APPENDIX 9

GEOLOGIC AND GEOMORPHIC INFORMATION REVIEW FOR SMITH CREEK BASIN

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I: Summary

This document is part of series of efforts by the California Geological Survey to address a set of critical questions. The questions were provided in a concept paper that is the foundation of the overall effort. CGS provided a series of work products with geologic emphasis to support the effort that include:

- A description of the role of landforms in the creation of habitat niches.
- Two public presentations in Fort Bragg, California
  - Focused on landscape evolution
- A three-track approach to data gathering, organization, and interpretation described in this document.

This document integrates the results of the above efforts. The document is organized by the following topics: Bedrock Geology, Hillslope Erosion, Roads, Large Woody Debris (LWD), and Channel Conditions. Subheadings for each topic are Key Concerns, Key Findings, and Explanation. Some topics are broken down into subtopics.

Overarching Findings

Overarching findings that apply across each of the topics are:

- Readily available data exist and provided a limited, somewhat blurry view of the geologic dynamics within the Smith Creek watershed and the encompassing Campbell Creek Planning Watershed.
- Numerous data gaps and data quality issues adversely impact the confidence in Interpretations of the watershed conditions and processes.
- To guide restoration activities, data requires supplementation to address questions brought up herein.

Viewed from broader contexts longer than a decade, data are not supportive of the “boiler-plate”, limited-scope, cumulative effects assessments found in THPs. The findings vary with the degree of rigor and confidence that is desired in the data. The data quality ranges from moderate to poor and the temporal and spatial coverage is spotty at best providing a blurry and possibly distorted view of sediment-related cumulative effects.

On the other hand, the picture of cumulative effects, if we accept the data at face value, substantially differs from the descriptions in THPs. The picture that emerges, if data are valid, true, and sufficient is the following interpretation which due to low confidence in the data should be considered as a working hypothesis.

1) The stream system that is out of equilibrium (Simon and Rinaldi, 2006) and shifting, possibly irreversibly to a new state which possibly may be within the long-term natural range of variation and has experienced;
   a. episodes of channel incision that necessitated morphological reclassification between 1994 and 2012 in the lower reach and between 2012 and 2015 in the upper reach;
   b. ongoing sediment delivery to Smith Creek from a population of landslides that are thought to have initiated recently to almost 90 years ago;
   c. intermittent spikes in harvest-related and road-related landslide activity, especially in the early 1970s and the 1990s; and
   d. ongoing aggradation caused by a persistent presence of debris jams that break-down and reform in the middle reach of Smith Creek, implying continual resupply of woody debris and sediment most likely due to ongoing bank erosion and channel incision in the middle reach and its tributaries.

A9-Table 1 shows the features, detailed in separate sections, used to develop the above scenario and how the various approaches agreed or disagreed. Detail for the individual processes are provided in separate sections. A9-Tables 2, 3, and 4 provide a timeline of significant watershed events derived from the available data.

The working hypothesis and other questions raised herein provide a basis for restoration planning which includes monitoring to determine trends and corrective measures.

Throughout this document, I described data issues as 1) data gaps, 18 times; 2) omissions, twice; 3) misclassification, once; 4) misrepresentation, once; 5) perishable, outdated, or obsolete, once each; 5) contradictory, once; 6) bias, three times and 7) generally lacking in important detail, many times. To illustrate the uncertainty about data and the importance of data gaps, I included 50 unresolved questions regarding the specific topic of sediment-related cumulative watershed impacts some of which cannot be accurately answered without decades of quality data which is not readily available and may not exist.

II: Introduction

The Campbell Creek Pilot Project Working Group was established as part of the Data and Monitoring Working Group. The group was formed under the umbrella of the Timber Regulation and Forest Restoration Program. Background information about these groups are available online at the Resources Agency website. The California Geological Survey is a member of these groups.

One task before the Campbell Creek Pilot Project Working Group relates to judging how well the cumulative effects of land use and restoration opportunities can be derived from readily available information contained in Timber Harvest Plan (THP) documents which are certified as the functional equivalent of environmental impacts assessment under CEQA. Supporting documentation can be either attached to the THP or incorporated by reference. Supporting documentation may include agency and industry data, either of which may have been collected and analyzed by consultants. The consultants included: Tim Best, John Coyle, Graham Matthew and Associates, Lee Benda and Associates.

Primary geologic concerns considered in THPs and their review is erosion, sedimentation of stream channels, and slope and channel stability. Do THPs include sufficient landslide data to judge the cumulative effects of forestry? How complete and reliable are landslide datasets? For landslides that deliver sediment to watercourses, what are the volumes, types, and grain sizes of the materials? How do the materials affect biological condition?

The primary goal of this document is to assess available information and provide meta-analysis for the following Critical Questions that were assigned to the Working Group within the narrow scope of geologic and geomorphic information.

- Is there adequate information available in past THPs and other available data sources to thoroughly and accurately characterize current biophysical and ecological conditions on the planning watershed?
- Are there major gaps in the types or quality of available information, on a planning watershed scale, that would be useful for THP preparation and review, and assessment of cumulative impacts?
- Do past THPs, collated on a planning watershed basis, contain the information needed to guide restoration at the planning watershed scale?
- What restoration needs or cumulative impacts can be identified from the planning watershed scale versus needing a different spatial context?

Focused Cumulative Effects Review of Smith Creek

Each timber harvest plan (THP) includes a statement as to how the plan under consideration may contribute to the background of historical cumulative effects and near-future effects. The documentation has evolved through time in response to concerns about the adequacy of the assessments. In earlier THPs the statement consisted of a checklist. Recent THPs provide narrative discussions that include the land use history of the watershed and its recovery. During the review process, agency staff review the assessments and have the option of rejecting any deemed inadequate. Plan approval asserts agreement with the assessments which struck a balance between agency and industry perspectives.

For Smith Creek basin, I reviewed the cumulative effects assessments for several THPs spanning from 1991 to 2015 and found them to be very similar, "boiler-plate" treatments which may be appropriate when little to no additional information is considered. The consistency between assessments may reflect the narrow focus of the proposed action within a ten-year context despite the broader context and timeframe of ecology and geomorphology processes. Additionally, I reviewed THP maps and Preharvest Inspection (PHI) reports and reference data to identify geologic and geomorphic information.

According to each of the cumulative effects assessments, 1) the historic land use prior to the forest practice rules had severely altered the Class I and II watercourses, 2) legacy effects persist, and 3) the proposed plan, operating under more stringent rules, would not significantly and adversely increase the cumulative impacts across the watershed. Underlying assertions are that 1) adherence to the forest practices rules is sufficient to prevent additional cumulative effects and 2) agency review and enforcement are sufficient. Assuming the assessments and those assertions are valid, it follows that this independent review of readily available information would prove corroborative. If so, legitimate restoration needs and opportunities might be recognized and validated through the review. This 24-year retrospective review and meta-analysis of cumulative effects assessments may reveal how the assessments and their conclusions have played out.

Comparison and Synthesis of Three Tracks

The Campbell Creek Pilot Project Working Group approached cumulative effects assessment via a three-track methodology. Each of the three tracks provided a different perspective of the cumulative effects of timber harvest. Each perspective served as a check-and-balance on the remaining perspectives. The three tracks were: 1) THP document review and data mining, 2) rapid assessment via remote sensing, and 3) modelling ranging from simple to sophisticated. The demand for efficiency underpinned each approach. As such, we were deliberately limited to the use of readily available information. Nobel Prize recipient, Werner Heisenberg's admonishment that states "What we observe is not nature itself, but nature exposed to our method of questioning" applies.

Each of the tracks has its benefits and its limitations. It is hoped that collectively the derived information will provide a more correct and coherent view of the cumulative effects of forestry and restoration opportunities by answering the following general questions.

1. What is the natural range of variation?
2. What are the current conditions?
3. What is the history of changing conditions?
4. How and how much has forestry improved or perturbed the conditions?
5. What is the trajectory into the future and how might intervention improve outcomes?

THP Data

Private forestland is owned and operated by landowners and their agents. They control access to their land and their data. Typically, they have the most intimate knowledge of the land that they manage. They are the producers of the greatest volume of readily available information. Agencies are granted access for the purposes of THP approval and sometimes for the sake of transparency, compliance, or mutual benefit.

Legal mandate forces the THP review process to be rapid, inclusive, and decisive. As such, review is streamlined and deadline bound with little energy devoted to collecting independent data or independent analysis. The rapid assessment and modelling tracks are intended to fill data gaps.

THPs provide industry data and perspective that has been reviewed and accepted by regulatory agencies. The documentation can be extensive but is not exhaustive and is inevitably a product subject to influences of persuasion. THPs have reported conditions at the various time intervals determined by harvest schedules and therefore allow a rough timeline of watershed events to be pieced together.

Rapid Assessment

The rapid assessment track provides an independent view of the history of land use and disturbance across the watershed without being prejudiced by prevailing opinion or slanted (persuasive) presentation but is limited to providing a macroscopic view. Aerial photos from 1947-2017 provide a timeline with good temporal resolution but poor spatial resolution.

Modelling

The modelling track can produce objective results but the "garbage in, garbage out" mantra applies. Like the rapid assessment, it provides a macroscopic and reductionist view that sometimes is superior in presentation than in substance and so can be misleading and oversimplifying. Modelling results have no temporal resolution and compress nearly a century-long timeline into a single composite.

Cumulative Effects Assessment

There are many aspects to cumulative effects and in the following I focus on the processes of soil erosion, mass wasting, and sedimentation of streams. The line of reasoning that I followed is as such: the cumulative effect of mass wasting and erosion will become amplified and apparent through the stream network. Aquatic conditions provide signals as to the level of stress the ecosystem is under and whether impacts are deleterious. Stream survey data and other stream observations should reveal the magnitude and variation of sedimentation related to land use, mass wasting, and erosion throughout the watershed. Below I evaluate the quality and validity of data and attempt to figuratively "trace" or in other words "follow the sediment" through the watershed from source to sink relying on readily available information.

A9-Table 1: Summary table showing a process-based crosswalk between the three tracks of inquiry for sediment related topics. Abbreviations are: CGS, California Geological Survey; CWE, cumulative watershed effects; DFW, Department of Fish and Wildlife; DEM, digital elevation model; LDA, large debris accumulation; and PHI, pre-harvest inspection.

Process	Feature	Rapid Assessment	THP Review	Modelling	Notes	Data Quality
Bedrock geology	Geologic structures	Folding and faulting defined litho-topographic domains	No mention	Used to construct erosion domains	Existing data is poor. Outcrop and road cut exposure is limited.	Profound data gap
Bedrock geology	Lithology	Poorly defined except for alluvium of which I mapped 34 locations	Little mention at scattered sites	Data is poor.	Although geomorphically important has received little attention outside of dissertations. Best (2015) stated that sandstone is more resistant to erosion than shale.	Profound data gap
Erosion	Erosion	Numerous litho-topographic domains mapped	Localized road points, landslides, and field-EHR	eEHR and erosion domains mapped		Adequate
Hillslope erosion	Landslides	Numerous domains mapped, axial rift mapped	Landslide inventories show abundant slides localized in litho-topographic domains	Hot spot analysis showed localized landslides along axial rift margins	Fair agreement with observed landslide locations within generalized unstable slopes	Incomplete and inconsistent. High resolution DEM is needed.
Hillslope erosion	Roads	NA	Sparse maintenance data lacks environmental connection	Erosion map developed	Fix-it pts lack diagnostic data	Poor fit for CWE
Channel erosion	Incised reaches	Incision predicted due to lithology,	2 inner gorges on PHI maps, general mention of incision in	Plan curvature suggests pervasive incision	Good agreement across each method	Spatially incomplete until high resolution

		deformation, and climate	CGS-PHI memos. DFW surveys indicate pronounced entrenchment			DEM can be field verified
Channel erosion	Knickpoints	Predicted as part of vertical ground deformation	DFW surveys indicate numerous LDA and a few bedrock controlled knickpoints	Abundant knickpoints throughout the network	DFW surveys covered only the lower 2/3s of the main stem while modelling covered entire watershed	Spatially very incomplete and poor time resolution.
Channel erosion/sedimentation	Chokepoints	Identified but not mapped	No specific mention	A few locations mapped	Good correspondence with some LDA	Spatially very incomplete. and poor time resolution.
Channel sedimentation	Aggraded reaches	Localized aggradation predicted by subsidence	1 mention in CGS-PHI memo, several LDA in DFW survey, described in THPs	Scattered and numerous flat reaches bounded by steep gradients	Good agreement between modelling and DFW survey and close agreement with THP reports, will improve with hi-res DEM	Spatially very incomplete and poor time resolution.
Channel sedimentation	LDA	No specific mention	1 CGS-PHI memo, 2 DFW surveys	See aggraded reaches	Modelling roughly corresponded to DFW survey	Spatially incomplete and poor time resolution.

