axis (i.e., *a/b*). The effects of diverse variables is captured through equations that link their role on landscape processes to *M* and *a/b*. The physics underlying this methodology was published in peer reviewed journals many years ago and is widely accepted (Dietrich et al., 1993; Montgomery and Dietrich, 1988, 1992, 1994). In addition to these foundational studies that include some validation of the equations, there have been subsequent validation studies confirming the utility of the equations for mapping individual processes, including for management purposes (Heimsath et al., 1999; Dietrich and Bellugi, 2001; Guimarães et al., 2003).

Five process domains were computed using equations of Dietrich et al. (1993). Process domains may be categorized on the basis of their hydrology or landscape erosion processes (Table 14). Landscape process modeling provided an indication of areas that are likely to be experiencing geomorphic processes given the interaction of topography, soils, climate, and land cover.

To determine whether any location in the landscape is saturated or unsaturated soil, the following equation was used where the inequality confirms saturation:

$$\frac{a}{b} > \frac{T}{q}M \tag{7.1}$$

where *T* is transmissivity and *q* is “runoff”, which is usually termed “net precipitation” (i.e., precipitation minus evaporation and other such losses such that the lost water is not available to infiltrate into the soil or runoff). In this equation the primary assumption is that there is hydrological steady state. The validation studies cited in the previous paragraph confirm that even though this assumption is rarely met, the results of applying this equation works very well, so the spatial pattern of landscape processes is not particularly sensitive to this assumption.

To determine whether any location in the landscape is experiencing channelization under steady state hydrology, the following equation was used wherein the inequality confirms channelization:

$$\frac{a}{b} > \frac{2\tau^3}{\rho_w^3 k v g^2 M^2 q} + \frac{T}{q}M \tag{7.2}$$

where τ is the critical shear stress for channelization, $\rho_w$is the density of water, *k* is surface roughness, υ is the kinematic viscosity of water, and *g* is the force of gravity. Based on previous field observations and tests of hillslope runoff processes, this equation additionally assumes laminar overland flow and the existence of a critical shear stress threshold for channelization. However, it is possible in some situations that the flow will be turbulent instead of laminar, and in that case an alternate equation is available (see Dietrich et al., 1993). It would take field studies to carefully assess whether to apply a laminar or turbulent threshold equation for each land cover type in a specific application to yield the best result.

To determine whether any location in the landscape is experiencing shallow landsliding under steady state hydrology, the following equation was used wherein the inequality confirms shallow landsliding:

$$\frac{a}{b} > \frac{\rho_s}{\rho_w}\left[1 - \frac{tan\theta}{tan\phi}\right]\frac{T}{q}M \tag{7.3}$$

where ρ_s is the dry bulk density of sediment, θ is slope, and φ is the internal friction angle. From this equation it is possible to identify two states of shallow landsliding - unconditionally stable and unconditionally unstable - that correspond to what can occur when any location is either fully saturated or bone dry, respectively:

Unconditionally stable: $$\boldsymbol{tan\,\theta < 0.5\,tan\,\Phi} \tag{7.4}$$

Unconditionally unstable: $$\mathbf{tan}\,\boldsymbol{\theta} > \mathbf{tan}\,\boldsymbol{\Phi} \tag{7.5}$$

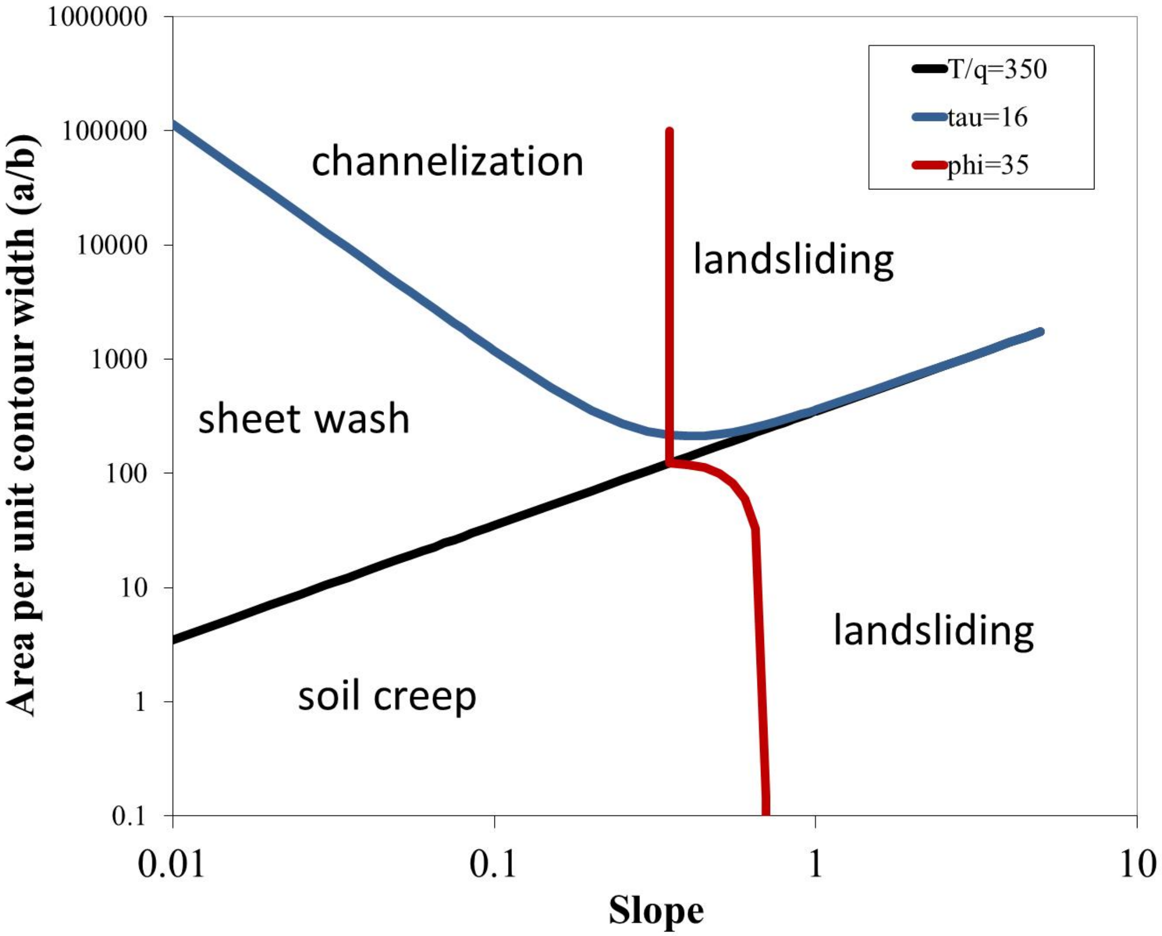


Figure 72. Example of a landscale process domain phase space plot. Parameter values used for this diagram are not necessarily those used for Battle Creek.

Table 14: Landscape conditions and associated hillslope process domains.

Landscape Condition	Process Domain
Unsaturated	Soil Creep
Saturated	Sheet Wash
Channelized	Channelization
Unconditionally Stable	Landslide (wet)
Unconditionally Unstable	Landslide (dry)

7.3 GIS Data Inputs

Geospatial data were retrieved for the Battle Creek watershed and analyzed using ArcGIS 10.3. Multiple data sources were queried to obtain necessary and current data files. The types of data that were needed consisted of spatially topography, precipitation, soils, and wildfire extent.

7.3.1 Topography

Topography is the most important variable controlling landscape processes. A digital file representing the topographic of the Earth's surface is called a digital elevation model (DEM). A DEM can come in different formats, but the most common type, which was used herein, is a grid file, also known as a raster file.

As mentioned in Section 3.1.3, the National Map (TNM) is a collaborative effort among the USGS and other local, government, and private entities working to improve and deliver topographic information for the U.S. Geographic information includes orthoimagery, elevation, names, hydrography, boundaries, transportation, structures, and land cover. Data are publicly available for download from the National Map website (http://nationalmap.gov/index.html) for use in landscape process analysis.

Topographic data (10-m resolution raster DEM) were downloaded from TNM for use in landscape process analysis for a rectangular region larger than the maximum areal extents of the Battle Creek Watershed.

A watershed boundary for Battle Creek was also obtained from TNM using the national hydrography layer. This boundary was used to clip the 10-m DEM to just fit the watershed area, providing a base map for topographic analyses (Figure 73). The elevation raster was used to produce a hillshade model for Battle Creek (Figure 74).

Because DEMs have a numerous sources of error and various problems for application in hydrological and geomorphic analyses, the common professional practice is to process them with a standard set of steps. The software ArcHydro was used this this purpose. Two key steps with this software were to fill landscape sinks and insert the known channel network (i.e., the USGS “blue line” hydrography) into the DEM to force water to aggregate into the pixels where the channel is known to be. These steps are required in order to have water flow from all locations in the watershed to the known channel network and out through the known watershed outlet. Given the processed DEM file, it was then possible to create a raster that quantified the flow direction from each cell to its steepest downslope neighbor (Figure 75). Flow direction was then used to create a raster of accumulated flow into each cell. Using the pixel cell dimensions and the flow accumulation raster, a raster of contributing area for each cell in the DEM was created. Dividing by pixel width allowed for a raster of contributing area per unit contour length (*a/b*) of every cell in the specified boundary. Slope was computed using the Spatial Analyst tool in ArcGIS (Figure 76).

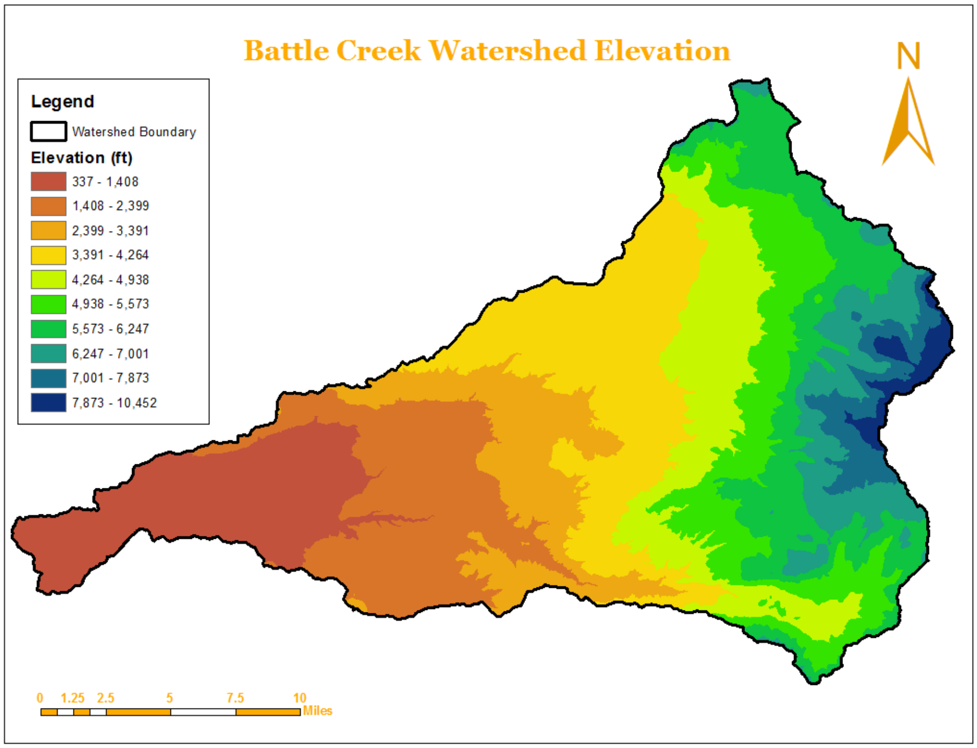


Figure 73: Battle Creek Watershed elevation map.

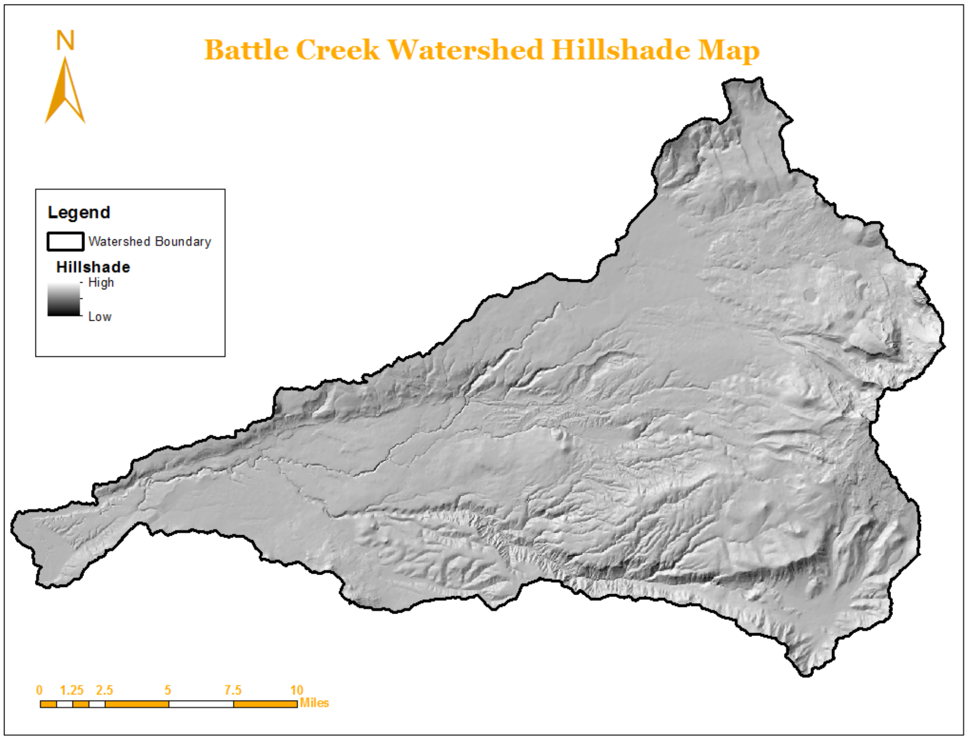


Figure 74: Battle Creek Watershed hillshade map.

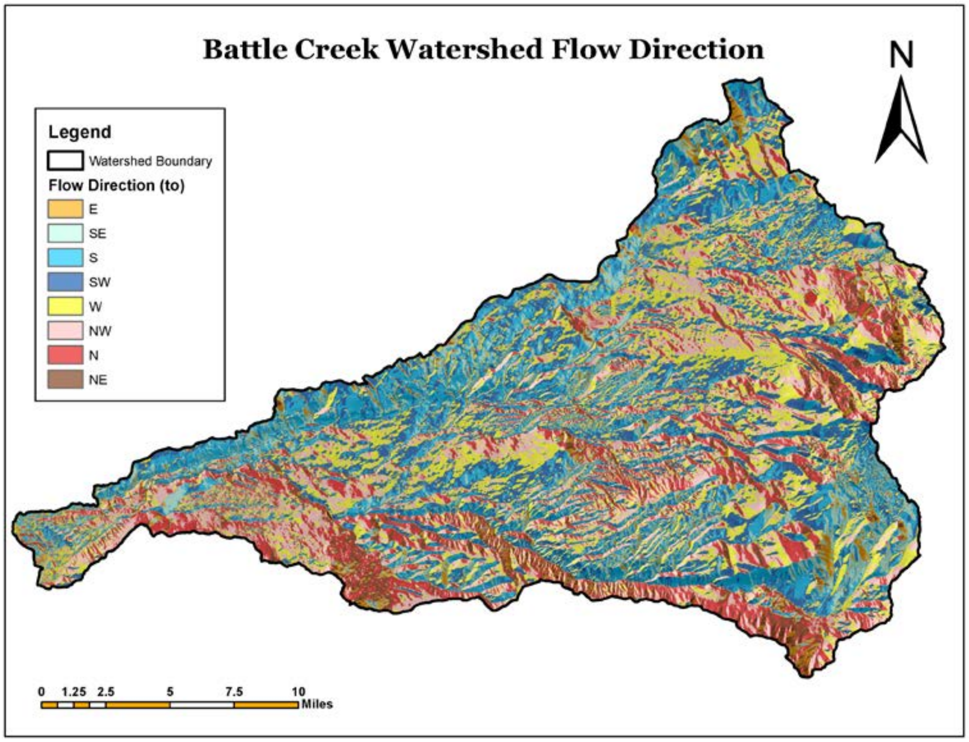


Figure 75: Battle Creek Watershed flow direction map.

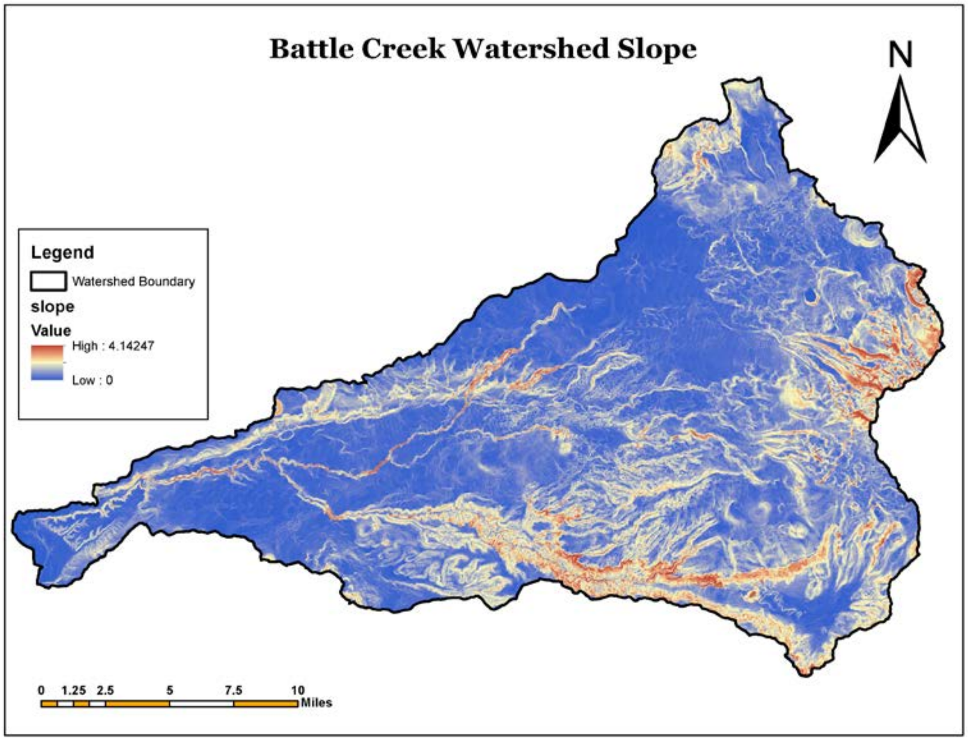


Figure 76: Battle Creek Watershed slope map

7.3.2 Precipitation

Spatially variable precipitation patterns interact with topography to influence landscape processes, so it is a required data input for landscape process analysis. For this study, the data that was needed was values that could represent a long-term steady state hydrological system, which is the main assumption of the analysis method. For the United States, suitable precipitation data is available from the OSU PRISM website as a raster file with 4-km resolution (see Section 5.1.1). The question is what available PRISM data would be appropriate to use for this study.

Mean annual precipitation data makes sense as one basis for analysis in that it represents the amount of rain that would be falling if it were raining every day at that amount. This is a good, conservation value to use. Therefore, one set of PRISM data downloaded and used in this study consisted of the 30-year (i.e., 1980 – 2010) mean annual precipitation.

However, California experiences a sustained dry period each year with little to no rainfall, so the mean annual precipitation data over-predicts what is occurring during the dry period and under-predicts what is occurring during the wet period. There are many ways to deal with this. The approach selected for this study was to counterbalance the conservation analysis with one that is highly aggressive in terms of having disproportionate high precipitation. This way, there is a conservative low analysis and an aggressive high analysis, effectively bounding the range of what is likely to be occurring. Considering the available data, the approach to getting an aggressive analysis is to use the month with the highest mean monthly precipitation. Based on the available long-term precipitation records for Battle Creek Watershed, December and January are the wettest months of the year, with January edging out December for 3 out of 4 sites (Figure 14). The January PRISM precipitation raster also contains the highest precipitation values over other months in Battle Creek. As a result, the PRISM data downloaded and used to represent an aggressive erosion analysis consisted of the 30-year (i.e., 1980 – 2010) mean January precipitation.

Rasters (at 4-km resolution) of mean annual precipitation and mean January precipitation were imported into ArcGIS and converted to metric units (mm/month). Next, the rasters were normalized to mean daily precipitation in units of m per day, which was used as the runoff variable (q) in the scenarios that were not intended to account for water losses associated with vegetative effects. This assumes that for bare land there is no evaporative loss during precipitation. For scenarios accounting for interception-induced evaporative loss, a further reduction in the runoff value was made using a loss factor, as explained in the text for those scenarios, making this a net precipitation variable.

A comparison of the two precipitation rasters using the same precipitation scale enables a clear picture of the large differences in magnitude, but somewhat similar spatial patterns (Figure 77; Figure 78). The January precipitation does show a pattern shift compared to the annual precipitation in that there is more area of higher precipitation in the South Fork Battle Creek subbasin in January than on average for the year. This is significant, because this subbasin also has a greater area of steep slopes (Figure 76).

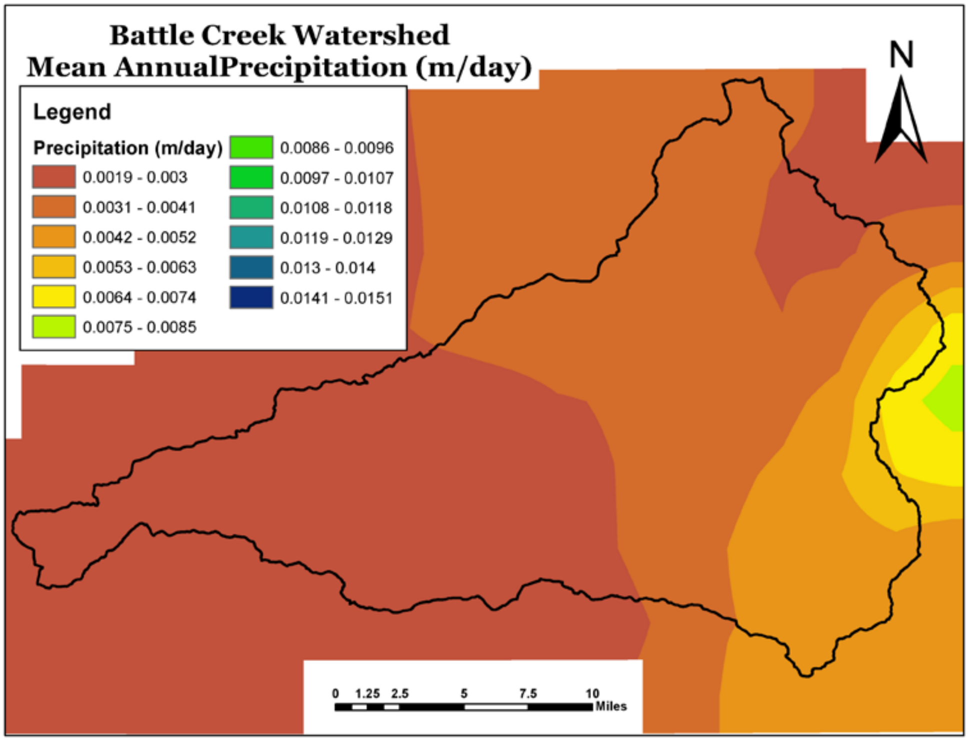


Figure 77: Battle Creek Watershed mean annual precipitation.

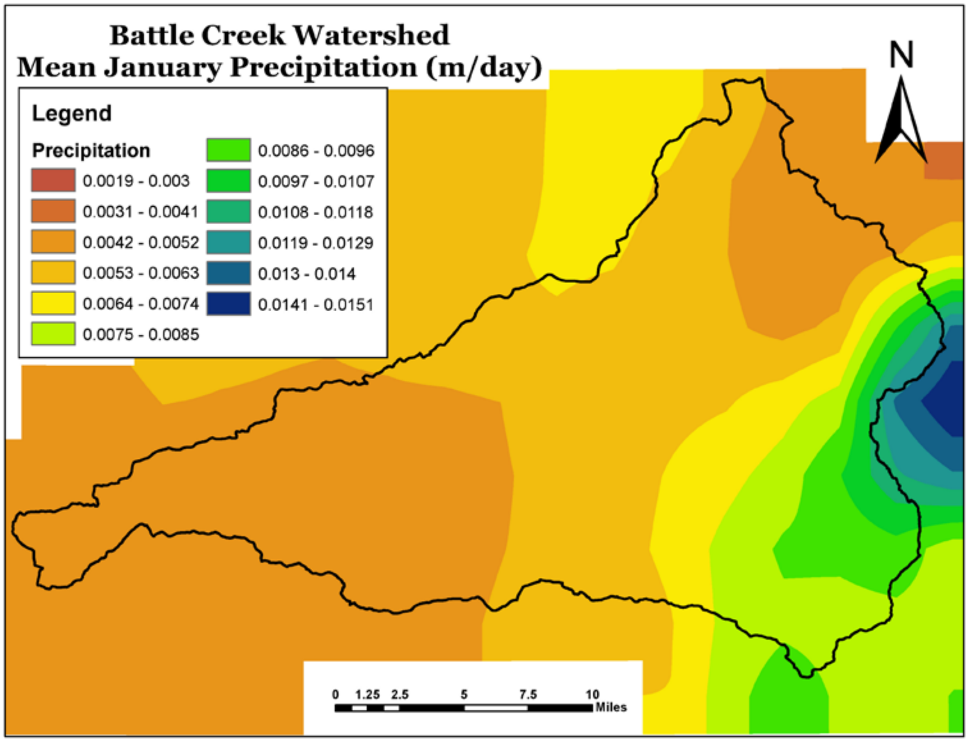


Figure 78: Battle Creek Watershed mean January precipitation.

7.3.3 Soils

Soils data were downloaded from the NRCS web soil survey (http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm) and processed using the soil data viewer tool in ArcGIS. All GIS files were projected in NAD 1983 (2011) State Plane California I FIPS 0401. The Battle Creek watershed is completely within Zone 1 of the State Plan Coordinate System, also known as the California Coordinate System, and was selected as the most suitable projection for analyses.

7.3.4 Wildfire

The role of wildfire on landscape processes was explored by evaluating the effect of the 2012 Ponderosa wildfire (Figure 7) on GIS outputs of landscape processes. CALFIRE provides a spatially explicit geographic database of historic wildfire in California (http://frap.fire.ca.gov/). For scenarios involving wildfire, soil properties were adjusted to simulate a nearly impermeable soil layer post fire thereby increasing surface runoff and affecting hillslope processes.

7.3.5 Constants and Parameters Held Constant

All scenarios tested used the same values in all raster cells for common constants (Table 15) and some parameters . The analysis for unconditionally unstable shallow landsliding used a φ of 45°, which is a well-known, suitable, and conservative value (Dietrich et al., 1993). For a less conservation outcome, one can try 35°, but that was not done herein. Similarly, no tests were performed to vary surface roughness (*k*), which has a simple linear effect on the threshold for channelization and therefore is less sensitive and interesting to explore. There is no spatially explicit dataset available for *k* for Battle Creek at this time to warrant trying to explore it. Future work could expand upon this study to explore this and other inputs and parameters more, if of interest and as more data becomes available. Surface roughness was held constant at the dimensionless value of 10,000, which applies to grass cover, a common cover on hills in Battle Creek and arguably representative of the litter floor under a forest canopy in the mountains. The basis for this value comes from Dietrich et al (1993) citing PhD field experiments by Wilson (1988):

> “Measurements of the runoff produced during this storm revealed that it had roughness properties compatible with a laminar flow description, i.e., the calculated-roughness varied inversely with Reynolds number, yielding a *k* (as defined above) of about 10,000 (Wilson 1988, p. 1091. Despite this large Reynolds number, the data gave no indication of reaching a constant roughness. We suspect that the flow was indeed turbulent, but the momentum defect caused by the vegetation resulted in a turbulent eddy diffusion coefficient that did not vary with height above the bed, giving a laminar-like flow resistance relationship.”

Table 15: Landscape process domain constants.

Constants	Symbol	Value	Units
water density	ρ_w	1000	kg/m^3
gravity constant	g	9.81	m/s^2
kinematic viscosity	ν	1.31×10^{-6}	m^2/s
seconds per day		86400	s/d

7.4 Landscape Process Experimental Design

The experimental design for this analysis involved parameterizing the equations from the previous section to match different conceptual scenarios for Battle Creek, and this was done using spatially explicit methods in ArcGIS 10.3. As per the standard reductionistic approach to scientific experimentation, a single baseline scenario was developed to represent the simplest situation, and then individual changes were made holding all other factors constant to see what the effect of each change would be. Finally, scenarios were made with a mix of effects to see what would result from specific combinations of factors to account for cumulative effects. For each scenario a map of the spatial pattern of landscape processes was produced in ArcGIS 10.3 using a standard workflow that implements the equations in Section 7.2 using Spatial Analyst.

Data inputs for topography (i.e., *M* and *a/b*) varied spatially across the landscape, but were held constant for all scenarios. This left *q*, *T*, and τ_c as available for testing. Of these, τ_c and *q* both have strongly nonlinear roles in channelization, so it is very difficult to discern how a unit change in one of them would affect the results. That warranted investigation. Although *T* has a linear effect on channelization in the same way that *k* does, available soils data provide an excellent database for spatially distributing *T*, thereby enabling thorough investigation into its effects in a way not possible for *k*.

A total of 14 scenarios were run, with half using mean annual precipitation and half using mean January precipitation. Scenarios were produced by manipulating the spatial pattern of equation parameters to account for different combinations of lumped and spatially explicit values representing land cover, soils, wildfire, and channel initiation. The experimental design evaluated the effects of each parameter independently with an additional mixed effects model (Table 16, Table 17). The set up for each scenario is described in the following subsections.

Table 16: Concepts for the landscape process domain scenarios.

A) Mean annual precipitation scenarios

Scenario #	*Scenario name*	*Parameter(s) Adjusted*
1	Topography	none
2	Land cover	Runoff
3	Soil Transmissivity	Transmissivity
4	Ponderosa Wildfire	Transmissivity
5	Channel Initiation	Critical Shear Stress (up)
6	Channel Initiation	Critical Shear Stress (down)
7	Mixed Model	Runoff, Transmissivity

B) Mean January precipitation scenarios

Scenario #	*Scenario name*	*Parameter Adjusted*
8	Topography	none
9	Land cover	Runoff
10	Soil Transmissivity	Transmissivity
11	Ponderosa Wildfire	Transmissivity
12	Channel Initiation	Critical Shear Stress (up)
13	Channel Initiation	Critical Shear Stress (down)
14	Mixed Model	Runoff, Transmissivity

Table 17. Data inputs and parameter values for the test scenarios.

	Adjusted constants			
Scenario	surface roughness	soil transmissivity	net precipitation*	critical shear stress
Symbol	k	T	q	tc
Units	-	m/d	m/d	Pa
1	10000	3	MAP	16
2	10000	3	MAP adjusted	16
3	10000	soils map	MAP	16
4	10000	1 burn; 3 else	MAP	16
5	10000	3	MAP	8
6	10000	3	MAP	32
7	10000	soils map	MAP adjusted	16
8	10000	3	MJP	16
9	10000	3	MJP adjusted	16
10	10000	soils map	MJP	16
11	10000	1 burn; 3 else	MJP	16
12	10000	3	MJP	8
13	10000	3	MJP	32
14	10000	soils map	MJP adjusted	16

*MAP and MJP are mean annual and mean January precipitation

7.4.1 Baseline Topography Scenarios

A baseline scenario of landscape processes was developed to demonstrate the primary role of spatially distributed topography in the spatial pattern of landscape processes. Dietrich et al. (1993) reported baseline parameter values of 17 m^2/d and 160 - 320 dynes/cm^2 (16 - 32 N/m^2) for T and τ_c, respectively. The value for T was not based on soils data for their study area, as little geospatial data existed at that time, but was determined by back-calculation on the basis of DEM curvature analysis to get all divergent cells unsaturated and all convergent cells saturated. For Battle Creek in 2015, ample soils data is available, so instead of using that value, the baseline scenario used a uniform soil transmissivity of 3 m^2/d, as this was found to be the mean value for spatially explicit soils data in the Battle Creek watershed. For the critical shear stress value, the range of 16 - 32 Pa (1 Pascal equals 1 N/m^2) was stated by Dietrich et al. (1993) to be appropriate for disturbed, poorly vegetated surfaces on the basis of the Ph.D. dissertation of Reid (1989), who investigated channel incision by surface runoff in grassland catchments. No data was available to spatially distribute τ_c in Battle Creek Watershed, but this baseline value range was tested with different scenarios herein, as described below. Since a range was tested, the baseline value chosen made sense to be in the middle of the range, so 16 Pa was used as the baseline value.

