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Assessment of Soil Creep Sediment Generation for Total Maximum Daily Load Development in a Northern Coastal California Watershed

A dissertation submitted in partial satisfaction of the

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Doctor of Environmental Science and Engineering

by

Matthew Scott Buffleben

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The dissertation of Matthew Scott Buffleben is approved.

Mel Suffet

Terri Hogue

Richard F. Ambrose, Committee Co-Chair

Stanely Trimble, Committee Co-Chair

University of California, Los Angeles

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DEDICATION

I wish to dedicate this work to my loving wife, Deb, for all the support and encouragement she has given me throughout the years.

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VITA

November 5, 1969	Born New Orleans, Louisiana
1992-1993	Engineering Student Assistant Ocean Engineering Lab, University of California, Santa Barbara
1993	B.S. Mechanical Engineering University of California, Santa Barbara
1995-1997	Research Assistant Department of Environmental Health Sciences, UCLA
1996-1998	Teaching Assistant – *Introduction into Environmental Health Science* Department of Environmental Health Sciences, UCLA
1997	M.S. Environmental Health Science University of California, Los Angeles
1998-1999	Research Assistant Environmental Science and Engineering Program, UCLA
1999-Present	Water Resource Control Engineer California Regional Water Quality Control Board North Coast Region
2003	California Professional Engineer in Civil Engineering

PUBLICATIONS AND PRESENTATIONS

Duke, L. D., M. Buffleben, and L. A. Bauersachs (1998), Pollutants in storm water runoff from metal plating facilities, Los Angeles, California, *Waste Management. 18* (1), 25-38.

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ABSTRACT OF THE DISSERTATION

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Matthew Scott Buffleben

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Professor Richard F. Ambrose, Co-Chair

Professor Stanley Trimble, Co-Chair

Sediment budgets are often used to help determine the anthropogenic impact on water quality and channel morphology and are useful for prioritizing restoration activities to help recover endangered salmonid species. Soil creep, a process in which colluvium is slowly supplied to the stream banks and delivers sediment to streams, is often estimated in sediment budgets developed for steep watersheds. Previous sediment budgets have shown that soil creep is an important sediment source in pristine watersheds and may be a significant sediment source in logged watersheds. Many sediment budgets use an empirical soil creep formula to

estimate the amount of sediment delivery from this process. However, relying on empirical formulae to estimate soil creep sediment delivery with little to no field evaluation could lead to large errors in its estimation.

This study investigated soil creep sediment delivery and the methods used to estimate its magnitude with a focus on three small forested watersheds within the Elk River watershed in northern California. Elk River is listed as a sediment impaired water body under Section 303(d) of the Clean Water Act and a Total Maximum Daily Load (TMDL) is being developed for the watershed.

Field surveys to determine stream density were conducted in logged and nearly pristine watersheds and showed that logging has increased the stream density. Two methods, measuring voids along a stream channel and large wood in channels, were used to estimate bank erosion and provide a check on soil creep estimates. Comparing the results to suspended sediment loads, measuring voids appears to be the superior method for estimating bank erosion. Furthermore, the bank erosion surveys showed logged watersheds had higher bank erosion rates.

Finally, methods for estimating soil creep sediment delivery are reviewed. Soil creep sediment delivery was estimated for the three watersheds and compared to the bank erosion rates, suspended sediment loads and other sediment sources. The resulting sediment budget reveals that soil creep is likely a minor source, < 1%, of sediment in the logged portions of the Elk River watershed. Future efforts need to focus on estimating other sediment sources, particularly logging-related increases in bank erosion and on ways to minimize this source of sediment.

CHAPTER 1

Introduction

With the passage of the Clean Water Act (1972 amendments to the Federal Water Pollution Control Act), which requires effluent limitations on point source pollution, the United States has made significant progress toward meeting the Clean Water Act goals of restoring and maintaining the chemical, physical, and biological integrity of the nation's waters. However, over 40,000 water bodies in the United States do not meet the goals of the Clean Water Act (USEPA, 2009). Excessive sediment has impaired the beneficial uses of water for nearly 6,500 water bodies (USEPA, 2009).

The predominate water quality problem in northern coastal California watersheds is impairment of salmonid habitat. Several salmonid species in the North Coast Region of the California Regional Water Quality Control Boards are listed under he Endangered Species Act. When NMFS Biological Review Teams (BRTs) updated the status of ESA-listed ESUs (evolutionarily significant units) of salmon and steelhead, they found that chinook, coho, and steelhead populations "continue to exhibit depressed population sizes relative to historical abundances," and trends continue downward in several areas (Good et al., 2005). These findings are of particular concern for the endangered Central California Coast Coho, whose range overlaps part of the North Coast Region. A number of coho populations in the southern portion of the range appear to be either extinct or nearly so, including those in the Gualala, Garcia, and Russian rivers (Good et al., 2005). Although there are several factors involved in the decline of salmonids, the destruction and modification of habitat are the primary reasons for decline in the western US (National Marine Fisheries Service, 2007a, 2007b).

Anthropogenic activities such as logging and its associated road building, which commonly occur in northern coastal California, can dramatically increase sediment loads (Reid, 1993 and Gomi et al., 2005). The increased sediment supply can negatively impact salmonid habitat in several ways. Excessive fine sediment can prevent adequate water flow through salmon redds, which can cause a high level of mortality by limiting the oxygen supply to salmon eggs and preventing the removal of metabolic wastes (Phillips et al, 1975; Tappel and Bjornn, 1983; Chapman, 1988). Increases in sediment supply can also decrease the pool depth and pool size (Lisle and Hilton, 1999), which reduces rearing habitat for salmonids. Decreases in clarity due to suspended sediment can cause direct effects, such as mortality, and indirect effects like decreases in growth rates due to reduced food supply (Newcombe, 2003).

Excessive sediment can also impair drinking water supply, which is another concern in some North Coast watersheds. High concentrations of sediment make water treatment difficult because the solids can both provide a medium for bacterial transport and be a barrier against chlorine disinfection (Tchobanoglous and Schroeder, 1985).

Also, excessive sediment can lead to changes in stream channel morphology. Aggradation, the filling of a stream channel with sediment, typically occurs when sediment inputs are increased beyond the stream's transport capacity. Aggradation may lead to decreased channel capacity, which can cause an increase in flooding frequency, magnitude and duration (Knighton, 1998). This increase in flooding can cause property damage or result in nuisance conditions by limiting access for landowners.

Sediment Budgets

Sediment budgets are useful tools to evaluate sediment impacts to water quality and channel morphology. A sediment budget is an "accounting of the sources and disposition of sediment as it travels from its point of origin to its eventual exit from a drainage basin" (Reid and Dunne, 1996). A variety of tools and resources are used to create the sediment budget, including existing monitoring information, aerial photography analysis, simple calculations, spreadsheet analysis, and computer models.

The dramatic effects of unregulated logging that occurred during the middle of twentieth century have been demonstrated in several sediment budgets (Madej, 1982; Roberts and Church, 1986). The increases of sediment delivery from the logging operations created sediment wedges, which made stream channels shallower and wider and provide poor salmonid habitat. These studies estimate that is will take several decades or more for the streams to transport the excess sediment out of the watersheds.

Sediment budgets for steep watersheds generally break the natural sediment delivery into two components: landsliding and soil creep. Soil creep is defined as the slow downslope movement of the soil mantle under the influence of gravity (WDNR, 1997). Soil creep is related to landsliding because soil creep helps to refill landslide scars (Dietrich and Dunne, 1978). Other soil displacing processes, such as tree wind-throw and animal burrowing, are implicitly included in most soil creep rates used in sediment budgets (WDNR, 1997).