A9-Table 2: Timeline of watershed events from circa 1952 to 1993. Smith Creek is divided into three reaches: the lower reach in the western domain, the middle reach in the central domain, and the upper reach in the headwaters in the eastern domain. Harvest dates in the timeline are placed according to year the THP was submitted. Actual harvesting may have occurred the following year. Question marks indicate a span of time for which no data has been found. Multiple year conditions or trends are shown as vertical text that spans multiple rows. Forty-five watershed events are identified spanning the century of timber management. For the eastern domain, there is an approximate 20-year period of little information.

Years	Lower Reach and tributaries		Middle Reach and tributaries		Upper Reach and tributaries	
circa 1920	General watershed-wide steam donkey and railroad clearcut per THP 1-13-031					
1937	Significant storms					
1938	Significant storms					
1945	Extensive fire per Best, 2015					
pre1947	Apparent watershed-wide spike in landslides per Coyle					
pre1952	General watershed-wide spike in landslides per Coyle and Best					
pre1952	One large landslide per Best		Landslides at Site D per Best continue to deliver sediment until 2012	Circa 1952-2012: ~53 years of landslide sediment delivery, channel incision, and aggradation	Several landslides, one reactivated in 1991	?
1954	Significant storms		Significant storms		Significant storms	
1955	Significant storms		Significant storms		Significant storms	
1964	Significant storms		Significant storms		Significant storms	
pre1965, post1952	?		Spike in landslide activity		Spike in landslide activity	
1966	Significant storms		Significant storms		Significant storms	
1974	Significant storms		Significant storms		Significant storms	
pre1975, post1965	One large landslide per Best		?		?	
pre1975, post1965	Extensive tractor-logging, road construction, and major spike in landslides per Coyle and Best				Two landslides	
pre1975, post1965	Landslides at Sites A and B deliver sediment until 2012	Circa 1970-2012: ~45 years of landslide sediment delivery	?		?	
pre1975, post1965	LWD removal		?		?	
1980s	?		**See Note 1**		?	
1983	Significant storms		Significant storms		Significant storms	
1987	?		**See Note 2**		?	
1991	January storms caused watershed-wide flooding and incision per THP 1-93-092.					
1991	Harvest activity		Harvest activity		Harvest activity	
1992	?		Harvest activity		?	
1993	Of 33,352' of Smith Creek, 43%pools >2', 73 pools per 1000' occuppying 21% of stream length per DFW, banks composed clay/silt/sand					

A9-Table 3: Continuation of the timeline of significant watershed events from 1994 to 2017.

1994	Rosgen C4 per DFW, 4 LDA per 1,000'	1994-2012: 4X decline in LWD, channel type changed from C4 to F4	Rosgen B4 per DFW, 1 LDA per 1,000'	1994-2012: Channel type remains B4	Rosgen B4 per DFW, 0.5 LDA per 1000'	1994-2013: Channel type changed from B4 to F4, aggradation
1994	Harvest activity beginning in 1993		?		?	
1994	Spike in landslide activity		2 landslides per Best		1 landslide per Best	
1996	Harvest activity beginning in 1995		Harvest activity		Harvest activity	
1997	Significant storms		Significant storms		Significant storms	
1998	Significant storms		Significant storms		Significant storms	
1998	Harvest activity beinning in 1997		Harvest activity		Harvest activity	
pre1999, post1987	1 large landslide		2 landslides per Best		1 landslide per Best	
1999	Significant storms		Significant storms		Significant storms	
2001	Harvest activity beginning in 1997		Harvest activity beginning in 1997		?	
pre2002, post1987	1 large landslide		?		?	
2003	Significant storms		Significant storms		Significant storms	
2005	Harvest activity		Harvest activity		Harvest activity	
2005/6	Significant storms		Significant storms		Significant storms	
2008	Harvest activity		Harvest activity		Harvest activity	
2012	Of 20,0073' of Smith Creek, 28%pools >2', 137 pools per 1000' occuppying 49% of stream length per DFW					
2012	**See Note 3**	?	See Note 4	?	Rosgen B4 per DFW, 0.5 LDA per 1000'	?
2013	**See Note 5**		Unstable, incised Class II tributaries with headcuts per CTM		?	
2013	Harvest activity		Harvest activity		Harvest activity. **See Note 6**	
2015	?		?		**See Note 7**	
2015	?				Harvest activity	
2016/7	Significant storms					

A9-Table 4: Notes to accompany tables 2 and 3.

Note 1: Severely aggraded with continued impacts due to the railroad grade that runs along the creek and remnant trestles that induced landslide at Site C since 1965(?) per CGS that continues to deliver sediment. Conditions also may relate to pre1975 landslide spike.
Note 2: In 1991, Class I and Class II streams aggraded with deposits that appear to have originated when the old growth was logged 70 years ago. The Class II stream were found to be **incised** in places per CalFIRE. Conditions also may relate to pre1975 landslide spike.
Note 3: Rosgen F4 per DFW, <1 LDA per 1000’, silt to cobble banks, sedimentation from Site A and B landslides
Note 4: Rosgen B4 per DFW. Sedimentation from Site C and D landslides, 6 LDA per 1,000’, gravel bed with bedrock, sand, and large cobble, silt to sand in banks, low embeddedness, shallow pools
Note 5: CGS geologist indicated in 2013 that the channel appeared to be actively downcutting and that the landslides appeared dormant.
Note 6: Rosgen F4 per the timber company, gravel bed, high embeddedness, shallow pools, high LWD, eroding RR grade
Note 7: Rosgen F4 per the timber company, gravel bed, high embeddedness, shallow pools, high LWD, eroding RR grade

III: Bedrock and Alluvial Geology

Key Concerns

- How does the distribution of hard versus weak bedrock define the configuration of the drainage network?
- To what degree is the observed channel entrenchment natural or anthropogenic?
- How is the rate of channel incision controlled and predetermined by variation in bedrock strength due to tectonic shearing or the distribution of weaker shale versus hard sandstone?
- Where is sediment generated? Where is sediment stored?
- Channel incision requires a mobile bedload of hard, coarse material to abrade the underlying substrate. What is the distribution of such material and where, in the watershed, is it produced?

Key Findings

- The central domain is probably the greatest source area of sediment, particularly in the form of shallow-seated landslides and bank erosion but there is very little relevant available information.
- It remains unknown whether the landslides deliver hard rock to the channels that would function as the cutting tools necessary to effect incision.
- For the middle reach which occupies the central domain, sediment production may counterbalance the tendency toward incision as currently expressed in the lower and upper reaches. Alternatively, harder bedrock may limit incision. Bedrock exposures occur in the bed of the middle reach but have not been described.

- Progressive rotation and offset of bedrock likely has been an underlying factor in the formation of knickpoints and waterfalls as well as numerous, small, and intermittent sediment basins.
- The Middle Fork and the South Fork of the Ten Mile River occupy the northerly and southerly lateral margins of an uplifted arch in the bedrock. Stretching of the bedrock along the axis of the arch created a rift zone in which Smith and Campbell Creeks formed. Refer to the Hot Spot Analysis section.

Explanation

Bedrock is the foundation of the forest and watershed. Geotechnical studies show that rock strength exerts a major control on sediment yield. Rock strength represents a combination of lithology and weakening through weathering and fracturing. In a recent study, Bywater-Reyes and others, 2017 found that suspended sediment yields following timber harvest are principally modulated by the lithology of the bedrock underlying the watershed.

Channel Incision and Rock Strength

The character of sediment and rock strength dictate channel incision rates (Sklar and Dietrich, 2001). Maximum erosion rates occur at a critical level of coarse-grained sediment where bedrock is only partially exposed. The grain size distribution of sediment supplied from hillslopes to stream networks is the fundamental control on bedrock channel gradients and topographic relief (Sklar and Dietrich, 2001). As such, landslide debris in stream channels may either promote incision or provide a protective bedload that retards incision (Bennett and others, 2016, Gilbert, 1877). Accurate mapping of channel sediment is critical to assessing sediment budgets particularly because remobilized historic sediment may be a significant source of ongoing impacts (Koehler and others, 2007).

Variation in Rock Strength

Geologic maps are often used to identify 1) the presence of geologic formations (in lieu of lithology) and 2) major geologic structures that weaken rocks. The information is rarely at a site-specific scale. A geologic formation may be a collection of diverse lithologies and hence rock strengths. Formations such as the Franciscan Assemblage (which underlies the Campbell Creek Planning watershed) are complex, anisotropic, and inhomogeneous. For example, Andras and others, 2005 determined millennia-scale erosion rates for the neighboring Bear Haven and Redwood Creek watersheds using geochemistry. The Franciscan Assemblage underlies each of the watersheds which are geologically and topographically similar to Campbell Creek and Smith Creek basins. Nonetheless, the erosion rates varied by as much as a factor of two, suggesting variation in rock strength may be controlling factor.

THP-based Geology Descriptions

THP-based descriptions of the arrangement and character of the bedrock that underlies the watershed are cursory in nature likely because of a paucity of known detail. I found no bedrock mapping at a watershed scale: only regional maps are available. Best (2015) states, “Topography is controlled, in part, by differential erosion of the underlying bedrock. Areas underlain by competent sandstone bedrock tend to be more resistant to erosion and form steeper gradient slopes compared to slopes underlain by relatively less resistant shale and siltstone. Best (2015) also states, “Field observations of weathered bedrock exposed in road cuts reveal the rock is variable in composition and strength but consistent with regional description.” Such general regional descriptions provide little detail to analyze. Four CGS-PHI memos report general lithology as exposed in road cuts in the western portion of the watershed. The observations are specific to areas visited during a PHI but are generalizations as well. The observations ranged from highly sheared, hard sandstone to highly sheared and weak shale. Collectively, those few observations show no systematic exposure of shale in the stream channels with sandstone on the hillsides nor do they show shale being limited to the eastern basin – both of which have reported in various geology reports. This represents a significant data gap.

Geomorphic Rapid Assessment

As part of the rapid assessment I subdivided the watershed into litho-topographic domains (as per Montgomery, 1999 – bearing in mind the lithology data gap) and discerned a four phase sequence of landscape evolution that explains the topography much better than the highly generalized lithology as has been relied on in the THP (industry and agency) geology reports. Phase one, four to two million years ago, is characterized by regional uplift of the bedrock above sea level, phase two, 2,000,000 to 11,000 years ago, is characterized by localized arching of the landscape and formation of the San Andreas Fault system, phase three, from 11,000 years ago to present, involves previously unmapped faulting that broke and offset bedrock in the watershed, and phase four relates to subsidence and tilting that effects the North Fork Smith Creek subbasin. Marine terraces along the Mendocino coast formed during phase two. The Noyo basin and the mouth of the Ten Mile River formed during phase three.

Taken together, Smith Creek, Campbell Creek, and South Fork Ten Mile River comprise a series of parallel streams with similar planforms. The streams are deflected toward the NW to NNW in a series of three to four offsets – presumably due to strike-slip faulting (Ouchi, 2004) although no such fault is found on published geologic maps. The most prominent deflection trends NW and is over one-mile long. The stream pattern is characteristic of strike-slip faulting, in general, and the San Andreas Fault, in particular, where large horizontal displacements create repeating patterns in stream networks. For the purposes of this project, a fault trace was mapped along the SF Ten Mile River which extends to fault exposures in the coastal bluffs as described by other workers. This fault appears to be the dominant geologic structure explaining the gross geomorphology encompassing the Smith Creek basin. At a finer scale, the geomorphology in the basin is more complicated and best described by subdividing the area into domains of litho-topographic similarity (as per Montgomery, 1999 – bearing in mind lithology data gap) and by stages of landscape evolution.