7.4.2 Distributed Land Cover Scenarios

Land cover intercepts rainfall providing temporary storage where it is subject to evaporation and transpiration. Evapotranspiration is the process by which liquid water at or near the surface becomes atmospheric water vapor reducing the amount of gross precipitation delivered to the landscape (Hornberger et al., 2014). Many field studies have explored the interception loss as a fraction of gross precipitation and a wide range of values have been reported for forest canopy and vegetation over a range of climates (Stewart, 1977; Herwitz, 1985; Carlyle-Moses and Gash, 2011).

To model the effects of land cover, a loss factor for specific land cover units was applied to precipitation data. Land cover data were downloaded from TNM at 30-m resolution in GeoTIFF format and processed for use in analysis. Land cover data collected in 2011 provide the most recent spatially explicit coverage for Battle Creek. Land cover map units for deciduous, evergreen, and mixed forest were given a loss factor of 0.25, consistent with the literature on forest interception. Shrub, herbaceous, and pasture units were also applied a loss factor of 0.25. Cultivated crops received a loss factor of 0.1. A loss factor was not applied to barren land, developed land, open water and wetlands. A loss factor of 0.25 was estimated as an average value representative of forest canopy and understory vegetation interception and evapotranspiration loss.

7.4.3 Distributed Soil Scenarios

Soil properties can vary extensively across the landscape. Soils have a saturated hydraulic conductivity (K_{sat}) that refers to the ease with which pores in a saturated soil transmit water. K_{sat} values are based on soil characteristics observed in the field with particular attention to structure, porosity, and texture. Soil transmissivity (T) by definition is depth-integrated hydraulic conductivity. To evaluate the effects of heterogeneous soil properties, the spatial distribution of T was computed for Battle Creek using soils data. The magnitude and rate of infiltration vary with T and thus affected hillslope erosional processes.

Soils surveys were downloaded from the USDA NRCS and processed in ArcGIS using the Soil Data Viewer tool. Spatially explicit rasters for soil depth and K_{sat} were created using a weighted average for soil components within a particular map unit. Spatially explicit T replaced the uniform value of 3 m^2/d used in the baseline topography scenario.

Soil data were processed using a weighted average aggregation. Aggregation is the process of reducing a set of component attributes to a single value to represent the map unit as a whole. A component was either a soil type or some non-soil entity, e.g. rock outcrop. The results of aggregating soil components using a weight average for map units do not reflect the presence or absence of limitations of the components which are not listed in the database. Aggregation must be completed because soil data provide delineated map units, but not components.

7.4.4 Ponderosa Wildfire Scenarios

The Ponderosa fire burned an area of ~28,000 acres in 2012. The effects of this wildfire were explored by adjusting the parameter soil transmissivity relative to the rest of the watershed. The wildfire burn area was assigned a value of 1 m^2/d with the remaining watershed retaining the baseline value of 3 m^2/d. Even though soils become extremely water retardant post-fire, they do still allow some subsurface flux of water that gets through the surface crust where the soil becomes cracked or broken through time, so a value of 1 was representative of the process. Although wildfire also changes q, k and τ_c, it was unclear how to account for all these effects, so on a reductionistic basis, just the effect on T was implemented. Future analyses could make more adjustments on the basis of expert knowledge and further evaluate the effects.

7.4.5 Channelization Alternative Scenarios

A threshold of erosion on the land surface is necessary for channelization. Channelization occurs when a τ_c is overcome inducing surface erosion. To evaluate the effects of channelization, different values of τ_c were input for two scenarios in addition to the baseline. The baseline topography scenario used 16 Pa, so two channelization scenarios were analyzed with a value half that and two with double that, so 8 and 32 Pa, respectively.

7.4.6 Mixed Model Scenarios

A mixed model scenario was analyzed to ascertain the cumulative effects of spatially distributed land cover, soil properties, and wildfire all together on the spatial pattern of landscape processes. As a result, this is the most realistic and complete scenario for what is occurring in the watershed. The loss fraction due to land cover from models 2 and 9 were adjusted for the wildfire burn zone reducing the loss fraction to 0 and applied to mean annual and mean January precipitation. Spatially variable soil transmissivity from models 3 and 10 were combined with the Ponderosa wildfire soil T of 1 from models 4 and 11. Critical shear stress was selected at 16 Pa as most representative of surface conditions from comparing models 1, 5, 6 and 2, 12, 13.

7.5 Landscape Process Results

The total area for which each process dominated the landscape was calculated in square miles for direct comparison amongst models and to assess the importance of individual parameters. Given that the watershed is ~ 368 mi^2 (953 km^2), the raw results were divided by total watershed area to yield relative percents for interpretation (Table 18). For 8 out of 14 scenarios, sheet wash had the largest areal extent and in that sense is the spatially dominant landscape process. Next was soil creep, which was the most extensive in 5 of the 6 remaining scenarios. In one scenario, sheet wash and soil creep had equal areal extents. Although channelization and landsliding span a very small percent of land surface area, they can produce a disproportionate amount of sediment and cause positive feedbacks that in turn generate more sediment. However, this analysis effort cannot discern whether the intensity of erosion for these two processes outweigh their limited area. It also does not account for sediment deposition, especially in channels.

In terms of the effects of different scenarios, the primary finding was that the proportion of soil creep vs. sheet wash erosion is most sensitive to soil characteristics, exemplifying the necessity for spatially explicit soils data and the importance of soils for assessing hillslope erosion processes. When transmissivity was taken from real soil data, then much more sheet wash erosion was predicted than when a constant approximating the mean value was used. Adding spatially explicit vegetation only had a small effect on the results, because the differences in interception are not that great, which is well known in the interception literature. Adding in effects in the area of the Ponderosa fire made a noticeable difference when soils were treated in a uniform way, but when soil transmissivity was distributed according to the soil survey then having the fire did not change the dominant process much relative to that. Note that it might dramatically increase the abundance of erosion, but it did not change the mechanism. This analysis cannot discern if there was a fire effect on the amount of sediment delivered. The results for each scenario are described in the following subsections.

Table 18. Relative percent land surface area that each landscape process was found to dominant in for each of 14 scenarios. Orange, bold format indicates the process with the most area in each scenario.

	Scenario number						
Process	1	2	3	4	5	6	7
A) Mean annual precipitation scenarios							
Soil Creep	**55.9**	**60.8**	40.6	**53.1**	**55.9**	**55.9**	43.3
Sheet Wash	39.0	34.7	**51.6**	41.2	36.5	39.8	**49.6**
Channelization	1.3	1.3	1.3	1.3	3.8	0.5	1.2
Landslide (wet)	2.7	2.2	5.4	3.3	2.7	2.7	4.7
Landslide (dry)	1.1	1.1	1.1	1.1	1.1	1.1	1.1

Process	8	9	10	11	12	13	14
B) Mean January precipitation scenarios							
Soil Creep	41.6	**46.6**	29.9	38.6	41.5	41.5	31.9
Sheet Wash	**50.8**	**46.6**	**60.0**	**53.0**	**45.7**	**51.9**	**58.6**
Channelization	1.8	1.8	1.8	1.8	6.8	0.7	1.6
Landslide (wet)	4.8	4.0	7.3	5.5	4.8	4.8	6.7
Landslide (dry)	1.1	1.1	1.1	1.1	1.1	1.1	1.1

7.5.1 Baseline Topography Results

The aforementioned parameters were input into the model to create a spatially explicit map of process domains corresponding to hillslope erosion processes for mean annual precipitation (Figure 80) and mean January precipitation (Figure 87). Model 1 evaluated mean annual precipitation under the assumptions of baseline conditions. Approximately 55.9% of Battle Creek experienced unsaturated conditions and the remaining 44.1% was susceptible to hillslope erosion by sheet wash (39%), channelization (1.3%), saturated landsliding (2.7%) and unsaturated landsliding (1.1%). Model 8 evaluated mean January precipitation under the assumptions of baseline conditions. Model 8 had a lower percent area of unsaturated land experiencing soil creep at 41.6% with the remaining 55.4% area of sheet wash (50.8%), channelization (1.8%), saturated landsliding (4.8) and unsaturated landsliding (1.1%).

7.5.2 Distributed Land Cover Results

Model 2 evaluated mean annual precipitation with base conditions accounting for land cover by applying a loss factor to land cover units (Figure 81). Due to the loss of runoff from interception, 60.8% of the landscape was unsaturated and indicated soil creep was the dominant runoff process. The remaining 39.2% was sheet wash (34.7%), channelization (1.3%), saturated landsliding (2.2%) and unsaturated landsliding (1.1%). Model 9 evaluated mean January precipitation with base conditions accounting for land cover and applied the same loss factor to land cover units for mean annual precipitation (Figure 88). Soil creep accounted for 46.6% landscape area with the remaining 53.4% as sheet wash (46.6%), channelization (1.8%), saturated landsliding (4.0%), and unsaturated landsliding (1.1%).

By decreasing the amount of gross precipitation reaching the land surface, less water is available for surface erosion. Percent areas for sheet wash, channelization, and saturated landsliding all decreased relative to baseline conditions (Model 1 and 8) for both mean annual and mean January precipitation models. Unsaturated landsliding was not dependent on surface saturation and thus was not affected by the reduction in precipitation.

7.5.3 Distributed Soil Results

Model 3 evaluated mean annual precipitation with base conditions accounting for soil characteristics (Figure 82). Approximately 40.6% of the land surface experienced soil creep with the remaining 59.4% as sheet wash (51.6%), channelization (1.3%), saturated landsliding (5.4%) and unsaturated landsliding (1.1%). Model 10 evaluated mean January precipitation with base conditions accounting for soil characteristics (Figure 89). Model 10 indicated 29.9% area undergoes soil creep, with the remaining 70.1 % as sheet wash (60%), channelization (1.8%), saturated landsliding (7.3%), and unsaturated landsliding (1.1%).

The addition of soil properties into the landscape model produced significant effects in the proportion of unsaturated to saturated process domains. Percent area of sheet wash and wet landsliding increased substantially for both mean annual and mean January precipitation (Table 18). Channelization displayed a slight increase and unsaturated landsliding remains constant. A limiting factor not addressed in the soils analysis is the cohesion of soils from vegetation providing further resistance to channelization and landsliding. Models 3 and 10 indicated the highest proportions of the landscape susceptible to hillslope erosion other than soil creep and identified a wider range of areas as potential sources of sediment in Battle Creek.

7.5.4 Ponderosa Wildfire Results

Model 4 evaluated mean annual precipitation with base conditions and assessed the effects of the Ponderosa wildfire (Figure 83). Approximately 55.9% of the land surface was modeled under soil creep with the remaining 44.1% as sheet wash (53.1%), channelization (1.3%), saturated landsliding (3.3%), and unsaturated landsliding (1.1%). Model 11 evaluated mean January precipitation with baseline conditions and assessed the effects of the Ponderosa wildfire (Figure 90). Model 11 displayed 38.6% watershed area as soil creep with the remaining 61.4% as sheet was (53.0%), channelization (1.8%), saturated landsliding (5.5%), and unsaturated landsliding (1.1%).

Relative to Models 1 and 8, Models 4 and 11 show marked increases in the areas of sheet wash and landsliding within the defined Ponderosa wildfire boundary. However, because this is a fraction of watershed area, the effect on the overall results was limited.

7.5.5 Channelization Results

Models 5 (Figure 84) and 12 (Figure 91) were computed with 8 Pa, while Models 6 (Figure 85) and 13 (Figure 92) were computed with 32 Pa. Table 16 displays percent areas for process domains in the scenarios. Reducing the parameter value in half more than tripled the areal extent of channelization, which is significant. Doubling the value did not quite reduce the areal extent by a factor of 3, but close to that. This sensitivity suggests that more work is needed to evaluate the most suitable value for use in Battle Creek Watershed, ideally even spatially distributing the value on the basis of surface soil and land cover data.

As a first step to deciding which value is most appropriate for now, locations of channel heads for the three values of τ_c were compared to streamlines on topographic maps. In lieu of field maps of channel head locations, topographic maps are the best representation for validation. For both mean annual precipitation and mean January precipitation, the baseline topography scenario yielded the best correlation between observed and predicted stream networks and channel head locations. Thus, the use of 16 Pa appears to be supported by the real-world conditions. In the future, field collection of channel head points in Battle Creek would allow for a more robust model to fit the parameters of critical shear stress and surface roughness.

7.5.6 Mixed Model Results

Model 7 was the mixed model for mean annual precipitation (Figure 86) and experienced 43.3% area dominated by soil creep. The remaining 56.7% were sheet wash (49.6%), channelization (1.2%), saturated landsliding (4.7%), and unsaturated landsliding (1.1%). Model 14 was the mixed model for mean January precipitation (Figure 93) and exhibited 31.9% of the land surface as soil creep. The remaining 68.1% were sheet wash (58.6%), channelization (1.6%) saturated landsliding (6.7%), and unsaturated landsliding (1.1%).

The spatial distribution of soil T highlighted the importance of soil properties for relative proportions of saturated vs unsaturated hillslope processes. The effects of wildfire were subdued in the context of variable soil properties. It is important to note that wildfire reduced the hydraulic conductivity of a soil, but the impact is relative to the soil properties for being subject to fire.

7.6 Landscape Process Discussion

Geospatial analysis of the pattern of landscape processes in Battle Creek revealed significant differences in processes on the basis of location and showed the relative roles of different factors in controlling which process has the greatest impact in terms of areal extent, which is often indicative of the largest sediment mass contributor for a watershed of this scale. By and large, sheet wash is the most spatially abundant process generating sediment in Battle Creek, and thus is likely to be extremely important to address in any sediment management considered. Rain-induced shallow landsliding was found to be particularly important for the South Fork of Battle Creek. It is also interesting that landsliding was predicted to be significant for the inner slopes along the channel in the mainstem and large tributaries.

Given this tool, it is now possible to develop specific questions about locations in Battle Creek and query the analyses to see what is anticipated to be going on there. Then it is possible to go out and do monitoring to see if the sites demonstrate in reality what is anticipated by the analyses. With such an effort it would be possible to refine the parameters of the analysis and get to a point to be able to make defensible conclusions about which activities are causing what effects and where in the watershed.

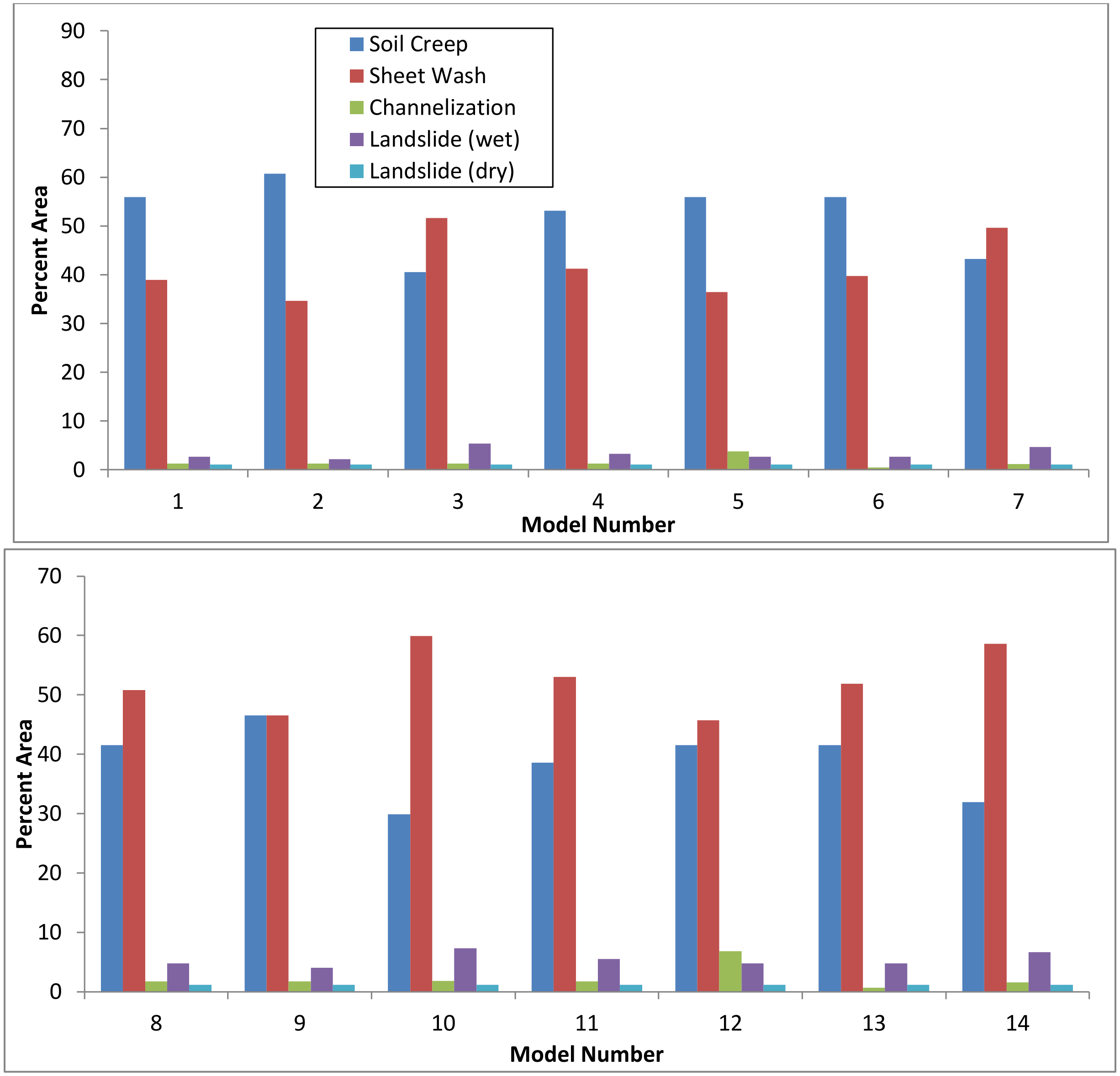


Figure 79: Percent Area for process domains in landscape models

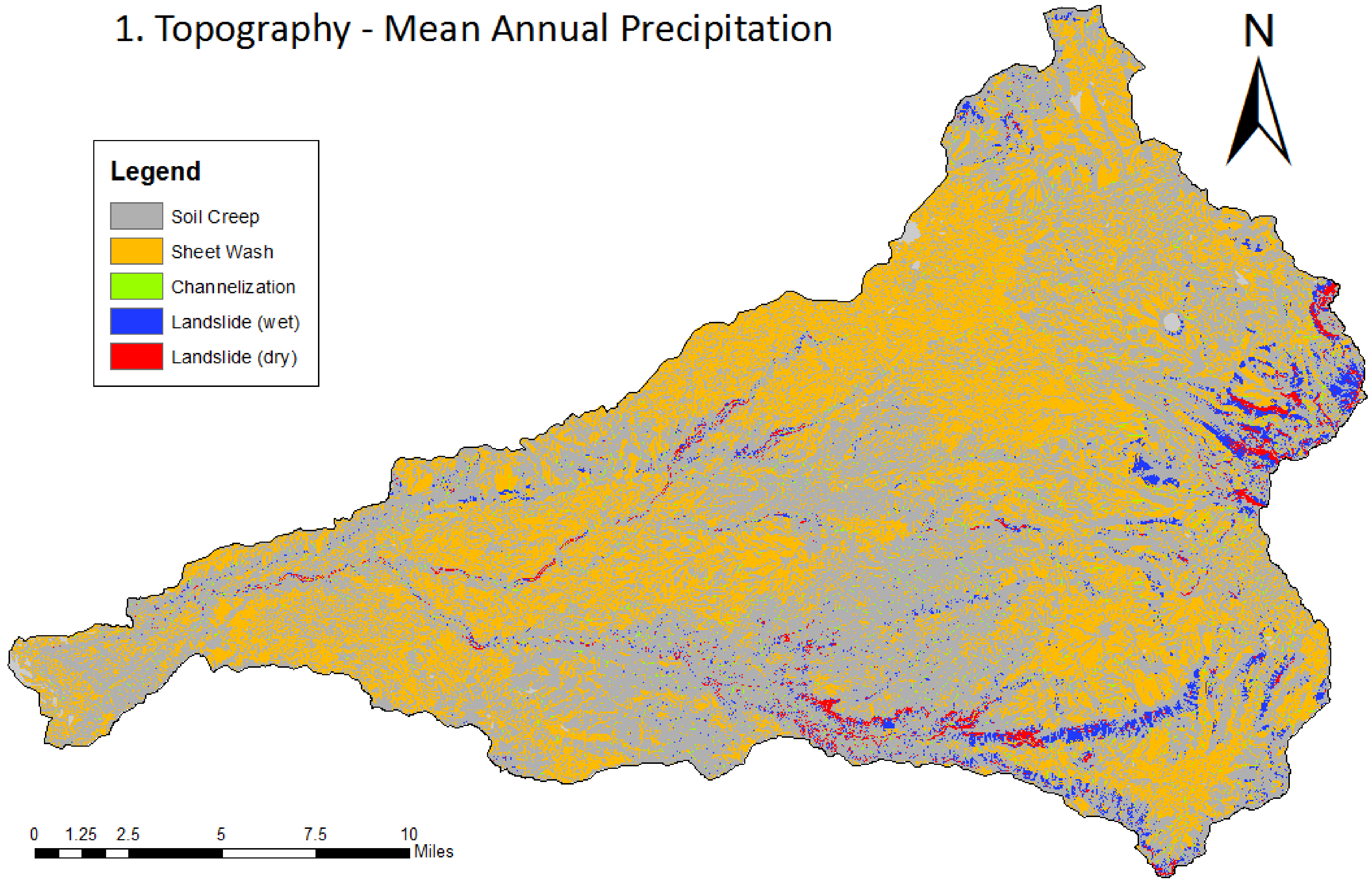


Figure 80: Landscape process domain model with topography and base parameters

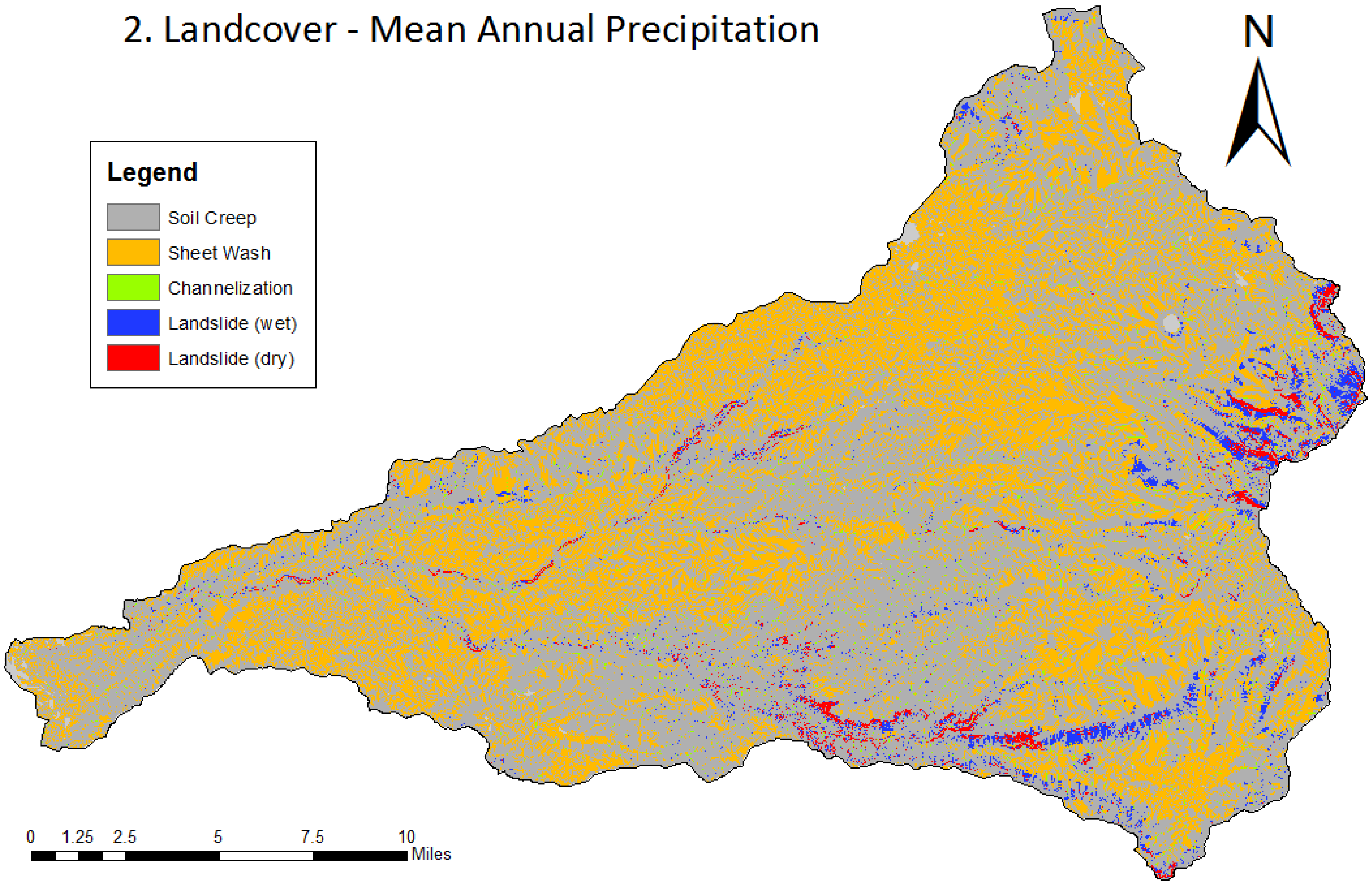


Figure 81: Landscape process domain model accounting for precipitation loss due to interception from landcover

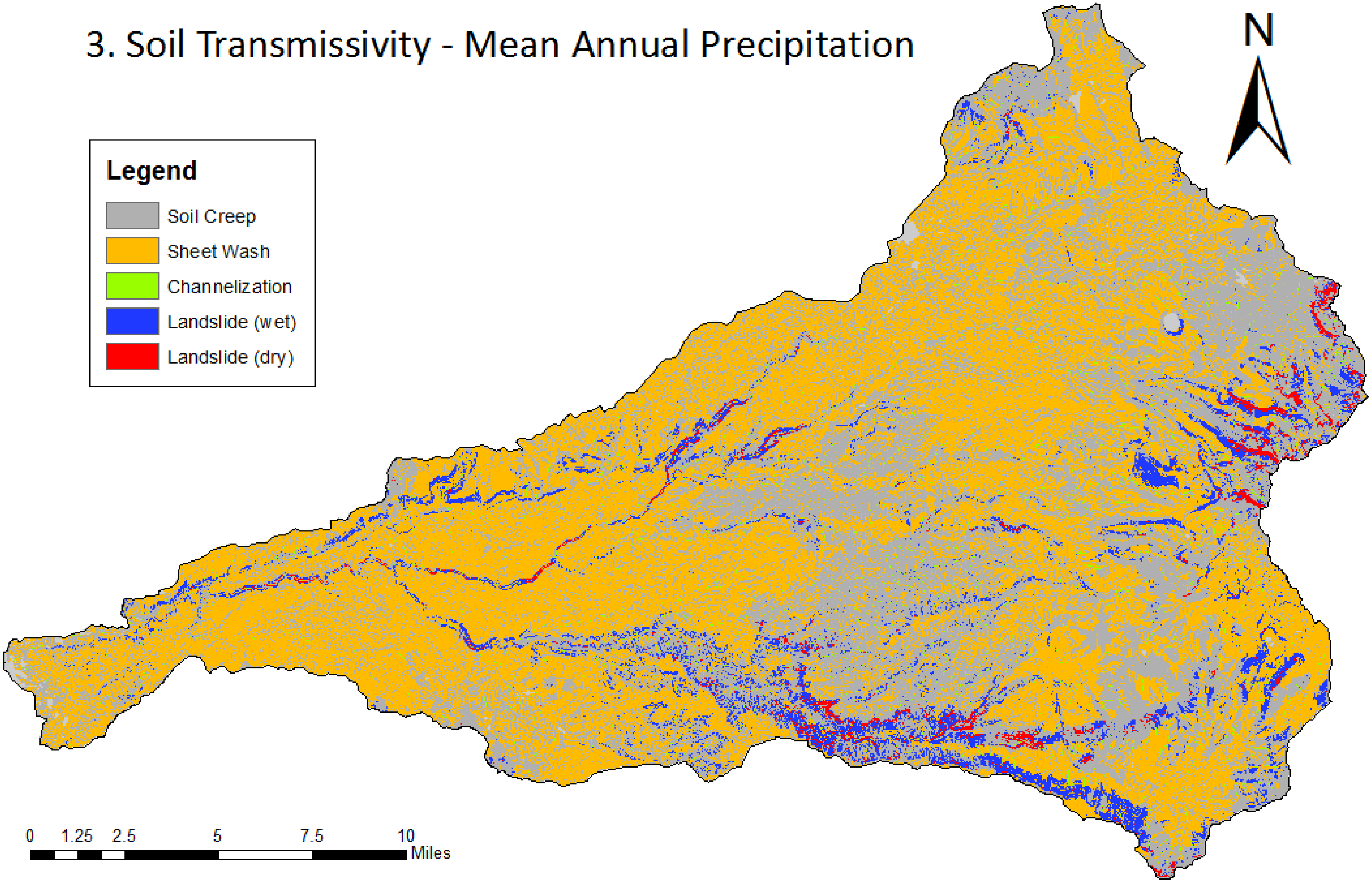


Figure 82: Landscape process domain model accounting for spatial variability of soil characteristics