Colluvium (i.e., the soil mantle) is assumed to be supplied to the bank by soil creep from the hillslope (Figure 1.1). The rate of sediment supply to the bank is equal to the rate of erosion from that bank if equilibrium conditions are assumed (Reid and Dunne, 1996). Soil creep rates are often used to check estimates of colluvial bank erosion rates.

In steep watersheds, soil creep can be a significant source of sediment. For example, Roberts and Church (1986) estimated that soil creep accounted for 30 to 50% of the sediment supplied to stream channels in British Columbia watersheds before they were logged. After logging, the relative contributions of soil creep to the stream channels decreased, but still accounted up to 15% of the sediment supply.

Many sediment budgets use an empirical soil creep formula to estimate the sediment delivery from this process. However, relying on empirical formulae to estimate soil creep sediment delivery with little to no field evaluation could lead to large errors in its estimation.

My dissertation evaluates sediment delivery from soil creep with a focus on three small watersheds within the Elk River watershed in northern coastal California. Sediment delivery from soil creep is calculated from field measurements of stream density. Bank erosion rates, determined by field surveys, are used as a check on soil creep delivery rates. Furthermore, soil creep sediment delivery is compared with other sediment sources in the watersheds. The resulting sediment budget is tested by comparing the estimates of sediment production to the suspended sediment loads in the small watersheds. The implications of the range of soil creep estimates for the sediment budget is discussed.

Total Maximum Daily Loads

Under section 303(d) of the Clean Water Act, states are required to identify all water bodies that do not meet water quality standards. For those "impaired" water bodies, the states must develop and implement Total Maximum Daily Loads (TMDLs). A TMDL "shall be established at a level necessary to implement the applicable water quality standards with seasonal variations and a margin of safety which takes into account any lack of knowledge concerning the relationship between effluent limitations and water quality" (Clean Water Act, §303(d)(1)(C)). In a general sense, a TMDL is a water quality attainment strategy and provides a framework for assessing the watershed condition, evaluating the sources of pollution contributing to the water quality impairment, and developing a water quality restoration plan for the watershed. The establishment of TMDLs in California is one of the most significant challenges facing the State Water Resources Control Board (SWRCB) and the Regional Water Quality Control Boards (RWQCB). In California, there are approximately 1,500 combinations of water bodies and pollutants that require TMDL development (SWRCB, 2001). For the North Coast Region, watersheds that contain stream reaches listed for sediment impairment under 303(d), comprise 61% of the region's area (CRWQCB, 2008).

A key component of TMDLs is the source assessment. For sediment TMDLs, the source assessment typically takes the form of a sediment budget. States are required to determine the maximum daily load that allows the water quality standards for that watershed to be met. That load, or loading capacity, is required to include a margin of safety and, if necessary, account for seasonal variations. Due to the significant yearly variation in sediment loads in northern coastal California, which can range over several orders of magnitude, the sediment budgets rely on long-term estimates of sediment input. These estimates are often derived by using sequential aerial photographs to evaluate the occurrence of major sediment sources such as landslides. The sequential photographs often bracket significant storm events (e.g. 1964, 1986, 1997 and 2003 storms). Therefore the sediment budgets "average" the estimated sediment delivery over the air photo period, which is generally over a period of decades.

While calculating the TMDL on a daily basis is a legal requirement, US Environmental Protection Agency (USEPA) recognizes that it is impractical for land managers to measure sediment loads, or sediment discharges, on a daily basis. Therefore, the TMDL is expressed as an average annual load which should be evaluated as a long-term (e.g. 10 - 15 year) running average (USEPA, 2007a). Furthermore, USEPA expects progress toward the TMDL to be evaluated by estimating the total sediment load relative to the natural load (USEPA, 2007a), which is why the loading capacity is expressed as a percentage of natural loads in addition to being provided as an absolute load. The underlying assumption is that while sediment delivery is very episodic, which could make the determinations of progress towards the TMDL very difficult, the ratio of total sediment to natural is not as sensitive to episodic events.

Twenty sediment TMDLs have been completed in the North Coast Region. The estimated sediment loads and loading capacity, i.e. the TMDL, are shown in Table 1-1. For most northern coastal TMDLs, the loading capacity has been set at or near 125% relative to the natural background sediment loads (Table 1-1). Since current estimates of sediment loading in these northern coastal watersheds average 228% relative to natural background, significant reductions in sediment discharges are required to meet the TMDL.

For all the emphasis in TMDL design on evaluating the ratio between the total and natural loads, there is evidence that TMDL sediment budgets in the North Coast Region significantly underestimate this ratio. When comparing the measured suspended sediment discharge for two small watersheds that have undergone several logging cycles with one nearly pristine watershed in northern coastal California, Manka (2005) found the total sediment discharge in the managed watersheds was 10.2 and 22.0 times the background watershed's sediment discharge, i.e., 1,020% to 2,200% relative to background. Klein et al. (2008) compared turbidity, which is strongly correlated with suspended sediment concentrations, between 28 watersheds that had continuous turbidity and stage recording stations in northern coastal California. These watersheds were divided into groups based on their harvest rates for the last twenty years. The turbidity levels from the group of high-harvest watersheds were 469% relative to the zero-harvest watersheds. However, by removing the second-growth watersheds from the zero-harvest group of watersheds and comparing just the nearly pristine old-growth watersheds to those with highest harvest levels, the ratio of total-to-natural turbidity increases to 717% (R. Klein, unpublished data). These studies indicate that the actually total-to-natural sediment discharge ratio could be much higher than those estimated in the TMDL studies (average = 228%, median = 177%, Table 1-1). Underestimation of the total-to-natural sediment load ratio could result if the sediment budgets either are not accurately estimating the sources of sediment or are not categorizing the sediment sources correctly between management and natural. Underestimating the total-to-natural sediment ratio could mean that the measures outlined in the TMDLs may not be adequate to meet water quality standards.

One reason TMDL sediment budgets may not be accurately estimating the total-to-natural sediment load ratio is that they could be overestimating natural sediment loads. My dissertation examines the possibility that TMDL studies have overestimated soil creep.

Elk River Watershed

This study focuses on three small watersheds within the Elk River watershed (Figure 1.2), which was listed as an impaired water body under Section 303(d) of the Clean Water Act in 1997. Water quality problems cited under the listing include sedimentation, threat of sedimentation, impaired quality of irrigation water, impaired quality of domestic water supply, impaired spawning habitat, increased rate and depth of flooding due to sediment, and property damage. Erosion, sediment discharge, and sedimentation has significantly modified the channel conditions of Elk River and its tributaries such that a threat to public health, safety, and property is present from increased incidence and magnitude of routine flooding, constituting a nuisance condition according to the Porter-Cologne Water Quality Control Plan. Coho, chinook and steelhead are present in the watershed and are listed as threatened species under the Endangered Species Act.

The Elk River watershed is a moderately sized watershed (137 km^2) located south of Eureka, California. Elk River originates in the seaward slopes of the California Coast Range and drains into Humboldt Bay.

The Elk River watershed has a Mediterranean climate with wet winters and a prolonged dry season during the summer. Roughly 90% of the annual precipitation occurs during the rainy season (October through April). Snow is rare in this watershed. Mean air temperature varies little throughout the year and ranges from 9°C in January to 13°C in June with the summer temperatures moderated by fog (Hart Crowser, Inc., 2005).