The Campbell Creek Planning Watershed crosses three NW-oriented bands of varying litho-topographic characteristics that can be referred to as an eastern domain, and central domain, and a western domain. The Albion River watershed lies approximately 17 miles to the south of Campbell Creek and occurs within a similar set of geomorphic bands (Fuller and Custis, 2004) that parallel structural patterns in the Campbell and Smith Creek basins. For example, the central domain consists of 1) at least three parallel fault zones that define the rugged topography and appear to break the east-west profiles of ridgelines, 2) numerous alluvial flats that may represent relict sag ponds due to fault or landslide movements, 3) apparently subsiding and tilted sub-basins, e.g., North Fork Smith Creek basin, and 4) two isolated zones of substantially more subdued and apparently mature topography characteristic of the east and west bands flanked by faults. The topology of the drainage network varies substantially between each domain and controls sediment routing and storage (Walley and others, 2017) as revealed by the rapid assessment. The topology is in turn controlled by the distribution of bedrock. Sediment transport models that do not accounted for such fundamental controls are likely to produced flawed results.

Need for Geologic Framework

The findings of the geomorphic rapid assessment provided much more relevant detail than has been the standard in the THP-related documents.

Without a proper geologic framework, explanations of the spatial and temporal distribution of landslides have been inconclusive or overly simplistic. The domains provide a better understanding of the landscape history and help to distinguish geologic controls on stream channel conditions and differentiate anthropogenic influences. The domains provide information as to where, in the watershed, bedrock may be most weakened by shearing. The distribution of lithology remains undetermined. Nonetheless, domains provide a framework for future work.

As part of the modelling track, I developed an erosion map, as described below, and evaluated the relevance of the geologic stages and domains to the localization of erosional processes. In regard to erosion, phases three and four are the most significant. The central domain is probably the greatest source area of sediment, particularly in the form of shallow-seated landslides and bank erosion but there is very little relevant information available. For the middle reach which occupies the central domain, sediment production may counterbalance the tendency toward incision as currently expressed in the lower and upper reaches. Alternatively, the bedrock may be resistant to incision. This represents a significant data gap.

IV: Hillslope Erosion

Erosion

Key Concerns

- Sedimentation of water resources
- The plan-by-plan basis of documenting and addressing erosion in the THP process results in a patchwork of incomplete data coverage, both spatially and temporally.
- The legacy of outdated forest practices such as gullies and landslides remain but are obscured underneath the blanket of vegetation. In some case, these sites are still episodically eroding and are not fully accounted for.
- Cumulative watershed effects analysis is hamstrung due to the lack of a solid database that covers the entire basin and extends decades into the past.

Key Findings

- The watershed is heavily forested in the uplands and lowlands are grassy prairie providing protective covering for the soil to reduce erosion.
- THP documents report erosion, on a plan-by-plan basis, in the following manner: 1) erosion hazard ratings (one site per harvest unit), 2) road maintenance and repair locations, 3) unstable areas, and 4) erosion sites in an erosion control plan - only the two most recent THPs.
- The data regarding erosion sites and road work sites provides a spatially explicit, historic perspective of observed erosion. However, the data is perishable and its significance is short-lived because once the work is conducted, the issues are generally resolved.
- Agency staff possess and sometimes use an electronic erosion hazard rating (eEHR) model that provides ratings across broad regions. The ratings report calculations for susceptibility to inter-rill erosion. The scope is limited to predicting suitability of proposed yarding methods and road construction. Volumetrically, the most important geomorphic processes of mass wasting and channelized, fluvial erosion are not reflected in the ratings.
- I prepared a more comprehensive erosion map that adds consideration of mass wasting plus channelized and fluvial erosion. The erosion map predicts susceptibility to erosion and mass wasting across the Smith Creek basin.
    - An independent set of erosion data points were extracted from THP and PHI maps. Another independent set of shallow-seated landslide data was available as a GIS file from Tim Best. The two sets of points were combined to create a population of 461 erosion sites in order to validate the erosion map's predictive accuracy. Eighty-seven percent (361/416) of the erosion sites occur within 10 meters of areas that the erosion map showed as more likely to experience erosion. I need to clip out Campbell Creek and focus on Smith Creek only.
    - The erosion map distinguishes areas that primarily shed sediment from areas that primarily store sediment.
    - The erosion map indicates that sediment production (area-weighted) from the central domain may be double the production from the western and eastern domains combined.

- The total acreage of known and predicted areas of sediment production due to shallow-seated landslides is nearly double the acreage of the area available for sediment transport and storage – suggesting that spikes in sediment generation could disproportionately affect watercourses.

Explanation

Detection

The watershed is heavily forested in the uplands and lowlands are grassy prairie providing protective covering for the soil to reduce erosion. In addition to protecting soil from erosion, vegetation also cloaks it from view, especially in aerial photographs but also during field inspections. The watershed is typically inspected along roads and anadromous steam channels. With thick vegetation the range of sight is very limited and so detection of erosion more than 100 feet off of roads is severely limited. Steeply incised topography adds another by limiting sight angles. Harvest units do reveal erosion. Past THPs mainly describe active road-related erosion and unstable ground. However, there is no record of past erosion such as along legacy infrastructure. The past erosion belongs in the sediment budget as far as judging cumulative effects of sediment. But the data are nonexistent.

Geomorphic mapping and erosion modelling can be a helpful proxy by providing a watershed view of inherent erosion susceptibility and thus help define where the distribution of past erosion. Debris slide slopes are an example of a geomorphic features which are susceptible to erosion as much as they are to mass wasting. A susceptibility map provides for general predictions but lacks a temporal dimension.

Erosion Hazard Ratings

The FPRs require, at the time of THP development, that erosion hazard ratings are calculated based on predicted ground cover after harvest is complete. Ratings are also used to restrict yarding methods and guide the installation of drainage structures. Actual post-harvest conditions may vary. As vegetation regrows subsequent to harvest, the ground cover increases substantially and the erosion hazard thusly decreases. It is important to realize that ratings as reported in THPs are valid for only a small number of years and quickly become outdated.

The eEHR map of watershed-wide erosion hazard ratings was developed to show in a general way the variation in erodibility due to inherent soil and topographic properties. It does not and cannot represent either actual erosion or any particular timeframe. However, the map does provide a reference as to locations where greater care or scrutiny may be appropriate in planning and regulating timber harvests.

At the watershed scale, we assumed an average ground cover of 85%: however, we acknowledge that this broad brushstroke cannot be equally representative for the various vegetation types (redwood forest, oak woodland, and prairie) or the recency and intensity of harvests (e.g. anything from a 1-year old clearcut to an old selection cut) within the watershed. Additionally, this watershed scale map does not consider mass wasting (e.g., landslides or geomorphic features related to landslides) or fluvial erosion (e.g. debris flows, gullies, streambank erosion, etc.) that are known to be present in the watershed.

Erosion Map

At a coarse level, the spatial distribution of erodibility follows the underlying pattern of three litho-topographic domains and included steep areas. Refer to the Bedrock section. Road-related erosion is an example of imposed erosion the distribution of which mimics the road network especially in areas of high susceptibility. I refer to such roads as "geo-connected" roads and discuss the topic in the Roads section.

Based on geologic domains and landslide mapping, I partitioned the domain map into erosion domains based on eEHR, synthetic debris slide slope model, etc. As an independent test of the erosion map, I compared the distribution of erosion sites taken from THPs. The distribution of the erosion sites matches very well with areas of high erosion susceptibility shown on the erosion map.

The composite erosion map and its component layers provide raster-based generalizations of erosion susceptibility. Each cell in the composite raster grid contains an overall score representing the potential significance of underlying factors i.e., landslides, slopes, soils, and rock weakening. Scores for underlying factors are recorded in separate rasters. The scores quantify the spectrum from erosion to sedimentation across the watershed based geomorphic features, topography and hydrology. Erosion is reflected as positive integers while sedimentation as negative integers. Figure 1 shows the proportion of the total score for each domain.

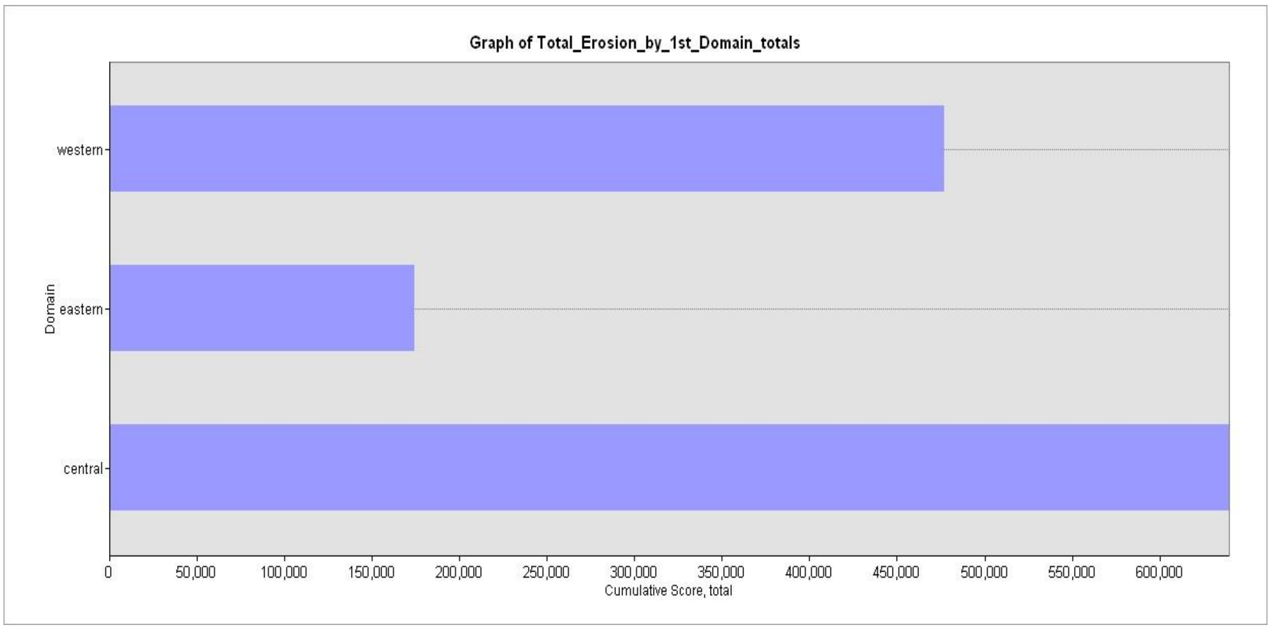

Figure 1: Distribution of erosion susceptibility by domain.

The importance of the central domain becomes more prominent in Figure 2 which shows the distribution of erosion susceptibility across the domains normalized by area.

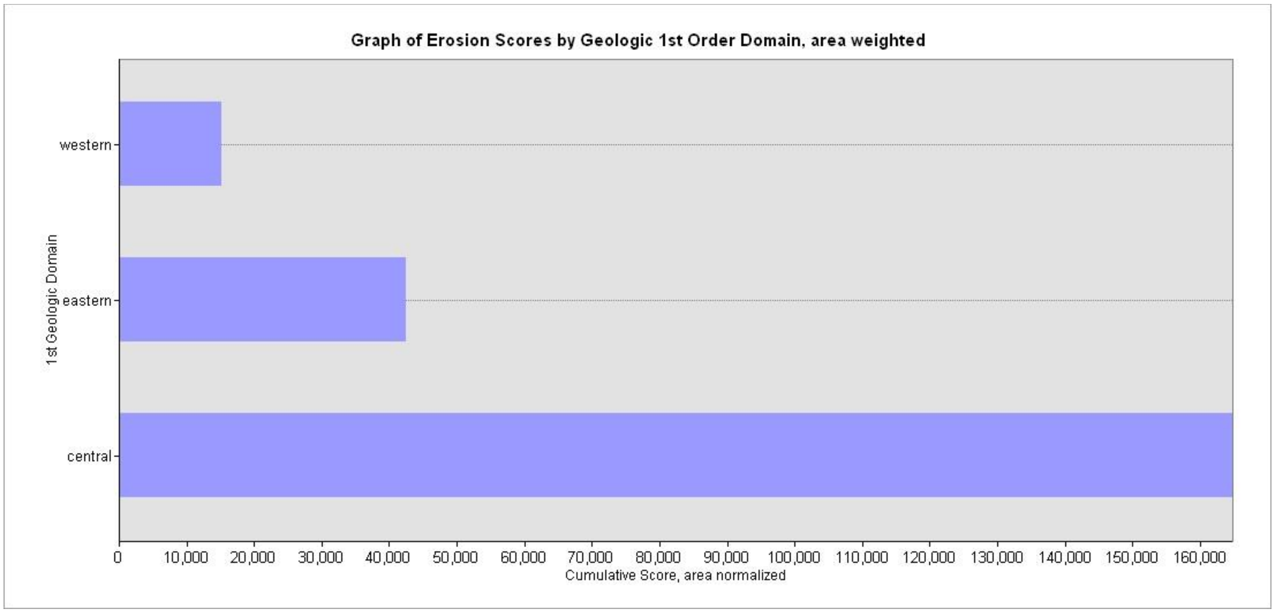

Figure 2: Area-weighted distribution of erosion susceptibility by domain.