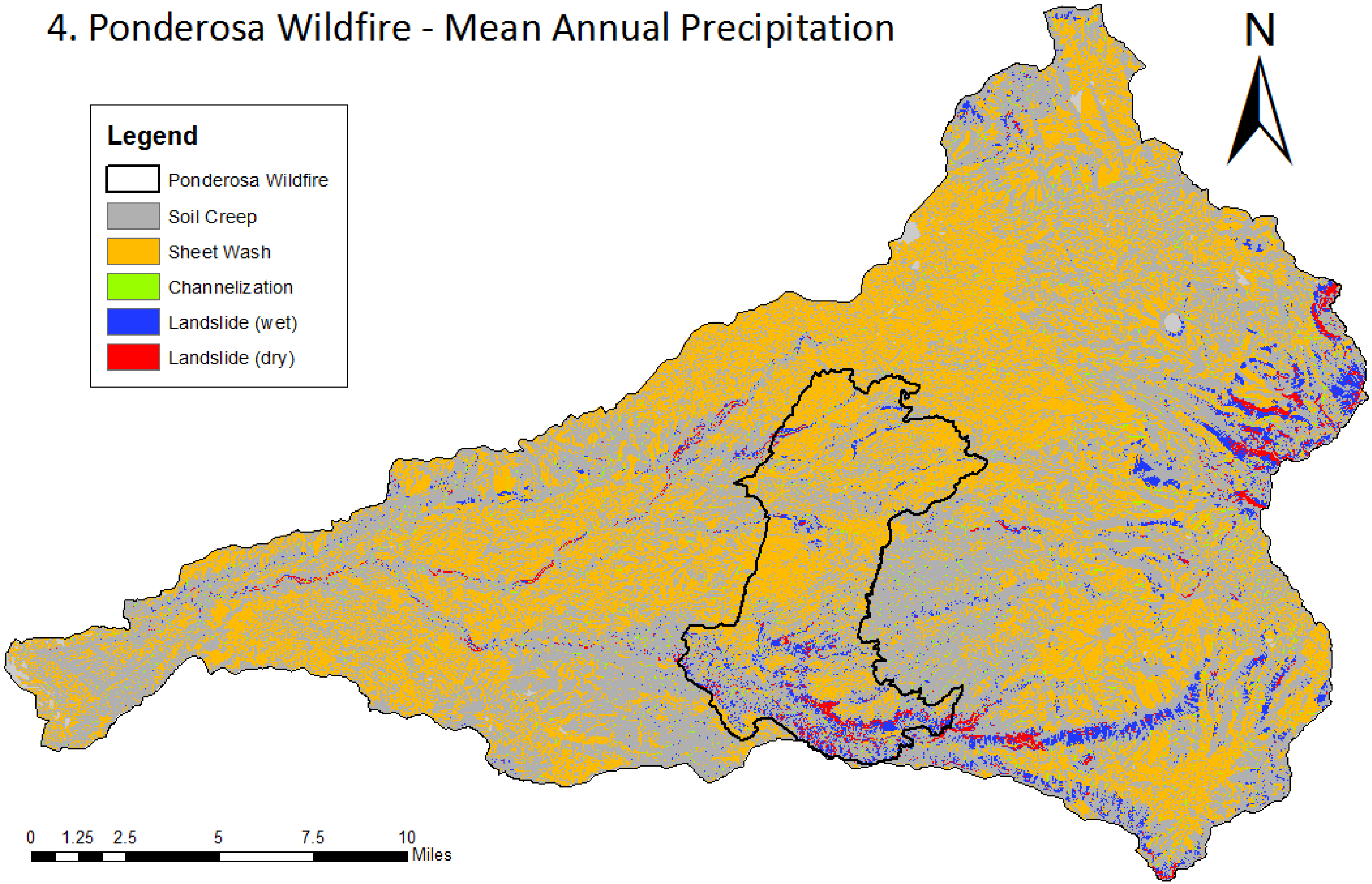


Figure 83: Landscape process domain model accounting for 2012 Ponderosa wildfire

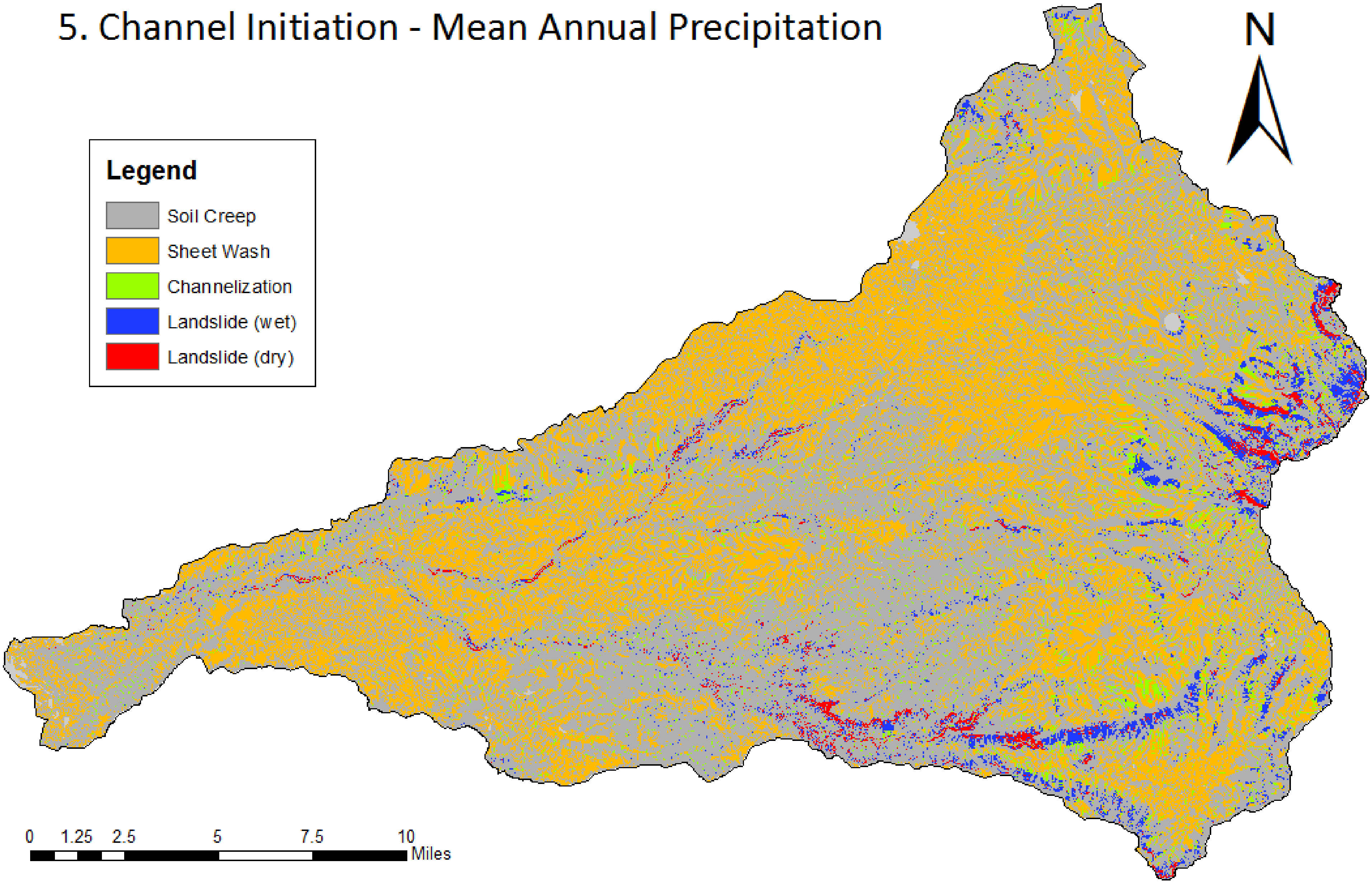


Figure 84:Landscape process domain model accounting for channelization with a boundary shear stress of 8 N/m^2

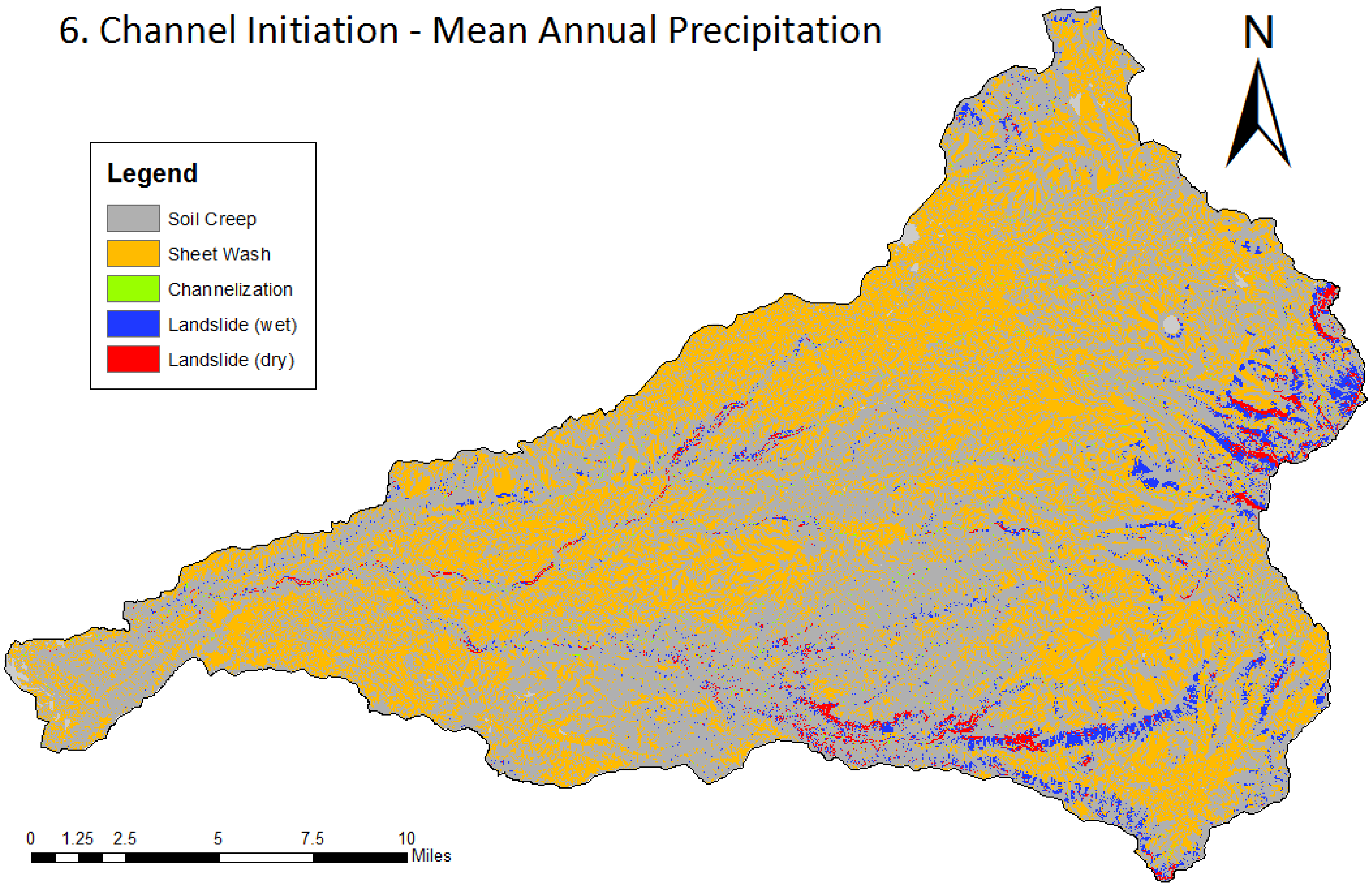


Figure 85: Landscape process domain model accounting for channelization with a boundary shear stress of 32 N/m^2

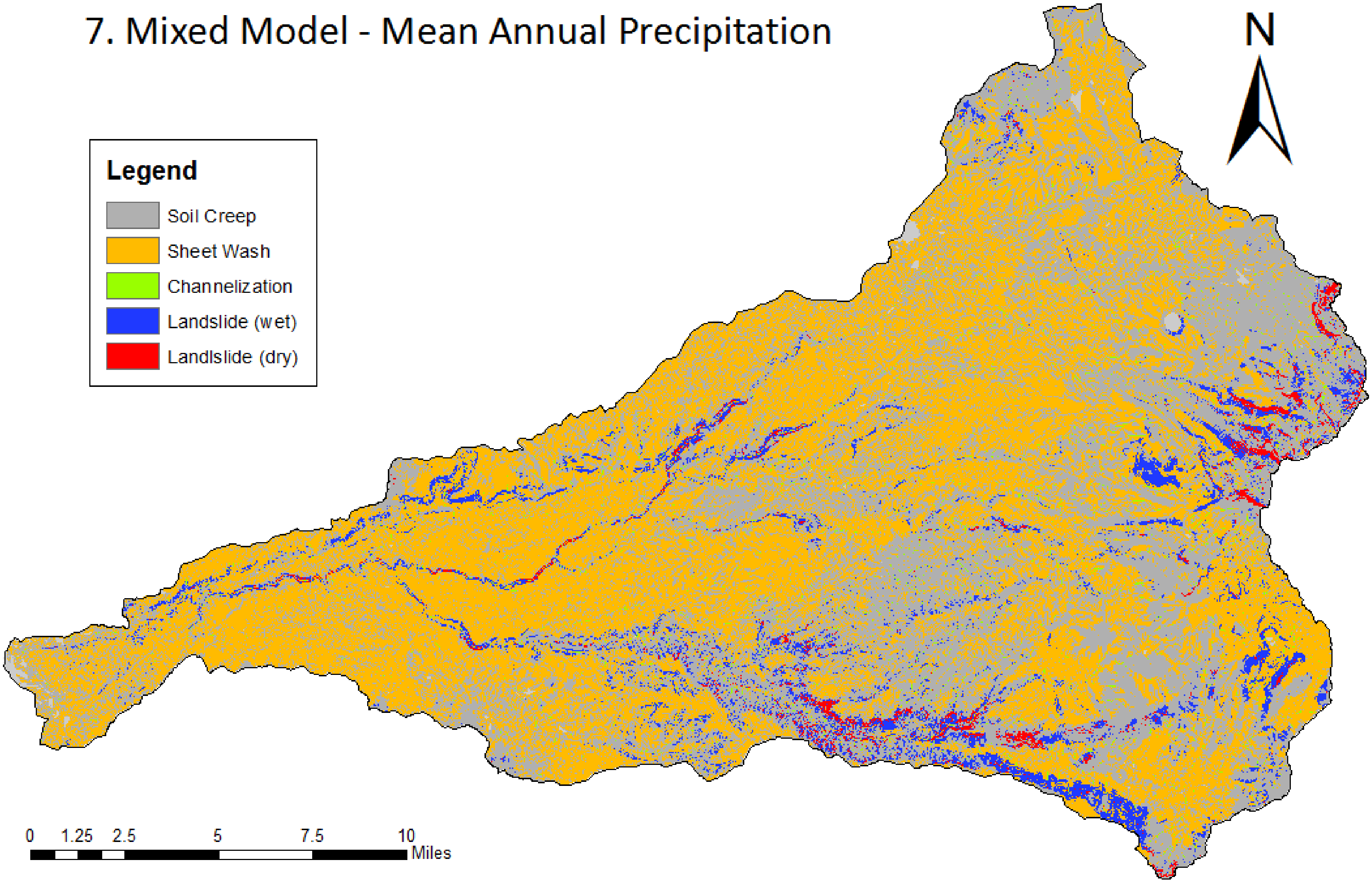


Figure 86: Landscape process domain model synthesizing all individual model runs

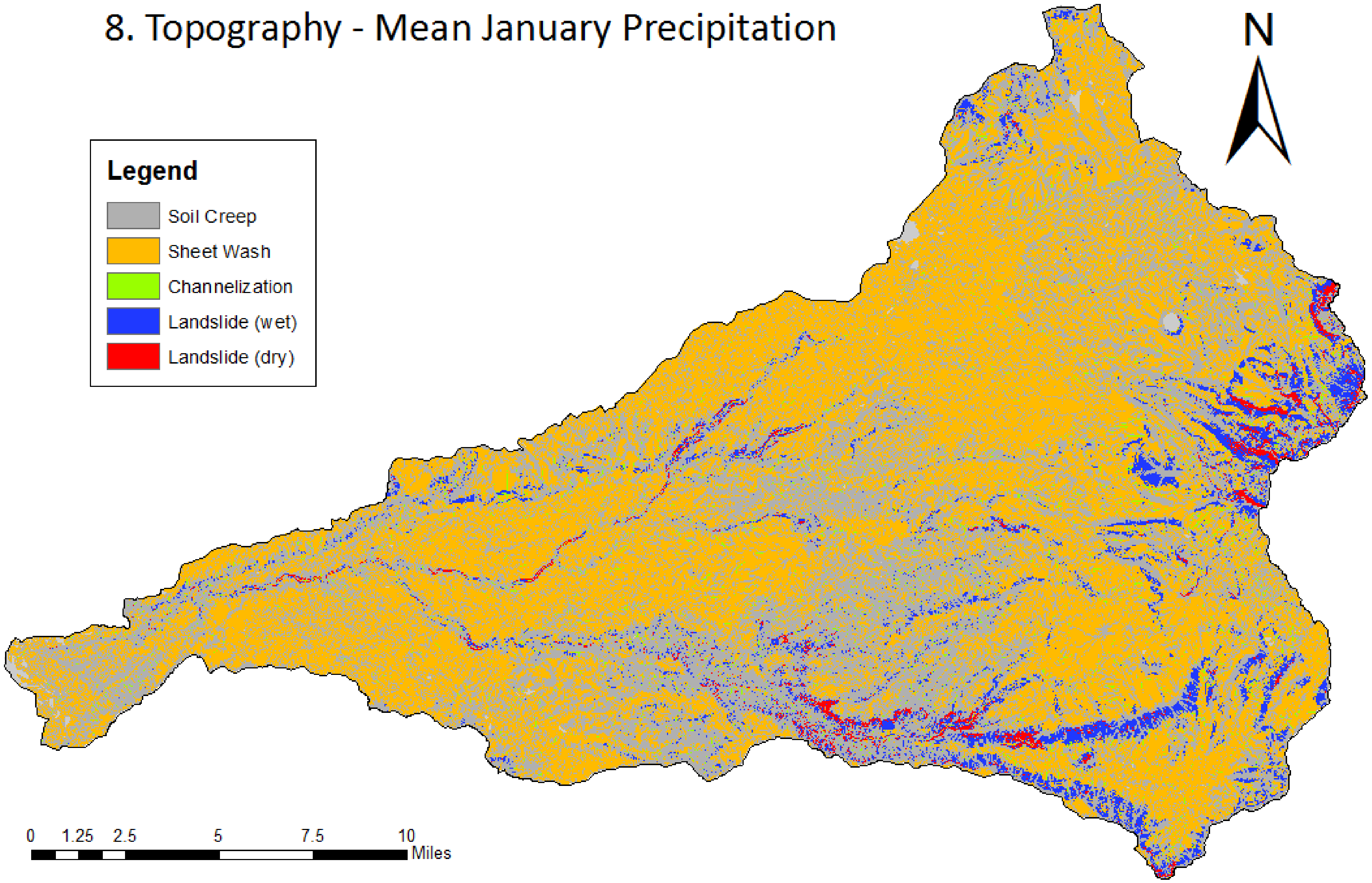


Figure 87: Landscape process domain model with topography and base parameters

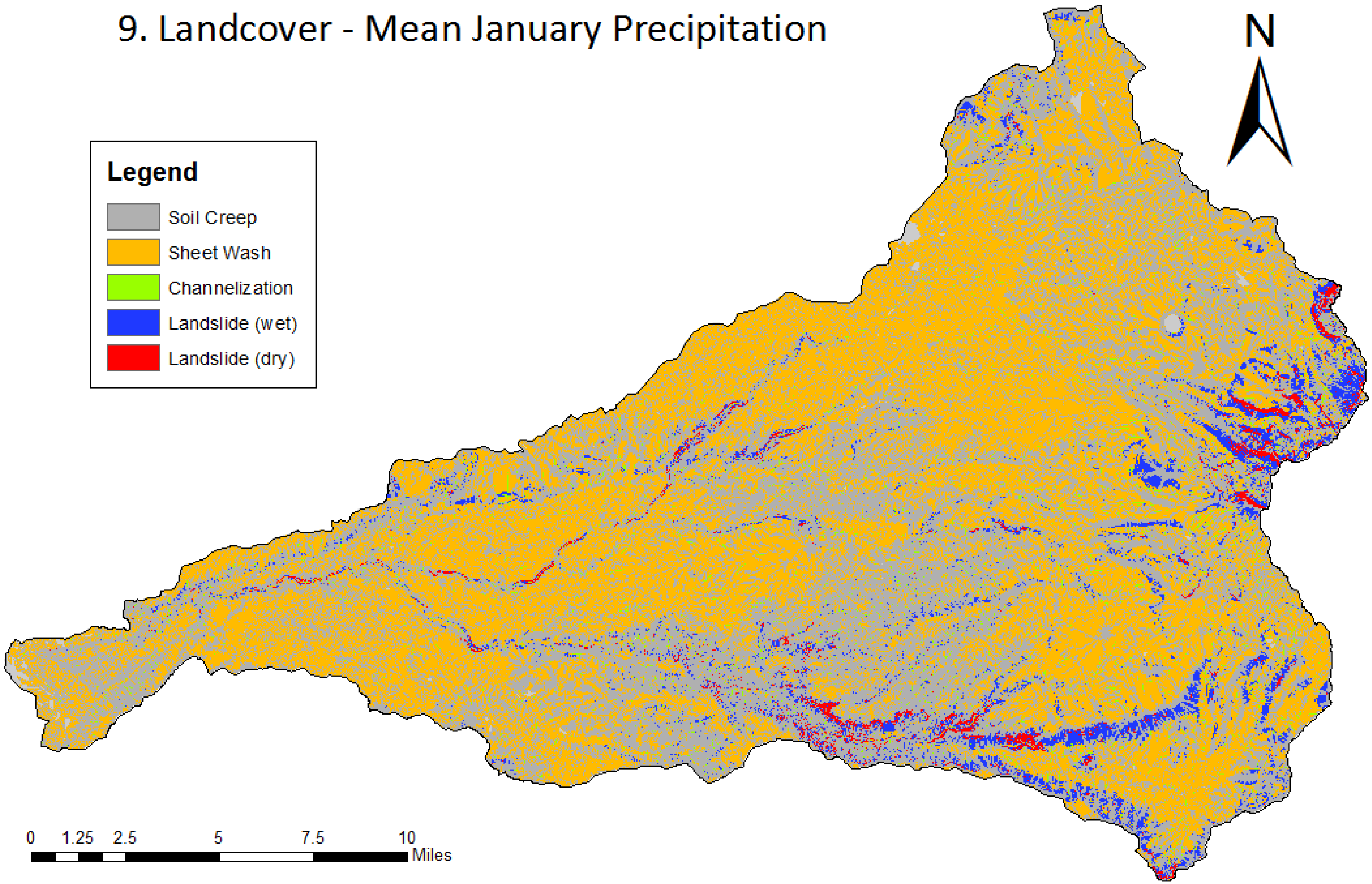


Figure 88: Landscape process domain model accounting for precipitation loss due to interception from landcover

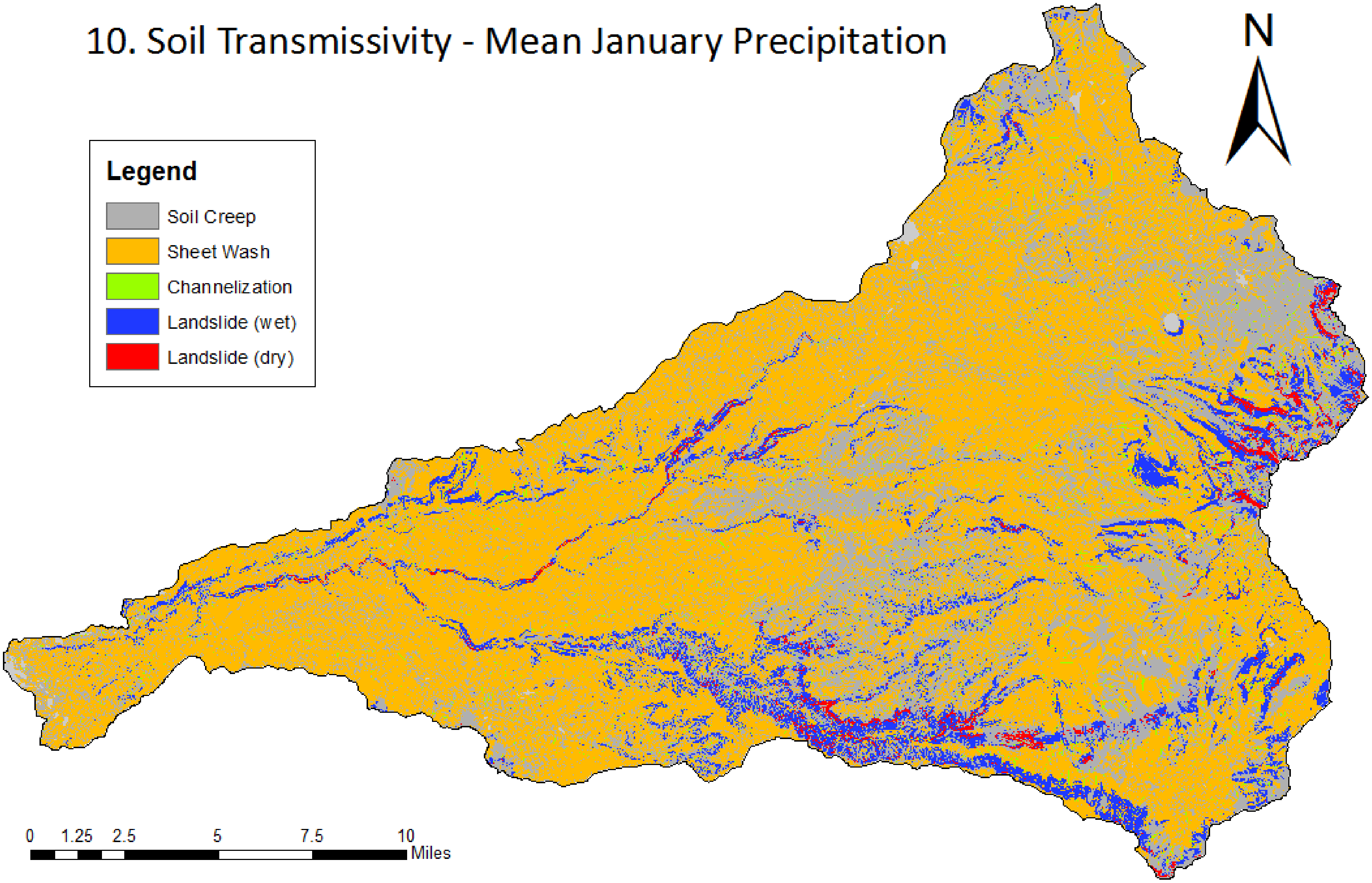


Figure 89: Landscape process domain model accounting for spatial variability of soil characteristics

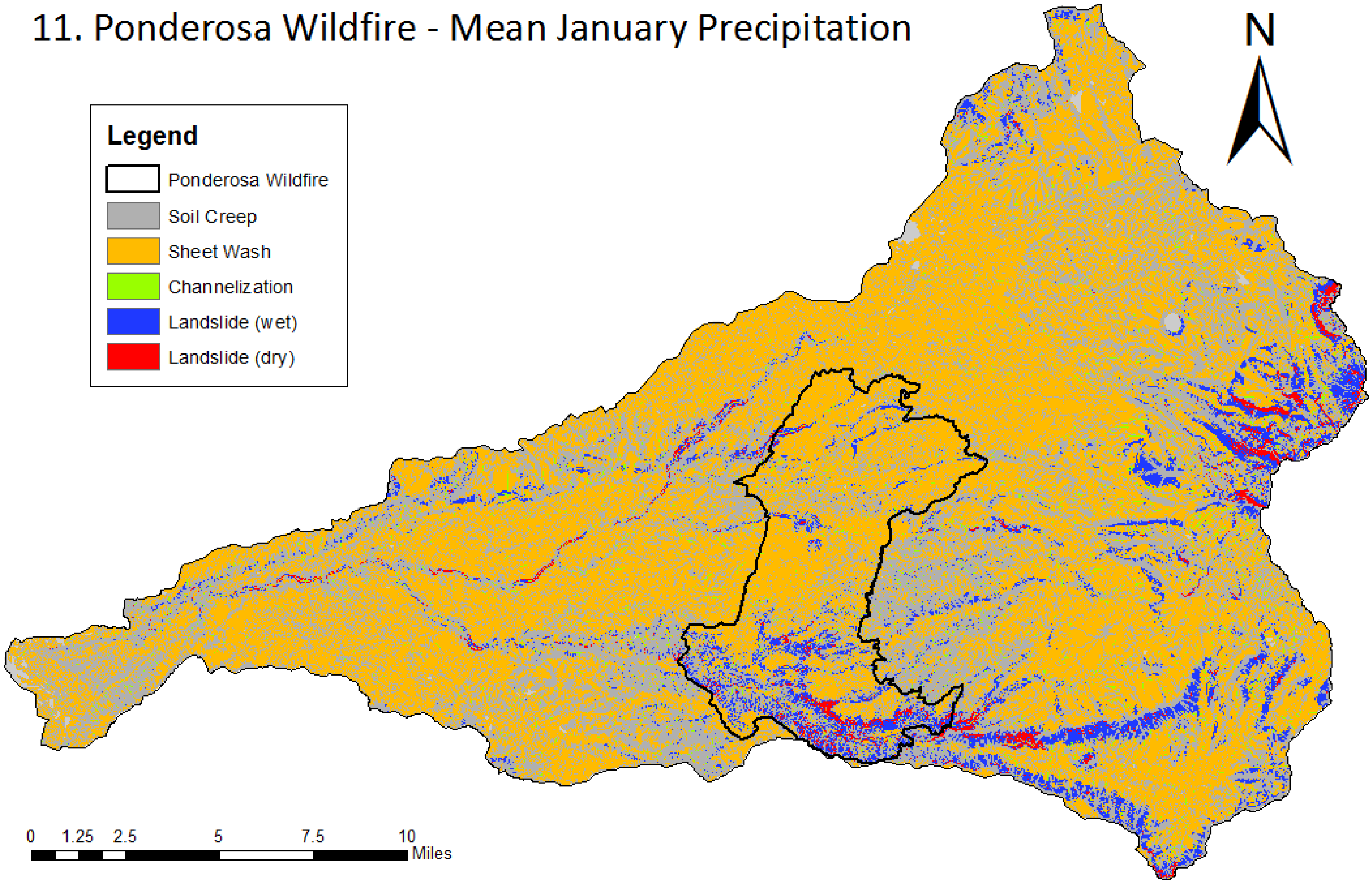


Figure 90: Landscape process domain model accounting for 2012 Ponderosa wildfire

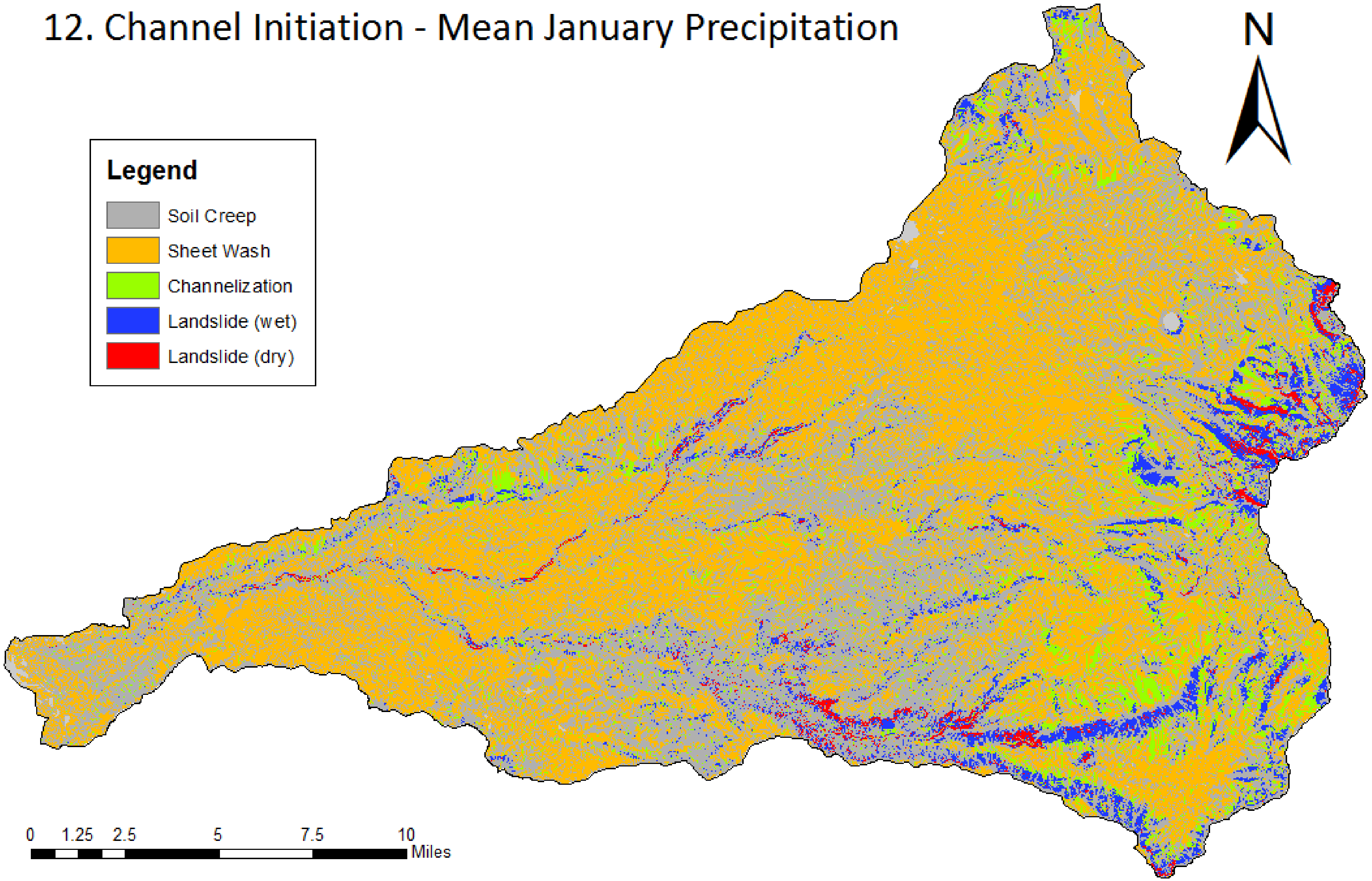


Figure 91: Landscape process domain model accounting for channelization with a boundary shear stress of 8 N/m^2