Forest stands in Elk River are dominated by redwood (*Sequoia sempervirens*) and Douglas-fir (*Pseudotsuga menziesii*), with grand fir (*Abies granis*), Sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga heterophylla*), incense cedar (*Calocedrus decurrens*), western red cedar (*Thuja plicata*), and pacific madrone (*Arbutus menziesii*) common in some locations. Big leaf maple (*Acer macrophyllum*), willow (*Salix lasiandra*), and red alder (*Alnus rubra*) are the dominant deciduous tree species found in riparian zones and are also found in disturbed areas where a high degree of compaction or soil loss has occurred (Manka, 2005).

Manka (2005) installed three turbidity/suspended sediment monitoring stations in the Elk River watershed. These monitoring stations are ideally located to investigate the impacts of timber harvesting. The three watersheds share similar physical characteristics but have different harvest histories. For example, the three watersheds have similar size. South Branch North Fork Elk River is 4.9 km^2. Corrigan Creek is adjacent to South Branch and is 4.4 km^2 in size. Located approximately two kilometers to the southwest is Little South Fork Elk River, which drains an area of 3.1 km^2. Also, all three watersheds have the same orientation and are located the same distance from the ocean, so they lie within the same isohyetal bands of average precipitation (Manka, 2005). The watersheds average between 1600 and 1650 mm of precipitation annually (Hart Crowser, Inc., 2005).

The three watersheds share similar bedrock (Figure 1.3 and Table 1-2). Bedrock in the three watersheds consists primarily of marine and non-marine sedimentary rocks units of the mid-Tertiary to Quaternary-age deposits of the Wildcat Group. The Wildcat Group typically consists of poorly to moderately consolidated siltstone and fine-grained silty sandstone with some lenses of pebble conglomerate. These rocks are moderately susceptible to deep-seated landsliding, with rotational displacements in massive units and translation along planar weaknesses such as bedding planes, joints and fractures. However, in some areas, more strongly indurated deposits can sometimes stand in relatively steep sustained slopes. Rock units of the Wildcat Group readily weather into non-plastic clayey silts and clayey sands (MLs and SCs as per the Unified Soil Classification System) that are susceptible to transport by colluvial processes and are often relatively permeable. Significant thicknesses of residual and colluvial soils derived from Wildcat Group materials on relatively steep slopes can be especially prone to shallow soil slips and debris slides (Marshall and Mendes, 2005).

Underlying the Wildcat Group materials in unconformable depositional contact are rock units of the Late Cretaceous Yager terrane of the Coastal Belt of the Franciscan Complex. Yager terrane material is exposed in the deeper portions of the valleys in these watersheds where the streams have incised through layers of Wildcat to expose the underlying Yager units. Yager terrane material underlying these areas typically consists of well-indurated arkosic sandstone (sandstone with feldspar as a prominent constituent) and argillite (clay-rich mudstone and shale). The Yager terrane material underlying the Elk River drainage consists of sheared and highly folded mudstone. Slopes underlain by this material are often irregular and lack well-developed sidehill drainages. The slaking, shearing and deep weathering results in deep-seated flow-type failures on moderate slopes. On steep convergent slopes with watercourses, an initial deep-seated rotational or translational failure of this material can sometimes develop into a far-traveling debris torrent due to the low internal cohesion of the sliding mass (Marshall and Mendes, 2005).

The streambed in channels draining areas underlain by Wildcat units are often dominated by silts and sands and have a high potential for suspended sediment loads, while streambed in channels that have downcut into the Yager units expose material ranging from well-consolidated bedrock to cobbles and gravel (Hart Crowser, Inc., 2005). Each of the main channels in the three watersheds has downcut through the overlying Wildcat unit and exposes the Yager units.

The three watersheds also have similar hillslope gradients. A high quality 1-m Digital Elevation Model (DEM; Sanborn, 2005) derived from laser altimetry (known as LIDAR: Light Detection and Ranging) was used to determine the hillslope gradient for the three watersheds used in this study. Figure 1.4 shows the slope distribution of the three watersheds. South Branch of the North Fork Elk River and Corrigan Creek have nearly identical portions (47% and 48% respectively) of steep hillslopes (hillslope gradient greater than 40%), while Little South Fork Elk River has slightly more area (57%) in this steep hillslope category.

The primary difference between the three watersheds is their management histories. Most of the South Branch North Fork watershed was first logged in the 1970s, although small areas were harvested in the 1940s and 1960s as well. A second logging entry occurred throughout the entire watershed in the late 1980s and early 1990s, consisting of partial-cut and clear-cut harvests with tractor yarding. The western portion of the Corrigan Creek watershed was first logged in the 1950s and the eastern portion in the 1970s. The eastern portion experienced a second logging entry in the late 1980s and early 1990s, consisting of partial-cut and clear-cut harvests with tractor yarding (Manka, 2005). The western portion of the watershed has recently experienced a second logging entry. The portion Little South Fork Elk River examined in this dissertation is primarily an old-growth redwood forest. In the early 1990s, a 2.3-kilometer road was constructed adjacent to the upstream portion of the stream channel. The maximum width of disturbance from the road construction and the adjacent logging was 61 m (Pacific Watershed Associates, 2007). This area of the Little South Fork watershed was included in the Federal purchase of the Headwaters Forest Reserve in 1999. The road was subsequently decommissioned. A complete slope restoration, including excavation of stream crossings and recontouring of hillslopes, was completed in 2003 (Manka, 2005).

Dissertation Structure

The objective of my dissertation is to develop reasonable estimates of soil creep sediment delivery for use in a sediment budget being developed for the Elk River watershed sediment TMDL. Field surveys are conducted in the three small watersheds described above to refine the sediment delivery estimates.

To determine the stream length used to estimate soil creep sediment delivery, Chapter 2 describes the field surveys used to determine the watershed stream density. The impacts of the management history on location of channel heads are also evaluated.

Bank erosion rates can be used as a check on soil creep rates. Chapter 3 compares two field methods used to estimate bank erosion. One method measures the voids along stream channels while the other method measures large woody debris to estimate bank erosion rates. The bank erosion rates for both methods are compared to suspended sediment loads as a check on their reasonableness.

Soil creep rates and four examples of soil creep delivery estimates are reviewed in Chapter 4. Soil creep delivery estimates that meet TMDL requirements are then developed for the three watersheds. Soil creep delivery rates are compared with other sediment sources in the watersheds. The resulting sediment budget is tested by comparing the estimates of sediment production to the suspended sediment loads in the small watersheds. The implications of the range of soil creep estimates for the sediment budget and TMDLs is discussed.

Chapter 5 contains the conclusions of the dissertation. After reviewing the results of the previous chapters, it also discusses the potential for management activities to increase soil creep rates and describes monitoring components that are essential for resolving some of the uncertainties contained in northern coastal California sediment budgets.

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Table 1-1. Sediment loads estimates from Northern California TMDLs (note: numbers have been rounded).