The erosion map in Figure 3 shows the values of erosion susceptibility with green (negative values) to red (positive values) color ramp. Stream channels are focused areas of water flow and potential bank and bed erosion.

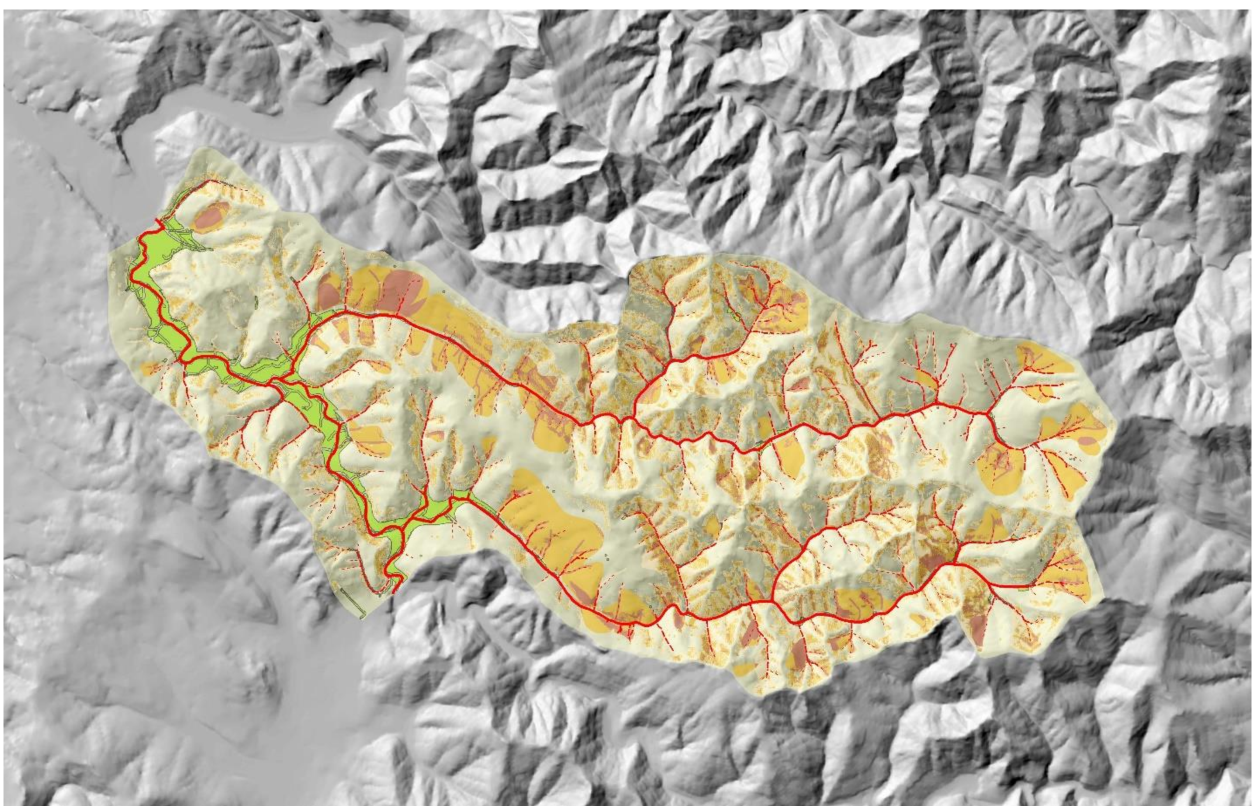

Figure 3: Erosion susceptibility map for Smith Creek displayed as a green to red color ramp indicating low to high values respectively.

Mass Wasting

Key Concerns

- Public safety and sedimentation of water resources.
- Sustainability of the road network.

Key Findings

- Landslide detection via aerial photographs in forested areas is moderately effective.
  - De facto field verification indicates 30-50% of shallow-seated landslides may be undetected via aerial photography.
- CGS-PHI memos contain limited but important field observations that provide de facto field verification.
  - Observations are extremely limited. Only two observations document conditions along Smith Creek.
  - Observation sites are pre-selected by THP preparers and reviewers.
- The landslide inventories have not been updated since 2006.
- A 2012 DFW stream survey of the lower 2/3s of Smith Creek confirms the presence of four landslides mapped by Best; however, they suggest that all the slides impacted the channel contrary to the Best's interpretation that only one did.
- A comparison between sediment yields determined from Best's and Coyle's datasets of shallow-seated landslides showed strong agreement in the total volume (approximately 6,700 tons per square mile) and timing of sediment delivered to watercourses.
- Landslide sediment yield from both datasets indicate two periods of pronounced activity; a period between ~1940 to 1952 and a period in the early 1970s with the latter exceeding the former by a factor of two.
- As part of a rapid assessment, I examined aerial photographs that are available to agency staff. Throughout the Smith Creek basin, I detected a few additional landslides, both dormant and historically active. This was not a comprehensive effort; instead it was intended to evaluate the validity and thoroughness of the existing landslide inventories.
- Based on the de facto field verification, true landslide activity could be greater by a factor of two to four over what has been detected in aerial photographs; thus sediment yield estimates should be increased accordingly.
- Landslide inventories indicate that landslide activity relates to episodes of threshold exceedances and it has been nearly 40 years since the last extreme episode. The extreme episodes stemmed from outdated logging practices coinciding with fire and flood.
- THP documents from 1991 to 2015 show a period of pronounced slide activity between 1991 (coincident with a spike in even-aged logging) and 2000 (coincident with even-aged logging from 1997-2001), a lesser peak of activity from 2010-2015, and general slide activity between 1960 and 1980.
- The interval between THPs and subsequent associated observations is 6 to 14 years in the western domain, 6 to 24 years in central domain, and 6-11 years in the eastern domain. The interval between storm runoff events that produce bank-full flows that are geomorphically effective is usually two years. Thus, the sampling interval seems to be much greater than the recurrence interval of potentially important geomorphic events that consequently are poorly documented confounding interpretation of cumulative effects.
- The interval between stream surveys is 28 years, much too long.

Explanation

Data Validation and Error Analysis via Comparison between Aerial Photo-based Landslide Inventories

I compared landslide data from three different sources (CGS and two consultants, John Coyle and Tim Best) and its use in deriving sediment budgets which along with streambed data (DFW surveys, THP observations) provide the closest approximation of cumulative impacts due to erosion and sedimentation. None of the landslide inventories can be consider either definitive or authoritative. I evaluated the validity of aerial photo-based landslide inventories by 1) comparing different inventories and 2) comparing interpretations of landslide activity and impacts with field observations. I focused on consistency between data sets to 1) judge validity and data gaps to then 2) judge data sufficiency for data-driven cumulative effects interpretation. I compared the data-driven interpretations against the historical narratives provided in THPs in the Cumulative Effects section of this document.

Comparison between Best dataset and CGS Map (Kelley, 1983)

Best (2015) explained that his landslide mapping shows more landslides and a broader expanse of debris slide slopes than the CGS map (Kelley, 1983) which is one of a 30-year old series of over 40 landslide maps of varying quality. In many other watersheds, the CGS maps are the only source of landslide data. The CGS map shows deep-seated landslides and debris slide slopes. Best modified the boundaries of these features and may have added a few unrecognized features but the differences are small. The CGS landslide map shows very few shallow-seated landslides compared to the other inventories. One of the possible reasons for discrepancy may be related to reliance on a single set of aerial photos; whereas the other inventories used 8 and 11 sets. The difference is profound suggesting that the CGS map is outdated and should be considered as superseded by the more thorough efforts of Coyle and Best.

Comparing Coyle and Best Landslide Frequencies

Another comparison was made against landslide inventory work performed in support of the TMDL development. John Coyle (Graham Matthews and Associates, 2000) mapped 198 shallow slides in the Smith Creek basin using aerial photos. Coyle detected approximately 20% more slides than Best. Coyle's photo set included 11 years, spanning 57 years (1942-1999). Best's photo set included 8 years, spanning 54 years (1952-2006). Both Coyle and Best reported a very important finding. They reported that the vast majority of the shallow-seated slides (by count and volume) that delivered sediment to watercourses initiated during two periods or episodes; prior to 1952 and prior to 1975. This finding appears reasonable due to the prior deforestation and fire that was evident in the 1947 and 1952 aerial photos that were examined.

Confounds

Nonetheless the conclusion is less exceptional when the following confounds are taken into account. The confounds distort the temporal frame and may create false spikes in landslide frequencies.

First, the ability to detect shallow-seated landslides in aerial photography is greatly influenced by vegetation. In a heavily forested area, vegetation removal may expose hidden landslides. The detection ratio (number of slides detected/number of actual slides) is very high (perhaps >0.9) after vegetation removal and much lower (<0.5-0.7) under dense forest as evaluated below under the Ground-truth heading. This singular effect may create the illusion of a 20-40% increase in landslide frequency.

Secondly, another concern regards significant differences in the resolution of time throughout an aerial photo set. In the case of Coyle's set the average time between photo acquisitions was 5.2 years. In the case of Best's set, the average was 6.8 years. Landslides were interpreted to have occurred between the date of oldest photos that did not show the slides and the date of the earliest photos that did show the slides, i.e., landslides are assigned to time periods (bins) spanning 5-7 years on average. However, the time period represented in the earliest photo in each set is poorly constrained.

The earliest photos may reveal landslides that occurred decades prior -especially in the case of reactivation or continual activity. Given the young revegetation, landslides up to 20 years old were possibly detected the earliest photo of each set. Therefore, if landslide frequencies were constant, a 20-year bin would contain at least triple the number slides than a 5 to 7-year bin. Even if we assume the first bin to be only ten years, the illusion of a false 130-200% spike in landslide activity could result.

Using Best's data set of shallow-seated landslides, the pre1952 bin contains double the number (90 versus 43) in the 1965 to 1974 bin. These two confounds result in a large margin of error which may explain the skewed distribution. Lastly, Coyle used an earlier set of photos from 1942 as well as the 1952 photos used by Best. To evaluate the potential significance of slides that occurred more than a decade earlier than the photo acquisition, I combined Coyle's pre1942 and 1942 to 1952 slides into one bin, 80% of which occurred prior to 1942. In other words, 80% of the landslides in Best's pre1952 bin may have initiated a decade earlier. This confirms the concern of a potential false spike due to skewed data.

Hence, shallow-seated landslides detected in aerial photos predate the photos for a period ranging from many years earlier to immediately before depending on photo quality and revegetation. Consequently, the true temporal frame of landslide activity cannot be deduced with high confidence; thus blurring cause-and-effects relationships and confounding interpretations by requiring data to be crudely binned.

Validation and Error Analysis via Ground-truth

Rigorous ground-truthing of aerial photo-based landslide inventories usually involves random or targeted sampling strategies focused on the level of detection and the accuracy of attributes assignments. That level of effort was not feasible in this case. Instead, I reviewed THP documents to link ground-level descriptions of unstable ground to the Best landslide inventory which is available as GIS point data.

False Positives

Best (*pers. comm.*) incorporated limited ground-truthing into the effort while Coyle (Graham Matthews and Associates, 2000) did not. Additional de facto ground-truthing occurred during PHIs especially if attended by an agency geologist. Because the Best inventory was provided as a GIS file, it was useful in evaluating map relations and comparison against THP and PHI maps. Of 164 shallow-seated landslides in the Smith Creek basin (as mapped by Best), 12 (7%) were independently confirmed by a CGS geologist during PHIs since 1987. None were refuted indicating that false positives (erroneous detections) were not obvious where examined and may not be problematic. The vast majority of the PHI-recognized landslides were heavily vegetated according to memos; thus, hindering remote recognition in aerial photography which indicates the methodological limitations of aerial photo-interpretation.