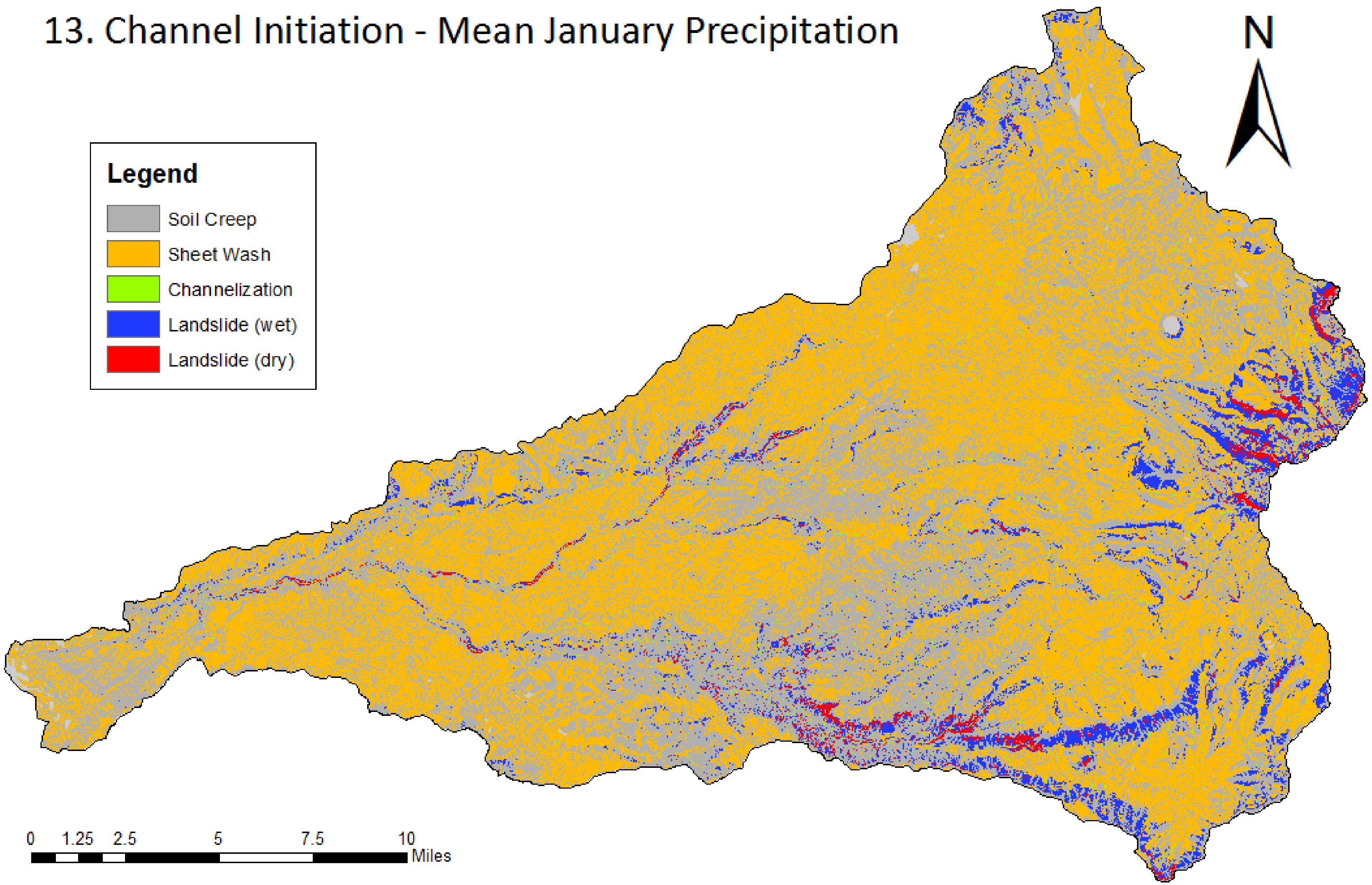


Figure 92: Landscape process domain model accounting for channelization with a boundary shear stress of 32 N/m^2

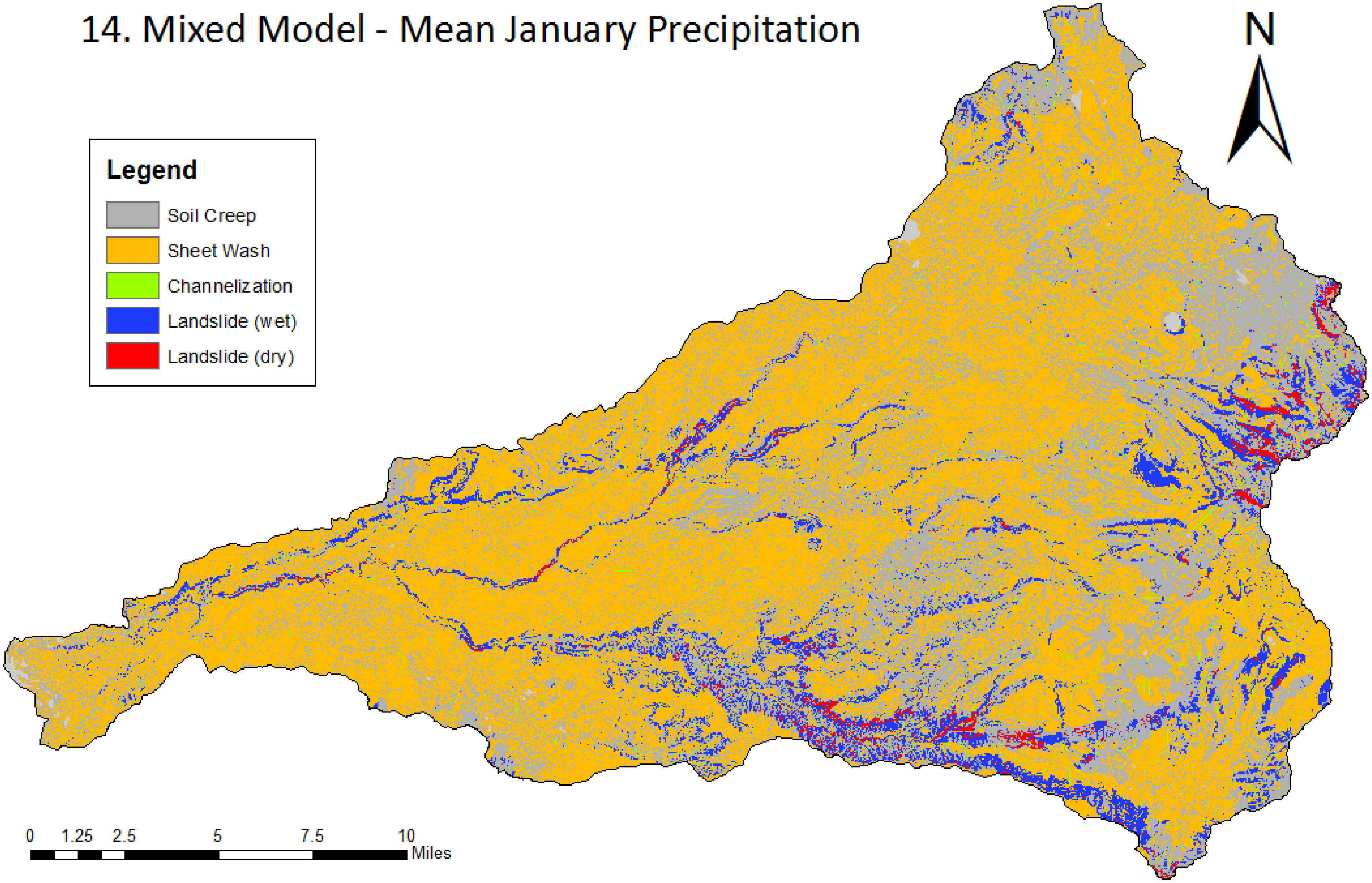


Figure 93: Landscape process domain model synthesizing all individual model runs

8 SUPPLEMENTAL TASKS

The Battle Creek watershed assessment includes tasks supporting the aforementioned activities. Field work, lab work, site visits, and meetings were all necessary components of administering and successfully executing the project. Additionally responsibilities and tasks are identified and outlined below.

8.1 Field Work

Jameson Henkle documented field activities recording specific tasks completed upon returning from each site visit. Ten field campaigns to the Battle Creek Watershed were executed independently from May 2014 – May 2015. Field trips involved the reconnaissance, construction, maintenance, and deconstruction of field monitoring sites. Other related activities include watershed exploration and photography, including time-lapse photography, and field-meetings.

May 20, 2014

The Battle Creek Working Group led today's field trip and was attended by ~15 individuals from various organizations including Fish and Wildlife, Regional Water Quality, SPI, PG&E, and Battle Creek Conservancy. The morning toured 3 locations on Canyon Creek, a tributary to North Fork Battle Creek, in the Ponderosa Fire burn zone. These stops highlighted the effects of poor road construction and how gullies, culverts, and crossings are impacting sediment delivery. These areas showed significant production from hillslopes displaying deep gullying of pre-fire swales. A tremendous amount of loose, unconsolidated fine sediment is available.

County roads appear to be unregulated. They are not up to best management practices as are upgrades to private timberland roads for the THP process and could be localized heavy contributors of sediment.

Widespread application of herbicide on the landscape to kill off understory growth to allow for replanting of timber is observable in land boundaries. The lack of understory vegetation will increase potential for sheet flow erosion.

Steve Tussing delivered a preliminary report on his repeat surveys on physical stream metrics from 2001, 2012, 2013 and found increasing fine sediment below burn areas.

After lunch we visited a fish dam that was built in 2013 on a tributary to Mainstem Battle Creek. At first glance it doesn't seem like a fish dam is correct in a watershed deemed the most likely to restore salmonid habitat, but this looks to be a political agency project.

Steve Tussing from Battle Creek Conservancy, Shane Edmunds from Regional Water Quality, and Tricia Hamelberg from FWS were very enthusiastic about us and will be good contacts to collaborate with.

DWR have recently installed gages on both North Fork and South Fork. Weather stations are distributed throughout the watershed capturing elevation bands.

Nov 9, 2014 - Nov 11, 2014

Greg Pasternack and Jameson Henkle investigated potential sites for hydrological monitoring in Battle Creek. Steve Tussing, the coordinator for the Battle Creek Watershed Conservancy connected Jameson with private landowners in Battle Creek. Geoff Watson who owns land on Digger Creek, a tributary of North Fork Battle Creek granted permission to access and build a station on his property. Ron Reid is the landowner for South Fork Battle Creek and also granted permission to install a site co-located with the Department of Water Resources (DWR) streamgage. Scott Hamelberg is the project leader at the Coleman National Fish Hatchery. A meeting occurred with Scott and permission was granted to build a site on CNF property on Mainstem Battle Creek. Reconnaissance on North Fork Battle at the location of a DWR gage occurred but landowner permission has yet to be granted.

We met with UC Davis Cooperative extension members in Red Bluff, Ca.

A monitoring site on Digger Creek was built including a pressure transducer for measuring water surface elevation and digital turbidity sensor. Both sensors are connected to a datalogger contained in a waterproof locked box adjacent to the stream. The build was completed on Nov. 11 and left fully operational. A digital turbidity sensor was installed on South Fork Battle Creek on Nov 11 and connected to a datalogger contained in a locked box on the left bank adjacent to the DWR control box. Two of four identified monitoring locations were successfully installed and operational. Digital cameras collecting time-lapse photography were also installed at both sites.

Nov 20th 2014

Jameson Henkle attended the Battle Creek Working Group meeting at the Fish and Wildlife Office in Red Bluff, CA. He delivered a short introduction and briefly described the watershed assessment he is conducting in Battle Creek. Continued networking efforts occurred during and after the meeting.

A field trip to Digger Creek and South Fork Battle Creek to download data and verify functionality of monitoring sites was completed post-meeting. Jameson met with Guy Chetelat and Whitney Brown from the Central Valley Water Quality Control Board and demonstrated field grab sample techniques. Guy and Whitney are collaborators that will aid in water sample collection.

Dec 10, 2014 – Dec 15, 2014

A large storm event battered Battle Creek on December 5th and caused the digital turbidity sensor at South Fork Battle Creek to disconnect from the datalogger as indicated by collaborators from Central Valley Water Quality. In preparation for a large hydrometeorological event predicted by the climate models, Jameson traveled to Battle Creek to troubleshoot any problems with monitoring equipment and sample the event. He retrieved field equipment to bring back and test in the office. The camera at South Fork Battle Creek was inundated from the previous storm and was also retrieved. Digger Creek was found operational for all equipment. Data and photos were downloaded.

The storm event began on Wednesday, Dec 10 and heavy rainfall ensued for two days. Jameson collected a total of 88 grab samples from the four identified monitoring sites of Mainstem Battle Creek, North Fork Battle Creek, South Fork Battle Creek, and Digger Creek. He successfully captured samples on both the rising and falling limbs of the hydrograph over the duration of the storm. Samples will be processed for turbidity, concentrations, and grain-size in the laboratory.

Jan 7, 2015

Jameson Henkle and Greg Pasternack traveled to the office of Sierra Pacific Industries (SPI) in Anderson, Ca. SPI is a private landowner in Battle Creek involved in timber harvest operations. Steve Tussing coordinated the meeting and was also present. Jameson delivered a presentation on current projects in Battle Creek and ideas for future work. Dr. Cajun James is the principal researcher for natural resources at SPI and discussed some of her current experiments and monitoring efforts in the basin. Discussion about current work and potential collaboration was the objective of this meeting.

Jameson and Greg attended another meeting with Guy Chetelat, Ben Letton, and Shane Edmunds at the Central Valley Water Quality Control Board office in Redding, Ca coordinated by Jameson. They discussed the current status for the Battle Creek watershed assessment.

January 17-21, 2014

Jameson installed turbidity sensors at South Fork Battle Creek and North Fork Battle Creek on January 17-18. Singe stage sediment sample bottles were also installed at South Fork Battle Creek to assess the feasibility of implementing a more rigorous in situ sampling program for capturing rising limb water-sediment samples.

Jameson explored the upper watershed of South Fork Battle Creek on January 20 from the alluvial valley where Mineral, Ca is located down through the incised portion of South Battle Creek and into the wildfire burn zone. He hiked a portion of South Battle Creek to a large waterfall named Angel Falls. Near Manton, Ca he explored Ponderosa Way and collected water and sediment samples near Bluff Springs.

Jameson met with Shane Edmunds and Griffin Perea of the Central Valley Regional Water Quality Control Board in Manton, Ca on Tuesday January 21 and showed them the Digger

Creek, South Fork and North Fork Battle Creek monitoring sites. He gave a demonstration of field grab sample techniques and is coordinating efforts to monitor turbidity and collect samples. Jameson then attended the Battle Creek Working Group meeting located at the Department of Fish and Wildlife office in Red Bluff, Ca

Jan 31 – Feb 1, 2015

Jameson deconstructed the South Fork Battle Creek Monitoring Site. The installation was co-located with a District of Water Resources (DWR) streamgage. Jameson used existing infrastructure to secure a digital turbidity sensor to a pressure treated 2x6 board of lumber. DWR indicated that the monitoring equipment was jeopardizing their abilities to accurately record water surface elevations and the turbidity sensor must be moved. The site was deconstructed and all materials brought back to UC Davis.

The North Fork Battle Creek is also co-located with a DWR operated streamgage. The sensor at this site was attached to a tree near the streamgage. The serial cable for the digital turbidity sensor had previously been strung through metal conduit that was then secured to DWR conduit via hose clamps. This was also unacceptable as indicated by DWR and needed to be removed. Jameson kept the sensor in the same location, but removed all points of contact between UC Davis and DWR monitoring equipment. The site was rebuilt and operating at time of departure. A time-lapse photograph was installed at NFBC facing downstream towards the turbidity sensor.

February 4, 2015

Jameson Henkle and Dr. Andrew Gray traveled to South Fork Battle Creek to reinstall the digital turbidity sensor. Jameson was granted permission from Tehama County Flood Control Department to drill into the concrete wall adjacent to the bridge and install a pressure treated 2x6 board. A digital turbidity sensor and multiple single stage sediment samplers were attached to the lumber. The serial connection cable runs up the length of the concrete wall and connects to a datalogger contained in a locked box secured to a 2 in metal conduit that is cemented into the ground. The site was online on operating at time of departure.

March 31, 2015

Jameson traveled to the Battle Creek watershed for a one day field campaign. He met with Shane Edmunds from SCWRB to exchange water-sediment samples collected by waterboard staff at the Redding office. He visited all four monitoring sites (MSBC, NFBC, SFBC, DCK) for maintenance and sampling.

Mainstem Battle Creek was sampled at the diversion dam upstream from Coleman National Fish Hatchery. Many photographs were collected and a potential location for a turbidity sensor to be installed for water year 2016 was identified.

Upon arrival, north Fork Battle Creek had a dead 12 volt battery. The Campbell Scientific CR510 datalogger internal battery was also dead. All turbidity data was lost from the site. He replaced the battery and cleaned the OBS-3 turbidity sensor. Photographs from the time-lapse camera were downloaded and batteries replaced. The camera was moved to face upstream and attached to a tree mount for a better view of the channel. The OBS-3 sensor was cleaned and remains above the water surface level at base flow. He collected a grab sample at base flow.

South fork Battle Creek also had a dead 12 volt battery upon arrival. The CR510 unit at this site was upgraded for memory and internal battery before deployment and turbidity data was stored until the time of zero power. The data were downloaded and battery replaced. The single stage sediment samplers collected samples at a water surface elevation of 7 ft and 8 ft corresponding to DWR streamgage heights. Samples were transferred to Nalgene bottles and the sediment samplers replaced. These samples correspond to a storm in February and will be evaluated for accuracy in relation to the sediment rating curve for SFBC. The OBS-3 sensor was cleaned and remains above the water surface level at base flow. He collected a grab sample at base flow.

At Digger Creek, the sensor was covered with biofouling and turbidity readings were very high at ~600 NTU. These erroneous readings date back to mid-February. The current installation is in need of rebuilding with a new sensor orientation and shield located upstream to guard from leafy debris getting trapped. The debris was removed and sensor cleaned. Data were downloaded from the CR510 datalogger. The sensor was clean and remains submerged, although data are not representative of conditions. He collected a grab sample at base flow.

May 13, 2015

Jameson Henkle traveled to Battle Creek to deconstruct monitoring sites for water year 2015. He removed all turbidity monitoring equipment and retrieved the single time-lapse camera remaining at NFBC. He collected the final water-sediment samples of the season and photographed sites at low-flow. Jameson met with Steve Tussing from the BCWC to discuss potential collaborative efforts in the future. He also met with SWRCB staff Ben Letton and Griffin Perea to retrieve water-sediment samples collected by SWRCB and give an update on current progress. Jameson explored the upper NFBC watershed and photodocumented areas of interest such as McCumber Reservoir.

8.2 Lab Work

Jameson processed water-sediment samples collected in the field in the sediment analysis laboratory at UC Davis. Samples were stored in a refrigeration unit until time of processing to inhibit algal and microbial growth that may bias sediment concentrations. Protocols and datasheets were developed for all analyses including turbidity, SSC, and POM. Hard copies of protocols were printed and located in the laboratory notebook with datasheets to record all results. Results were then entered into Excel for further analyses.

All samples were processed for turbidity using a HACH 2100p turbidimeter. The turbidimeter was calibrated according to the user's manual at the beginning of the water year. The instrument was checked for accuracy using turbidity standards on subsequent lab processing.

All lab samples were processed for suspended sediment concentrations. Samples with turbidity values greater than 20 NTU were separated into fine- and coarse-grain sediment fraction using a 65-µm sieve before filtering through a 0.15-µm glass-fiber filter according to ASTM international standards. Glass-fiber filters were numbered before pre-washing and baking at 105° C for 2 hours. Pre-washed and labeled filters were placed in petri dishes and stored in a desiccant chamber until weighing on an analytical balance at the 0.00001 scale. The prepared filters were stored in a desiccant box until time of processing.

The coarse-fraction of sediment was sieved from the sample while pouring into a graduated cylinder. The volume of water was measured in a 1000 mL graduated cyclinder with 10 mL accuracy. Coarse-sediment was than rinsed with deionized water from the sieve into an aluminum boat and placed in the oven at 105® C until all visible liquid had disappeared. Samples remained in the oven for 2 hours thereafter. The remaining water-fine-sediment mixture was poured through the pre-washed and labeled glass-fiber filter attached to a vacuum pump. Processed filters were placed on a baking sheet and baked in the oven for 2 hours at 105® C. Filters and petri dishes were desiccated before weighed on the mass balance. All data were recorded by hand on datasheets in the sediment analysis binder.

Water-sediment samples with turbidity values greater than 20 NTU were evaluated for percent organic matter (POM). Petri dishes for coarse-fraction and glass-fiber filters for fine-fraction were fired in a muffle furnace after the final weighing for suspended sediment concentration. Samples were fired for 1 hour at 550®C then reweighed using the mass balance once cool. The mass difference between pre-fire and post-fire samples was computed as a percentage to evaluate the percentage of suspended sediment concentration constituting organics.

Deionized water was used to rinse filters, graduated cylinders, petri dishes, beakers, and any other equipment contacting the water-sediment mixture. Care was taken to clean all necessary apparatus between samples to minimize laboratory processing bias. Laboratory methods were developed a priori of processing and are summarized in a flow model in Figure 94.

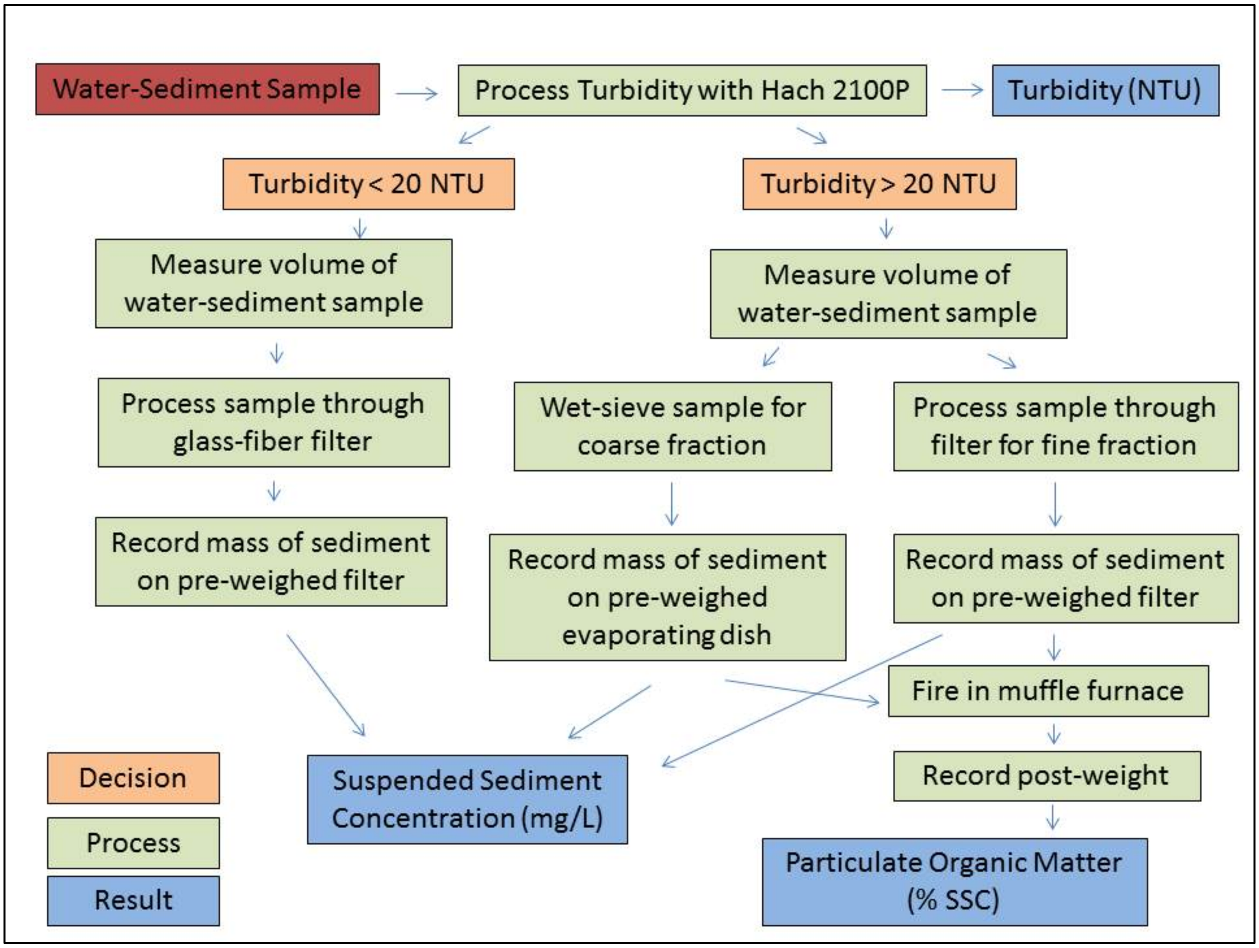


Figure 94: Laboratory flow model for processing water-sediment samples

8.3 Imagery

Site visits were photo-documented covering the range of conditions and flows present at each time of visit. Digital photographs at each of the four monitoring sites include equipment, location of sample collection, and views upstream and downstream from sampling site. Photographs were captured looking upstream and downstream from the bridges on NFBC and SFBC. Additional photographs from features of interest in the Greater Battle Creek watershed were collected to highlight potentially important factors contributing to sediment.

Time-lapse photographs were collected in the field using a Bushnell Trophy Cam Trail Camera. Two cameras were installed in the field on November 10th, 2014. Cameras were set to capture photographs continuously at 15-minute intervals. A camera on SFBC was installed upstream of the bridge on Manton Road attached to a tree on the right bank and targeted at a large cut bank. The December 5th, 2014 flood event submerged the camera at SFBC rendering it inoperable. The camera was retrieved and data salvaged. Photos were processed into a short movie and it presents a graphical description about the rate of increase for water surface elevation on the rising limb of the hydrograph. A camera at DCK was installed on a tree on the left bank facing upstream from the location of the turbidity sensor. Both the December 5th and December 11th events were captured and data was successfully processed into short time-lapse movies.

The camera on DCK was unintentionally installed on private land without permission. The left bank of Digger Creek is not owned by Geoff Watson. The residents discovered the time-lapse camera on their property and aggressively asked for its removal. No suitable location on the right bank was found. The camera was relocated to NFBC at the sampling location looking downstream on January 19th, 2014. The camera was moved to face upstream on March 31st 2015 after downloading all photographs and assessing the picture quality at this angle.

Photos were downloaded at time of each site visit and batteries replace to ensure the operability of time –lapse photography. Short videos were captured from a hand-held digital camera during the December 11th, 2014 storm event. They display high flows at all four monitoring sites. All time-lapse and still photographs, and videos are organized by date of collection and are delivered in supplementary DVDs.

8.4 Meetings

A kickoff meeting between the State Water Resources Control Board (SWRCB) and UC Davis was held at the university campus on September 15, 2014. The goals and expectations of the project were discussed between UCD and SWRCB. Steve Tussing of the BCWC was present and discussed the Conservancies current project and work in the basin.

The Battle Creek Working Group is a multi-stakeholder collaborative effort working towards a sustainable restoration project in Battle Creek that formed in 1998. They hold bimonthly meetings to discuss topics and events occurring in Battle Creek. Jameson attended the BCWG field trip on May 20th, 2014 for his first visit to the watershed. He attended BCWG meetings at the FWS office in Red Bluff, Ca on November 20, 2014 and January 21, 2015.

Jameson Henkle and Greg Pasternack met with Dr. Cajun James from Sierra Pacific Industries (SPI) on January 7th, 2015 to discuss UC Davis research objectives. Upper management from SPI and Steve Tussing from the BCWC were also present. Another meeting directly after with SWRCB at the Redding, Ca office occurred to update the water board on the status of the watershed assessment.

Jameson met with SWRCB staff in the field to demonstrate grab sampling techniques at sediment monitoring sites in Battle Creek. He met with Guy Chetelet and Whitney Brown on November 20th, 2014 and with Shane Edmunds and Griffin Perea on January 21st, 2015. Jameson met with Shane Edmunds briefly on March 31st, 2015 to collect and exchange water-sediment samples. Jameson and Ben Letton met on May 12, 2015 to exchange water-sediment samples and discuss the current status of the watershed assessment.

A meeting was held on April 9th, 2015 in Sacramento, Ca at the Board of Forestry attended by UC Davis, SWRCB, Sierra Pacific Industries, CALFIRE, California Department of Fish and Wildlife, and the Battle Creek Watershed Conservancy. Dr. Cajun James from SPI discussed her research and monitoring efforts in Battle Creek. Jameson delivered a presentation on the status of the Battle Creek Watershed Assessment with an interactive round table discussion. Steve Tussing discussed the role and priorities for the BCWC.

On May 13th, 2015 Jameson met with Steve Tussing from the BCWC to discuss his current and future monitoring efforts in relation to the watershed assessment and his PhD dissertation. Steve discussed his expected Environmental Protection Agency proposal and the potential for aligning the two projects to implement a long-term sediment monitoring project analyzing suspended sediment in the basin. Jameson then met with SWRCB staff Ben Letton and Griffin Perea and updated them about current progress on the watershed assessment. Griffin reported on the SWRCB in-house monitoring program and details about morphologic changes on SFBC.

8.5 Safety Plan

Jameson developed a safety protocol prior to field work in Battle Creek (Section 12.2). The safety protocol has local emergency contact information and instructions on how to respond to various emergencies. A paper copy was printed and present in the field on every site visit. Safety information was shared with field assistants prior to each field campaign and actions to be taken in the event of an accident. Safety in the field is of utmost importance and was emphasized with partners before, during, and after field outings.

9 SEDIMENT IMPACTS

9.1 US EPA Assessment Approaches

As explained in Section 2.6.1, the US EPA considered five potential approaches for the development of water quality criteria in terms of suspended load and bedload sediments. Therefore, the first step in evaluating sediment impacts in Battle Creek is to evaluate whether it is possible to apply any or all of these approaches at this time to render conclusions about the status of Battle Creek:

There is no data available to enable a toxicological dose-response approach specifically for Battle Creek using data from Battle Creek.

There is no data available to enable a conditional probability approach specifically for Battle Creek using data from Battle Creek.

There has been no WARSSS study implemented in Battle Creek, though some available data might be of use for such an analysis were it to be performed.

There are few water body uses in Battle Creek, but there is a potential for harm to the beneficial use taking place at the Coleman Fish Hatchery. The hatchery uses Battle Creek water to rear spring-run Chinook salmon. Hatchery staff report that in recent years since the wildfire there has been extremely elevated levels of very fine sediment clogging their filtration system, with some of the finest sizes making it through. It would be feasible to conduct a sediment impact analysis for the hatchery, but at this time that has not been done and there are insufficient data in hand to enable such an analysis.

There are some data available for the reference condition biocriteria approach. As reported in Section 3.6.1, previous studies have highlighted different findings out of the available results. Ward and Moberg (2004) found that no sampled sites were in poor condition, though certain sites were identified as having poor condition in specific metrics. Tussing and Ward (2008) reported an increase in favorable biological conditions from 2001-2002 to 2006. KA (2009) interpreted the lack of positive scores reported in the lower Mainstem and South Fork Battle Creek for almost any macroinvertebrate index to be consistent with the pattern of upland disturbance and cumulative watershed effects. These results suggest nuanced conditions open to interpretation as opposed to a clear signal of poor conditions, as has been found in many streams in California where agriculture and urbanization have heavily degraded water quality. However, it is very important to note that these studies were all done before the 2012 Ponderosa Fire, and thus they do not convey what has happened as a result of the fire. Therefore, it would be highly sensible to undertake more studies to continue this assessment approach. Also, for future analyses, reference conditions might be available drawing on the large SWAMP database, which could enable the scoring of Battle Creek benthic macroinvertebrate results relative to results from comparable streams throughout California.