Watershed	Size (km^2)	Natural ($t\ km^{-2}\ a^{-1}$)	Management ($t\ km^{-2}\ a^{-1}$)	Total ($t\ km^{-2}\ a^{-1}$)	Total (percent of natural)	TMDL ($t\ km^{-2}\ a^{-1}$)	TMDL (percent of natural)	Reference
Albion River	111	96	152	249	258%	144	150%	USEPA 2001a
Big River	469	110	110	220	200%	138	125%	USEPA 2001b
Eel River, North Fork	749	291	140	430	148%	364	125%	USEPA 2002
Eel River, Middle Fork	1950	201	10	211	105%	211	105%	USEPA 2003a
Eel River, South Fork	1785	378	331	708	188%	472	125%	USEPA 1999b
Eel River, Upper Main	1782	109	54	162	149%	136	125%	USEPA 2004
Eel River, Middle Main	1349	181	83	264	146%	226	125%	USEPA 2005
Eel River, Lower Main	774	251	272	523	208%	315	125%	USEPA 2007a
Garcia River	295	57	427	483	852%	193	341%	USEPA 1998a
Gualala River	774	133	294	427	321%	166	125%	USEPA 2001c
Mad River	1243	313	553	867	277%	376	120%	USEPA 2007b
Mattole River	767	1016	1786	2802	276%	1261	124%	USEPA 2003b
Navarro River	816	410	271	681	166%	512	125%	USEPA 2000a
Noyo River	293	130	74	204	157%	165	127%	USEPA 1999a
Redwood Creek	738	532	1131	1664	313%	666	125%	USEPA 1998c
Scott River	2106	157	105	262	167%	196	125%	CRWQCB 2005
Ten Mile River	311	109	111	220	202%	137	125%	USEPA 2000b
Trinity River	4978	379	197	575	152%	474	125%	USEPA 2001d
Trinity River, South Fork	2414	239	130	369	154%	258	108%	USEPA 1998b
Van Duzen River	1111	596	157	753	126%	642	108%	USEPA 1999c
Average	1241	284	319	604	228%	353	134%	
Median	795	220	155	429	177%	242	125%	

Table 1-2. Watershed size and geology.

Watershed	Watershed Size (km^2)	Geology (percent area)	
		Wildcat	Yager
South Branch North Fork Elk River	4.9	83%	17%
Corrigan Creek	4.4	75%	25%
Little South Fork Elk River	3.0	71%	29%

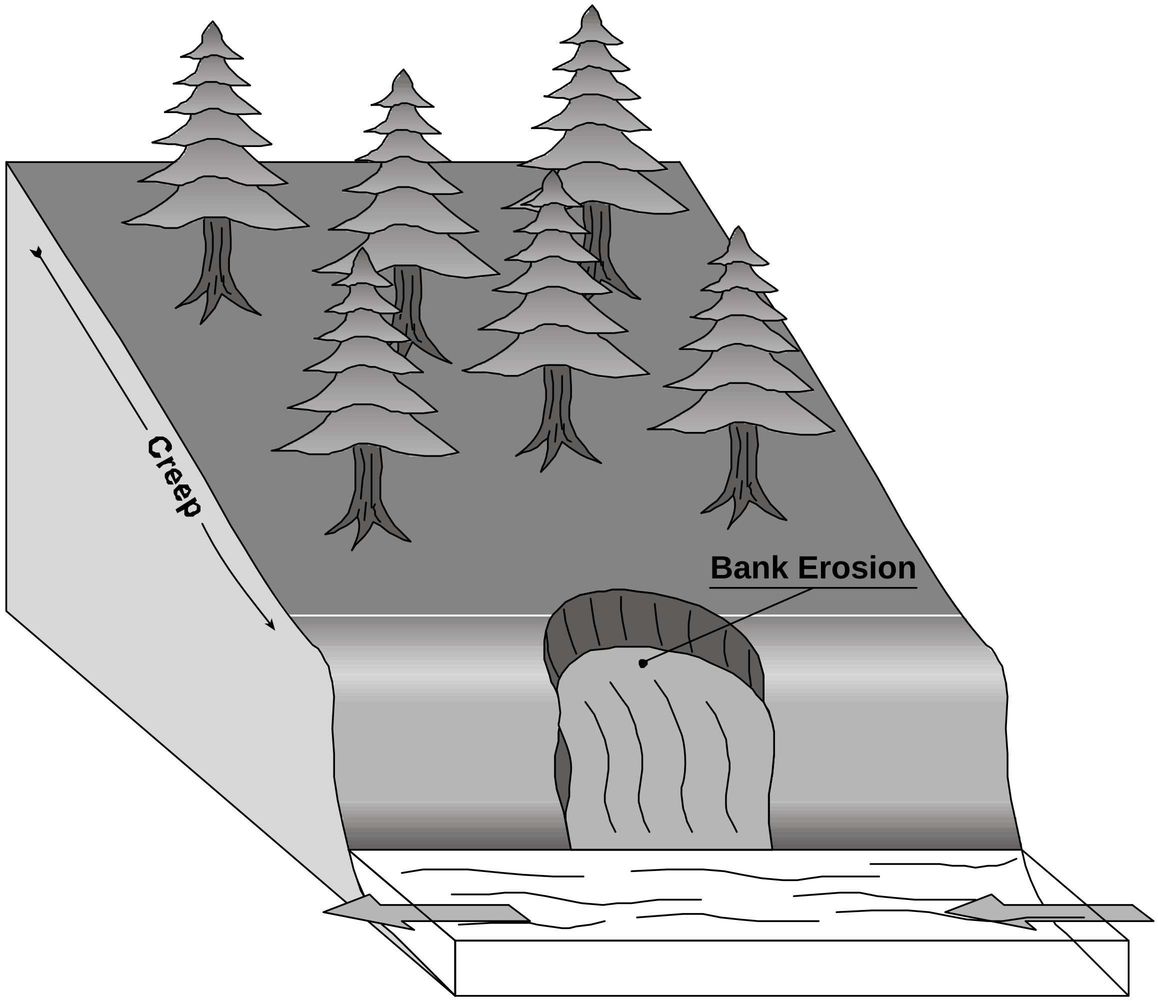

Figure 1.1. Soil creep and bank erosion.