False Negatives

I reviewed THPs from 1991 to 2015 which covered 1,617 acres of the 3,482 acres of Smith Creek basin, representing 46% of the basin (most of the 54% of the basin that is not part of the following analysis lies in the central domain). In that 46% of the basin, I extracted documentation of 49 landslides of which, nine occurred within 100 meters of landslides in the Best inventory of 164 landslides. Given the small scale of the THP maps, I suggest that 100 meters is reasonable spatial error and that the nine slides may equate to the those in the Best landslide inventory. The remaining 40 of the slides documented in THPs but not in the Best inventory may represent either additional slides undetected by Best or substantial mapping errors. Assuming the maps are reliable, that means 40 additional slides per 1,617 acres or 0.025 slides per acre. Applying the ratio to the full area of the Smith Creek basin, yields 86 (0.025 slides per acre times 3482 acres) potentially additional slides in the Smith Creek basin -presumably in the much steeper central domain excluded from this analysis. Adding the 86 additional slides to the Best inventory indicates an adjusted total of 250 shallow-seated landslides.

Based on the adjusted inventory count of slides, 20% (49/250) of the slides were documented in THP documents that span 46% of the watershed. The Best landslide inventory of 164 represents 66% (164/250) of all potentially discoverable landslides. In other words, THP and PHI maps, if assumed accurate to 100 meters, provide a poor sample of landslides. Alternatively, THP and PHI maps may be unreliable in content and locational accuracy. Aerial photo-based inventories provide a better but under-representative sample. The additional 40 slides that were recorded as part of a PHI but not part of the Best data, indicate false negatives may be problematic in the landslide inventories. This degree of detection bia**s** is common in heavily forested settings resulting in moderate uncertainty and underscores the importance of understanding data reliability.

Landslide Activity

There is little information on ongoing instability or reactivation of individual landslides.

Best's inventory indicated the year of the photo in which each slide first appeared. Later photographs also showed the slides which may have remained active, became dormant, or reactivated. Best's inventory did not systematically provide information regarding continued activity.

Of the slides that are documented in both the Best inventory and THPs, THP documents provided little information related to landslide activity. However, notes on 28 of the THP-identified slides included age estimates based on the age of post-slide vegetation growth. Relying on that THP data, I evaluated time-space distributions. The time-distribution showed a major period of slide activity between 1991 and 2000, a lesser peak of activity from 2010-2015, and general slide activity between 1960 and 1980. All of the 28 slides lie within 30 meters of either a road or harvest unit. Many of the slides occur in two distinct time-space clusters - one tight time-space cluster in the western domain (1991-2000, above the stream restoration site) and a broader time-space cluster on the south-facing slopes of the eastern domain. Given that the spatial coverage is 46% of the basin, other time-space clusters may exist but remain undocumented in either the Best inventory or the THP record. By acreage, THPs peaked in 1998, 2001, 2005, 2008, and 2015. The spatial and temporal pattern in the 28 slides may be reflective of the underlying distribution of THPs representing a sample bias. A different pattern of THPs may show a different clustering of landslides.

Delivery to a Watercourse

The 2012 DFW stream survey provides the only source of field verification of landslide impacts to watercourses. The survey covered 20,061 feet of the main stem of Smith Creek. That represents just 11% of the 175,824 feet of streams in the basin. The DFW survey noted four streamside landslides that they referred to as either erosion sites or landslides. I assumed the sites were noted due to probable or real impacts to the channel.

Each of the four sites appear to have been include in the Best landslide data based on close proximity. However; of the four streamside landslides, only the large debris slides at one site were consistently classified in the Best dataset and in a CGS-PHI memo – providing ground verification. Best indicated that the slides delivered sediment to Smith Creek in apparent agreement with the stream survey. None of the other sites were identified by Best as impacting Smith Creek which I consider to be false negatives in terms of delivering streamside landslides. That finding suggests that use of aerial photos is unreliable in detecting sediment delivery in riparian zones.

The four sites of assumed landslide impact to Smith Creek are as follows:

Site A: At 10,296 feet upstream of the mouth, within the F4 reach, a landslide with a volume of 770 cubic yards was identified both by Best and the stream survey. Best indicated the slide initiated in 1975. However, Best did not indicate that the slide impacted Smith Creek contrary to the stream survey.

Site B: In another location 13,067 feet upstream of the mouth (upper limits of the F4 channel), an identified erosion site corresponds with debris slides initiated by 1975 (volume of 15,901 cubic yards or roughly 24% of the total of delivering landslides in Best data) as identified in Best's dataset and confirmed during by CGS during the PHI for THP 1-90-058MEN.

This appears to be the most significant sediment source contributing sediment to Smith Creek with 20 pieces of LWD impounding sand and gravel for 86 feet upstream. Subsurface stream flow through the mass was noted.

Site C: Another substantial erosion site, at 15,615 feet upstream from the mouth, corresponds to “severe” aggradation and bank erosion due to stream deflection from remnant trestles as observed during the PHI for THP 1-87-566MEN. The CGS PHI memo assumed the bank erosion initiated in 1965. The height of bank erosion was estimated at 45 feet and so should be classified as a landslide. Best mapped the slide and indicated that the debris slide was active in the 1952 and 1974 but did not consider it to deliver to Smith Creek.

Site D: A third substantial erosion site is located 16,320 feet upstream of the mouth. The slide is 80 feet high with a volume 440 cubic yards as determined by Best who dates the activity to 1952 and did not think sediment delivery occurred. The stream survey indicates that this slide is partially revegetated. Being over 60 years old, the fact that the debris slide was only partially revegetated signifies ongoing erosion.

Cumulative Effects Analysis

Estimates of Landslide Impacts to Watercourses

I compared the data and interpretations of Best and Coyle regarding landslide magnitude and sediment delivery to watercourses. I applied Coyle’s (Graham Matthews and Associates, 2000) method to Best’s data.

- Coyle selected landslides that were judged as delivering sediment to watercourses.
- Coyle calculated sediment yield by multiplying landslide volumes by a conversion factor (1.48 tons per cubic yard) and a delivery ratio (0.166, 0.50, or 0.833). The total sediment-yield across the entire photoset equals 6,770 cubic yards.
- Best recorded sediment delivery as either yes or no.
- Best database provides cubic yard estimates instead of sediment yield.
- Selecting only the landslides that Best indicated sediment delivered to a watercourse and applying the intermediate delivery ratio of Coyle (0.50), the sediment-yield for the entire photoset calculated to 6605 cubic yards.

The comparison showed strong agreement between the aerial photo-based inventories.

- Landslide sediment yield from both datasets indicate two periods of pronounced activity; between ~1940 to 1952 period and in the early 1970s with the latter exceeding the former by a factor of two.
- The DFW survey indicates that streamside sites that experienced delivery of landslide debris may be underestimated by a factor of four in the Best’s database; however, the comparison is weak due to the small number of sites.

Volumetrically, the pre1975 landslides exceeded the pre1952 slides by a factor of 2 to 3. The actual proportion of that volume that entered the stream network is unknown. Because of the greater volume and lesser intervening time, sediment from the pre1975 events is more likely to remain in the channels in places. Does in-channel sediment remain from pre1975, or pre1952 landslides? If so, where is it stored and how has it affected habitat? Are conditions improving?

Field-based Estimates of Soil Creep and Bank Erosion in Analogous Areas

Despite the close agreement between sediment yields based on aerial photo-based landslide inventories, the results have been challenged.

Lee Benda and Associates (Andras and others, 2005) found that cosmogenic radionuclide derived erosion rates for neighboring watersheds were 240% higher than that determined based on aerial photo-based landslide inventories.

Lee Benda (Benda and Associates, 2004) estimated soil creep and bank erosion based on field data from other portions of the Ten Mile River and the Noyo River watersheds. The report states, “sediment production from soil creep (i.e., bank erosion) and streamside landsliding derived from the wood budget was 600 t km-2 yr. This is, on average, 750% higher than the 77 t km-2 yr-1 in the Ten Mile TMDL.” That interpretation did not include the effects of debris flows which in the Redwood Creek part of the study contributed 37% of LWD.

If applicable, this proof-by-analogy supports impressions that the air photo-based landslide inventories seriously underrepresent sediment delivery – whether natural or anthropogenic.

1990s Spike in Landslide Activity

THP data of landslide activity during the 1990s is shown in A9-Table 5.

1. One set of skid trail-caused gullies formed in an area that had not been recently harvested. Although the age is unknown, that it was related to a skid trail indicates that the erosion was harvest related.
2. One large landslide and two fill failures occurred in a 1991 clearcut within 5 years of harvest under THP 1-86-072.
3. An additional fill failure occurred on a landslide that initiated by 1952 meaning that the road was built across the slide at some point prior to 2013.
4. One deep-seated landslide formed in a 1991 clearcut, eight years after harvest occurred
5. A pre-existing landslide reactivated in a 1988 harvest unit.
6. A 1999 deep-seated landslide formed three after a selection harvest. A clearcut unit under the same plan had no post-harvest landslides.
7. Five landslides, two debris flows, a debris slide, and gullies formed one to two years after a selection harvest.

Table 5: Harvest related landslide activity from 1986 to 2015. Shading indicates temporal-spatial groups.

Domain	**Occurrence Year**	**Event**	**Source**
Eastern	1952(Best)-1986(THP)	1 stream diversion caused gully	THP 1-86-072, Best
Eastern	1986	harvest	THP 1-86-072
Eastern	1991	clearcut	THP 1-91-110
Eastern	1991-1996	1 large landslide	THP 1-96-274
Eastern	1991-1996	2 fill failures	THP 1-96-274
Eastern	1999(Best) prior to harvest	1 set of skid trail caused gullies	THP 1-01-206, Best
Eastern	1981(THP)-1999(Best)	1 landslide	THP 1-01-206, Best
Eastern	1991(THP)-1999(Best)-2001(THP)	1 fill failure, no recent harvest	THP 1-01-206, Best
Eastern	2001	Clearcut	THP 1-01-206
Eastern	1991	Clearcut	THP 1-91-110
Eastern	1952(Best)2013(THP)	1 fill failure on 1952 slide	THP 1-13-031

Eastern	Dormant(THP) - 1999(Best)	1 deep-seated landslide	THP 1-13-031, Best
Eastern	1988	Harvest	THP 1-88-030
Eastern	1978(THP) -1999(Best)	1 reactivated landslide	THP 1-88-030, Best
Eastern	1996	Clearcut	THP 1-96-128
Eastern	1996	Selection	THP 1-96-128
Eastern	Dormant(THP) - 1999(Best)	1 deep-seated landslide	THP 1-13-031, Best
Western	1990	commercial thin	THP 1-90-058
Western	1990	1 debris flow	THP 1-93-092
Western	1991	commercial thin	THP 1-91-439
Western	1991-1998	3 landslides	THP 1-98-029
Western	1991-1998	2 landslides, skid trail caused gullies, and debris slide	THP 1-98-029

Figure 4 shows the temporal distribution of THPs and shows spikes centered on 1991 and 1998.

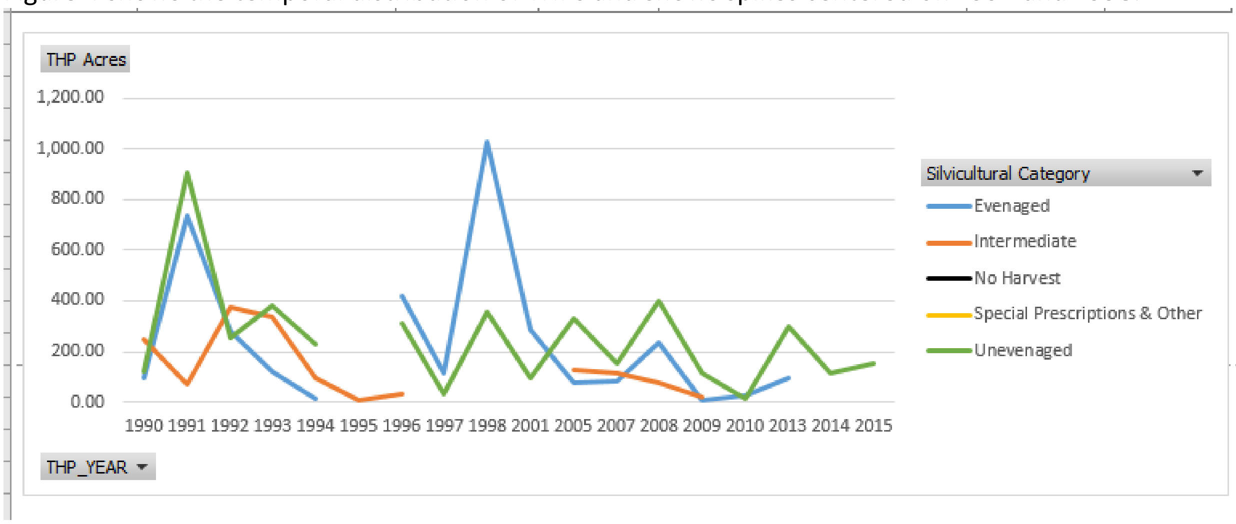

Figure 4: Acres under THP by year

Hot Spot Analysis

In recognition of the limited reliability of landslide detection from aerial photo-interpretation, two hot spot analyses using the data points from the landslide inventory were conducted to generalize the geographic data and to show broader areas of higher probabilities for landslides, referred to as hot spots. The hot spots were compared against 1) areas of high to extreme erosion hazard ratings, 2) slope, 3) geologic structures.