Overall, there is far too little data available to use the US EPA approaches for assessing sediment impacts. What little data is available is inconclusive.

9.2 Sediment Budgeting Assessment Approach

As reported in Section 2.6.2, several studies have approached the question of sediment impact assessment by conducting sediment budgets. Sediment budgets may be used to identify primary sources of sediment and then figure out which best management practices are most beneficial and cost effective. The UC Davis and US EPA Colusa Basin Study was an excellent example of a sediment budget implemented for a large watershed in California in the vicinity of Battle Creek, but in that case it was done only once in the late 1970s and there has been no long term monitoring or follow up since.

The scientific situation for Battle Creek is far worse than that for Colusa Basin in that no sediment budget study has even been done. Without a sediment budget framework, the various individual studies of sediment that have been done cannot be placed into a process-based context. Further, the data quantity is too poor to enable comparison with data from other Central Valley Rivers. Whereas California maintains the GrandTab database centralizing the escapement estimates of the late-fall, winter, spring, and fall-run Chinook salmon in the California Central Valley, there is no equivalent centralized database for sediment data in the Central Valley. Systematically insufficient monitoring of sediment precludes comparative evaluation. Therefore, it is not possible to perform a sediment impact assessment on the basis of sediment budgeting for Battle Creek either in terms of figuring out its internal relative sediment sources or by comparing high-quality observations between major watersheds of comparable size and condition.

9.3 Methodological Findings

The methods heretofore described provide as detailed analyses as possible given the available data for characterizing streamflow and sediment at the watershed scale in Battle Creek. The following methods were applied to observe hydrologic and sediment processes and were found to be effective at understanding essential aspects of suspended sediment at the watershed scale:

- Historical data for streamflow in Battle Creek used to characterize the hydrologic regime at the watershed and subwatershed scale for MSBC (n=72), NFBC (n= 15), and SFBC (n=15), where n = number of years monitored.
- Historical climate data exist over a range of scales which were used to characterize the precipitation regime from source to sink.
- Sediment is highly correlated with discharge and sediment rating curves provide a feasible method for characterizing suspended sediment transport. Historical sediment sampling was too limited to distinguish fine versus coarse sediment dynamics.
- Turbidity is highly correlated with SSC..
- Turbidity records the magnitude and duration for floods and can be used in the evaluation of fluvial sediment effects on water quality.
- Collecting samples over a range of flows is critical for the production of robust rating curves.
- Time-lapse photography provided powerful visual documentation for the erosive forces of flood events.
- Landscape process models produced and analyzed in a GIS provided powerful spatially explicit hypotheses and interpretations about surface erosion susceptibility. This enabled targeting of key areas in the watershed for further analysis.

- Landscape process modeling found that surface erosion is highly influenced by soil characteristics as well as by wildfire.

9.4 Suspended Sediment Flux Findings

SFBC is the main contributor of suspended sediment to the main channel delivering 88% of the total volume delivered from both SFBC and NFBC. No historical sediment data exists for NFBC and SFBC to make comparisons as for MSBC. The South Fork Battle Creek ridge was subject to the 2012 wildfire and has experienced significant gullying on the north wall. Ponderosa way has been documented as contributing fine sediment from road-stream crossing failures. An aerial flyover recorded the extent of surface erosion in 2014 and the videos are in supplemental material.

Although SSC was similar in 2015 as in historical records, the watershed sediment flux at MSBC for WY 2015 was observed to have increased significantly over historical data for similar flow regimes. The increase in suspended sediment could be attributable to the two main disturbances discussed previous of land use and wildfire, but insufficient historical and on-going monitoring has been done to say for certain. SFBC is most susceptible to high intensity rainfall and erodible area given its steep low elevation and fire history.

Although turbidity data were sparse for WY 2015, the December 3rd storm event was captured at DCK. Turbidity spiked to over the 2000 NTUs threshold of the turbidity sensor and remained outside the range of measurement for 40 minutes. Elevated turbidity levels remained above 200 NTUs for approximately 12 hours. Persistent high turbidity levels can diminish and affect feeding behaviors for aquatic organisms, as well as cause physical harm to fish species. Fine sediment can clog fish's gills and lower an organism's resistance to disease and parasites. Some fish may eat sediments, causing exposure to contaminants attached to particles in suspension (EPA, 2012).

9.5 Data Uncertainties

Data collected during WY 2015 were representative of suspended sediment transport at the watershed scale. Suspended sediment monitoring at a gaging station collects the integrated signal of all sediment sources located upstream, which is a superior approach to monitoring sediment flux and water quality impacts compared to assessing net sediment storage in pool tail outs during summer. Careful design of the gaging network can help constrain the reaches where sediment is deposited, but specific locations of fine sediment deposition cannot be deduced from the gage data alone. The sources of sediment are modeled with the GIS landscape process domain analysis and provide maps to target further data collection for specifying individual sediment sources. Monitoring did not include bedload transport and thus underestimate the actual amount of total load being transported through Battle Creek.

10 FUTURE DIRECTIONS

The preceding analyses establish as much of a baseline condition for suspended sediment transport as is possible based on available data at this time by computing annual load estimates at existing streamgage sites for MSBC, NFBC, and SFBC. An additional site at DCK was also monitored, but a lack of discharge data for this site prevents the computation of annual sediment load for this subcatchment. Continued monitoring of suspended sediment by grab sampling methodology is recommended to compare interannual variability and the effects of individual storms. Methods similar to those applied here should continue to observe trends in sediment processes by evaluating SSC, turbidity, and organics.

A comprehensive monitoring plan would include a multiscalar approach to suspended sediment monitoring at gages targeting both NFBC and SFBC above, within, and below the perimeter of the Ponderosa wildfire. GIS analysis indicated that South Fork Battle Ridge is highly susceptible to surface erosion, and in WY 2015 SFBC transported 88% of the total combined sediment load of NFBC and SFBC.

The SFBC streamgage is located just above the confluence with mainstem and collects an integrated signal of all the upstream inputs. To target the magnitude and distribution of sediment being delivered to SFBC, four additional sites are recommended at the wildfire downstream perimeter, wildfire upstream perimeter, the topographic transition from Mineral valley to Battle Ridge, and a headwater stream relatively unaffected by land use. Monitoring at SFBC would include two additional sites at the wildfire perimeter upstream and downstream. Sites would be monitored for suspended sediment through grab sample collection and equipped with pressure transducers to record continuous stage data. Site would also be measured for discharge to establish a discharge-rating curve that would allow a continuous discharge record to be applied to SSC to compute sediment flux estimates at multiple locations on each branch.

It is recommended that permanent turbidity monitoring stations be installed at MSBC, NFBC, and SFBC. These sites are key for understanding the total sediment flux in Battle Creek and relative rolls of the north fork and south fork subbasins. Turbidity stations would provide detailed data on sediment transport during storm events and could be used to quantify the effects of surface runoff and streamflow on sediment transport over a range of flows.

The spatial distribution of precipitation patterns produces unique responses in streamflow and sediment transport for SFBC and NFBC although they are adjacent. A further study connecting the link between the magnitude and duration of precipitation at current precipitation gages and the response in sediment transport at proposed monitoring stations would help to characterize how weather patterns are affecting fluvial processes in Battle Creek.

A computational model as recommended by Myers (2012) to develop a sediment budget in Battle Creek would help identify sources of fine sediment relative to the hypotheses generated by the landscape process modeling performed in this study. Taken together, the conceptual model presented by Myers, the landscape processes geospatial model from this study, and a complete sediment budget for the basin would aid in water resource and habitat management.

11 REFERENCES

Acornley RM, Sear DA. 1999. Sediment transport and siltation of brown trout (Salmo trutta L.) spawning gravels in chalk streams. Hydrological Processes 13: 447-458.

Alabaster JS. 1972. Suspended Solids and Fisheries. 395–406 pp.

Alabaster JS, Lloyd R. 1982. Water criteria for freshwater fish. 2nd Edition. Butterworth Scientific, London, UK. 361 pp.

(APHA) American Public Health Association. 1992. Standard methods for the examination of water and wastewater. 18th ed. Washington, DC.

Anderson CW. 2005. Turbidity (ver. 2.1): U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chap. A6., sec. 6.6, Sept. 2005, accessed [4/21/2015], from http://pubs.water.usgs.gov/twri9A6/.

Arcement GJ, Schneider VR. 1989. Guide for Selecting Manning’s Roughness Coefficients for Natural Channels and Flood Plains. US Geological Survey Water-Supply Paper 2339. 44 pp.

Armentrout S, Brown H, Chappell S, Everett-Brown M, Fites J, Forbers J, McFarland M, Riley J, Roby K, Villalovos A. 1998. Watershed Analysis for Mill, Deer, and Antelope Creeks."US Department of Agriculture. Lassen National Forest. Almanor Ranger District. Chester, CA 6.

Asselman NEM, Middelkoop H. 1995. Floodplain sedimentation: quantities, patterns and processes. Ear. Surf. Proc. and Landforms 23(6): 561-573.

Asselman NEM. 2000. Fitting and interpretation of sediment rating curves. Journal of Hydrology 234: 228-248.

ASTM International. 2002. Standard Test Methods for Determining Sediment Concentration in Water Samples.

Barbour MT, Gerritsen J, Snyder BD, Stribling JB. 1999. Rapid bioassessment protocols for use in streams and wadeable rivers: Periphyton, benthic macroinvertebrates and fish. 2nd Edition. EPA 841-B-99-002. U.S. Environmental Protection Agency; Office of Water; Washington, D.C. 337 pp.

Bash JB, Berman C, Bolton S. 2001. Effects of turbidity and suspended solids on Salmonids. Final Research Report on Research Project T1803 to the Washington State Transportation Center. 92 pp.

Beschta RL, Jackson WL. 1979. The intrusion of fine sediments into a stable gravel bed. Oregon State University, Forest Research Laboratory, Paper 1264. 7 pp.

Bilotta GS, Brazier RE. 2008. Understanding the influences of suspended solids on water quality and aquatic biota. Water Research 42: 2849-2861.

Birtwell IK. 1999. The effects of sediment on fish and their habitat. Fisheries and Oceans Canada. West Vancouver Laboratory, BC. 34 pp.

Black M. 2001. Shasta salmon salvage efforts: Coleman National Fish Hatchery on Battle Creek, 1895–1992. Fish Bulletin 179 1: 177-268.

Blatt H. 1967. Provenance determinations and recycling of sediments. Journal of Sedimentary Petrology 37(4): 1031-1044.

Blum MD, Tornqvist TE. 2000. Fluvial responses to climate and sea-level change: a review and look forward. Sedimentology 47(Suppl. 1): 2-48.

Boening DW. 2000. Ecology effects, transport, and fate of mercury: a general review. Chemosphere 40: 1335-1351.

Boggs S. 1968. Experimental study of rock fragments. Journal of Sedimentary Petrology 38: 1326–1339.

Booth AM, Roering JJ. 2011. A 1-D mechanistic model for the evolution of earthflow-prone hillslopes. Journal of Geophysical Research 116: F04021.

Börk KS, Krovoza JF, Katz JV, and Moyle PB. 2012. The rebirth of California Fish & Game Code 5937: water for fish. University of California, Davis Law Review 45: 809-913.

Boubée J, Dean TL, West DW, Barrier RFG. 1997. Avoidance of suspended sediment by the juvenile migratory stage of six New Zealand freshwater fish species. New Zealand Journal of Marine and Freshwater Research 31(1): 61-69.

Boulton AJ. 2007. Hyporheic rehabilitation in rivers: restoring vertical connectivity. Freshwater Biology 52: 632-650.

Bowes MJ, House WA. 2001. Phosphorus and dissolved silicon dynamics in the River Swale catchment, UK: a mass-balance approach. Hydrological Processes 15: 261-280.

Bowes MJ, Leach DV, House WA. 2005. Seasonal nutrient dynamics in a chalk stream: the River Frome, Dorset, UK. Science of the Total Environment 336: 225-241.

Bronmark AL. 2005. The biology of lakes and ponds. Oxford University Press, Oxford.

Brown AL. 1987. Freshwater ecology. Heinmann Educational Books, London.

Brown R. and W. Kimmerer. 2004. A Summary of the October 2003 Battle Creek Workshop.

Brown RA, Pasternack GB. 2014. Hydrologic and topographic variability modulate channel change in mountain rivers. Journal of Hydrology 510: 551-564.

Brunsden D, Thornes JB. 1979. Landscape sensitivity and change. Transactions of the British Geographers, New Series 4: 462-484.

Bryan GW, Langston WJ. 1992. Bioavailability, accumulation and effects of heavy metals in sediments with special reference to United Kingdom estuaries: a review. Environmental Pollution 76: 89-131.

Buffington JM, Montgomery DR. 1999. A procedure for classifying and mapping textural facies in gravel-bed rivers. Water Resources Research 35(6): 1903-1914.

Bull WB. 1991. Geomorphic responses to climatic change. The Blackburn Press.

Buol SW, Southard RJ, Graham RC, McDaniel PA. 2011. Soil genesis and classification, 6th edition. Wiley-Blackwell, New York.

Cagle F. 1998. Geomedicine in the Salton Basin: Geology and geothermal resources of the Imperial and Mexicali Valleys. San Diego Association of Geologists, San Diego, L. Lowell, Editors. 169-187 pp.

Carley JK, Pasternack GB, Wyrick JR, Barker JR, Bratovich PM, Massa DA, Reedy GD, Johnson TR. 2012. Significant decadal channel change 58-67 years post-dam accounting for uncertainty in topographic change detection between contour maps and point cloud models. Geomorphology, doi:10.1016/j.geomorph.2012.08.001.

Carlyle-Moses D and JC Gash. 2011. Rainfall interception loss by forest canopies. Forest Hydrology and Biogeochemistry. DF Levia, D Carlyle-Moses and T Tanaka, Springer Netherlands. 216: 407-423.

Caux PY, Moore DRJ, MacDonald D. 1997. Ambient water quality guidelines (criteria) for turbidity, suspended and benthic sediments. Technical Appendix. Prepared for BC Ministry of Environment, Land and Parks. 146 pp.

(CDFG) California Department of Fish and Game. 1993. Restoring Central Valley streams: A plan for action.

(CDWR) California Department of Water Resources. 2014. California’s most significant droughts: Comparing historical and recent conditions. 136 pp.

Chapman DW. 1989. Critical review of variables used to define effects of fines in Redds of large salmonids. Transactions of the American Fisheries Society 117(1): 1-21.

Constantine JA, Pasternack GB, and Johnson MB. 2005. Logging effects on sediment flux observed in a pollen-based record of overbank deposition. Earth Surface Processes and Landforms 30: 813-821.

Cook-Tabor C. 1995. Effects of suspended sediments on Salmonids. USFW Western Washington Fishery Resource Office. 11 pp.

Coombs JS and JM Melack. 2013. Initial impacts of a wildfire on hydrology and suspended sediment and nutrient export in California chaparral watersheds. Hydrological Processes 27(26): 3842-3851.

Clarke SJ, Wharton G. 2001. Sediment nutrient characteristics and aquatic macrophytes in lowland English rivers. Science of the Total Environment 266: 103-112.

Cloern JE. 2001. Our evolving conceptual model of the coastal eutrophication problem. Marine Ecology Progress Series 210: 223-253.

Cohn TA, DeLong LL, Gilroy EJ, Hirsch RM, Wells DK. 1989. Estimating constituent loads. Water Resources Research 25(5): 937-942.

Collins AL, Walling DE, Leeks GJL. 1998. Use of composite fingerprints to determine the provenance of the contemporary suspended sediment load transported by rivers. Earth Surface Processes and Landforms 23: 31-52.

Correll DL. 1998. The role of phosphorus in the eutrophication of receiving waters: A review. Journal of Environmental Quality 27: 261-266.

(CRBRWQCB) Colorado River Basin Regional Water Quality Control Board. 2002a. Sediment/siltation total maximum daily load for the Alamo River. 105 pp.

(CRBRWQCB) Colorado River Basin Regional Water Quality Control Board. 2002b. Sediment/siltation total maximum daily load for the New River. 69 pp.

(CRBRWQCB) Colorado River Basin Regional Water Quality Control Board. 2005. Sediment/siltation total maximum daily load for the Imperial Valley drains: Niland 2, P and Pumice drains. 48 pp.

(CSPA) California Sportfishing Protection Alliance. 2011. Letter to Marily Woodhouse of the Battle Creek Alliance.

D&A Instruments. 1991. OBS-3 owner’s manual.

Decoursey DG. 1985. Mathematical models for nonpoint water pollution control. J. Soil and Water Conservation 40:5:408-413.

De Roo APJ, Wesseling CG, Ritsema CJ. 1996a. LISEM: A single event physically-based hydrologic and soil erosion model for drainage basins: I. Theory, input and output. Hydrological Processes 10: 1107–1117.

De Roo APJ, Offermans RJE, Cremers NHDT. 1996b. LISEM: A single event physically-based hydrologic and soil erosion model for drainage basins: II. Sensitivity analysis, validation and application. Hydrological Processes 10: 1119–1126.

Dietrich EW. 1982. Settling velocity of natural particles. Water Resources Research 18 (6): 1626-1982.

Dietrich WE and T Dunne. 1993. The channel head. in K Beven and MJ Kirkby (Eds.), Channel Network Hydrology, J. Wiley and Sons, 175-219 pp.

Dietrich WE, Bellugi D, and R. Real De Asua. 2001. Validation of the shallow landslide model, SHALSTAB, for forest management. In Land Use and Watersheds: Human Influence on Hydrology and Geomorphology in Urban and Forest Areas (Eds., M. S. Wigmosta and S. J. Burges), American Geophysical Union, Washington, D. C.. doi: 10.1029/WS002p0195.

Downing-Kunz MA, Schoellhamer DH. 2013. Seasonal variations in suspended-sediment dynamics in the tidal reach of an estuarine tributary. Marine Geology 345: 314-326.

Droppo IG, Ongley ED. 1994. Flocculation of suspended sediment in rivers of southeastern Canada. Water Research 28(8): 1799-1809.

Dunne T, Agee J, Beissinger S, Dietrich W, Gray D, Power M, Resh V, Rodrigues K. 2001. A scientific basis for the prediction of cumulative watershed effects. The University of California Committee on Cumulative Watershed Effects. University of California Wildland Resource Center Report(46): 107.

Edwards TK, and GD Glysson. 1999. Field methods for measurement of fluvial sediment: USGS Techniques of Water-Resources Investigations, book 3, chap. C2, 89 pp.

Einstein HA, Krone RB. 1962. Experiments to determine modes of cohesive sediment transport in salt water. Journal of Geophysical Research 67(4): 1451-1461.

Ellen SD, and CM Wentworth 1995. Hillside materials and slopes of the San Francisco Bay Region, California. US Geological Survey Professional Paper 1357. Washington, D.C.: United States Government Printing Office.

Elliott JM. 1977. Some methods for the statistical analysis of samples of benthic invertebrates. Scientific Publication No. 25. Freshwater Biological Association. Ambleside, England. 156 pp.

Endicott CL, McMahon TE. 1996. Development of a TMDL to reduce non-point source sediment pollution in Deep Creek, Montana. Report to Montana Department of Environmental

Quality. Department of Biology, Fish and Wildlife Program, Montana State University. Bozeman, Montana.

Etcheber H, Taillez A, Abril G, Garnier J, Servais P, Moatar F, Commarieu M. 2007. Particulate organic carbon in the estuarine turbidity maxima of the Gironde, Loire and Seine estuaries: Origin and lability. Hydrobiologia 588: 245-259.

European Inland Fisheries Advisory Committee. 1964. Water quality criteria for European freshwater fish, Report on finely divided solids and inland fishes. International Journal of Air and Water Pollution 9: 151-168.

Farnsworth KL, Warrick JA. 2007. Sources, dispersal, and fate of fine sediment supplied to coastal California: U.S. Geological Survey Scientific Investigations Report 2007–5254. 77 pp.

Ferguson R. 1986. River loads underestimated by rating curves. Water Resources Research 22(1): 74-76.

Finlayson BL. 1985. Soil creep: a formidable fossil of misconception. In Geomorphology and Soils (Richards, K.S., Arnett, R. R., and Ellis, S., eds.). George Allen and Unwin, London, p. 141-158.

Francis MK, Calabrese RV, Phongikaroon S. 2006. Novel probe for the in situ measurements of particle size distributions. Review of Scientific Instruments 77: 123704.

Francoeur SN, Biggs BJF. 2003. Short-term effects of elevated velocity and sediment abrasion on periphyton communities. North American Benthological Society. NABStracts.

Fraser RH, Barten PK, and CD Tomlin. 1996. SEDMOD: spatially explicit delivery model for sediment and associated nonpoint source pollutants. American Water Resources Association Symposium on GIS and Water Resources, Ft. Lauderlade.

Gabet EJ, and T Dunne. 2003. Sediment detachment by rain power. Water Resources Research 39(1): 1002.

Gallo K, Moyer C, Lanigan S. 2003. Interagency Regional Monitoring Northwest Forest Plan Aquatic and Riparian Effectiveness Monitoring Program.

Garcia M, Parker G. 1991. Entrainment of bed sediment into suspension. Journal of Hydraulic Engineering 117(4): 414-435.

Gomez B, Brackley HL, Hicks DM, Neff H, Rogers KM. 2004. Organic carbon in floodplain alluvium: Signature of historic variations in erosion processes associated with deforestation, Waipaoa River basin, New Zealand. Journal of Geophysical Research 109: FO4011.

Goñi M, Hatten JA, Wheatcroft RA, Borgeld J. 2013. Particulate organic matter export by two contrasting small mountainous river systems from the Pacific Northwest, U.S.A. Journal of Geophysical Research – Biogeosciences. 118: 1-23. doi: 10.1002/jgrg.20024

Goñi MA, Yunker MB, Macdonald RW, Eglinton TI. 2005. The supply and preservation of ancient and modern components of organic carbon in the Canadian Beaufort Shelf of the Arctic Ocean. Marine Chemistry 93: 53-73.

Gordon ND, McMahon TA, Finlayson BL. 1992. Stream hydrology: An introduction for ecologists. Wiley, New York. 448 pp.

Graham AA. 1990. Siltation of stone-surface periphyton in rivers by clay-sized particles from low concentrations in suspension. Hydrobiologia 199: 107–115.

Graham DN and MB Butts. 2005. Chapter 10 Flexible integrated watershed modeling with MIKE SHE. In: Watershed Models, VP Singh and DK Frevert (eds.). CRC Press, Boca Raton, FL, USA, 245-272 pp.

Gray AB, Warrick JA, Pasternack GB, Watson EB, Goñi MA. 2014. Suspended sediment behavior in a coastal dry-summer subtropical catchment: Effects of hydrologic preconditions. Geomorphology 214: 485-501.

Gray AB, Pasternack GB, Watson EB, Warrick JA, Goñi MA. 2015a. The effects of El Niño Southern Oscillation cycles on the decadal scale suspended sediment behavior of a coastal dry-summer subtropical catchment. Earth Surface Processes and Landforms 40: 272-284.

Gray AB, Pasternack GB, Watson EB, Warrick JA, Goni MA. 2015b. Effects of antecedent hydrologic conditions, time dependence, and climate cycles on the suspended sediment load characteristics of the Salinas River, California. Journal of Hydrology 525: 632-649.

Gray LJ, Ward JV. 1982. Effects of sediment releases from a reservoir on stream macro-invertebrates. Hydrobiologia 96 (2): 177–184.

Gregory KJ, Madew JR. 1982. Land use change, flood frequency, and channel adjustments. In Hey RD, Bathurst JC, and Thorne CR, Editors, Gravel-bed rivers. John Wiley, Chichester.

Greig SM, Sear DA, Carling PA. 2005. The impact of fine sediment accumulation on the survival of incubating salmon progeny: Implications for sediment management. Science of the Total Environment 344: 241-258.

Greimann BP. 2001. Hydrology of North Fork and South Fork Battle Creeks: Battle Creek Salmon and Steelhead Restoration Project, California, Bureau of Reclamation: 62.

Griggs GB, Hein JR. 1980. Sources, dispersal, and clay mineral composition of fine-grained sediment off central and northern California. The Journal of Geology 88(5): 541-566.

Guimarães RF, Montgomery D, Greenberg H, Fernandes N, Gomes R, Carvalho Júnior OA. 2003. Parameterization of soil properties for a model of topographic controls on shallow landsliding: application to Rio de Janeiro. Eng Geol 69: 99–108.

Guy, HP, and Norman VW. 1970. Field methods for measurement of fluvial sediment, chap. C2 of Applications of hydraulics (book 3): U.S. Geological Survey Techniques of Water-Resources Investigation. 59 pp.

Hadley RF and SA Schumm. 1961. Sediment sources and drainage basin characteristics in upper Cheyenne River Basin. US Geological Survey Water-Supply Paper 1531-B, 198.

Hairsine PB, Rose CW. 1991. Rainfall detachment and deposition – sediment transport in the absences of flow-driven processes. Soil Science Society of America Journal 55(2): 320-324.

Harmel RD, Cooper RJ, Slade RM, Haney RL, Arnold JG. 2006. Cumulative uncertainty in measured streamflow and water quality data for small watersheds. Transactions of the ASABE 49: 689-701.

Hawkins CP, Norris RH, Hogue JN, Feminella JW. 2000. Development and evaluation of predictive models for measuring the biological integrity of streams. Ecological Applications 10: 1456-1477.

Hawkins RH. 2002. Survey of methods for sediment TMDLs in western rivers and streams of the United States. Grant # 827666-01-0 final report, USEPA Office of Water, Washington DC. 51 pp.

Hedges JI. 1992. Global biogeochemical cycles: progress and problems. Marine Chemistry 39: 67-93.

Hedges JI, Keil RG. 1995. Sedimentary organic matter preservation: an assessment and speculative synthesis. Marine Chemistry 49: 81-115.

Hedges JI, Keil RG, Benner R. 1997. What happens to terrestrial organic matter in the Ocean. Organic Geochemistry 27(5/6): 195-212.

Heimsath AM, Dietrich WE, Nishiizumi K, Finkel RC. 1999. Cosmogenic nuclides, topography, and the spatial variation of soil depth. Geomorphology 27(1-2): 151-172.

Helsel DR, Hirsch RM. 2002. Statistical methods in water resources—hydrologic analysis and interpretation. US Geological Survey Techniques of Water-Resources Investigations book 4, chap. A3, Washington, DC. 510 pp.

Henley WF, Patterson MA, Neves RJ, Lemly AD. 2000. Effects of sedimentation and turbidity on lotic food webs: a concise review for natural resource managers. Reviews in Fisheries Science 8(2): 125-139.

Heppell CM, Wharton G, Cotton AC, Bass JAB, Roberts SE. 2009. Sediment storage in the shallow hyporheic of lowland vegetated river reaches. Hydrological Processes 23: 2239-2251.

Herwitz SR. 1985. Interception storage capacities of tropical rainforest canopy trees. Journal of Hydrology 77(1): 237-252.

Hestir EL, Schoellhamer DH, Morgan-King T, Ustin SL. 2013. A step decrease in sediment concentration in a highly modified tidal river delta following the 1983 El Niño floods. Marine Geology 345: 304-313.

Heywood MJT, Walling DE. 2007. The sedimentation of salmonid spawning gravels in the Hampshire Avon catchment, UK: Implications for the dissolved oxygen content of intragravel water and embryo survival. Hydrological Processes 21: 770-788.

Hicks DM, Gomez B, Trustrum NA. 2000. Erosion thresholds and suspended sediment yields, Waipaoa River Basin, New Zealand. Water Resources Research 36(4): 1129–1142.

Hornberger GM, Wiberg PL, Raffensperger JP, D'Odorico P. 2014. Elements of Physical Hydrology, Johns Hopkins University Press.

Horowitz AJ. 2003. An evaluation of sediment rating curves for estimating suspended sediment concentrations for subsequent flux calculations. Hydrological Processes 17: 3387-3409.

House WA. 2003. Geochemical cycling of phosphorus in rivers. Applied Geochemistry 18: 739-748.

Howarth RW, Billen G, Swaney D, Townsend A, Jaworski N, Lajtha K, Downing JA, Elmgren R, Caraco N, Jordan T, Berendse F, Freney J, Kudeyarov V, Murdoch P, Zhao-Liang Z. 1996. Regional nitrogen budgets and riverine N and P fluxes for the drainages to the north Atlantic. Biogeochemistry 35(1): 75-139.

Hudson PF. 2003. Event sequence and sediment exhaustion in the lower Panuco basin, Mexico. Catena 52(1): 57–76.

Hughes RM. 1995. Defining Acceptable Biological Status by Comparing with Reference Conditions. In: Davis W and Simon T, eds. Biological assessment and criteria: Tools for water resource planning and decision making. Lewis Publishers, Boca Raton, Florida. 31-47 pp.

Ingraham BL, Lin JC. 2002. Geochemical tracers of sediment sources to San Francisco Bay. Geology 30(6): 575-578.

James C. 2011. SPI water quality monitoring bailey creek watershed a major tributary of Battle Creek.

James C. 2014. Post-wildfire salvage logging, soil erosion, and sediment delivery - Ponderosa Fire, Battle Creek watershed, Northern California preliminary results. Sierra Pacific Industries.

James C and L MacDonald. 2012. Greater Battle Creek turbidity monitoring: Update and additions. Sierra Pacific Industries.

Jones & Stokes. 2001. Site Assessment for the California Red-Legged Frog.

Jones & Stokes. 2002. California Spotted Owl Survey Results.

Jones & Stokes. 2005. Battle Creek Salmon and Steelhead Restoration Project final environmental impact statement/environmental impact report. Volume I: Report. July. (J&S 03035.03.) Sacramento, CA.

Jones KC, de Voogt P. 1999. Persistent organic pollutants (POPs): state of the sciences. Environmental Pollution 100: 209-221.

Jones KB, Neale AC, Nash MS, Van Remortel RD, Wickham JD, Riitters KH, O'Neill RV. 2001. Predicting nutrient and sediment loadings to streams from landscape metrics: A multiple watershed study from the United States mid-Atlantic region. Landscape Ecology 16: 301-312.

Kamer K, Fong P, Kennison RL, Schiff K. 2004. The relative importance of sediment and water column supplies of nutrients to the growth and tissue nutrient content of the green macroalga Enteromorpha intestinalis along an estuarine resource gradient. Aquatic Ecology 38: 45-56.

(KA) Kier Associates. 2001. Draft Battle Creek Salmon and Steelhead Restoration Project Adaptive Management Plan.

(KA) Kier Associates. 2003. Use of Spatial Data for Battle Creek Watershed Assessment.

(KA) Kier Associates. 2009. Aquatic Habitat Conditions in Battle Creek and Their Relationship to Upland Management. 34p.

Kaul LW, Foelich PN. 1984. Modeling estuarine nutrient geochemistry in a simple system. Geochmica et Cosmochimica Acta 48: 1417-1433.

Kirkby J. 1978. Hillslope hydrology. Wiley.

Knighton D. 1984. Fluvial Forms and Processes. Edward Arnold, New York. 400 pp.

Koch EW. 2001. Beyond light: Physical, geological and geochemical parameters as possible submersed aquatic vegetation habitat requirements. Estuaries 24(1): 1-17.

Kondolf GM, Wilcock PR. 1996. The flushing flow problem: defining and evaluating objectives. Water Resources Research 32(8): 2589-2599.

Krone RB. 1962. Flume studies of the transport of sediment in estuarial shoaling processes. Final report, Hydraulic Engineering Laboratory and Sanitation Engineering Research Laboratory. University of California, Berkeley. 129 pp.

Krongvang B, Laubel A, Larsen SE, Friberg N. 2003. Pesticides and heavy metals in Danish streambed sediment. Hydrobiologia 494: 93-101.

Laflen JM, Lane LJ, Foster GR. 1991. The water erosion prediction project- a new generation of erosion prediction technology. J. Soil and Water Conservation 46(1): 34-38.

Lake RG, Hinch SG. 1999. Acute effects of suspended sediment angularity on juvenile Coho salmon (Oncorhynchus kisutch). Canadian Journal of Fisheries and Aquatic Science 56(5): 862–867.

Lebo ME, Sharp JH. 1992. Modeling Phosphorus cycling in a well-mixed coastal plain estuary. Estuarine, Coastal and Shelf Science 35: 235-252.