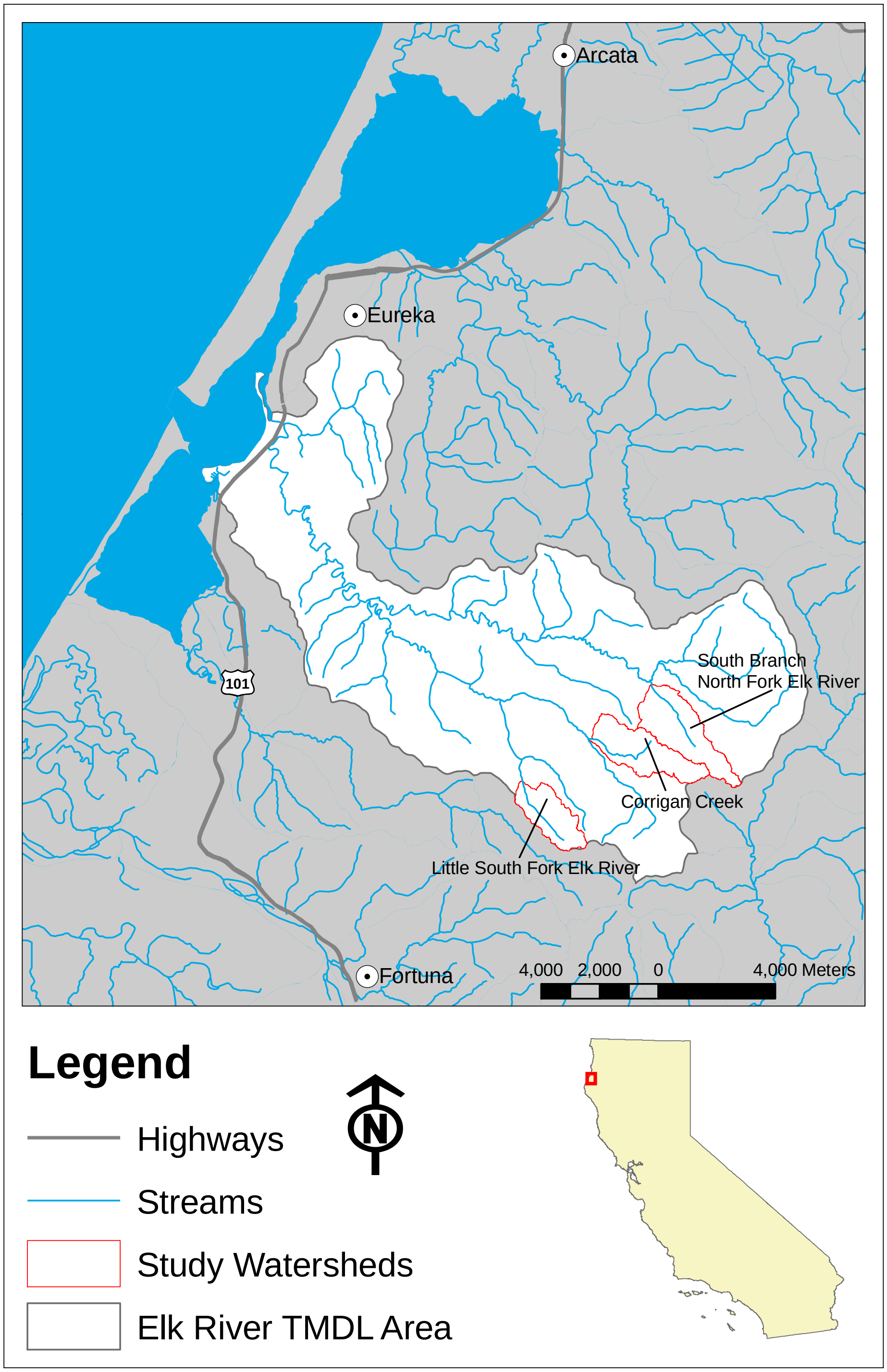

Figure 1.2. Elk River Watershed and the surveyed watersheds.

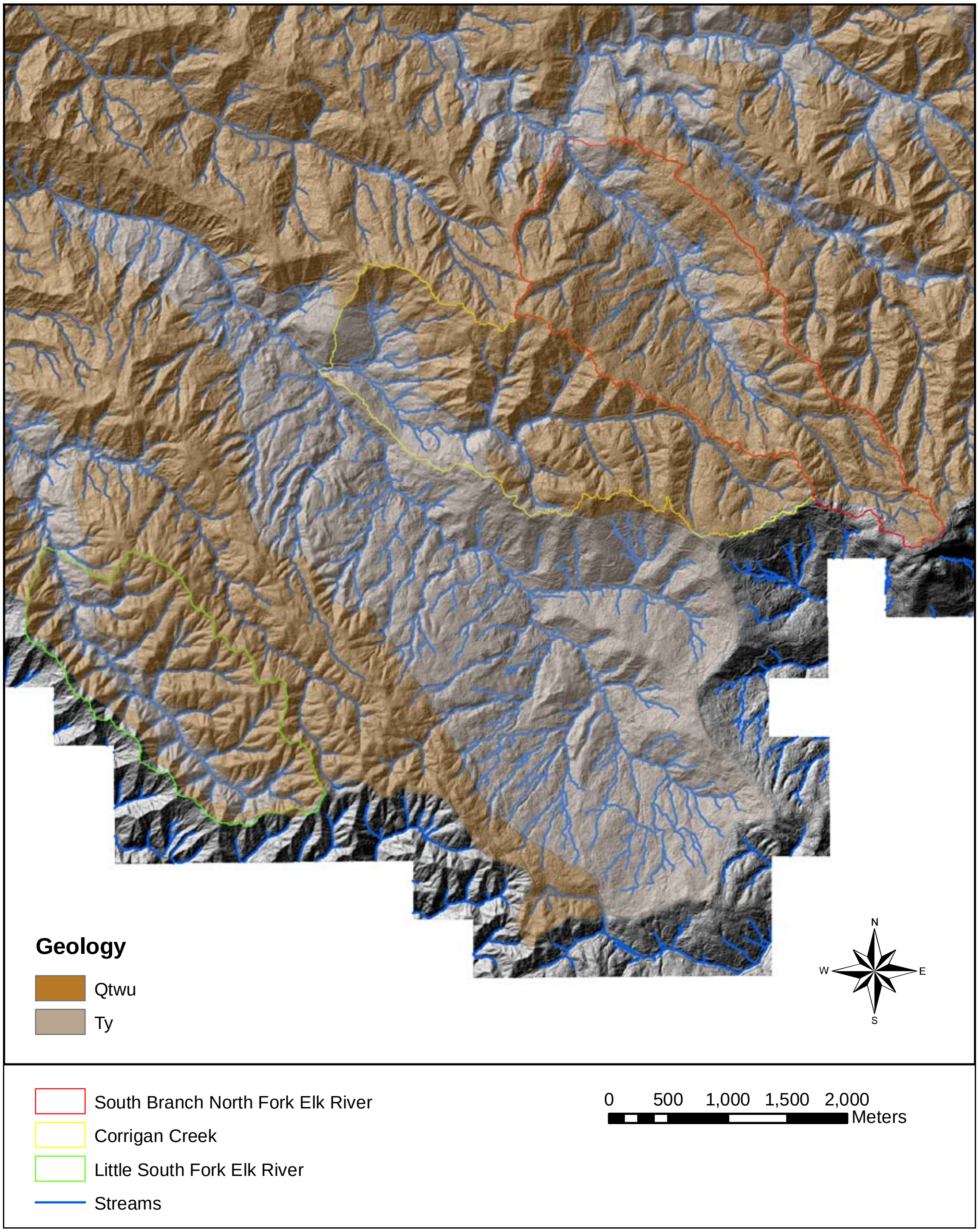

Figure 1.3. Shaded relief map of the watersheds used in this study. Qtwu is the Wildcat Group and Ty is Yager terrane. Streams assume a 2.0 ha drainage area for stream initiation.

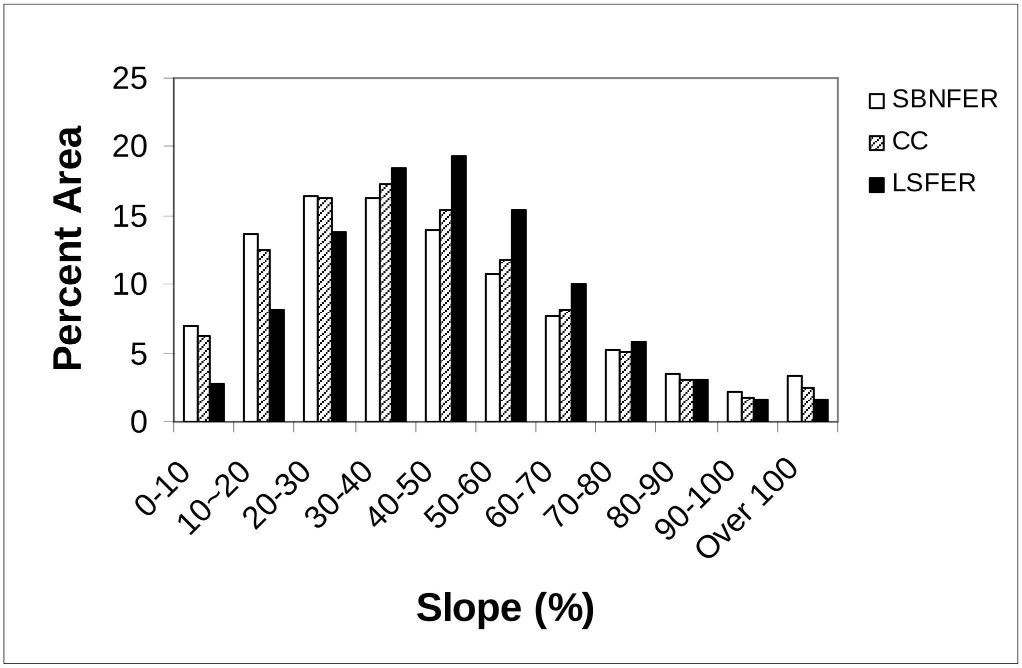

Figure 1.4. Hillslope gradient comparison for South Branch North Fork Elk River (SBNFER), Corrigan Creek (CC), and Little South Fork Elk River (LSFER).