One analysis included all the shallow-seated landslides from the Best dataset and showed the central domain to be the most significant hot spot in apparent agreement with the erosion map, see the Erosion Map section. A second analysis included only the landslides that occurred away from streams and roads to better define background hillslope instability. The second analysis showed the strongest correlation was to geologic structures; specifically, to the margins of the axial rift of a fold formed during Phase 2 of landscape evolution, see the Bedrock Geology section. However; hot spot analysis could not include the possibly 86 false negatives in the landslide data set which are possibly concentrated in the central domain. The false negatives, if identified, may strengthen the finding of the major significance of the central domain.

V: Roads

Key Concerns

- Identifying linkages between forest roads and streambed sediment is not straightforward and has not been successful in repeatable studies (Al-Chokhachy and others, 2016).
- According the TMDL, roads are the most significant, controllable source of anthropogenic erosion.
- Sedimentation of water resources and the hydro-connectivity of roads to watercourses
- Road assessment as apparently performed in THP preparation and agency review amounts to generating a punch list of fix-it points but does not consider the long-term interaction between the road network and the immediate environment. Such an assessment does not support assessment of cumulative impacts on a watershed basis.

Key Findings

- Data regarding the mutual interaction of the road network and the environment is lacking. This data gap is critical if CWEs are to be evaluated.
- In the absence of an environmentally-aware road assessment, I have used the erosion map, described in the Hillslope Erosion section, to connect environmental data to road segments and the road network.

Explanation

Although THPs often present road mitigation points for areas that lie within the limits of a given plan, the data are parsed, spatially and temporally, by THP boundaries and not provided as a detailed history on a watershed basis. Current or legacy roads that may be impacting the environment outside of a THP may not be disclosed during the THP review process. It is the rule rather than the exception that 5-10% of similar road systems result in ~90% of the environmental impacts. Important sediment sources may go unrecognized. This represents a data gap.

Sediment conditions in stream channels have been related to aquatic habitat (DFW 2012, 1994). Various methods have been employed. Al-Chokhachy and others, 2016 evaluated the current knowledge regarding linkages between forest road erosion and streambed sediment metrics. They found that very few studies have been conducted and results are radically inconsistent. From the combination of their literature review and their own detailed field study, they concluded that “limited empirical evidence exists to specifically quantify the effects of forest roads on aquatic ecosystems and effectively target restoration” and that “sediment production from roads and delivery to streams varies substantially within and across landscape settings”. Their last point underscores the need to partition the landscape (See the Bedrock and Alluvial Geology section). It seems that the current state of knowledge and science is inadequate to thoroughly and accurately characterize sediment conditions and linkages to forestry.

Roads older than 1990 constituted the majority of the network. Throughout Smith Creek basin, three years of road construction from 1990 to 1992 entered erodible areas along ridgelines and mid-slope landslide benches. Collectively, this period of road building was the largest increase of roads in erodible areas since 1990. The road GIS data derived from THPs does not differentiate the year built for roads built prior to 1990, thus hindering further analysis. This period of road building coincides with the eastern of the two time-space clusters comprising the 1990s spike in landslide activity. Three of the 1990s landslides were reported as fill failures, one of which occurred within a landslide that formed prior to 1952.

The density of watercourse crossings is highest in the eastern domain (n= 32) where slopes are less steep and roads are likely more sustainable although, three fill failures have occurred there. Only three watercourse crossings occur in the western and eight in the central domains. Wet area crossings are most common in the western domain along benches of ancient dormant landslides. Cursory examination of old growth stumps on these landslides suggest that the stumps have not been tilted indicating centuries of stability; although no detailed supporting evidence is available. Each of the domains contained eight landslide-road interaction points per the reviewed THPs. They are densest in the western domain. Of those deemed active, seven lie in the western, three in the central, and five lie in the eastern domain. The western and central domains had three landslide-road interactions in the last 20 years; while the eastern had two. Again, this distribution is skewed according to the time-space pattern of THP development.

THP maps provide road points slated for treatment as of the time of the THP. As part of the THP process, the road points would be treated; thus, making that information obsolete. However, the number and type of treatments needed to upgrade the road system reflected either the prevailing state of the road system or increased standards. However, a resolvable data gap is the lack of a digital map of road points extending at least two decades from which the environmental performance of the road network could be ascertained. To work around that data gap, I rated each road segment by the relative magnitude of inherent landscape erodibility from the erosion map I described above under the Hillslope Erosion heading. The central domain contains the roads rated highest in this approach. The lack of road assessment data prevents calibration of the approach.

VI: LWD

Key Concerns

Large woody debris provides channel structure and habitat complexity in alluvial sections of streams. Are the current levels of wood loading adequate for salmonid habitat?

Key Findings

- DFW stream surveys (1994 and 2012) measured the occurrence of existing LDA and recommended LWD enhancement as recently as 2012 but did not specify reaches.
- Between 1994 and 2012, LDA increased six fold in the central reach while declining four fold in lower reach, suggesting the need for reach-specific recommendations. Records of intentional LWD augmentation are not available.
- THP 1-13-031 states that high flows in 2003 and 2005/06 redistributed stored sediment, exposed buried LWD and suggests that high flows resulted in bank erosion, implying changeable conditions that may need to be accounted for in LWD recommendations.
- THP 1-98-029MEN reported two active landslides above the lower reach of Smith Creek, one which clearly moved since the 1991 harvest. These potential LWD sources do not correspond to slides in the Best dataset.

Explanation

Benda (2004) prepared a study, Wood Recruitment to Streams, for the timber company. The study included two basins (Redwood Creek and Bear Haven) that border the Smith Creek watershed. Benda concluded that 44% (Bear Haven) and 46% (Redwood Creek) of LWD derived from bank erosion and had a residence time of 71 years. The residence time implies that the wood noted in the 1994 and 2012 DFW surveys likely recruited in more recent times rather than as a consequence of early (pre1947) logging. Benda determined that streamside landslides contributed 14% in Redwood Creek and 25% in Bear Haven. If that finding holds for Smith Creek, then the six fold influx of LWD in the central reach possibly reflects either an uptick in landsliding or bank erosion or both between 1994 and 2012. The Best dataset shows two landslides along the reach that occurred between 1987 and 1999 and so may either predate or fall within the 1994-2012 period. The relationship of the increased wood load to landsliding is inconclusive and leaves us with either significant bank erosion or mobilization of stored LWD from Class II and Class III tributaries as alternative explanations. THP 1-13-031 stated that high flows in 2003 and 2005/06 redistributed stored sediment, exposed buried LWD and suggests that high flows resulted in bank erosion. No supporting data was provided or referenced. Is there other evidence of increased channel or bank erosion? Does the increase in LDA and the timber company statements that wood loading is “moderate” contradict the DFW conclusion that LWD should be artificially augmented, particularly for the middle reach? Figure 2 indicates that the central domain is probably by far the largest sediment source. Following Benda’s findings of limited travel distances for recruited wood, then the wood loads in the middle reach should also be the proportionally high.

VII: Channel Conditions

Key Concerns

- Anadromy
- Downcutting
- Bank erosion
- Sedimentation
- Cumulative effects

Key Findings

- Cumulative watershed effects assessments in THPs are narrative depictions with minimal verifiable details.
- Reliance on anecdotal history of watershed conditions may be necessary but can be fallacious.
- Information in THPs needed for CWE assessment is spotty at best. Large data gaps confound meaningful interpretations.
- Little data regarding channel conditions exists for the North Fork of Smith Creek. I conducted an aerial photo and DEM-based rapid assessment of the North Fork that partially addresses the data gap.
- Rosgen channel types include C4, B4, and F4 (entrenched). There may have been a transition to F4 in reaches.
- The frequency of repeated stream data collection campaigns is too low to reasonably establish trends and to associate them to watershed events. This represents a temporal data gap.

Explanation

Anadromy

THP 1-13-031MEN summarized the findings from the 2012 DFW and revised the limits of anadromy according to their supplementary aquatic assessment observations. THP 1-13-031MEN included harvest units in the watersheds of both the Smith and Mill Creeks. The Cumulative Impacts section of the plan provided the most recent narrative history of the watersheds available at the time. The narrative provided a generalized summary of the timeline of land use for both watersheds; although the lack of specificity made it difficult to extract information specific to a particular watercourse at a particular time period. The narrative concluded that Smith Creek is continually recovering, without active intervention, from the early history of intense logging; however, fails to mention the 1992 DFW survey or compare it to the 2012 DFW survey to support the conclusion. The narrative does not explain the rationale for the omission. No definition of recovering is provided. Again, the DFW surveys provided the only empirical and quantifiable, location-specific data of stream bed conditions from which change could be located and quantified.

The most recent descriptions of channel conditions come from the Aquatic Habitat Assessment in THP 1-13-031MEN that evaluated Class I and Class II channel conditions and determined:

- Anadromy ends at a 6-foot-tall waterfall and cascade on NF Smith Creek,
- Anadromy ends at a large headcut in a debris jam on Gulch B
- Gulch A is moderately entrenched (I could not find a map that identifies the gulches by name)

- In the main stem of Smith Creek, embeddedness, aggradation, bank cutting, bank mass wasting, down cutting, and scour were minimal according to the timber company's interpretation of the DFW 2012 survey. However, a LWD jam blocks fish passage on Smith Creek 100 feet above Gulch A.

Key messages from THP 1-13-031MEN are:

- Moderate loads of LWD occur in the Class I and II reaches.
- Many of the Class II and III reaches are entrenched with steep unstable banks.
- A 100-ft wide alluvial flat surrounds the restoration site.

Downcutting

Unfortunately, there are more questions than answers in the section reflecting a critical data gap.

Channel incision indicates a disturbance that produced excess transport capacity relative to the quantity of bed load inputs from within the watershed due to landslides and erosion (Simon and Rinaldi, 2006). The process can progress as a series of knickpoints (Simon and Rinaldi, 2006). Knickpoints and channel incision can lead to landslides due to toe erosion (Bigi and others, 2006 and Bennett and others, 2016). As stream discharges fluctuate so does the balance between sediment supply and transport capacity rendering inaccurate erosion models that rely on a single discharge value (Turowski and Rickemann, 2008).

I used a 5-meter DEM to map knickpoints and chokepoints along stream channels. Knickpoints may be bedrock controlled or debris/sediment controlled. Bedrock-controlled knickpoints may represent lithologic changes, fault displacements, or sediment scour. Knickpoints may represent fish passage barriers. I mapped numerous, relatively flat sections of stream bounded by knickpoints as potential sections of aggradation. I referred to them as “high-low-high gradient reaches (HLH)”. The 2012 DFW stream survey data confirmed the presence of bedrock-controlled knickpoints and large debris accumulations (LDA).

What led to the entrenchment of the lower reach? What lead to the entrenchment of the upper reach, if it is valid? What are the current (most recent report is from 1991) sediment load conditions especially upstream of the North Fork confluence? Are the channels aggrading, degrading, or stable? What have been the trends in sediment transport?

- Downcutting could relate to tectonic uplift which has affected the area but UNAVCO GPS data indicate the Smith Ridge and probably the basin is currently subsiding which favors aggradation not incision.
- Downcutting could relate to reworking of deposits formed during episodes of aggradation perhaps landuse-related and subsequent return to lower sediment yields.
- The formation of a landslide dam across the creek would form a wedge of aggraded sediment that would become incised as the dam breached.
- Alternatively, downcutting could relate to increased stream power which may result from uplift, deforestation or climate change. If we believe the data that the channel has entrenched since 1994, then deforestation of the basin by 1930 can likely be ruled out because of the time lag. However, did the deforestation and fire initiate a process that was slow to start yet self-perpetuating? Was a critical threshold of bed erosion crossed similar to the landslide threshold subsequent to the deforestation?
- Perhaps, either the effective shear stress of the bed has decreased or stream power increased. Flood flows after 1994 may have exceeded a threshold of channel bed stability and initiated a self-perpetuating sequence of downcutting into lower “soft” layers with lesser effective shear stress.
- Lastly, a recent experimental study showed that a long history of redd excavation during spawning could stimulate channel incision. Effectively, each excavated redd is a transient knickpoint among thousands that seasonally pulse through the channel (Fremier and others, 2017).