Leidy RA, Becker GS, Harvey BN. 2005. Historical distribution and current status of steelhead/rainbow trout (*Oncorhynchus mykiss*) in streams of the San Francisco Estuary,California. Center for Ecosystem Management and Restoration, Oakland, CA.

Leithold EL, Blair NE, Perkey DW. 2006. Geomorphologic controls on the age of particulate organic carbon from small mountainous and upland rivers. Global Biogeochemical Cycles 20: GB3022.

Lewis J. 2014. An Analysis of Turbidity in Relation to Timber Harvesting in the Battle Creek Watershed, northern California September 2014.

Lindley ST, Schick RS, Mora E, Adams PB, Anderson JJ, Greene S, Hanson C, May BP, McEwan DR, MacFarlane RB, Swanson C, Williams JG. 2007. Framework for assessing the viability of threatened and endangered Chinook salmon and steelhead in the Sacramento-San Joaquin Basin. Vol. 5, Issue 1 [February 2007]. Article 4. http://repositories.cdlib.org/jmie/sfews/vol5/iss1/art4.

Lloyd DS, Koenings JP, LaPerriere JD. 1987. Effects of turbidity in fresh waters of Alaska. North American Journal of Fisheries Management 7: 34-45.

Lohmann R, Breivik K, Dachs J, Muir D. 2007. Global fate of POPs: Current and future research directions. Environmental Pollution 150: 150-165.

Long ER, Morgan LG. 1991. The potential for biological effects of sediment-sorbed contaminants tested in the National Status and Trends Program. NOAA Technical Memorandum NOS OMA 52. National Oceanic and Atmospheric Administration. Seattle, Washington. 233 pp

Loucks DP, Stedinger JR, Haith DA. 1981. Water resource systems planning and analysis, Prentice Hall, Englewood Cliffs, Ch. 9.

Macklin MG, Hudson-Edwards KA, Dawson EJ. 1997. The significance of pollution from historic metal mining in the Pennine orefields on river sediment contaminant fluxes to the North Sea. The Science of the Total Environment 194/195: 391-397.

MacDonald DD, Ingersoll CG, Berger TA. 2000. Development and evaluation of consensus-based sediment quality guidelines for freshwater ecosystems. Archives of Environmental Contamination and Toxicology 39 (1): 20-31.

MacWilliams ML, Wheaton JM, Pasternack GB, Kitanidis PK, Street RL. 2006. The flow convergence-routing hypothesis for pool-riffle maintenance in alluvial rivers. Water Resources Research 42, W10427, doi:10.1029/2005WR004391.

Madej MA. 2005. The role of organic matter in sediment budgets in forested terrain. IAHS-AISH 292: 9-15.

Makaske B. 2001. Anastomosing rivers: a review of their classification, origin and sedimentary products. Earth-Science Reviews 53: 149-196.

Malamud BD. and DL Turcotte. 2006. The applicability of power-law frequency statistics to floods. Journal of Hydrology 322(1): 168-180.

Martin JM, Meybeck M. 1979. Elemental mass-balance of material carried by major world rivers. Marine Chemistry 7(3): 173-206.

Marvin-DiPasquale M, Windham-Myers L, Agee JL, Kakouros E, Kieu LH, Fleck JA, Alpers CN, Stricker CA. 2014. Methylmercury production in sediment from agricultural and non-agricultural wetlands in the Yolo Bypass, California, USA. Science of the Total Environment 484: 288-299.

Matthaei CD, Weller F, Kelly DW, Townsend CR. 2006. Impacts of fine sediment addition to tussock, pasture, dairy and deer farming streams in New Zealand. Freshwater Biology 51: 2154-2172.

McElhany P, Ruckelshaus MH, Ford MJ, Wainwright TC, Bjorkstedt EP. 2000. Viable salmonid populations and the recovery of evolutionarily significant units. U.S. Dept. Commer. NOAA Tech. Memo. NMFS-NWFSC-42, 156 pp.

Mehta AJ, Hayter EJ, Parker WR, Krone RB, Teeter AM. 1989. Cohesive sediment transport 1: Process description. Journal of Hydraulic Engineering 115(8): 1076-1093.

Mehta AJ, Manning AJ, Khare YP. 2014. A note on the Krone deposition equation and significance of floc aggregation. Marine Geology 354: 34-39.

Meybeck, M. 1982. Carbon, nitrogen and phosphorus transport by world rivers. American Journal of Science 282: 401-450.

Meyers TJ, Swanson S. 1992. Variation of stream stability with stream type and livestock bank damage in northern Nevada. Water Resources Bulletin AWRA 28(4):743-754.

Milliman JD, Meade RH. 1983. World-wide delivery of river sediment to the oceans. The Journal of Geology 91(1): 1-21.

Milliman JD, Syvitski JPM. 1992. Geomorphic/Tectonic control of sediment discharge to the Ocean: The importance of small mountainous rivers. The Journal of Geology 100(5): 525-544.

Mirbagheri SA. 1981. Characterization and computer simulation modeling of suspended sediment transport in Colusa Basin Drain, California. PhD. Dissertation. University of California at Davis. Engineering. 634 pp.

Mirbagheri SA, Tanji KK, Krone R. 1988a. Sediment characterization and transport in Colusa Basin Drain. Journal of Environmental Engineering 114 (6): 1257–1273.

Mirbagheri S, Tanji KK, Krone RB. 1988b. Simulation of suspended sediment in Colusa Basin Drain. Journal of Environmental Engineering 114 (6): 1275–1294.

Montgomery DR, Buffington JM. 1993. Channel classification, prediction of channel response, and assessment of channel condition. TFW-SH10-93-002, WA Dept. of Natural Resources. 84 pp.

Montgomery DR. and WE Dietrich. 1988. Where do channels begin? Nature 336:232-234.

Montgomery DR. and WE Dietrich. 1992. Channel initiation and the problem of landscape scale. Science 255: 826-830.

Montgomery DR. and WE Dietrich. 1994. A physically-based model for topographic control on shallow landsliding, Water Resources Research 30(4): 1153-1171.

Mora MA, Anderson DW, Mount ME. 1987. Seasonal variation of body condition and organochlorines in wild ducks from California and Mexico. Journal of Wildlife Management 5(1): 132-140.

Moyle PB, Marchetti MP, Baldrige J, Taylor TL. 1998. Fish health and diversity: Justifying flows for a California stream. Fisheries 23(7): 6-15.

(MPCA) Minnesota Pollution Control Agency. 2008. Turbidity: Description, impact on water quality, sources, measures – A general overview. St. Paul Minnesota. 2 pp.

Myers T. 2012. Cumulative Watershed Effects of Timber Harvest and Other Activities Battle Creek Watershed, Northern California. 52 pp.

Naden PS. 2010. The fine sediment cascade. In: Sediment Cascades. Joh Wiley and Sons, Ltd. 271-305.

Napolitano M, Potter S, Whyte D. 2007. Napa River watershed sediment TMDL and habitat enhancement plan. Staff Report. California Regional Water Quality Control Board San Francisco Region. 142 pp.

Napper CO. 2001. Cumulative Watershed Effects Battle Creek Analysis of Beneficial Uses and Water Quality Criteria to Evaluate CWE Susceptibility

(NAS/NAE) National Academy of Sciences, National Academy of Engineering. 1972. Water Quality Criteria, 1972. U.S. Government Printing Office, Washington D.C. 604 pp.

Nesbitt HW, Young GM. 1996. Petrogenesis of sediments in the absence of chemical weathering: effects of abrasion and sorting on bulk composition and mineralogy. Sedimentology 43: 341-358.

Nesbitt HW, Young GM, McLennan SM, Keays RR. 1996. Effects of chemical weathering and sorting on the petrogenesis of siliciclastic sediments, with implications for provenance studies. The Journal of Geology 104(5): 525-542.

Newcombe CP, Macdonald DD. 1991. Effects of suspended sediments on aquatic ecosystems. North American Journal of Fisheries Management 11(1): 72-82.

Nittrouer JA, Viparelli E. 2014. Sand as a stable and sustainable resource for nourishing the Mississippi River delta. 7: 350-354.Northwest Hydraulic Consultants. 2014. Baseline Hydrologic Analyses for South Fork Battle Creek, Northwest Hydraulic Consultants: 30 pp.

Niyogi DK, Koren M, Arbuckle CJ, Townsend CR. 2006. Stream communities along a catchment land-use gradient: Subsidy-stress responses to pastoral development. Environmental Management 39: 213-225.

Noss DK, and PY Julien. 1996. Calculating upland erosion using GIS-GRASS, in. H.J. Morel-Seytoux, ed., Proceedings of the American Geophysical Union 16th Annual Hydrology Days, April 15-18, Colorado State University, Ft. Collins, CO.

Novotny V. 1986. Review of hydrologic and water quality models used for simulation of agricultural pollution, in Agricultural Nonpoint Source Pollution: Model Selection and Application, Developments in Environmental Modeling, Elsevier Press, NY, 9-35.

(NTAC) National Technical Advisory Committee to the Secretary of the Interior. 1968. Water quality criteria. Federal Water Pollution Control Administration. 234 pp.

Owens PN, Walling DE, Leeks GJL. 1999. Deposition and storage of fine-grained sediment within the main channel system of the River Tweed, Scotland. Earth Surf. Process. Landforms 24: 1061-1076.

Pandey PK, Soupir ML. 2014. Assessing linkages between E. coli levels in streambed sediment and overlying water in an agricultural watershed in Iowa during the first heavy rain event of the season. Transactions of the ASABE 57(6): 1571-1581.

Paquin-Gilmore S. 2007. Battle Creek Watershed Community Strategy.

Parametrix. 2003. Effects of turbidity on aquatic life and recreational and consumptive uses of water: A basis for revising Oregon's water quality criterion for turbidity. Prepared for Blue Heron Paper Company.

Parkinson D. 2014. Upper South Fork Battle Creek base Streamflow Study September 2014. 40 pp.

Pacific Gas & Electric. 2008. Battle Creek Hydroelectric Project FERC No. 1121 License Amendment Application for Battle Creek Salmon and Steelhead Restoration Project.

Pflüger Y, Rackham A, Larned ST. 2010. The aesthetic value of river flows: An assessment of flow preferences for large and small rivers. Landscape and Urban Planning 95: 68-78.

Pizzuto J, Schenk E, Hupp C, Gellis A, Noe G, Williamson E, Karwan D, O'Neal M, Marquard J, Aalto R, Newbold D. 2014. Characteristic length scales and time-averaged transport velocities of suspended sediment in the mid-Atlantic Region, USA. Water Resources Research 50(2): 790-805.

Rabeni CF, Doisy KE, Zweig LD. 2005. Stream invertebrate community functional responses to deposited sediment. Aquatic Sciences 67: 395-402.

Rasmussen PP, Gray JR, Glysson GD, Ziegler AC. 2009. Guidelines and procedures for computing time-series suspended-sediment concentrations and loads from in-stream turbidity-sensor and streamflow data: U.S. Geological Survey Techniques and Methods, book 3, chap. C4, 52 pp.

Redding JM, Schreck CB, Everest FH. 1987. Physiological effects on Coho Salmon and steelhead of exposure to suspended solids. Transactions of the American Fisheries Society 116: 737–744.

Reddy KR, Kadlec RH, Flaig E, Gale PM. 1999. Phosphorus retention in streams and wetlands: A review. Critical Reviews in Environmental Science and Technology 29(1): 83-146.

Reid, L. M. 1989. Channel incision by surface runoff in grassland catchments. Ph.D. dissertation, University of Washington, Seattle.

Reid LM and T Dunne. 1996. Rapid evaluation of sediment budgets, Catena Verlag.

Reiser DW, Ramey MP, Wesche TA. 1989. Flushing flows. In: Gore JA and Petts GE, eds. Alternatives in Regulated River Management. CRC Press, Boca Raton.

Reynolds JB, Simmons RC, Burkholder AR. 1988. Effects of placer mining discharge on health and food habits of Arctic Grayling. Water Resources Bulletin 25: 625–635.

Ritchie JC, McHenry JR. 1990. Application of radioactive fallout Cesium-137 for measuring soil erosion and sediment accumulation rates and patterns: A review. Journal of Environmental Quality 19: 215-233.

Ritter DF. 2011. Process Geomorphology. Wm. C. Brown Publishers, Dubuque, Iowa.

Robertson M. 1957. The effects of suspended materials on the reproductive rate of Daphnia magna. Publications of the Institute for Marine Science, University of Texas 4: 265–277.

Robertson MJ, Scruton DA, Gregory RS, Clarke KD. 2006. Effects of suspended sediment on freshwater fish and fish habitat. Canadian Technical Report of Fisheries and Aquatic Sciences 2644. 37 pp.

Rosgen DL. 1994. A classification of natural rivers. Catena 169–199.

Rouse H. 1937. Modern conceptions of the mechanics of fluid turbulence. Transactions of the American Society of Civil Engineers 102: 463–541.

Rouse H. 1939. Experiments on the mechanics of sediment suspension, Proceedings 5th International Congress on Applied Mechanics, Cambridge, Mass, 550-554.

Ryan PA. 1991. Environmental effects of sediment on New Zealand streams: a review. New Zealand journal of marine and freshwater research 25(2): 207-221.

Ryder GI. 1989. Experimental Studies on the Effects of Fine Sediments on Lotic Invertebrates. PhD thesis. University of Otago. Dunedin, New Zealand. 432 pp.

Sacramento River Watershed Program. 2010. The Sacramento River Basin.

Sadar MJ. 1998. Turbidity Science, HACH.

Sadeghi SHR, Mizuyama T, Miyata S, Gomi T, Kosugi K, Fukushima T, Mizugaki S, Onda Y. 2008. Development, evaluation and interpretation of sediment rating curves for a Japanese small mountainous reforested watershed. Geoderma 144: 198-211.

Santhi CR, Srinivasan JG, Arnold JR, Williams. 2005. A modeling approach to evaluate the impacts of water quality management plans implemented in a watershed in Texas. Environmental Modelling & Software. 21 (2006): 1141-1157.

Savabi MR, Flanagan DC, Hebel B, Engel BA. 1995. Application of WEPP and GIS-GRASS to a small watershed in Indiana. J. Soil and Water Conservation 50(5): 477-483.

Scatena FN. 1995. Relative scales of time and effectiveness of watershed processes in a tropical montane rain forest of Puerto Rico. In Natural and Anthropogenic Influences in Fluvial

Geomorphology (Costa JE, Miller AJ, Potter KW, Wilcock PR, eds.) American Geophysical Union, Washington, D. C. doi: 10.1029/GM089p0103.

Schumm SA. 1977. The Fluvial System. Wiley-Interscience, New York. 338 pp.

Sedell JR, Reeves GH, Hauer FR, Stanford JA, Hawkins CP. 1990. Role of refugia in recovery from disturbances: modern fragmented and disconnected river systems. Environmental Management 14: 711-724.

Selby MJ. 1987. Slopes and Weathering. In Human Activity and Environmental Processes (Gregory KJ, and DE Walling, eds.) John Wiley & Sonds Ltd., 183-205 pp.

Setmire JG, Wolfe JC, Stroud RK. 1990. Reconnaissance investigation of water quality, bottom sediment, and biota associated with irrigation drainage in the Salton Sea area, California, 1986-87. U.S. Geological Survey Water-Resources Investigations Report 89-4102. U.S. Geological Survey, Sacramento, California. 73pp.

Setmire JG, Schroeder RA, Densmore JN, Goodbred SL, Audet DJ, Radke WR. 1993. Detailed study of water quality, bottom sediment, and biota associated with irrigation drainage in the Salton Sea area, California, 1988-90. U.S. Geological Survey Water-Resources Investigations Report 93-4014. U.S. Geological Survey, Sacramento, California. 122 pp.

Shen HW and PY Julien. 1993. Erosion and sediment transport. In Handbook of Hydrology (DR Maidment, ed.). McGraw-Hill, Inc, New York, 12.1-12.61.

Simon A. 1992. Energy, time, and channel evolution in catastrophically disturbed fluvial systems. Geomorphology 5: 345-372.

Simon A, Hupp CR. 1992. Geomorphic and vegetative recovery processes along modified stream channels of West Tennessee. United States Geological Survey Open-File Report 91-502.

Slattery MC, Burt TP. 1997. Particle size characteristics of suspended sediment in hillslope runoff and stream flow. Earth Surface Processes and Landforms 22: 705-719.

Smalling KL, Orlando JL, Kuivila KM. 2005. Analysis of pesticides in surface water and sediment from Yolo Bypass, California, 2004–2005: U.S. Geological Survey Scientific Investigations Report 2005-5220. 20 pp.

Smith JD, Griffin ER. 1997. Flow, suspended sediment transport, and bank deposition in the Colorado River during the 1996 test flood. US Geological Survey. 43 pp.

Smith DG, Croker GF, McFarlane K. 1995. Human perception of water appearance 1. Clarity and colour for bathing and aesthetics. New Zealand Journal of Marine and Freshwater Research 29(1): 29-43.

Sommerfield CK, Nittrouer, CA, Alexander CR. 7Be as a tracer of flood sedimentation on the northern California continental margin. Continental Shelf Research 19: 335-361.

Soulsby C, Youngson AF, Moir HJ, Malcolm IA. 2001. Fine sediment influence on salmonid spawning habitat in lowland agricultural stream: A preliminary assessment. The Science of the Total Environment 265: 295-307.

Springborn M, Singer MB, Dunne T. 2011. Sediment-adsorbed total mercury flux through Yolo Bypass, the primary floodway and wetland in the Sacramento Valley, California. Science of the Total Environment 412: 203-213. DOI: 10.1016/j.scitotenv.2011.10.004

Stewart JB. 1977. Evaporation from the wet canopy of a pine forest. Water Resources Research 13(6): 915-921.

Stillwater Sciences, Dietrich WE. 2002. Napa River Basin Limiting Factors Analysis. Final Technical Report to the San Francisco Bay Water Quality Control Board. 88 pp.

Sundborg A. 1967. Some aspects on fluvial sediment and fluvial morphology I. General views and graphic methods. Geografiska Annaler, Series A, Physical Geography 49(2/4): 333-343.

Syvitski JPM. 2003. Supply and flux of sediment along hydrological pathways: Research for the 21st century. Global and Planetary Change 39: 1-11.

Syvitski JPM. 2008. Deltas at risk. Sustainability Science. DOI 10.1007/s11625-008-0043-3.

Syvitski JP, Morehead MD, Bahr DB, Mulder T. 2000. Estimating fluvial sediment transport: The rating parameters. Water Resources Research 36(9): 2747–2760.

Tanji KK, Singer M, Biggar J, Whittig L, Henderson D. 1978. Sediment production and transport in Colusa Basin drainage area. 1977-78 Annual Report to EPA on Grant No. 805462. University of California, Davis, Water Science and Engineering Paper No. 4016. 211 pp.

Tanji KK, Singer M, Biggar J, Whittig L, Henderson D, 1980. Nonpoint sediment production in the Colusa Basin drainage area. October 1978 – September 1979. Second-year annual progress report on EPA Grant No. R805462. University of California, Davis, Dept. Land, Air, and Water Resources. Water Science and Engineering Paper No. 4018. 379 pp.

Tanji KK, Singer M, Biggar J, Whittig L, Henderson D. 1981. Nonpoint sediment production in the Colusa Basin drainage area. 1979-1980. Third-year annual progress report on EPA Grant No. R805462. University of California, Davis, Dept. Land, Air, and Water Resources. Water Science and Engineering Paper No. 4019. 157 pp.

Tanji KK, Singer M, Biggar J, Whittig L, Henderson D. 1983. Nonpoint sediment production in the Colusa Basin drainage area, California. Final Report to the EPA on Grant No. 805462 and No. 807169. University of California, Davis. Department of Land, Air and Water Resources. Robert S. Kerr Environmental Research Lab. 112 pp.

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

Terraqua. 2004. Draft Battle Creek Salmon and Steelhead Restoration Project Adaptive Management Plan. Wauconda, Wa: 218.

Thomas R Payne and Associates, Kondolf GM Katzel M. 1994. Spawning gravel resources of Battle Creek, Shasta and Tehama Counties.

Thomas R Payne and Associates. 1995. Draft Battle Creek Fisheries Study Task 1: Instream Flow Study.

Thomas R Payne and Associates. 1998. Battle Creek Fisheries Studies Task 1: Instream Flow Study, California Department of Fish and Game: 45 pp.

Tisdall JM, Oades JM. 1989. Organic matter and water-stable aggregates in soils. Journal of Soil Science 33: 141-163.

Trimble SW. 1974. Man-induced soil erosion on the Southern Piedmont. Soil Conservation Society of America.

Trimble SW. 1999. Decreased rates of alluvial sediment in the Coon Creek Basin, Wisconsin, 1975-1993. Science 285: 1244-1246.

Troeh FR. 2005. Soils and soil fertility, 6th edition. Wiley-Blackwell, New York. 498 pp.

Troendle CA, Rosgen DL, Ryan SE, Porth LS, Nankervis JM. 2001. Developing a “reference” sediment transport relationship. Proceedings 7th Interagency Sedimentation Conference, March 25-29, 2001, Reno, NV.

Tucker GE, Bras RL. 1998. Hillslope processes, drainage density, and landscape morphology. Water Resources Research 34(10): 2751-2764.

Turowski JM, and SJ Dadson. 2010. The partitioning of the total sediment load of a river into suspended load and bedload: A review of empirical data. Sedimentology 57: 1126-1146.

Tussing SP, and MB Ward. 2008. Battle Creek Stream Condition Monitoring: 2006 Data Analysis Report and Correction to 2001 and 2002 Watershed Assessment . Terraqua Inc., Wauconda, WA. 26 pp.

(USBR) U.S. Department of the Interior Bureau of Reclamation. 2001. Battle Creek Salmon and Steelhead Restoration Project Scoping Report.

(USDA/NRCS) US Department of Agriculture/Natural Resources Conservation Service. 1985. Hillside vineyards unit Redwood Empire target area: Napa and Sonoma Counties, California. Davis, California: Soil Conservation Service. 1-6, and 43-63 pp.

(US EPA) US Environmental Protection Agency. 1985. Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms and Their Uses. Office of Research and Development, PB85-227049, Duluth, Minnesota.

(US EPA) US Environmental Protection Agency.1986. Quality criteria for water. Office of Water. EPA 440-5-86-001.

(US EPA) US Environmental Protection Agency. 1991. Guidance for water quality-based decisions: The TMDL process. US EPA publication 440/4-91-001. Washington, D.C.: Assessment and Watershed Protection Division.

(US EPA) US Environmental Protection Agency. 1999. Protocol for developing sediment TMDLs. EPA 841-B-99-004. Washington, D.C: US EPA Office of Water (4503F).

(US EPA) US Environmental Protection Agency. 2000. Mid-Atlantic highlands streams assessment. EPA/903/R-00/015. U.S. Environmental Protection Agency. Region 3. Philadelphia, PA. 364 pp.

(US EPA) US Environmental Protection Agency. 2003a. Developing Water Quality Criteria for Suspended and Bedded Sediments (SABS): Potential Approaches. Draft. Office of Water. US EPA Science Advisory Board Consultation. 58 pp.

(US EPA) US Environmental Protection Agency. 2003b. Strategy for water quality standards and criteria: Setting priorities to strengthen the foundation for protecting and restoring the nation’s waters. Office of Water. EPA-823-R-03-010. 900 pp.

(US EPA) US Environmental Protection Agency. 2003c. Ambient water quality criteria for dissolved oxygen, water clarity and Chlorophyll A for Chesapeake Bay and tidal tributaries. U.S. EPA, Chesapeake Bay Program Office, Annapolis MD. 343 pp.

(US EPA) US Environmental Protection Agency. 2006. Framework for developing suspended and bedded sediments (SABS) water quality criteria. Office of Water. EPA-822-R-06-001. 75 pp.

(US EPA) US Environmental Protection Agency. 2012. What are Suspended and Bedded Sediments (SABS)? In Water: WARSSS. Retrieved from http://water.epa.gov/scitech/datait/tools/warsss/sabs.cfm

(US EPA) US Environmental Protection Agency. 2015. WARSS website: http://water.epa.gov/scitech/datait/tools/warsss/ (last accessed 3/26/2015)

(US NRCS) U.S. Department of Agriculture/Natural Resources Conservation Service. 1967. Soil Survey of Shasta County.

(US NRCS) U.S. Department of Agriculture/Natural Resources Conservation Service. 1974. Soil Survey of Tehama County.

(USFWS) U.S. Fish and Wildlife Service, Brown, M. 2011. LiDAR Remote Sensing & Orthophoto Data Collection.

(USGS) U.S. Geological Survey. 1961. A study of methods used in measurement and analysis of sediment loads in streams. Report #13, the single-stage sampler for suspended sediment, United States Government Printing Office, Washington, D.C.

(USGS) U.S. Geological Survey. 1965. Methods for Collection and Analysis of Water Samples. Water Supply Paper 1454. 301 pp.

(USGS) U.S. Geological Survey. 2010. Geologic Map of Lassen Volcanic National Park and Vicinity, Ca.

(USGS) US Geological Survey. 2015. NAWQA Data Warehouse Home. http://cida.usgs.gov/nawqa_public/apex/f?p=136:1:0. Last accessed 11/04/2015.

Valentin C, Poesen J, Li Y. 2005. Gully erosion: Impacts, factors and control. Catena 63: 132-153.

Vanoni VA. 1975. Sedimentation engineering, ASCE, New York, N.Y.

Viessman W and GL Lewis. 2003. Introduction to Hydrology, Intex Educational.

Waananen AO, and JR Crippen. 1977. Magnitude and frequency of floods in California, Water Resources Division, US Geological Survey.

Wagener SM, LaPerriere JD. 1985. Effects of placer mining on the invertebrate communities of interior Alaska. Freshwater Invertebrate Biology 4: 208–214.

Walker KF. 1985. A review of the ecological effects of river regulation in Australia. Hydrobiologia 125: 111-129.

Walling DE. 1977. Assessing the accuracy of suspended sediment rating curves for a small basin. Water Resources Research 12(3): 531-538.

Walling DE. 1983. The sediment delivery problem. Journal of Hydrology 65: 209-237. Journal of Hydrology 65: 209-237.

Walling DE. 2005. Tracing suspended sediment sources in catchments and river systems. Science of the Total Environment 344: 159-184.

Walling DE, Fang D. 2003. Recent trends in the suspended sediment loads of the world’s rivers. Global and Planetary Change 39:111-126.

Walling DE, Moorehead PW. 1987. Spatial and temporal variation of the particle-size characteristics of fluvial suspended sediment. Geografiska Annaler, Series A, Physical Geography 69(1): 47-59.

Walling DE, Moorehead PW. 1989. The particle size characteristics of fluvial suspended sediment: an overview. Hydrobiologia 176/177: 125-149.

Walling DE, Owens PN, Leeks GJL. 1998. The role of channel and floodplain storage in the suspended sediment budget of the River Ouse, Yorkshire, UK. Geomorphology 22: 225-242.

Walling DE, Russell MA, Webb BW. 2001. Controls on the nutrient content of suspended sediment transported by British rivers.Science of the Total Environment,266(1): 113-123.

Walling DE, Owens PN, Waterfall BD, Leeks GJL, Wass PD. 2000. The particle size characteristics of fluvial suspended sediment in the Humber and Tweed catchments, UK. The Science of the Total Environment 251/252: 205-222.

Walling DE, Owens PN, Carter J, Leeks GJL, Lewis S, Meharg AA, Wright J. 2003. Storage of sediment-associated nutrients and contaminants in river channel and floodplain systems. Applied Geochemistry 18: 195-220.

Ward MB and WM Kier. 1999a. Battle Creek salmon and steelhead restoration plan, Kier Associates.

Ward MB and WM Kier. 1999b. Maximizing Compatibility Between Coleman National Fish Hatchery Operations, Management of Lower Battle Creek, Salmon and Steelhead Restoration, Kier Associates.

Ward MB and J Moberg .2004. Battle Creek watershed assessment: Characterization of stream conditions and an investigation of sediment source factors. Terraqua Inc. Wauconda, Wa: 77.

Ward MB, Tussing S, Moberg J, Nelle P. 2008. Battle Creek Stream condition monitoring plan.

Ward, M. B. and S. Tussing. 2008. Battle Creek stream condition monitoring plan application form.

Warrick JA. 2015. Trend analyses with river sediment rating curves. Hydrological Processes 29: 936-949.

Warrick JA, Rubin DM. 2007. Suspended-sediment rating curve response to urbanization and wildfire, Santa Ana River, California. Journal of Geophysical Research-Earth Surface 112(F2): 1–15.

Warrick JA, Mertes LAK. 2009. Sediment yield from the tectonically active semiarid Western Transverse Ranges of California. Geolical Society of America Bulletin 121(7–8): 1054–1070.

Warrick JA, Madej MA, Goñi MA, Wheatcroft RA. 2013. Trends in the suspended-sediment yields of coastal rivers of northern California, 1955-2010. Journal of Hydrology 489: 108-123.

Warrick JA, Washburn L, Brzezinki MA, Siegel DA. 2005. Nutrient contributions to the Santa Barbara Channel, California, from the ephemeral Santa Clara River. Estuarine, Coastal and Shelf Science 62: 559-574.

Wass PD, Leeks GJL. 1999. Suspended sediment fluxes in the Humber catchment, UK. Hydrol. Process. 13: 935-953. doi: 10.1002/(SICI)1099-1085(199905)13:7<935::AID-HYP783>3.0.CO;2-L.

Wells RR, Momm HG, Rigby JR, Bennett SJ, Bingner RL, Dabney SM. 2013. An empirical investigation of gully widening rates in upland concentrated flows. Catena 101: 114-121.

Wentworth CK. 1922. A scale of grade and class terms for clastic sediments. The Journal of Geology 377-392 pp.

Weston DP, You J, Lydy MJ. 2004. Distribution and toxicity of sediment-associated pesticides in Agricutlure-Dominated water bodies of California’s Central Valley. Environmental Science and Technology 38: 2752-2759.

White AS. 1985. Hillside vineyard inventory. Napa, California: Napa County Resource Conservation District.

Whitmore GP, Crook KAW, Johnson DP. 2004. Grain size control of mineralogy and geochemistry in modern river sediment, New Guinea collison, Papua New Guinea. Sedimentary Geology 171: 129-157.

Wilson CJ. 1988. Runoff and pore pressure development in hollows: Ph.D. dissertation, University of California, Berkeley, 284 pp.

Winterwerp JC. 2002. On the flocculation and settling velocity of estuarine mud. Continental Shelf Research. 22: 1339-1360.

Wolman MG. 1967. A cycle of sedimentation and erosion in urban river channels. Geografiska Annaler 49A: 385–395.

Woodhouse M. 2011. Report on Battle Creek Watershed and Digger Creek Turbidity, Post-harvest 2011.

Wright JF. 2000. An introduction to RIVPACS. In: Wright JF, Sutcliffe DW, Furse MT, Editors. Assessing the biological quality of freshwaters: RIVPACS and other techniques. Freshwater Biological Association, Ambleside, Cumbria, UK. 1-24 pp.

Wright JF, Moss D, Armitage PD, Furse MT. 1984. A preliminary classification of running-water sites in Great Britain based on macro-invertebrate species and the prediction of community type using environmental data. Freshwater Biology 14: 221-256.

Yamada H, Nakamura F. 2002. Effect of fine sediment deposition and channel works on periphyton biomass in the Makomanai River, Northern Japan. River Research and Applications 18: 481-493.

(YARMT) Yuba Accord River Management Team. 2010. Lower Yuba River Accord Monitoring and Evaluation Program. Marysville, CA.

(YARMT) Yuba Accord River Management Team. 2013. Lower Yuba River Accord, River Management Team Interim Monitoring and Evaluation Report. Marysville, CA.

Zhang ZL, Hong HS, Zhou JL, Huang J, Yu G. 2003. Fate and assessment of persistent organic pollutants in water and sediment from Minjiang River Estuary, Southeast China. Chemosphere 52: 1423-1430.