CHAPTER 2

Logging-Related Increases in Stream Density in a Northern California Watershed

Abstract

Although many sediment budgets estimate the effects of logging, few have considered the potential impact of timber harvesting on stream density. Failure to consider changes in stream density could lead to errors in the sediment budget. This study conducted field surveys in randomly selected catchments in three watersheds to determine the location of channels in the catchments. The drainage areas for identified channel heads were then delineated using a 1-m digital elevation model derived from laser altimetry. The two managed watersheds were heavily impacted by previous logging activities, particularly by tractor operations used to yard the timber out of the watersheds. The channel heads in the managed watersheds had smaller drainage areas than channels in a nearby old-growth watershed. Timber harvesting and the construction of skid trails used to transport timber to the road system led to increases in peak flow, ground water interception, soil compaction and drainage diversion, which reduced the drainage area necessary to initiate stream channels. The management activities led to a tripling of the drainage density in the managed watersheds. Furthermore, it appears that recent ground-based yarding operations have further extended stream channels upslope, potentially creating additional sources of sediment for downstream receptors. Although these results may be unique to these watersheds, the changes in drainage density due to management activities

found here emphasize the need to compare managed watersheds with undisturbed watersheds before using the current drainage network as a base-line for watershed investigations.

Introduction

Many watersheds in northern coastal California have been impaired by sediment discharges from non-point sources, particularly sediment sources related to logging activities. Efforts to assess the sediment impairment often include the construction of sediment budgets to create an "accounting of the sources and disposition of sediment as it travels from its point of origin to its eventual exit from a drainage basin" (Reid and Dunne, 1996). Sediment budgets identify sediment sources and provide estimates of sediment delivery which can help prioritize erosion control efforts (USEPA, 1999).

Although often overlooked, the extent of the stream network, or the drainage density, plays an important role in developing sediment budgets. Stream maps are needed to determine if discrete features (e.g. landslides) have delivered sediment to the network. The drainage density is also important for estimating sediment delivery from diffuse sediment-generating processes (e.g. bank erosion due to soil creep). However, topographic maps do not include the majority of headwater streams (Morisawa, 1956), which is a particular problem in areas under forest canopy (Benda et al., 2005). Therefore, conducting field surveys to determine the extent of the stream network in the watershed is often recommended (Montgomery and Foufoula-Georgiou, 1993 and WDNR, 1997). However, steam networks may change due to forest management activities, and estimated drainage densities based on only the current stream network could overestimate the natural drainage density. If the current stream distribution is used to estimate natural chronic sources of sediment and the stream network is more extensive than it had been prior to disturbance, the impacts of timber harvesting will be underestimated.

The point of transition from an unchanneled swale, also known as a zero-order basin (Dietrich et al., 1987), to a channel is referred to as the "channel head." The channel head is the upstream limit of concentrated water and sediment transport between definable banks (Dietrich and Dunne, 1993). Knighton (1998) describes five processes related to channel initiation: two by overland flow (Horton overland flow and saturation overland flow) and three by subsurface flow (seepage erosion, tunnel scour and shallow landsliding). These processes are not mutually exclusive, and all may be present even in a relatively homogenous landscape. However, landsliding is likely to predominate in steep areas, while overland flow and seepage erosion predominate in lower-gradient areas (Knighton, 1998). The location of the channel head is affected by climate, with wetter regions needing smaller drainage areas (Montgomery and Dietrich, 1988).

Hillslope gradient can also influence channel initiation. Montgomery and Dietrich (1988) found a strong inverse relationship between drainage area and valley gradient at the location of channel heads, especially where landslides initiated channels. Channel heads initiated by overland flow may also reflect a relationship between drainage area and gradient relationship (Montgomery and Foufoula-Georgiou, 1993), as may those of gullied channels (Prosser and Abernethy, 1996, and Vandekerckhove et al., 2000). However, there are circumstances where a plot of channel head drainage area versus slope at the channel head does not reveal a relationship. For instance, Dietrich et al. (1987) noted no systematic drainage area-slope relationship at sites in Oregon where channel head locations were thought to be controlled by the flow paths through fractured bedrock. Wemple et al. (1996) showed a weak and not statistically significant relationship between drainage area and hillslope gradient at channel heads for their study sites. Their observations indicate that hillslope gradient may not be a factor in channel initiation in some areas, allowing the extent of the stream network there to be estimated on the basis of drainage area alone. Furthermore, Jaeger et al. (2007) also noted that the lack of an area-slope relationship for sites located in Washington.

Given the dependence of drainage area on climatic conditions, it seems reasonable to expect that management activities that increase runoff may also decrease the drainage area and hence increase the drainage density. Roads increase runoff because road surfaces have lower infiltration capacity than natural slopes. Montgomery (1994) found the drainage area needed to support a channel head is smaller for drainages receiving road runoff. The inclusion of the road surface runoff with the channel network increased the drainage density by a factor 1.23 to 1.6 at field sites in Oregon and California respectively (Montgomery, 1994). Wemple et al. (1996) surveyed road segments in two Oregon watersheds and found that fifty-seven percent of the surveyed road length was connected to the stream network by roadside ditches some of which was due to increased gullying and the extension of watercourses into unchanneled swales. The drainage density increased by a factor of 1.21 to 1.50 depending on which road segments are assumed to be connected to streams.

Logging is also likely to have an effect on channel head location. Prosser and Soufi (1998) observed gulley initiation during large rainfall events following forest clearing. Increases in peak flow due to soil disturbances and reduction in evapotranspiration are well documented after logging (Guillemette et al., 2005) and are likely to play a large role in modifying channel head locations. In the redwood region, Lewis and Keppeler (2007) observed peak flow increases of as much as 300% in clear-cut watersheds, while the average two-year peak flow event increased by 27% in the logged watersheds. Increases in peak flow could exceed the thresholds related to the channel initiation processes and decrease the drainage area for channel initiation.

Few observations directly linking logging to increased stream density have been made. Pacific Watershed Associates (1999) surveyed cable-yarded clearcuts in northern coastal California to estimate the impacts on the stream network. Tractor-yarded areas were not included in their surveys in order to exclude the complicating effects of tractor disturbance in the channels. They found that valley catchments served as groundwater reservoirs in old-growth areas, with most runoff carried through a network of interconnected subsurface pipes that are intermittently exposed in the valley floor. The incised channels or gullied swales within the old-growth areas are discontinuous, inactive, and located much farther downstream (i.e., have larger drainage areas) than those identified in the clearcut drainages of the harvested areas. Pacific Watershed Associates concluded the swales in logged areas had experienced gullying in response to first-cycle harvesting. However, their surveys discovered renewed incision in only two of the fifty stream reaches associated with recent second-cycle harvesting. A study by O'Connor Environmental, Inc. (2005) found that the drainage areas for mature second-growth forest was nearly double that of recently harvested areas, but they considered their results inclusive because there was no significant difference in bank erosion area between the treated and control sites.

This study seeks to determine the effects of logging on stream network extent by comparing the stream density in two logged watersheds with that in a nearly pristine watershed. The field surveys also identified which channel initiation processes most important in these watersheds and which management features are associated with channel heads. This information will be used to help determine if the drainage density in the area can be estimated from drainage area alone or if a more complicated model is needed that also incorporates slope. The drainage density determined in the pristine watershed will be used to estimate soil creep sediment delivery in Chapter 4.