Bank erosion

Bank erosion is another phenomenon that requires attention. In entrenched or incised reaches, bank erosion can be prevalent if not ubiquitous throughout the network of the basin. Bank erosion occurs under many situations such as flow deflection against a bank, channel impingement from a landslide mass, along inner gorges, and undercutting of banks. Undercutting of banks and landsliding are the primary modes by which LWD enters watercourse. Benda (2004) found that for other drainages in the Ten Mile River watershed, bank undercutting accounted for 44 to 46% of LWD recruitment. Benda (2014) concluded "that establishing regional targets for wood loading and conducting compliance monitoring to verify them is questionable in the naturally dynamic and spatially heterogeneous stream environments in northern California." Benda's conclusion underscores the need for reach-specific data and highlights the inappropriateness of relying on analogous inferences based on reference reaches.

The THPs include narrative descriptions of such conditions but I have found it difficult to analyze that information spatially. The 1994 DFW survey reports that sand/silt/clay composed the stream banks while sand/gravel/cobble compose the bed. Unfortunately, that was a global description and does not indicate whether the C4 or F4 reaches differed. Different substrates may erode vastly differently (See the Bedrock and Alluvial Geology section).

Sedimentation

Along the Class I and Class II streams throughout the Smith Creek basin, there are unconsolidated alluvial (if stratified) or colluvial (if unstratified) deposits that form flats along the watercourses. I mapped 34 locations. These were sites of sediment deposition at one time and may represent modern features (e.g., flood prone zones) or inactive relics of the geologic past (e.g., terraces). I found no field information as to the stratification of the deposits; consequently, their activity, origin, and age are unknown (See the Bedrock and Alluvial Geology section).

On the DEM, the streams appear to be inset into the deposits suggesting that the channels have incised and the deposits and are possibly stream terraces. How old are the deposits? There are no quantitative field data of bank heights or channel cross-sections. Do they represent sedimentation during the last century (Koehler and others, 2007)? Do they reflect fault movements or landslide dams that may have created temporary impoundments? Do they flood? If so, how frequently? Are they relic features that renewed during pulses of logging-derived sedimentation? The 2012 DFW survey indicates a higher degree of channel entrenchment than 1994. These unconsolidated deposits would be susceptible to such incision which would be recorded as increased bank heights.

From the DEM, I mapped flat reaches bounded by steep gradients. I defined them as triplet sequences of high gradient, low gradient, and high gradient (HLH). Due to the large grid size of the DEM relative to channel width, they may be terraces, flood-prone zones, debris jams, vertically offset segments in fault zones, or adjoining hillslopes. Ideally, this exercise should be performed on a higher resolution DEM from which the channel can be more precisely modelled. Nonetheless, given the watershed history and anecdotal data indicating Smith Creek was aggraded after early logging, I compared their location, distribution, and extent to reports of aggradation in THP documents and found close similarity. Once a higher resolution DEM is available, the exercise should be repeated and further evaluated.

Based on the observations (by agency and industry staff) documented in THPs (1987, 1991, 2013, and 2015) and stream surveys and the HLH, many portions of Smith Creek and tributaries experienced sediment accumulations. The THP documents interpret these deposits as lingering effects of past logging. The incorporation of cull logs in sediment in the stream beds suggests that they deposited together; however, the in-channel materials have been reworked multiple times as noted in THP 1-13-031MEN which states that high flows in 2003 and 2005/06 redistributed stored sediment, exposed buried LWD and suggests that high flows resulted in bank erosion. This mixing of old and younger debris confounds interpretations.

Cumulative Effects

According to the Cumulative Impacts section of the THP 1-13-031MEN, Smith Creek was clearcut by 1920 and burned (in 1945 per Best, 2015) and then the streams were cleared of woody debris in the 1980s. These two actions suggest that the creek is deficient in LWD. How far upstream did the wood clearance extended is not indicated. Did the stream clearance extend into the middle reach 3 miles from the mouth where LDA was observed? Remnants of a railroad trestle remain below the north fork confluence which may suggest that the wood clearance did not extend this far upstream.

THP 1-13-031MEN states, "Sediment induced watershed cumulative effects occur when earthen materials are deposited by surface or mass wasting erosional processes into the fluvial system at separate locations and the effects on the stream system are then combined at a downstream location to produce an adverse change in water quality or channel conditions." It also states, "I did not see any evidence of active ongoing erosion. I did not see evidence of recent watercourse aggradation, accelerated stream bank cutting or active mass wasting." Key words are "active" and "recent" and are debatable. It also states the natural background rates may be 500% higher than determined in the TMDL (see Mass Wasting section). And it states that high flows in 2003 and 2005/06 redistributed stored sediment, exposed buried LWD and suggests that high flows resulted in bank erosion which contradicts the statement that erosion was not seen during plan preparation.

In order to validate or supplement the above statements, I perused readily available information and conducted a DEM-based assessment. Most of the volume of information regarding stream bed conditions are anecdotal observations with little to no supporting data. Empirical and quantifiable data are limited.

- DFW conducted two stream surveys, one in 1992 and another in 2012.
- To map "restorable" Class I streams, the timber company walked channels to determine both current and potential ends of anadromy along Smith Creek and Class I tributaries. This information is contained in the timber company's Aquatic Habitat Assessment contained in THPs 1-13-031MEN (focused on the lower and middle reaches) and 1-15-107MEN (focused on the upper reach).

The two DFW surveys (1994 and 2012) evaluated habitat and covered the lower three miles (the lower reach) of the main stem while the upper two miles (the middle reach) were surveyed only in 1994. North Fork Smith Creek has not been surveyed by DFW (but the timber company walked the tributary to define restorable reaches and provided the only channel bed observations for those streams). Both DFW surveys characterized grain size for channel substrates but did not distinguish the lithology of the material which indicates source, durability and environmental persistence (See the Bedrock and Alluvial Geology section). Both DFW surveys defined two reaches on the main stem based on Rosgen Types.

THP documentation provide snapshots in time and space of various reaches of Smith Creek and tributaries. The documentation referred to herein includes submitted plans with PHI and Preconsultation reports, prepared by either CALFIRE foresters or CGS geologists. I reviewed all CGS PHI reports dating from 1987 to 2013 and THPs dating from 1991 to 2015 for information on channel conditions. The documents reflect both spatial and temporal variability beyond the general impressions made by, and apparently contradict**,** the Cumulative Watershed Effects discussions and the DFW stream surveys. Generalizations of conditions over the entire basin tend to lose important details that pertain to impacts and restoration potential. Methods and terminology of characterizing channel conditions have remained essentially the same across the ~25-year span of these observations. This apparent consistency, if assumed, allows the observations to be grouped together as a set that spans the lower, middle, and upper reaches. The DFW surveys fill in several gaps in the industry stream data.

For convenience in this section Smith Creek is separated into four reaches: lower, middle, upper reaches, and North Fork. Class II and III tributaries are grouped with the respective reaches of Smith Creek.

Lower Reach Conditions

Key Findings

- For Smith Creek in general, there may be sufficient anecdotal evidence to believe that the creek was severely affected by old-growth logging.
- Based on an increased entrenchment ratio between 1992 and 2012 as indicated by two DFW stream surveys, the lower reach of Smith Creek appears to have incised since 1992. The 1994 survey classified the lower reach as C4 while the 2012 survey classified it as F4 indicating either a misclassificatio**n** or a significant increase in channel entrenchment.
- In the lower reach, the apparent lack of layers of gravel or coarser material in the banks indicates an environmental transition (or reversal) from slack water to swift water deposition. Does this change imply natural or anthropogenic disturbance? Or is it within the natural range of variation? The stream is cutting down into older, finer alluvial material. Or is it? Why? This could relate to several distinct scenarios.
- Neither the 1992 nor the 2012 surveys state that sediment was a limiting factor. Nor do they state that sediment was not a limiting factor as suggested in the Preconsultation report for a stream restoration project in THP 1-13-031MEN. This is a misrepresentation of data. Between 1994 and 2012, LDA increased six fold in the central reach while decreasing fourfold in the lower reach where the stream restoration project is located.
- THP 1-93-092MEN stated that 1) Smith Creek and especially the Class II tributaries, are downcutting into stored sediment and 2) the January 1993 storms caused extensive overbank flooding throughout the watershed and deep scouring occurred in Smith Creek and Class II tributaries. THP 1-13-031 states that high flows in 2003 and 2005/06 redistributed stored sediment, exposed buried LWD and suggests that high flows resulted in bank erosion.
- A potential very significant landslide and data gap appears in aerial photos to have failed between 1988 and 1992. The feature covers an area of 12,759 square yards and is located at mile-1 of the lower reach. Based on imagery, the feature may have blocked the channel and created a sediment reservoir that extended miles upstream. Eventual breaching of the landslide dam could have led to rapid incision into reservoir of sediment. This apparently shallow-seated landslide was likely as much a 3 yards deep. Therefore, the volume could have been as much as 38, 277 cubic yards, which is three times larger than the largest shallow-seated landslide in the Best database. It lies within a larger deep-seated presumably dormant landslide. There is no information in the documents or other data to either support or refute the scenario. This bears further evaluation since it singularly represents 20% of the landslide volume of entire Best dataset.
- Between 1953 and 1975, according to the Best dataset, 2 large landslides (15,901 cubic yards) impacted Smith Creek along what is the upper end of the F4 reach (restoration reach).
- Between 1984 and 1988, several clearcut timber harvests (up to 50-acres each) took place along the lower reach, followed by another harvest (THP 1-91-439) less than a decade later which was completed in 1993.
- Five new slides occurred directly upslope of the restoration site between 1993 and 1998. They occurred within THP 1-91-439 harvest units.
- New landslides, identified in 1999 aerial photos, occurred with a total volume of 1,365 cubic yards.
- In 2012, no recent delivery of sediment from landslides was noted.
- Much of the alluvium filled the valley during higher relative sea levels prior to uplift-caused emergence. However, some unknown portion of the valley fill is undoubtedly flood deposits formed more recently. No work

has been done to date the layers and relate them to sediment generating episodes such as are evident in 1947, 1952, pre1980 and 1992 aerial photos.

- Comparison of the 1994 versus 2013 LDA occurrences in lower Smith Creek shows a fourfold decrease.

Explanation

Circa 1950-1980 per Best Dataset

The landslide history along the lower reach may provide insight into the channel conditions. Between 1953 and 1975, according to the Best dataset, 2 large landslides (15,901 cubic yards) impacted Smith Creek along what is the upper end of the F4 reach (restoration reach). In 1990, the CGS geologist classified on of the upper portion of the landslides as dormant but did not describe the channel raising the question, “What does dormant mean?” The landslides together comprise 24% of all the delivering landslide volumes for the entire Smith Creek basin for all years evaluated in the Best data. The landslides delivered to the creek; however, how much is not known but given their size and the terrain, they probably delivered sediment over a span of several years.

Perhaps, the slide material caused local aggradation or blockage of the channel, in which case, the channel must be incised into unsorted slide debris rather than stratified alluvium. However, no information regarding those local details have been found. A landslide dam scenario is feasible but no information exists to either confirm or deny it. A serious data gap for CWE assessment.

Lower Reach Conditions per 1994 and 2012 DFW Stream Surveys

Both the 1994 and 2012 surveys distinguished the lower two miles (the lower reach) from the remainder of the creek at a location where the valley widens significantly into an area that PHI maps indicate to be an inner gorge and a flood-prone zone. This location is roughly at the head the alluvial valley. For the first two miles (the lower reach), the 1994 survey classified the stream as C4 while the 2012 survey classified it as F4 indicating either a misclassification or a significant increase in channel entrenchment. Both surveys classified the remainder of the survey as B4. The 2013 Aquatic Assessment report (focused on the lower and middle reaches) attached to THP 1-13-031MEN neither mentions nor explains the difference.

The categorical distinction between C4 and F4 channels is the entrenchment ratio, >2.2 and <1.4, respectively. Category B4 is intermediate. The metric is the ratio of the width of the flood-prone area to channel bankfull width. In order of increasing entrenchment, a C4 channel would have to transition into a B4 and then ultimately an F4. Evidence of the transition, if it occurred, would include transient knickpoints. There is no data to suggest that the currently F4 reach showed either spatial or temporal transitions into a B4 state raising uncertainty about the data. This may simply be due to low spatial and temporal resolution in the data and survey protocols.