Zhang Z, Wang S, Sun G, McNulty SG, Zhang H, Li J, Zhang M, Klaghofer E, Strauss P. 2008. Evaluation of the MIKE SHE Model for Application in the Loess Plateau, China. Journal of the American Water Resources Association 44(5): 1108-1120. DOI: 10.1111/j.1752-1688.2008.00244.x

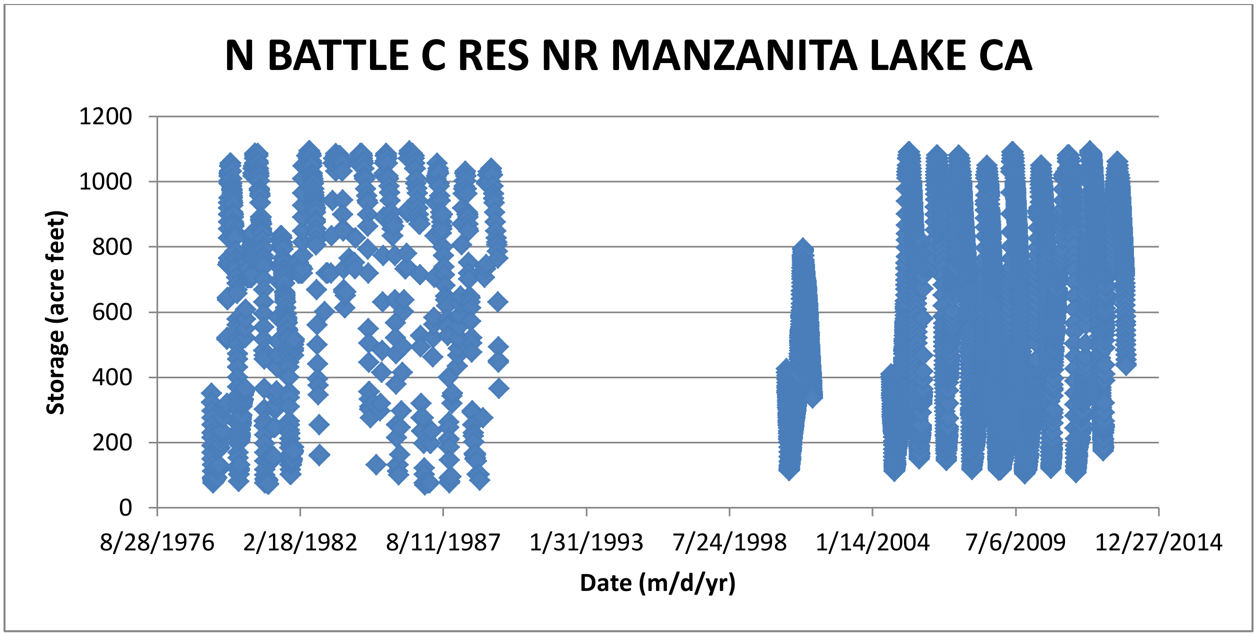
Zhou X, Li A, Jiang F, Lu J. 2015. Effects of grain size distribution on mineralogical and chemical compositions: a case study from size-fractional sediment of the Huanghe (Yellow River) and Changjiang (Yangtze River). Geological Journal 50: 414-433.

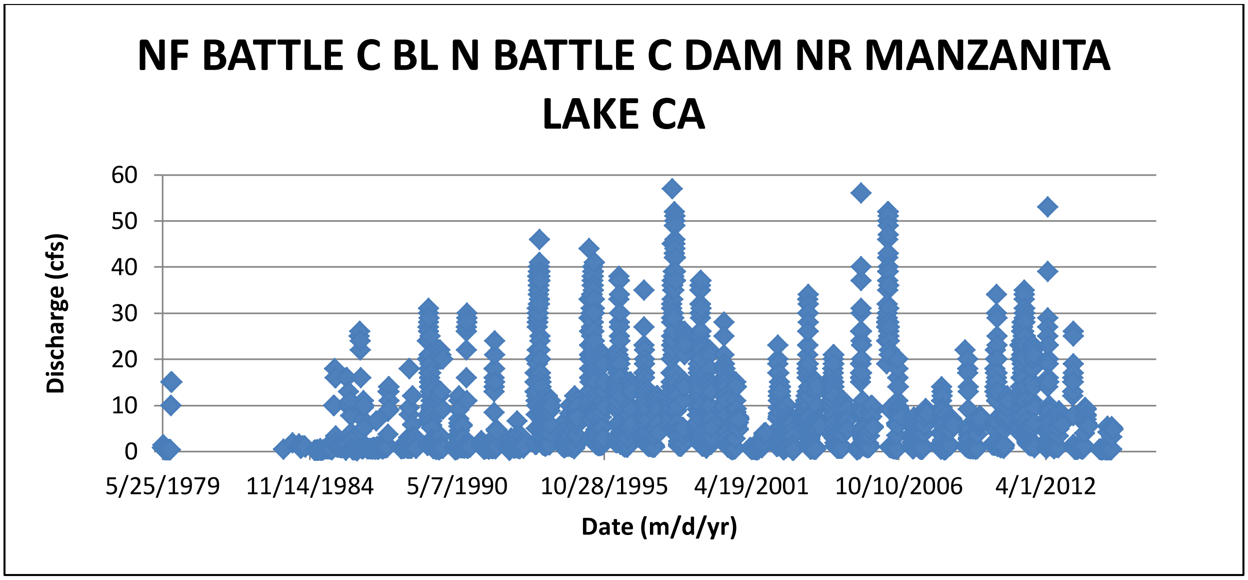
Zhu Y, Lu XX, Zhou Y. 2007. Suspended sediment flux modeling with artificial neural network: An example of the Longchuanjiang River in the Upper Yangtze Catchment, China. Geomorphology 84: 111-125.

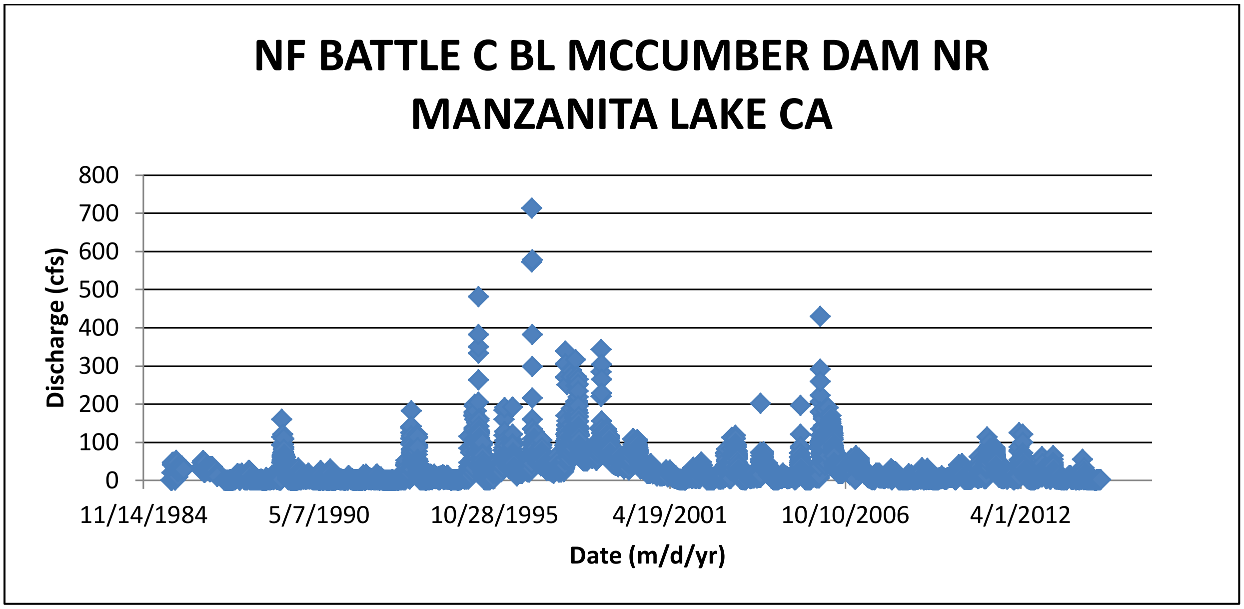
12 APPENDICES

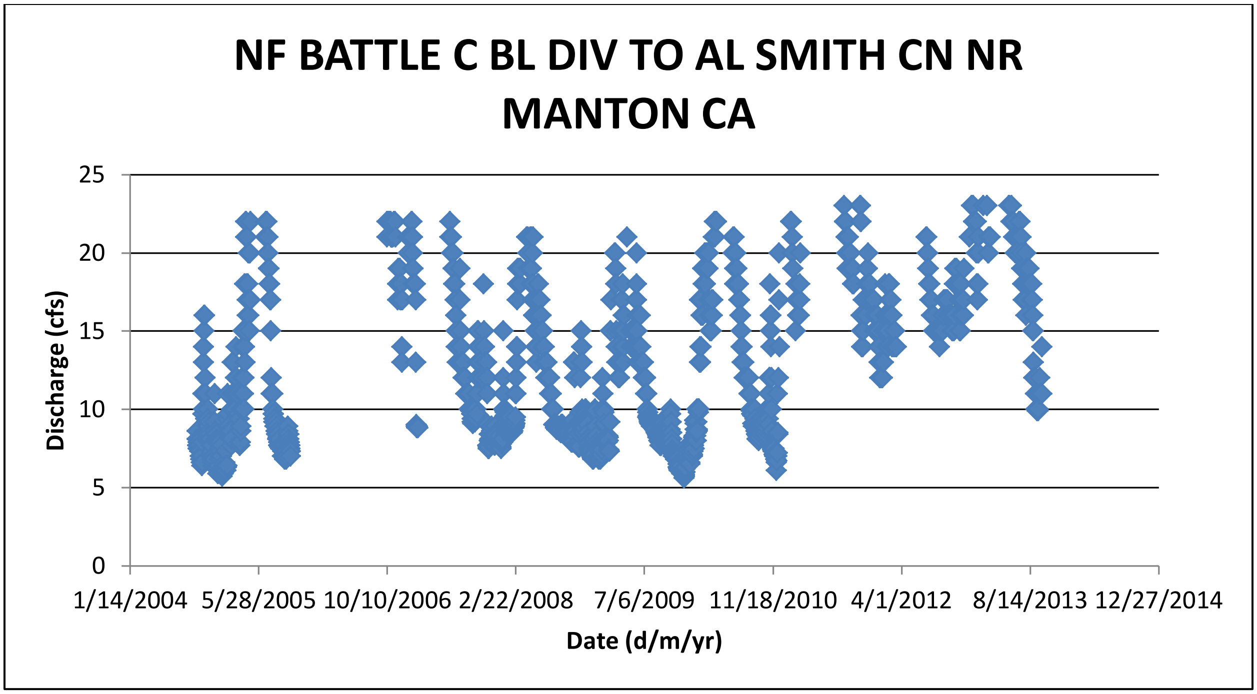
12.1 Appendix 1: USGS diversion information

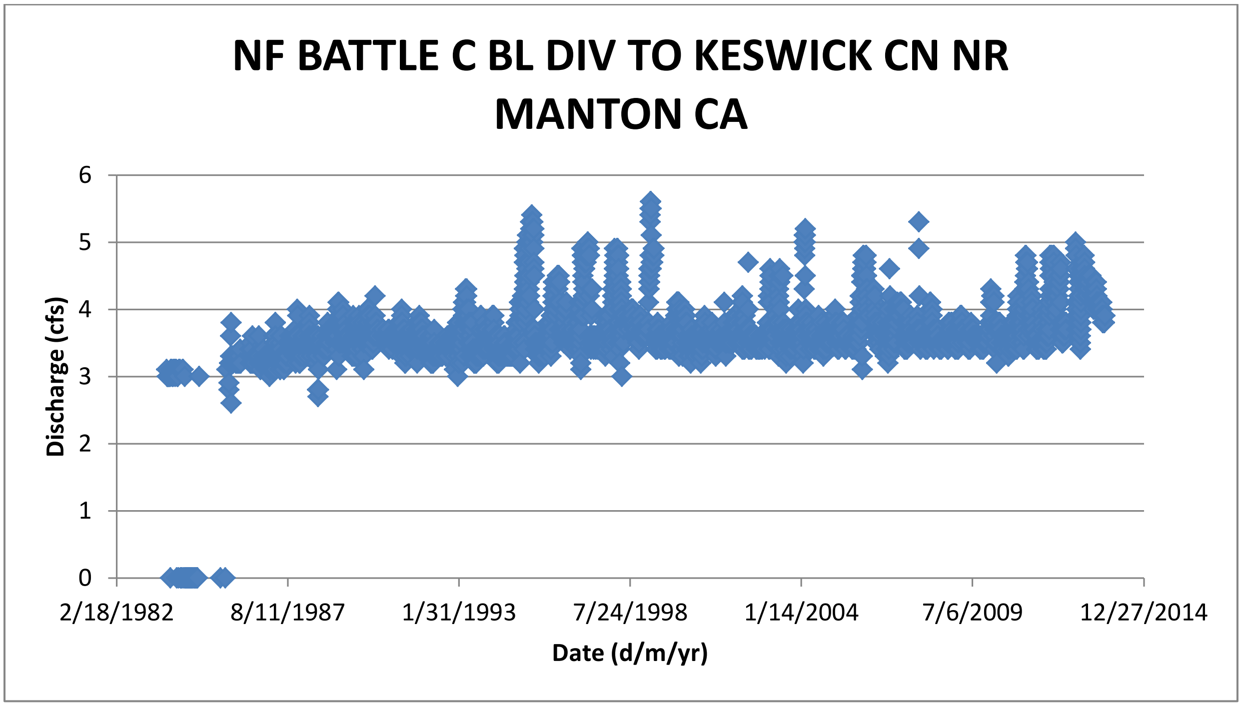
River	Site Number	Site Name
North Fork Battle Creek	11376010	N BATTLE C RES NR MANZANITA LAKE CA
North Fork Battle Creek	11376015	NF BATTLE C BL N BATTLE C DAM NR MANZANITA LAKE CA
North Fork Battle Creek	11376025	NF BATTLE C BL MCCUMBER DAM NR MANZANITA LAKE CA
North Fork Battle Creek	11376040	NF BATTLE C BL DIV TO AL SMITH CN NR MANTON CA
North Fork Battle Creek	11376050	NF BATTLE C BL DIV TO KESWICK CN NR MANTON CA
North Fork Battle Creek	11376140	NF BATTLE C BL DIV TO XCOUNTRY CN NR MANTON CA
North Fork Battle Creek	11376150	NF BATTLE C BL DIV TO EAGLE CY CN NR MANTON CA
North Fork Battle Creek	11376160	NF BATTLE C BL DIV TO WILDCAT CN NR MANTON CA
North Fork Battle Creek	11376420	NF BATTLE C BL DIV TO EAGLE CY CN NR MANTON CA
South Fork Battle Creek	11376440	SF BATTLE C BL DIV TO INSKIP CN NR MANTON CA
South Fork Battle Creek	11376460	SF BATTLE C BL DIV TO COLEMAN CN NR MANTON CA

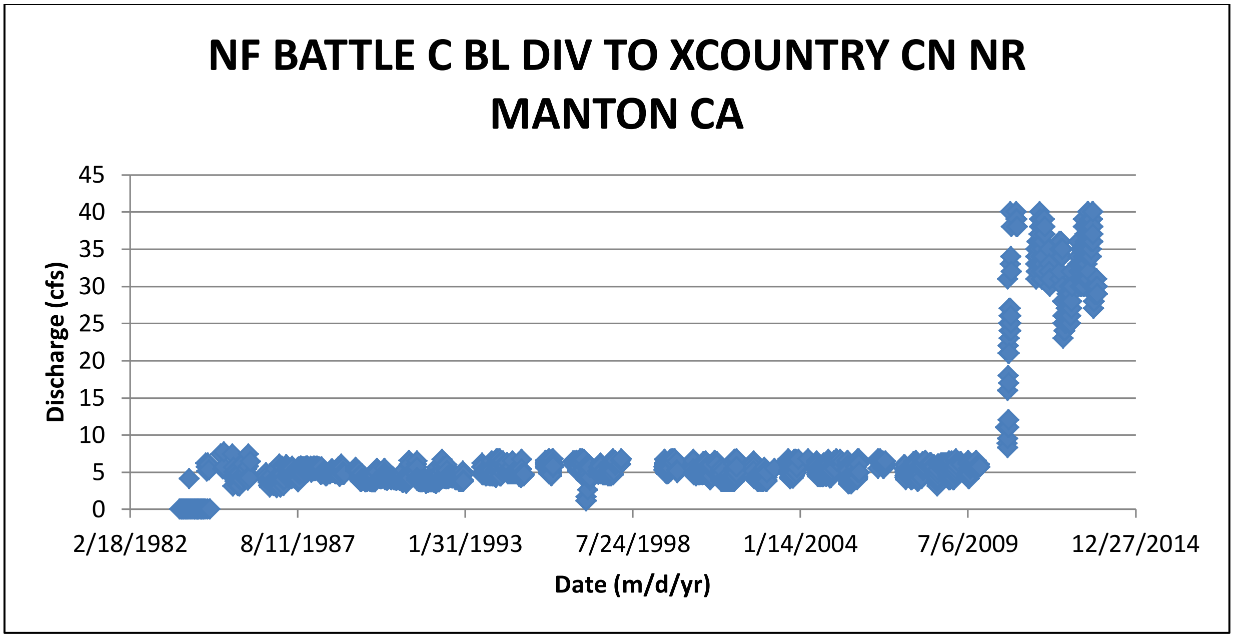


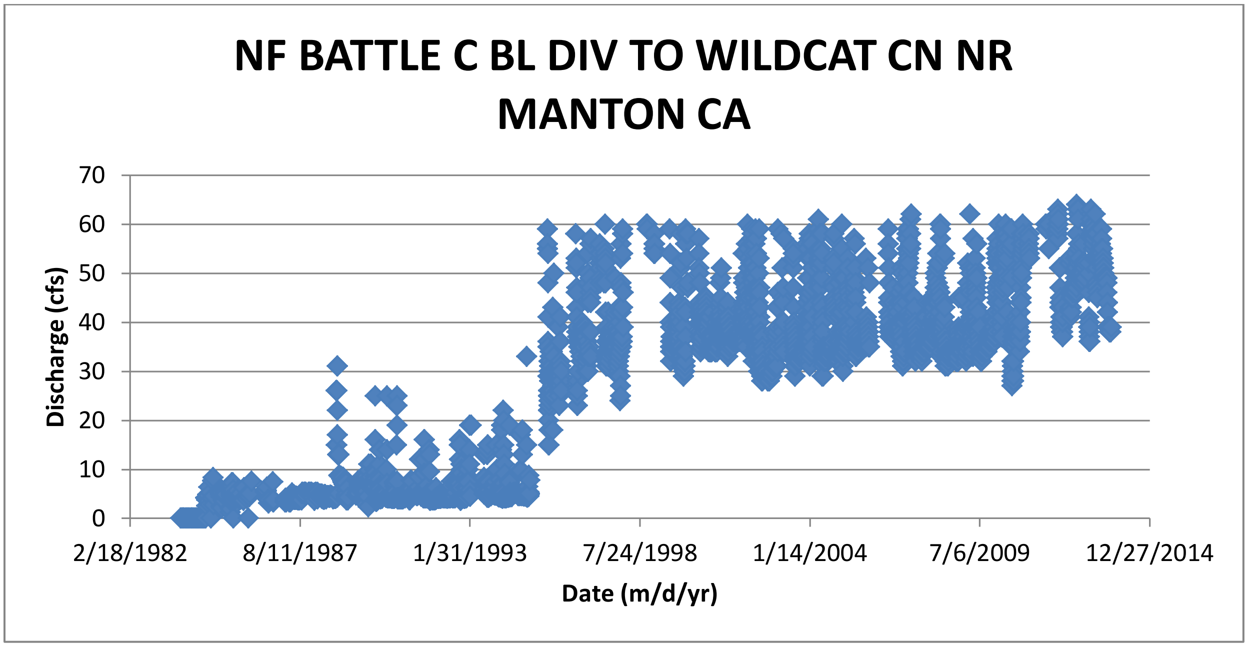

NF BATTLE C BL N BATTLE C DAM NR MANZANITA LAKE CA
Discharge (cfs)
60
50
40
30
20
10
0
5/25/1979
11/14/1984
5/7/1990
10/28/1995
4/19/2001
10/10/2006
4/1/2012
Date (m/d/yr)

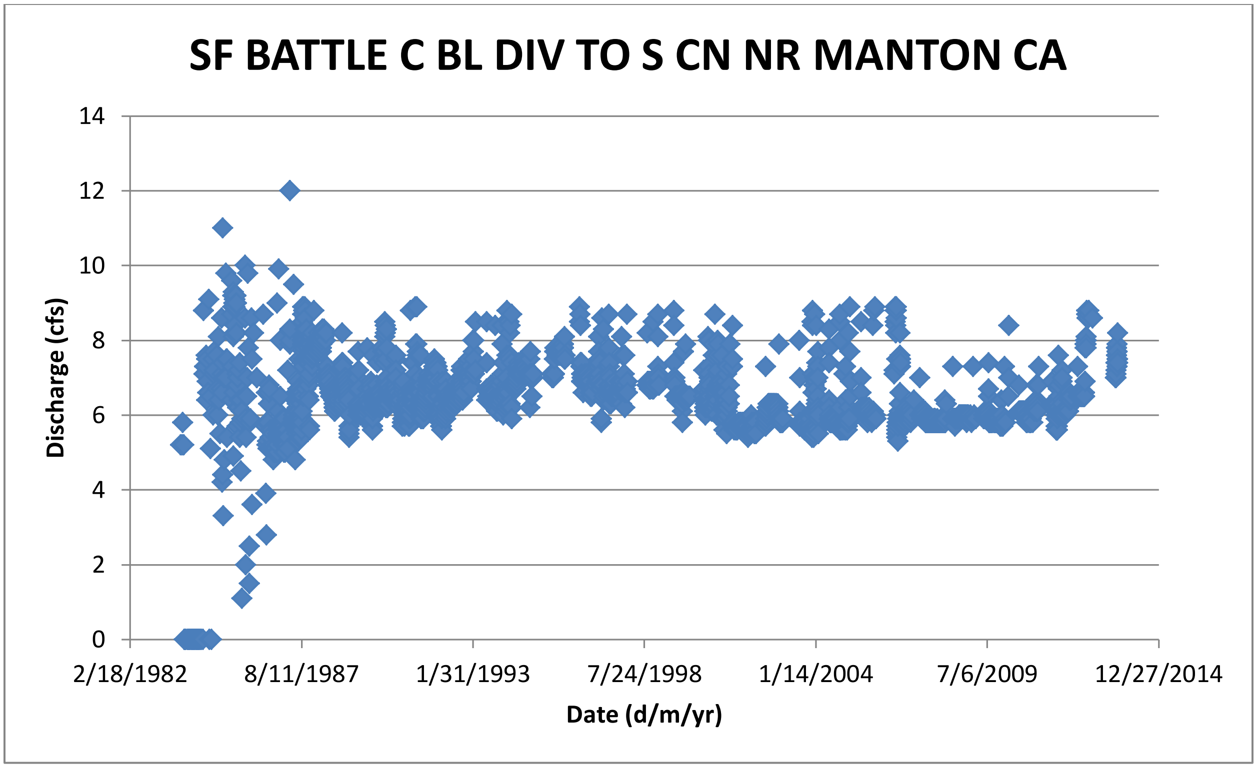

NF BATTLE C BL MCCUMBER DAM NR MANZANITA LAKE CA
Discharge (cfs)
800
700
600
500
400
300
200
100
0
11/14/1984
5/7/1990
10/28/1995
4/19/2001
10/10/2006
4/1/2012
Date (m/d/yr)

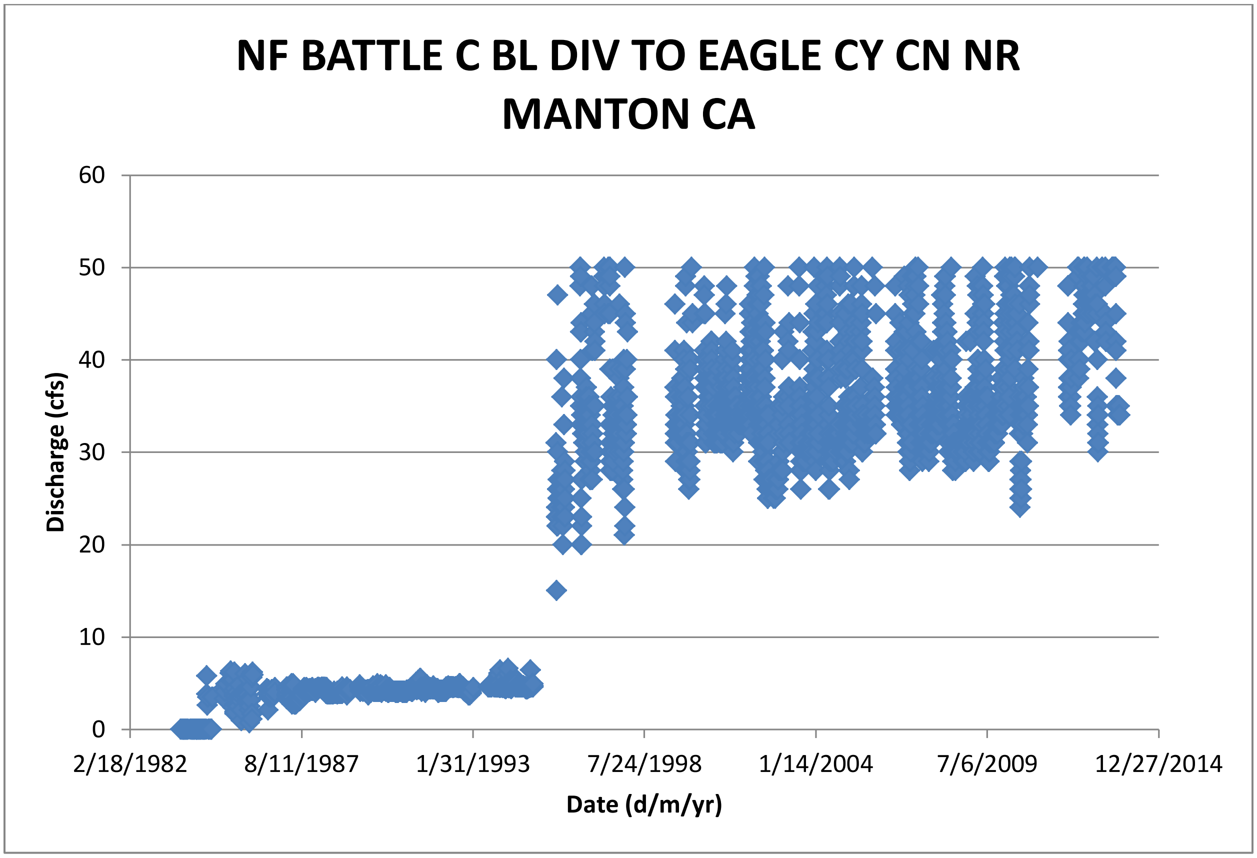

NF BATTLE C BL DIV TO AL SMITH CN NR MANTON CA
Discharge (cfs)
0
5
10
15
20
25
1/14/2004
5/28/2005
10/10/2006
2/22/2008
7/6/2009
11/18/2010
4/1/2012
8/14/2013
12/27/2014
Date (d/m/yr)


NF BATTLE C BL DIV TO KESWICK CN NR MANTON CA
Discharge (cfs)
0
1
2
3
4
5
6
2/18/1982
8/11/1987
1/31/1993
7/24/1998
1/14/2004
7/6/2009
12/27/2014
Date (d/m/yr)

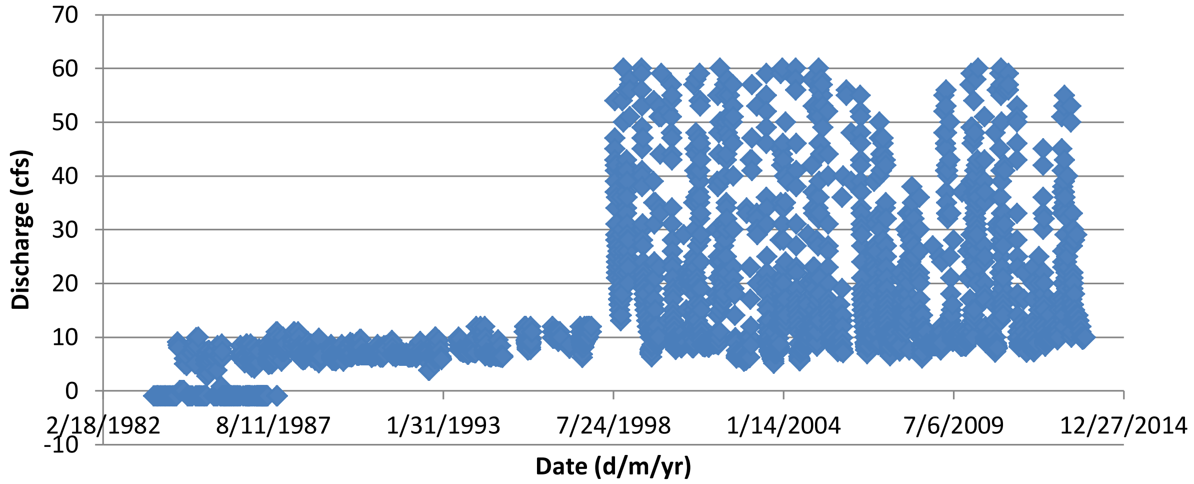

NF BATTLE C BL DIV TO XCOUNTRY CN NR MANTON CA
Discharge (cfs)
45
40
35
30
25
20
15
10
5
0
2/18/1982
8/11/1987
1/31/1993
7/24/1998
1/14/2004
7/6/2009
12/27/2014
Date (m/d/yr)


NF BATTLE C BL DIV TO WILDCAT CN NR MANTON CA
Discharge (cfs)
70
60
50
40
30
20
10
0
2/18/1982
8/11/1987
1/31/1993
7/24/1998
1/14/2004
7/6/2009
12/27/2014
Date (m/d/yr)

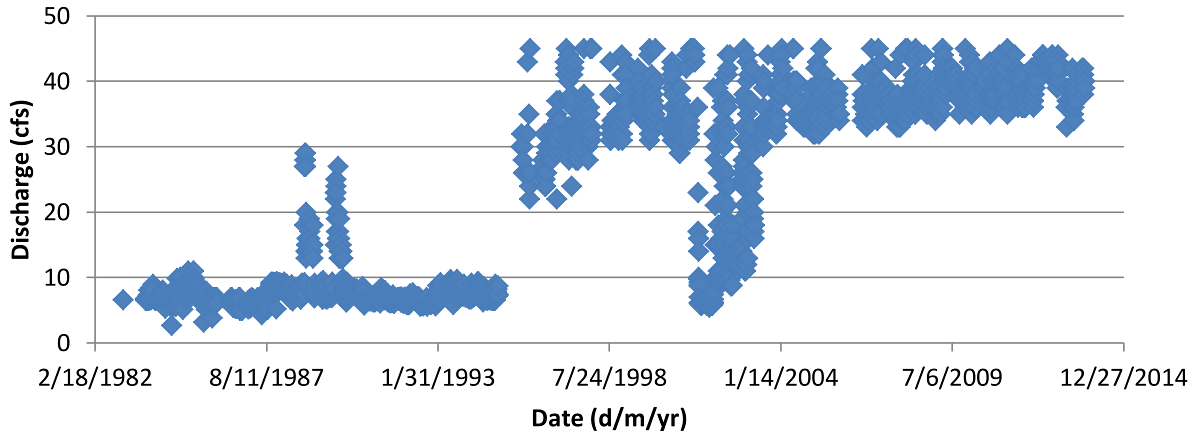

SF BATTLE C BL DIV TO S CN NR MANTON CA
Discharge (cfs)
14
12
10
8
6
4
2
0
2/18/1982
8/11/1987
1/31/1993
7/24/1998
1/14/2004
7/6/2009
12/27/2014
Date (d/m/yr)


NF BATTLE C BL DIV TO EAGLE CY CN NR MANTON CA
Discharge (cfs)
60
50
40
30
20
10
0
2/18/1982
8/11/1987
1/31/1993
7/24/1998
1/14/2004
7/6/2009
12/27/2014
Date (d/m/yr)

SF BATTLE C BL DIV TO INSKIP CN NR MANTON CA



SF BATTLE C BL DIV TO COLEMAN CN NR MANTON CA



12.2 Appendix 2: Protocols

Grab Sample Protocol

Battle Creek Suspended Sediment Sampling and Processing Protocol

A grab sample is collected in an open container from a single point at or near the turbidity sensor at ~ 0.6 water depth. Grab samples are collected with an open-mouth bottle attached to a telescoping pole. Water samples should be collected before any other work is done at a site in order to reduce the potential for disrupting the bed material.