Methods

In Elk River watershed, located near Eureka, California, three subwatersheds were surveyed to determine the catchment area needed for channel initiation and to examine the influence of valley gradient on the location of channel heads. The three watersheds share similar bedrock, which primarily consists of the sedimentary rocks of the mid-Tertiary to Quaternary-age deposits of the Wildcat Group, a poorly to moderately consolidated siltstone and fine-grained silty sandstone. The Late Cretaceous Yager terrane of the Coastal Belt of the Franciscan Complex, a sheared and highly folded mudstone, is exposed in the deeper portions of the canyons of the watersheds (Marshall and Mendes, 2005). The three watersheds have average hillslope gradients of 23° to 24°. These watersheds experience a Mediterranean climate with dry summers and wet winters and with an average annual precipitation of 1650 mm. Snow rarely falls on these coastal watersheds (Hart Crowser, Inc., 2005). Forest stands in Elk River are dominated by redwood (*Sequoia sempervirens*) and Douglas-fir (*Pseudotsuga menziesii*).

The primary difference between the three watersheds is their management history. Most of the South Branch North Fork Elk River (SBNFER) watershed was first logged in the 1970s, though small areas were harvested in the 1940s and 1960s as well. A second logging entry occurred throughout the entire watershed in the late 1980s and early 1990s, consisting of partial-cut and clear-cut harvests with tractor yarding. The western portion of the Corrigan Creek (CC) watershed was first logged in the 1950s and the eastern portion in the 1970s. The eastern portion experienced a second logging entry in the late 1980s and early 1990s, consisting of partial-cut and clear-cut harvests with tractor yarding (Manka, 2005). Within the three years prior to the field survey, the western portion of CC was primarily commercially thinned and tractor-yarded, although portions were clear-cut and cable-yarded. The portion Little South Fork Elk River (LSFER) surveyed in this study is primarily an old-growth redwood forest. In the early 1990s, a 2.3-kilometer road was constructed adjacent to the upstream portion of the stream channel. The maximum width of disturbance from the road construction and the adjacent logging was 61 m (Pacific Watershed Associates, 2007). This area of the LSFER watershed was included in the Federal purchase of the Headwaters Forest Reserve in 1999. The road was subsequently decommissioned. A complete slope restoration, including excavation of stream crossings and recontouring of hillslopes, was completed in 2003 (Manka, 2005).

As noted above, the two managed watersheds were primarily clear-cut and tractor yarded. Tractors would have been used to create layouts for felling the larger redwoods (to protect them from shattering upon ground impact) and to create skid trails to move the logs to the road network. The skid trail network is quite extensive in these watersheds (Figure 2.1). Measurements on air photos indicate the skid trail density is 32.9 km km^{-2} in SBNFER and 31.4 km km^{-2} in CC (Table 2-1).

Since it is impractical to conduct surveys of the entire watershed for even these relatively small watersheds due to the amount of field time that would be required to do so, the watersheds were divided into catchments from which a random selection of catchments was surveyed. Catchments within the three watersheds were delineated from a 1-m digital elevation map (DEM; Sanborn, 2005) derived from laser altimetry (known as LIDAR: Light Detection and Ranging), using Arc Hydro tools and the methods described in Olivera et al. (2002). A flow direction map was derived from the DEM using the premise that water will follow the path of steepest descent. Next, flow accumulation was calculated for each cell based on the number of cells draining into it. Using the flow accumulation map, streams were preliminarily defined by a threshold drainage area to delineate the catchment boundaries. Wemple et al. (1996) surveyed eleven channel heads in Oregon, which had an average drainage area of roughly two hectares. The present study presumed that a 2.0-ha drainage area for channel initiation would be sufficiently conservative to locate channel heads in headwater portions of the watersheds, but still divided the watershed into reasonably sized catchments that could be surveyed easily. Furthermore, setting the threshold drainage area at 2.0 ha for purposes of catchment delineation would prevent field crews from having to investigate areas downslope of headwater catchments in order to locate channel heads (i.e., field crews would likely locate one or more channel heads in headwater catchments that were based on a stream definition of two hectares). This does not mean that all catchments were greater than two hectares. The size of catchments downstream of headwater catchments depends on tributary alignment; therefore, these downstream catchments are not limited by size.

One potential problem with using the 1-m LIDAR DEM to delineate catchments is that flow paths are assumed to follow the surface topology. However, roads affect the surface topology and can alter the flow paths. When roads intersect swales, flow from swales can be inadvertently diverted down the road instead of into culverts passing underneath the road surface. Catchment boundaries were examined to determine the extent of diversions and although several occurrences were identified, the effects on the catchment area were minor and therefore no effort was undertaken to correct the DEM.

A simple random sample (SRS) of catchments was selected in each of the three watersheds. These catchments were inspected between October 2005 and May 2006. A few catchments selected by the SRS were small (< 0.10 ha) and were not visited. Table 2-2 shows the number and size of the catchments that were surveyed in the watersheds for this study and Figure 2.2 through Figure 2.4 show an overlay of the randomly selected catchments. Based on a nearby rain gauge located in Eureka, the inspections occurred during a wetter than average winter period (148 cm of rainfall, 58% greater than the average annual precipitation; California Data Exchange Center).

Field crews were provided with large scale maps (typically 1:4000) of the catchments that were derived from the 1-m DEM. The maps identified cells that had a flow accumulation greater than 500 m^2, which were generally located in well-defined swales. Typically, field crews would hike up all swales in the catchments to locate channel heads. Other areas in the catchments were also traversed.

Channel heads were defined as the farthest upslope location of a channel with well-defined banks (Montgomery and Dietrich, 1988). Although landslides themselves do not produce channels, they often expose erodible material with a low infiltration capacity, so subsequent erosion by overflow can initiate channelization (Dietrich et al., 1993). Small-scale landslides were identified as channel heads in this study when there were well-defined banks below the landslide. Since the stream channels typically begin as discontinuous segments, some subjectivity is introduced in identifying channel heads. Also, field crews found access to portions of the catchments difficult due to thick vegetation and old logging debris, which would result in a slight overestimation of drainage area in logged watersheds.

The locations of the channel heads were recorded using a Global Positioning System (GPS; Trimble GeoExplorer 3) and differentially corrected in the office to reduce errors in signals received by the GPS. If GPS reception was poor, a laser range finder was used to determine the distance to a known location (e.g., a road crossing or tributary junction). Along with the location, other attributes recorded include slope (as measured with a clinometer to a point approximately five meters above the channel head), type (e.g., spring, head cut), and management activities (e.g., presence of roads, skid trails, yarding corridors, stand age).

The drainage area for a channel head was defined as the upslope area draining into that feature (Shreve, 1969). The drainage areas were delineated under the assumption that flow paths follow the surface topography downslope and therefore surface topography defines both the surface and subsurface drainage catchments (Freer et al., 2002; McDonnell, 2003). Several steps were taken to determine the drainage areas at the channel head locations. These steps were necessary because the GPS channel head locations did not correspond to flow paths derived from the 1-m DEM. This difference is not unexpected both because the GPS accuracy is only 5 to 10 meters or more when operating under a closed canopy, and because the LIDAR-generated DEM is expected to depict some real short-wavelength topography, such as fallen logs or stumps, as well as random errors that could affect the flow paths derived from the DEM surface. Therefore, to determine the drainage area at the channel head, the GPS point representing the channel head was moved to the closest cell that had the greatest flow accumulation. These locations were generally positioned along the axis of the swales. The average adjustment for the channel head point was five meters, although the adjustment was greater than ten meters for several points. If the channel head was between two large flow paths that were separated by only a few meters, the drainage area for that channel head was recorded as the sum of flow accumulations for both flow paths. These adjustments generally resulted in modification in the drainage area of much less than 0.1 ha. One surveyed catchment in SBNFER was removed from the analysis when it was determined that the GPS channel head was located outside the catchment boundaries.