Lower Reach 1998 Conditions per THP 1-98-029

No new channel information was found in the THP which relied on the 1994 DFW survey; however, according to the THP five landslides developed on slopes that were harvested in 1991. The slides initiated sometime between 1991 and 1998. There is no mention of any significance to watercourses; although, Class III watercourses were affected and connect to Smith Creek. Did the landslides precede or following the landslides? Did the delivery of sediment from the landslides alter the conditions reported in the 1994 DFW survey? The new (as of 1991-1998) slides are located upslope of the restoration area in the lower reach.

Lower Reach 2013 Conditions per THP

THP 1-13-031MEN relies on the 2012 DFW stream survey as documentation of prevailing conditions. Additionally, the THP included a stream restoration project for a portion of the lower reach. Agency staff visited the proposed site prior to approving the project in a Preconsult. A subsequent report provides a few additional details for the restoration site.

Lower Reach, 2013 Conditions per CGS Preconsult

The geologist observations occurred in a portion of the F4 reach (2013) that was subject of a wood enhancement project. The geologist indicated that Smith Creek appeared to be actively downcutting in this flood-prone zone but did not note why. This observation corroborates that this portion of the reach is entrenched and suggests that the channel may have changed from C4 in 1994 to F4 in 2012 over the 19 years between stream surveys. But the later survey does not address this inconsistency. The geologist believed that the material exposed in the stream banks dates back thousands of years. The geologist did not claim that alternative scenarios were either considered or ruled out.

There are no records that either subdivide the F4 reach or indicate any knickpoints that may have migrated upstream. I mapped via DEM, knickpoints and found 13 knickpoints per mile in this portion of the F4 reach, suggestive of downcutting. Downcutting may be a process of recovery from past aggradation caused by the large landslides prior to 1975, over 38 years prior and/or the five landslides that occurred on the north-facing slopes above this reach between 1991 and 1998. But there is no information about how the 1991-1998 landslides impacted the channel.

Middle Reach Conditions

Key Findings

- Channel conditions along the North Fork Smith Creek are not well documented.
- Along slopes in the basin that drain through the middle reach, Best mapped 106 landslides that have a total volume of 55,531 cubic yards of material. How much of this material delivered to streams?
- A large volume landslide occurred prior to 1952 and likely affected channel conditions.
- In 1987, the lower part of the middle reach was described as “severely aggraded”.
- In 1991, sediment loads in this reach and connecting Class II watercourse were described as “higher than normal”.
- In 1994 and 2013, moderate amounts of LWD impounded sediment wedges.
- Bedrock is exposed in the channel bed, in places.
- DFW surveys (in 1994 and 2012) do not state that sediment either is or is not a limiting factor. Instead, the surveys recommend augmentation of LWD as a general recommendation for Smith Creek in total.
- In 1996, good stream habitat conditions were noted in the upper part of the middle reach which shows little impact. This portion of the reach occupies an alluvial flat which is distinctly different than the gorge through which is occupied by the lower part of the middle reach. This important distinction is missed when data is generalized.

Explanation

Middle Reach 1987 to 2012 Conditions per DFW Stream Surveys

Both surveys reported bedrock exposure in the streambed and several bedrock-controlled “waterfalls” which are knickpoints. I mapped via DEM, knickpoints and faults along this reach and found 4 knickpoints per mile. I attempted to map these bedrock exposures from the stream surveys but found the spatial uncertainty with the original streams survey data difficult to confidently reckon. Within this reach, I remote-sensed and map several faults with vertical offsets that cross Smith Creek and would presumably offset bedrock to form knickpoints.

Neither stream survey indicated that sediment was a limiting factor in this reach. Bedrock exposures argue that this reach is not completely buried in sediment; however, relic logging deposits appear to have remained until 2013. Neither the geologist observations (see below) nor the DFW steam surveys indicate the lithology of the bedrock or streambed material.

Middle Reach circa 1952 per Best

Prior to 1952, according to Best, thee significant landslides delivered to the same section of the creek with a total volume of **5,830 cubic yards**; however, the amount that delivered is unknown.

Middle Reach 1987 (13,000-19,000' from mouth) Conditions per Agency Geologist

In the Middle reach, 6 years before the stream survey, the CGS geologist described the channel. The geologist observations occurred in a portion of the B4 reach in the area of overlap between the DFW stream surveys. Although the geologist observations were limited to 1.33 miles of the 5 miles (27%) of the main stem of Smith Creek, they provide the only information from a geologist perspective that augment the DFW and the timber company survey data. The geologist indicates that this reach was severely aggraded and that remnant railroad trestles have triggered a landslide by deflecting flow.

Both stream surveys (6 and 26 years later) confirmed the presence of large debris accumulations (LDA) in the same portion of the middle reach with an apparent reduction through time. Nonetheless on a watershed-wide scale, the stream surveys both recommended addition of LWD to improve habitat. Regional data suggests that the frequency of LWD in Smith Creek is low.

The CGS geologist did not note the pre1952 landslides which may have washed away or revegetated in the intervening 35 years. (Or the omission may reflect an incomplete or casual nature of the observations and reporting.) The timing of this observation relative to wood clearance in the 1980s is not known nor is whether the wood clearance extended into this reach. The geologist believed that the sediment in the stream bed dated back several decades to the old-growth harvest. Although the interpretation may be valid, it cannot be verified. This statement blurs the line between observation and interpretation with no actual data to support it. The statement may be correct or it may reflect a case of confirmation bias.

Middle Reach 1991 Conditions per THP

CalFIRE forester, William Todd Baxter in the PHI memo for THP 1-91-048MEN described the channel conditions for the north-facing slopes along the B4 reach of Smith Creek. The THP states, "The Class I and Class II streams also appear to be carrying higher than normal levels of stream bed sediment deposits. These deposits appear to have originated when the old growth was logged 70 years ago. The Class II stream were found to be **incised** in places." Baxter also states in answer to Review Team question 7, "I expect this bedload to slowly work its way out of the drainage over the next 200 years. I inspected Smith Creek at several locations to track sediment movement. The movement of sediment appears to be a very slow rate. There has been minimal movement of sediment in recent years because of low water flows related to the drought."

Middle Reach 1996 Conditions (19,000-22,000' from mouth) per THP

Channel conditions were reported for a segment of Smith Creek and a Class II tributary in the middle reach. The surveyed Smith Creek reach occupies a sizable alluvial flat. The assessment rated the creek as being in "Good Condition" with slight signs of the following: embeddedness, pool filling, aggrading, bank cutting, down cutting, scouring, debris clearing, debris jamming, canopy reduction, and recent flooding. There was no mention of streamside landslides. In the Class II tributary that joins Smith Creek within the surveyed area, the same conditions and overall rating were reported.

North Fork Smith Creek

Key Findings

- A road or railroad extended along the North Fork and excavation may have altered streamside slopes.
- Scattered areas of alluvium or colluvium occur along the creek.
- Numerous knickpoints, including a bedrock-controlled waterfall occur in along the North Fork and tributaries.
- An apparent spike in landslide activity prior to 1952 possibly increased sedimentation of the creek.

Explanation

Virtually no information was found regarding channel conditions along the North Fork Smith Creek except for an evaluation of the limits of anadromy. As such, I relied on information derived during the rapid assessment to deduce what channel conditions may exist.

The rapid assessment focused on North Fork Smith Creek and for reference conditions used a reach of Smith Creek above the North Fork confluence. The reference reach is possibly very similar to the lower North Fork. In 2013, DFW conducted a stream habitat survey along the reference reach providing field data for comparison to interpretations for the NF based on this assessment.

The basin of the Nork Fork of Smith Creek was deforested, either by clearcut or fire or both, as indicated by aerial photographs taken in 1947. Tim Best, CEG suggested in an engineering geology report, that the deforestation may have occurred sometime during the 1920's or the 1930's. This suggests that at least 70 years to possibly over 90 years have elapsed since the deforestation. The removal of trees from the riparian corridor would have curtailed or suppressed the recruitment of large woody debris into the stream channel for many decades.

Subsequent timber harvests have been limited to smaller patches. Recent aerial photographs show that the slopes and stream environments have reforested. Given the elapsed time, the oldest trees are likely mature and even-aged. The timber harvests that occurred in the 1980's to present have created openings and patches that contain younger seral stage stands (15, 17, 18, 24, 26, and 32 years old) separated by the mature stands.

A railroad line extended along Smith Creek for logging purposes. I could not determine whether or not a spur ran up the North Fork Smith Creek. Nonetheless, a forest road reportedly did and seems to be evident in aerial photographs from 1963 and 1984. Photographs from intervening years show streamside canopy that blocks the view of the road. Pete Caferatta, CALFIRE, examined recent aerial photographs of the streamside canopy and concluded that the potential of recruitment of large woody debris into the stream channel was generally moderate; however, he noted that DFW and Campbell Global work in the Campbell Creek planning watershed suggests that wood loading is low. The DFW survey indicate the riparian canopy was composed of two-thirds hardwood and one-third redwood providing a dense canopy measured at 97% closed. Stream temperatures in June were considered suitable for salmonids.

Sites of landslides were previously mapped by Graham Matthews, Tim Best, and the California Geological Survey. The maps indicate that the basin is susceptible to mass wasting, especially along steep slopes. CALFIRE produced an Erosion Hazard Rating map that determined that much of the basin exhibits high to extreme erosion hazard. Collectively, the maps suggest that sediment loads would be expected to be relatively high periodically and that road construction and timber harvest may have temporarily accelerated erosion rates, especially prior to 1941 and in the 1960's.

Given the landslide history and that sediment residence time in stream channels can be decades or more, it seems reasonable that sediment loads would be moderate to high for the NF Smith Creek basin. Given that LWD seems deficient and its important role in retaining sediment and forming pools in stream channels, it seems reasonable to conclude that the NF Smith Creek would have less pool frequency and volume and less habitat complexity than it would otherwise. This conclusion is supported by stream habitat data from 2012 for the main stem Smith Creek which experienced a similar disturbance history. The recommendations for LWD enhancement led to a stream restoration project that added large wood to the Smith Creek.

This rapid assessment used a time-series of aerial photographs to identify geomorphic features and land use history with reference to climate and weather records. This assessment developed a disturbance timeline and yielded conclusions that were collaborated by habitat data in Smith Creek which provides an apparently valid reference reach. The rapid assessment produced a disturbance timeline that helps explain stream channel conditions and restoration opportunities.

Upper Reach

Key Findings

- Data of channel conditions in the upper reach beyond the limits of anadromy are scarce.
- There is general reference to recent landslides in the inner gorge of the upper reach.
- The timber company classified the channel as F4, i.e., entrenched.
- Conditions in the lower part of the upper reach are impacted by logging debris e.g., sediment and wood.

Explanation

Upper Reach 2015 Conditions per THP 1-15-107

In 2015, the timber company classified the upper reach as F4 rather than B4. Did the upper reach transition into an F4 class in 21 years? The entrenchment ratio determines whether a channel is classified as a B4 or F4. A ratio greater than 2.2 would be classed as F4 while a lower ratio would be classed as B4. No measurements or cross-sections are available to determine if the channel is one or the other or perhaps a close call subject to change depending on where one looks? It could also be a matter of scale. The DFW determination was a generalization of over 20,000 feet of stream while the timber company evaluation focused on a much shorter (~2,000 feet) reach. The 2015 Aquatic Assessment report (THP 1-15-107MEN) neither mentions or explains why there's a difference. Does the difference only reflect a margin of error in classification when ratios are close to 2.2? Or if we accept both determinations are correct given their respective scales, can we assume that portions of the longer B4 reach may be or have become (in two years) more entrenched than others? Was there a significant flow event that scoured the bed? The data are unclear.

The 2015 Aquatic Assessment Report reported the following conditions along 1,000 feet of F4 channel: gravel bed, high embeddedness, shallow pools, high LWD, and continued erosion of the railroad bed. Characteristics of 1,000' of channel were described as being aggraded with embedded gravels, shallow pools, and abundant logging debris that provides LWD. Also noted is continued erosion from legacy road and unstable banks. Although, the spike of landslide activity during the 1990s occurred upstream of these conditions, neither mention nor assessment of linkages in THP documentation. A serious data gap for CWE assessment.

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