Sample Collection with telescoping pole

1) Label sample bottle with site name, date, time, collector name, and sample number
2) Insert telescoping pole into water with open end facing upstream.
3) Rinse 3X by filling bottle at end of pole and emptying back into river
4) Fill pole bottle underwater, turn open end towards the surface and retrieve sample.
5) Transfer water sample from telescoping pole sample bottle to labeled sediment sample bottle. Repeat as needed to fill sample bottle.
6) Repeat process to collect 1) grab sample and 2) control sample.
7) Place samples in cool storage (i.e. refrigerator or ice chest) until time of processing.

Safety Protocol

PROFESSOR GREG PASTERNACK

BATTLE CREEK HEALTH AND SAFETY PLAN

IN THE EVENT OF AN EMERGENCY DIAL 911

Policy Statement

It is the policy of the college to protect the health and safety of all employees whether in an office, laboratory or field research site. It is the responsibility of each employee and their field supervisor and major professor to guard against accidents and to be prepared to the fullest extent possible for normal work conditions and emergencies. The following guidelines and resources may serve as a starting point and are in addition to those promulgated by the campus (e.g. UC Davis Policy and Procedure Manual 370-05). It is the responsibility of each employee and supervisor to read and comply with these guidelines and regulations.

General Introduction

All science, whether conducted in a controlled indoor laboratory or in an outdoor field setting, requires regular safety training and thorough consideration of safety issues specific to individual research projects. The office of Environmental Health & Safety exists as a safety consulting resource for UC Davis departments and personnel. Also available are several examples of safety protocols, guidelines and procedures developed by various units within the college to help in the formation of safety protocols for particular projects or activities. Ultimately, safety rests with each individual. Individuals are responsible for their own safety and, through their actions, the safety of those around them.

Introduction to Field Safety

Field research is defined here as comprising work activities conducted primarily for the purpose of research, undertaken by employees or students of the university outside of an office or research laboratory. Ultimately, field research involves some risk from both the research activities and chance events that are unpredictable and unavoidable. Part of the risk can be greatly reduced by awareness of hazards and exercising good judgement. Risk in field research may include, but is not limited to, the risk to physical health, emotional well-being and personal safety. The risks may arise because of the nature of the research itself, from the physical climate, or from the political, social, economic and cultural environment of the field work location. For the descriptions to follow, the following definitions are employed:

* A principal investigator (PI) is a faculty member who assembles a team to carry out field research.

* A field supervisor is a person appointed by a principal investigator to directly oversee field research on location.

* A field worker is a person who carries out research under the direction of a field supervisor.

Solitary field research activities in remote areas are strongly discouraged. Field research involving particularly hazardous locations or activities should be conducted by two or more people and only after full assessment of the risks and available controls and safety procedures has been made. In circumstances where field research necessitates solitary field research, the solitary field worker assumes the responsibilities of field supervisor. A method of regular communication should be implemented, including steps to follow if a scheduled contact is not made.

Every individual field researcher has the right to refuse, at any time, to participate in any activity that they feel may endanger their health or safety or that of another person.

Field Supervisor Safety Plan Preparatory Information

1. Scheduling:

Research on Battle Creek will be performed year-round, with turbidity and streamflow monitoring occurring during the wet season.

2. Weather

The climate is cold in winter with snow occurring in the upper portions of the watershed. Monitoring will be conducted below average snow level but monitoring sites are susceptible to winter events. Nights can be very cool. The rainy season goes from November through May, with small storms through July. On cloudless days the sun is very bright and it reflects off the bedrock, so sunglasses, hats, and sunscreen are needed. During winter and spring a minimum of 64 oz (~2 liters) of drinks are required per person per day. In the summer, high temperatures can be very hot (>100°F). Sunscreen and plenty of drinking water are required. The minimum water quantity required when the temperature is over 95°F is 96 oz (~3 liters) of drinks.

3. Protective clothing and equipment

Safety equipment: Mobile phone service is present at Coleman National Fish Hatchery.

Mobile phone service is intermittent in the Manton area. The nearest business with phone service is located at Manton Corners (Manton Road, Manton Ca 96059). A first aid kit obtained from room V219 and extra water are required on all field excursions.

Field equipment: all field equipment will be provided.

Special clothing: when needed, chest-waders and wading boots, dry suits, and life jackets will be provided.

Clothes: Consequently, field workers should bring many layers of clothing suitable for day and night use. Workers should have polypro layers suitable for wearing under waders. Quick-drying clothes are highly desirable. Rain gear is suggested November-May. The river water is very cold, even throughout the hottest parts of the summer. In-water work requires insulated waders, boots, and gloves.

4. Medical Facilities

St. Elizabeth Community Hospital is located at 2550 Sister Mary Columba Drive, Red Bluff, Ca 96080. To get there, turn south on S. Main Street from Highway 36 in downtown Redbluff and continue straight until reaching hospital. Driving distance from Manton area field sites is approximately 32 miles and driving time is approximately 50 minutes. Driving distance from Coleman National Fish Hatchery site is approximately 27 miles and driving time is approximately 35 minutes.

For more immediate emergencies, go to the Manton CalFire station at 31200 Manton Road, Manton, Ca 96059 or call at 530-474-3124. At Coleman, contact the administration on site or call, 530-365-8622.

5. Key contact phone numbers in case of emergency

Prof. Greg Pasternack (cell: 530-902-3758; office: 530-754-9243)

LAWR office 530-752-0453

For on-site injuries, also call EH&S at 530-752-1493.

See separate listing for all project contacts

6. Land access

Field sites are located on private land. Landowner permission was obtained before installation and monitoring of any field data was conducted.

South Fork Battle Creek is public access on private land owned by Ron Reid, 530-474-5106

Digger Creek is private lands with accessed granted by landowner Geoff Watson, 530-474-4110 or 530-474-5664

Coleman National Fish Hatchery: Contact Scott Hamelburg, 530-365-8622

7. Local Resources

Restaurants

There are many restaurants in Red Bluff and Redding, Ca.

Manton Corners is a general store with basic food and supplies

Supplies

There are hardware and lumber stores in Red Bluff and Redding, Ca:

The Home Depot located on N. Main Street, Red Bluff.

Redding has a battery store: Batteries plus Bulbs, 1355 Churn Creek Road, Redding, Ca 96003, 530-221-5415

Hotel and Campgrounds

Red Bluff and Redding have multiple hotel options

Red Bluff Recreation Area is US Forest Service campground located on the Sacramento River 2 miles south of Red Bluff. (530-934-3316)

8. Potential hazards

Most fatal field research accidents are related to vehicle travel. All state and local laws, rules and regulations must be followed. Defensive driving should be practiced. Drivers should switch at the first sign of fatigue, or, if alone, should stop when too tired to continue safely. University vehicles must not be used for personal or recreational purposes.

A primary threat is associated with working in or alongside roadways. Workers are at risk of being struck by passing vehicles.

High flows associated with storm events present a threat to workers. Slippery conditions, streamside vegetation, and unstable stream banks could cause a worker to fall into a stream. The risks of such a fall include hypothermia, bodily injury, and drowning.

For in-river work, boulders may be present below the water level, unseen by the researcher, which may trip or snag a person's foot. To avoid potential entrapments, researchers should only wade when river conditions permit. Specifically, wading should not be conducted when depth exceeds three feet and/or velocity exceeds three feet per second. Should a researcher be swept away by the current, the primary concern is to avoid foot entrapments. The swimmer should keep their feet up high, off the stream bed, point their feet downstream, and swim out to the side of the river as soon as possible.

9. Safety Instructions for Specific Dangers

8-hour Injury Reporting – The following injuries must be reported to EH&S (530-752-1493) as soon as practically possible but no longer than 8 hours after the employer knows or with diligent inquiry would have known of the death or serious injury or illness. A serious injury or illness is one that requires inpatient hospitalization in excess of 24 hours, or for any loss of limbs, permanent disfiguration, eye injury, or death.

Heat Stress, Cramps, Exhaustion, and First Aid – The symptoms of heat stress and exhaustion are fatigue, headache, nausea, chills, dizziness, fainting, and loss of coordination. Heat cramps are muscle spasms in the legs, arms, or stomach caused by loss of salts from sweating. To avoid these wear cool clothing, drink plenty of water and sports drinks containing salts, rest more often in the shade as the temperature rises. For first aid, move immediately to a shaded area, give cool water to person if conscious, give sports drink to person to replenish salts. If unconscious, seek immediate medical attention.

Poison Oak – Poison Oak plants are common along the west coast and may be found in fencerows, forests, pastures, shady areas, and stream banks. This woody shrub can grow from 1 to 6 feet tall, or as climbing vines wrapped around other trees or shrubs. *All* parts of the plant contain the poisonous oily substance "urushiol" which can produce painful irritation and blistering of the skin. The poisonous oil is active all year round. Touching any of the plant parts or objects that have contacted the plant can transfer the toxin to people. Do not burn the plant as it may send the toxin into the air as droplets that can be inhaled. Poison Oak can usually be identified by its leaves. In the spring, the leaves of young plants are shiny red, turning to shiny green as they mature. In the fall, poison oak foliage changes from green to orange and red. The leaves usually grow in groups of three on a shared stalk ("Leaves of three, let it be."). The leaflets are rounded at the tips and alternate on the stem. The leaf surfaces can be glossy or slightly hairy, usually 1 to 4 inches in length with lobed or toothed edges. In the spring, poison oak yields small clusters of greenish-white flowers. In the summer, greenish-white fruit resembling berries grow. Poison oak oils cause allergic reaction in nearly 85% of people exposed to the plant. Symptoms can begin within a few hours or arise 2-5 days later. The rash of poison oak typically occurs 24-48 hours after contact. The most frequent symptoms are rash in the form of blisters (sometimes in a line), blisters that may eventually break open, ooze, then dry or crust over, swelling of the contact area, red blotches that can be raised of flat, and intense itching. More severe symptoms include fever, stomach cramps, nausea, and overall body swelling. These severe symptoms should be reported to a physician immediately. Prevention of these reactions includes learning to identify and stay away from poison oak plants. Wear long sleeve shirts, long pants, and boots. Wash all clothing and tools after exposure. Skin lotions containing “bentoquatum” offer some protection before contact. Washing the skin immediately after contact using an outdoor skin cleanser is also helpful.

West Nile Virus – This virus is spread by mosquitoes that feed on infected birds and then infect humans. Only certain species of mosquitoes carry the virus. Mosquitoes are most abundant from May through October. The majority of people and animals infected with the virus do not experience any symptoms. Some may experience a mild to moderate illness, which include fever, headache, fatigue, and bodyaches. Occasionally a skin rash on the trunk of the body and swollen lymph glands may occur. In rare cases, the virus can cause more serious conditions of encephalitis, whose symptoms include headache, high fever, neck stiffness, stupor, disorientation, coma, tremors, convulsions, muscle weakness and paralysis. To avoid mosquito bites, wear long sleeves, socks, and pants, and use insect repellent. If possible, avoid dawn and dusk when mosquitoes are most active.

Lyme Disease – This disease is spread through the bite of deer ticks (nymph stages are the size of a pinhead). Symptoms include headache, fever, chills, fatigue, joint pain, and a characteristic skin rash at the site of the bite that looks like a red bulls-eye. May through July is the season for high-tick activity. Protection includes avoiding tick infested areas, avoiding contact with overgrown grass and shrubs, wearing light-colored clothing (helps spot ticks), wearing long pants and long sleeve shirts, tucking pant legs into socks, and using insect repellent on exposed skin and clothing. Check yourself and field assistants at the end of the field day. See Tip #7 for instructions on tick removal.

Rocky Mountain Spotted Fever – is caused by a species of bacteria that is spread by the bite of hard ticks or exposure to crushed tick tissues, fluids, or feces. It generally takes several hours of attachment and feeding by the tick to transmit the bacteria. RMSF is difficult to diagnose in its early stages and initial symptoms may include fever, nausea, vomiting, severe headache, muscle pain, and lack of appetite. Later symptoms are rash, abdominal pain, joint pain, and diarrhea. The rash may appear 2-5 days after the onset of fever. Prevention and treatment are similar to those of Lyme Disease (#5).

Tick Removal – to remove ticks, use the following procedures:

Use fine-tipped tweezers or shield your fingers with a tissue, paper towel, or rubber gloves. When possible, a person should avoid removing ticks with their bare hands.

Grasp the tick as close to the skin surface as possible and pull upward with a steady, even pressure. Do not twist or jerk the tick as this may cause the mouthparts to break off and remain in the skin.

Do not squeeze, crush, or puncture the body of the tick because its fluids may contain the infectious virus.

After removing the tick, thoroughly disinfect the bite site and wash your hands with soap and water.

Save the tick for inspection in case you become ill. This will help your doctor make an accurate diagnosis. Place the tick in a plastic bag and put it in the freezer. Include the date and location of the bite with the tick.

Rattlesnakes – Many species of rattlesnakes occur in the West. Rattlesnakes are diurnal. The snakes feed at night. Rattlesnakes occur from sea level to 11,000 feet. The snakes make a rattling sound to warn off invaders. The snakes are normally solitary except in the colder climates where the snakes over winter in dens together. The snakes travel from the den when warmer weather comes. The snakes are good swimmers. The snakes have scales that vary in color from yellow to brown to black and have dark V or diamond shaped markings on their backs. Rattlesnakes usually, but not always, warn the invader of their space by rattling their tail. (Santa Catalina Island rattlesnake does not have a rattle as a warning). Wear boots or other high top shoes and long pants when in an area known to have rattlesnakes. Be on the look out and watch where you sit on rocks or walk through grassy areas. The rattle is a warning to get out of the way. If you spot a snake give it at least 6 feet of clearance. “First aid for snake bites, wash the bite with soap and water, immobilize the bitten area and keep it lower than the heart, and get medical help within 30 minutes.” **DO NOT use ice or any other type of cooling on the bite area. No tourniquets, electric shock or incisions in the wound should be made.** “Basic signs like pain, swelling and bleeding, along with more complicated reactions such as ecchymosis (purple discoloration), necrosis (tissue dies and turns black), low blood pressure, and tingling of lips and tongue give medical professionals clues to the seriousness of bites and what treatment route they should take.” (Quotes are from the FDA Consumer revised in Nov. 2002.)

Bears – Bears will attack if they are surprised, feel they are in danger, wish to protect their territory or if they have cubs. “The best way to avoid danger is to avoid the bear. But if you cannot avoid them, make sure they see you first. As you walk or travel through bear territory, and if you cannot see more than 50 to 100 feet in front of you, call out every few minutes until you enter a clear area. Some people call out, others sing, some wear bear-bells”. The point is to make a lot of noise. “In most cases the bear will move off the trail and watch you pass. They rarely look for a confrontation. If you see a bear, talk to the bear.” Make sure it sees you. Hold your arms high above your head. This will make you look like a much bigger animal to the bear. “Continue to talk and slowly back away.” A female bear with cubs is very dangerous and very protective. She may attack even though you are a distance away from her. “If you are in a camp, before anything else, put your food, trash, cooking gear, fuel, soaps and toiletries up a bear pole or tree. They must be at least 12 feet (4 meters) to be secure. Then place your camp a safe distance away.” (Quotes are from arcticwebsite.com)

<u>Mountain Lion</u> – Although encounters with mountain lions are rare, it is still a possibility. “Mountain lions are plentiful in areas where there is a large deer population. As long as the food source is there, the lions do not bother humans generally but in leaner times, the lions have been known to stalk and also attack humans on the trail.” Try to avoid being alone in mountain lion territory. Make noise as you walk. “The noise you make will generally scare the lion away and halt any confrontation.” Always give plenty of space between you and the lion so that the lion can escape and get away. “Mountain lions usually do not like confrontation, so always, if you do happen to have contact, leave a wide berth between you and the lion for its escape.” “Never run away from a mountain lion. Running stimulates a mountain lion’s natural instinct to chase.” Be sure if you make contact with the lion to stand up as tall as possible. “By making yourself look larger it intimidates the lion and often makes them turn and run.” If you have a jacket on, open it and flap it about, yell, throw stones “but make sure you react so that the cat knows that you are the one in control, not him.” Never turn your back on a lion, squat down or bend over. “Research has shown that when a human bends over that person looks like a four legged prey to a large cat of any type. Avoid stooping, leaning over, squatting, or bending at the waist…” “If you are attacked, fight back. Never succumb or roll into a ball. Hit as hard as possible especially to the head area. If you can retrieve a stick or large rock, use it as a weapon. If face to face with the cat, go for the eyes by clawing or throwing sand in the face of the cat. Mountain lions will usually strike the back of the head and especially the neck so be vigilant to protect these areas and if at all possible remain standing or face to face with the animal once it is attacking. If attacked from behind, try to reposition yourself to meet the cat face to face. The cat may weigh between 100-150 lbs. Report mountain lion attacks to Fish and Game or a Ranger as soon as possible. Get medical attention.

<u>Wildfire</u> – Think about wildfire before you have to deal with it. Know your field area and potential evacuation routes in case of wildfire. Keep vehicle parked and prepared for easy evacuation. You may not have time to turn your vehicle around or look for the keys. If caught without time to evacuate, then move to the stream bed or an area without vegetation (e.g. bedrock outcrop). If campfires are allowed in your field area, then ensure that your fire is completely out before leaving it unattended.

Fire information for the Tahoe National Forest can be found at http://www.fs.fed.us/r5/tahoe/fire/index.shtml and (530) 265-4531.

Additional sources of wildfire incident information can be obtained from:

National Interagency Fire Center (NIFC): http://www.nifc.gov/

CalFire: http://cdfdata.fire.ca.gov/incidents/incidents_current

Field Worker Safety Plan Preparatory Information

Project Summary:

The project goal is to monitor turbidity using digital turbidity sensors located instream and visit sites periodically through the water year to download data and collect samples.

1. Anticipated Project Tasks

Collect water samples

Download Data

Measure discharge for Digger Creek

2. Accommodations

Day trips will be most common

Camping in developed campgrounds for extended stays

I have read and understood the safety guidelines.

Name	Date

12.3 Appendix 3: Grab Sample Turbidity Values.

Lab ID	Site	Date	Time	Sample ID	Collector	NTU 1	NTU 2	NTU 3	NTU Avg
1	SFBC	11/11/2014	16:15	C	JEH	1.2	1.0	1.0	1.1
2	SFBC	11/11/2014	16:15	G	JEH	1.9	1.5	1.9	1.8
3	DCK	11/20/2014	15:30	C	JEH	0.8	0.8	0.8	0.8
4	SFBC	11/20/2014	14:45	C	JEH	1.3	1.0	1.3	1.2
5	SFBC	11/20/2014	14:45	G	JEH	1.3	1.1	1.0	1.1
6	SFBC	11/26/2014	13:45	C	WB	1.0	1.2	1.1	1.1
7	DCK	11/11/2014	10:55	C	JEH	4.1	3.6	3.8	3.8
8	DCK	12/4/2014	11:10	1-G	GC	38.7	39.4	39.3	39.1
9	DCK	12/4/2014	11:10	2-C	GC	40.5	43.9	43.0	42.5
10	SFBC	12/4/2014	11:35	1-G	GC	194.0	191.0	187.0	190.7
11	DCK	11/11/2014	10:55	G	JEH	0.5	0.5	0.6	0.6
12	SFBC	12/4/2014	11:35	2-C	GC	182.0	180.0	179.0	180.3
13	DCK	11/20/2014	15:20	G	JEH	1.5	1.3	1.6	1.5
14	DCK	11/26/2014	12:50	G	WB	0.7	0.6	0.6	0.6
15	DCK	11/26/2014	12:55	C	WB	0.8	0.8	1.0	0.9
16	SFBC	12/11/2014	13:55	G	WB	1372.0	1372.0	1366.0	1370.0
17	DCK	12/11/2014	14:10	G	WB	1398.0	1392.0	1420.0	1403.3
18	SFBC	12/10/2014	13:45	1	JEH	15.9	14.4	13.9	14.7
19	DCK	12/10/2014	14:30	2	JEH	1.7	1.6	1.7	1.7
20	SFBC	12/11/2014	14:00	C	WB				
21	NFBC	12/10/2014	16:05	3	JEH	19.1	20.6	21.1	20.3
22	MSBC	12/10/2014	18:30	4	JEH	11.3	12.2	12.0	11.8
23	NFBC	12/10/2014	19:35	5	JEH	16.6	14.3	17.2	16.0
24	SFBC	12/10/2014	19:45	6	JEH	21.8	22.4	21.3	21.8

25	DCK	12/11/2014	14:15	C	WB				
26	DCK	12/10/2014	20:15	7	JEH	3.5	3.1	3.1	3.2
27	MSBC	12/10/2014	21:40	8	JEH	29.5	34.6	30.4	31.5
28	NFBC	12/10/2014	22:35	9	JEH	22.6	18.5	15.0	18.7
29	DCK	12/10/2014	23:15	11	JEH	791.0	789.0	786.0	788.7
30	SFBC	12/10/2014	22:50	10	JEH	23.5	25.0	22.8	23.8
31	MSBC	12/11/2014	0:15	12	JEH	22.3	25.7	23.3	23.8
32	MSBC	12/11/2014	1:30	13	JEH	27.3	23.8	26.2	25.8
33	NFBC	12/11/2014	2:20	14	JEH	63.6	52.1	50.4	55.4
34	SFBC	12/11/2014	2:35	15	JEH	309.0	315.0	313.0	312.3
35	DCK	12/11/2014	3:00	16	JEH	267.0	256.0	263.0	262.0
36	MSBC	12/11/2014	4:15	17	JEH	79.5	83.6	78.5	80.5
37	MSBC	12/11/2014	6:40	18	JEH	191.0	188.0	182.0	187.0
38	NFBC	12/11/2014	7:45	19	JEH	250.0	250.0	243.0	247.7
39	SFBC	12/11/2014	8:10	20	JEH	1244.0	1244.0	1206.0	1231.3
40	DCK	12/11/2014	8:30	21	JEH	991.0	981.0	987.0	986.3
41	SFBC	12/11/2014	8:55	22	JEH	1394.0	1366.0	1388.0	1382.7
42	NFBC	12/11/2014	9:05	23	JEH	395.0	389.0	394.0	392.7
43	MSBC	12/11/2014	10:40	25	JEH	429.0	433.0	428.0	430.0
44	SFBC	12/11/2014	12:15	26	JEH	1258.0	1272.0	1278.0	1269.3
45	NFBC	12/11/2014	12:40	27	JEH	629.0	632.0	630.0	630.3
46	DCK	12/11/2014	13:10	28	JEH	2145.0	2157.0	2145.0	2149.0
47	SFBC	12/11/2014	14:20	29	JEH	1156.0	1176.0	1156.0	1162.7
48	NFBC	12/11/2014	14:45	30	JEH	1772.0	1762.0	1742.0	1758.7
49	DCK	12/11/2014	15:15	31	JEH	1000.0	996.0	1012.0	1002.7
50	SFBC	12/11/2014	17:00	32	JEH	942.0	918.0	904.0	921.3
51	NFBC	12/11/2014	17:10	33	JEH	954.0	958.0	944.0	952.0
52	DCK	12/11/2014	17:40	34	JEH	687.0	693.0	688.0	689.3
53	SFBC	12/11/2014	18:55	35	JEH	835.0	837.0	822.0	831.3
54	NFBC	12/11/2014	19:00	36	JEH	693.0	684.0	686.0	687.7

55	DCK	12/11/2014	19:15	37	JEH	427.0	438.0	437.0	434.0
56	DCK	12/11/2014	20:20	38	JEH	374.0	376.0	372.0	374.0
57	SFBC	12/11/2014	20:35	39	JEH	606.0	605.0	599.0	603.3
58	NFBC	12/11/2014	20:45	40	JEH	489.0	490.0	484.0	487.7
59	MSBC	12/11/2014	21:40	41	JEH	633.0	625.0	623.0	627.0
60	MSBC	12/11/2014	22:50	42	JEH	518.0	519.0	524.0	520.3
61	NFBC	12/11/2014	23:40	43	JEH	285.0	285.0	282.0	284.0
62	SFBC	12/11/2014	23:50	44	JEH	361.0	349.0	347.0	352.3
63	DCK	12/12/2014	0:15	45	JEH	186.0	185.0	182.0	184.3
64	NFBC	12/12/2014	0:40	46	JEH	258.0	259.0	258.0	258.3
65	SFBC	12/12/2014	0:50	47	JEH	311.0	302.0	311.0	308.0
66	MSBC	12/12/2014	1:40	48	JEH	336.0	335.0	331.0	334.0
67	NFBC	12/12/2014	2:35	49	JEH	196.0	191.0	194.0	193.7
68	SFBC	12/12/2014	2:45	50	JEH	229.0	226.0	231.0	228.7
69	DCK	12/12/2014	9:20	51	JEH	73.4	70.8	68.1	70.8
70	SFBC	12/12/2014	9:40	52	JEH	165.0	165.0	167.0	165.7
71	NFBC	12/12/2014	9:55	53	JEH	117.0	114.0	107.0	112.7
72	DCK	12/12/2014	10:40	54	JEH	60.9	61.8	58.7	60.5
73	SFBC	12/12/2014	10:55	55	JEH	135.0	135.0	133.0	134.3
74	NFBC	12/12/2014	11:10	56	JEH	114.0	112.0	112.0	112.7
75	MSBC	12/12/2014	12:05	57	JEH	115.0	113.0	117.0	115.0
76	MSBC	12/12/2014	12:45	58	JEH	124.0	124.0	123.0	123.7
77	SFBC	12/12/2014	14:30	59	JEH	138.0	138.0	132.0	136.0
78	NFBC	12/12/2014	14:40	60	JEH	80.7	83.4	78.4	80.8
79	DCK	12/12/2014	15:00	61	JEH	40.8	37.3	38.2	38.8
80	DCK	12/12/2014	18:15	62	JEH	33.0	34.5	33.9	33.8
81	SFBC	12/12/2014	18:40	63	JEH	94.7	96.6	96.9	96.1
82	NFBC	12/12/2014	18:50	64	JEH	76.1	71.5	71.6	73.1
83	MSBC	12/12/2014	19:40	65	JEH	81.8	79.3	80.4	80.5
84	MSBC	12/12/2014	19:50	66	JEH	76.4	74.2	73.4	74.7

85	NFBC	12/12/2014	20:30	67	JEH	70.9	67.3	69.7	69.3
86	SFBC	12/12/2014	20:40	68	JEH	83.9	83.0	84.2	83.7
87	DCK	12/12/2014	20:55	69	JEH	29.9	30.7	30.1	30.2
88	DCK	12/13/2014	8:15	70	JEH	17.6	17.3	17.2	17.4
89	SFBC	12/13/2014	8:50	71	JEH	48.9	48.2	48.8	48.6
90	NFBC	12/13/2014	9:00	72	JEH	45.0	46.1	42.5	44.5
91	MSBC	12/13/2014	9:45	73	JEH	45.5	43.9	45.7	45.0
92	MSBC	12/13/2014	10:25	74	JEH	51.7	48.3	50.1	50.0
93	NFBC	12/13/2014	11:05	75	JEH	39.4	40.0	36.7	38.7
94	SFBC	12/13/2014	11:15	76	JEH	45.6	48.3	46.4	46.8
95	DCK	12/13/2014	11:30	77	JEH	15.4	15.7	15.1	15.4
96	DCK	12/13/2014	15:30	78	JEH	16.6	15.8	16.9	16.4
97	NFBC	12/13/2014	15:45	79	JEH	43.2	45.9	42.7	43.9
98	SFBC	12/13/2014	15:55	80	JEH	43.6	43.3	40.7	42.5
99	DCK	12/13/2014	21:35	81	JEH	12.3	10.4	10.6	11.1
100	SFBC	12/13/2014	21:55	82	JEH	34.8	35.3	33.3	34.5
101	NFBC	12/13/2014	22:05	83	JEH	31.5	30.3	31.7	31.2
102	MSBC	12/13/2014	22:50	84	JEH	32.0	29.5	28.4	30.0
103	DCK	12/14/2014	11:45	85	JEH	7.1	7.1	7.2	7.1
104	SFBC	12/14/2014	14:15	86	JEH	23.1	23.1	23.2	23.1
105	NFBC	12/14/2014	14:25	87	JEH	19.0	19.4	18.4	18.9
106	MSBC	12/14/2014	15:15	88	JEH	22.5	21.9	21.9	22.1
107	MSBC	12/14/2014	15:30	89	JEH	21.6	21.9	20.9	21.5
108	DCK	1/2/2015	12:55	G	WB	0.5	0.6	0.5	0.5
109	DCK	1/9/2015	13:55	G	WB	0.5	0.5	0.6	0.5
110	NFBC	1/18/2015	14:30	G	JEH	7.1	6.6	7.6	7.1
111	DCK	2/1/2015	13:00	G	JEH	1.0	0.9	1.0	1.0
112	DCK	3/31/2015	11:45	G	JEH	0.6	0.5	0.5	0.5
113	MSBC	3/31/2015	11:45	G	JEH	1.5	2.4	2.0	2.0
114	SFBC			7.0 ft	SS	63.0	55.4	56.0	58.1

115	SFBC	3/31/2015	13:15	G	JEH	1.0	1.0	1.1	1.0
116	DCK	3/12/2015	13:15	G	SE	0.9	0.6	1.3	0.9
117	NFBC	1/9/2015	14:20	G	WB	1.7	1.5	1.2	1.5
118	MSBC	3/12/2015	14:45	G	SE	1.6	0.9	1.3	1.3
119	SFBC			8.0 ft	SSSS	145.0	149.0	149.0	147.7
120	MSBC	1/31/2015	12:00	G	JEH	2.4	1.9	2.5	2.3
121	NFBC	1/31/2015	15:45	G	JEH	1.5	2.6	1.8	2.0
122	SFBC	1/2/2015	12:50	G	WB	2.5	2.9	2.2	2.5
123	SFBC	1/31/2015	16:15	G	JEH	2.5	1.5		2.0
124	SFBC	1/20/2015	9:15	G	JEH	19.4	19.7	19.1	19.4
125	NFBC	3/31/2015	12:50	G	JEH	2.0	1.2	1.1	1.4
126	NFBC	3/12/2015	13:40	G	SE	2.1	1.4	1.5	1.7
127	SFBC	3/12/2015	13:25	G	SE	4.5	3.8	4.4	4.2
128	DCK	1/17/2015	?	G	JEH	1.3	1.3	1.1	1.3
129	NFBC	1/20/2015	9:00	G	JEH	2.9	3.0	3.0	3.0
130	MSBC	1/18/2015	15:15	G	JEH	3.7	3.5	3.7	3.6
131	DCK	1/20/2015	8:45	G	JEH	1.1	0.9	0.8	0.9
132	BLUFF SPG	1/19/2015	12:05	G	JEH	7.0	7.5	7.1	7.2
133	NFBC	1/2/2015	13:15	G	WB	1.6	1.5	1.9	1.7
134	SFBC	1/9/2015	13:40	G	WB	2.5	2.5	3.0	2.7
135	BLUFF SPG	1/19/2015	12:40	G	JEH	21.9	21.3	21.1	21.4
136	MSBC	1/31/2015	12:15	G	JEH	3.6	2.6	4.4	3.5
137	SFBC	1/18/2015	12:45	G	JEH	2.9	2.5	2.7	2.7
138	SFBC	1/17/2015	14:45	G	JEH	3.0	3.4	2.8	3.1
139	NFBC	1/17/2015	14:44	G	JEH	3.9	2.7	2.7	3.1
140	NFBC	5/7/2015	9:45	G	SE	0.9	0.9	1.0	1.0
141	DCK	5/7/2015	10:15	G	SE	1.8	1.9	1.1	1.6
142	SFBC	5/7/2015	10:40	G	SE	1.4	1.9	2.2	1.8

143	MSBC	5/7/2015	9:05	G	SE	1.0	2.2	1.3	1.5
144	MSBC	5/12/2015	14:20	G	JEH	1.2	1.6	1.5	1.4
145	SFBC	5/12/2015	16:40	G	JEH	1.4	1.5	1.5	1.5
146	DCK	5/13/2015	8:30	G	JEH	2.1	2.2	2.2	2.2
147	NFBC	5/12/2015	15:30	G	JEH	1.0	1.1	1.2	1.1