Statistical analysis was carried out using MINITAB™. The drainage areas for the channel heads were compared using box plots and tested for normality using the Anderson-Darling normality test. Log transformation improved the normality of the drainage area distribution so the log-transformed drainage areas were used in regression analysis, with local valley slope as the independent variable. The nonparametric Mann-Whitney test was used for pair-wise tests of the equality of the population medians for the channel-head drainage areas between the watersheds.

The drainage density in the managed watersheds was compared with that in undisturbed portion of LSFER to estimate the increase in drainage density due to the management of these watersheds. This comparison was accomplished by using the channel-head drainage areas in the surveyed watersheds to define the upstream extent of channels for old-growth and logged conditions. In a process similar to that described above for delineating catchments, GIS was used to derive the stream length for the different drainage areas, and the total stream length was then divided by the watershed area to calculate the stream density.

Results

The numbers of channel heads identified in the surveyed catchments are shown in Table 2-3. For the managed watersheds, SBNFER and CC, channel heads were found in most of the catchments and several catchments in these watersheds had multiple channel heads. Few catchments, one in SBNFER and six in CC, had no channel heads. The catchments without channel heads were not headwater catchments. While one of the catchments without channel heads was large (> 8 ha), most were small (<3 ha) and none of these catchments had a major drainage axis or swale within their boundaries, which limited the drainage area within these catchments. It is likely that the limited drainage area in these catchments prevented erosion thresholds from being exceeded.

Box plots of the drainage areas for channel heads are shown in Figure 2.5 and the drainage areas of the channel heads are shown in Table 2-3. The range in drainage area at the channel heads exceeds an order of magnitude and the distributions are skewed to the right. The average drainage size in these watersheds is 0.69 ha and 0.98 ha and the median is 0.42 and 0.72 ha for SBNFER and CC respectively.

Catchments in LSFER are separated into two categories depending on whether or not the road passed through the catchments. Results for the five catchments that contain portions of the road are similar to those from the other managed watersheds. While three of these catchments did not have channel heads, these catchments are small (averaging 0.6 ha in size) and did not contain major swales. It is likely that even with the road being present, erosion thresholds were not exceeded due to the small drainage areas. For the two catchments with channels, the channel heads were clearly associated with the road and the drainage areas for these channel heads reflect the road location in the catchment.

Nine catchments within LSFER were not affected by the road construction. Five of these catchments had no channels (Table 2-3). While three of these catchments did not have swales and therefore had small drainage areas, two of the catchments were very large with drainage areas of 4.85 and 5.29 ha. In fact, these two large headwater catchments without channel heads exceeded the drainage area for the four catchments with identified channel heads, which had drainage areas that ranged from 1.33 to 4.73 ha and had average and median drainage areas of 3.10 and 3.15 ha respectively. It appears that the area of the two large catchments without channel heads is below the erosion thresholds necessary to initiate a channel head. If so, it seems appropriate to include the area of these two catchments as a minimum value in determining the drainage area needed to initiate channels in the undisturbed portions of LSFER. Including these two catchment areas raises the average and median drainage area to 3.75 and 4.22 ha respectively.

The field surveys disclosed the presence of small sinkholes along the unchanneled swale axes of in LSFER. These small sinkholes were typically 0.5 to 2 m in depth with a diameter of 0.2 to 0.5 m and are commonly adjacent to small steps in the valley floor. Drainage areas for the upslope sinkholes ranged from 0.18 to 1.90 ha, with an average and median drainage area of 0.57 and 0.43 ha, respectively. Very small flows were either audible or visible in these sinkholes. These sinkholes were not considered to be channel heads since they only revealed the presence of subterranean soil pipes along the swale axis and did not expose a channel with well defined bed and banks. It possible that the sinkholes are related to mountain beaver (*Aplodontia rufa*) burrows.

Figure 2.6 compares the local valley slope with drainage area at the channel head. To test for a relationship between slope and drainage area, regression analysis was conducted using the log-transformed drainage areas, because the drainage areas were not normally distributed (Anderson-Darling normality test, $p = 0.000$). Using all the channel head data in the regression analysis resulted in a poor, insignificant relationship ($R^2 = 0.064$, $p = 0.093$). However, examining Figure 2.6 reveals three potential outliers that have large drainage areas for their local valley slopes. The channel head located in LSFER was associated with the road location in the catchment and therefore may truly be an outlier. The other two potential outliers, one in CC and the other in SBNFER, were springs near the outlet of very long and planar catchments. Removing these outliers improved the relationship ($R^2 = 0.0176$) which was significant ($p = 0.006$), but the relationship is still poor as indicated by the low R^2 value.

This poor relationship indicates that slope is not an important factor in determining drainage density in these watersheds.

To help determine which channel forming processes are important in these watersheds and to determine how timber management may be affecting these processes, management features associated with the channel heads were noted (Table 2-4). For purposes of this categorization, a cutbank related channel head indicates that the channel head was located at a road or skid trail cutbank and where it appears that seepage erosion or saturation overland flow are the important channel forming processes at these locations. Cutbank channel heads likely intercept shallow groundwater. Channel heads were categorized as "tunnel scour" or "landslide" if these channel forming processes were present.

Most channel heads in the managed watersheds are associated with some type of management feature, the most common of which are skid trails. This result is not unexpected considering the high skid trail density in these watersheds (Table 2-1). Seepage erosion and saturation overland flow are important channel-forming processes along road and skid trail cutbanks. Tunnel scour is also commonly associated with skid trails. An example of a channel head formed by tunnel scour in a skid trail is shown Figure 2.7. Landslides appear to be a minor process in channel-head formation in these watersheds.

The median drainage areas for channel heads in SBNFER and CC are significantly different than that for LSFER ($p = 0.0062$ and 0.0138 respectively). Furthermore, the p-values decrease when the two large catchments without channel heads were included in the LSFER. The drainage areas for the managed watersheds, SBNFER and CC, were combined and the median drainage area was used to construct estimated stream networks for managed conditions in the three watersheds. Likewise, the median drainage area for undisturbed catchments in LSFER, including the two large catchments where channel heads were not present, was used to construct stream networks for old-growth forested conditions in the three watersheds. Stream networks for forested and managed conditions were then compared to estimate the drainage density resulting from the timber management (Table 2-5). This analysis assumes that 1) the undisturbed portions of LSFER are representative of the natural drainage density, and 2) the median drainage area including the two large catchments where channel heads weren't detected represents the drainage area needed to overcome erosion thresholds and therefore initiate stream channels. The drainage density in the managed forests was to 2.7 to 3.1 times the natural drainage density.

Discussion

Impacts of harvest history

Our surveys in the unaltered portions of the old-growth forest indicate that subterranean soil pipes play an important role in the transportation of runoff, since infiltration rates are high and overland flow rarely occurs in undisturbed forested watersheds. Sink holes revealing the presence of soil pipes were located in unchanneled swales only short distances from ridgelines, thereby having small drainage areas. The depth of these sinks holes, 0.5 to 2 m, is approximately the depth to the relatively impermeable bedrock observed in road cuts and small landslides in the area. It appears that these soil pipes form a well-developed subterranean network and are stable enough to carry stormflows large distances downstream.

However, erosion thresholds are eventually overcome when several unchanneled swales merge. Although observations are few, it appears that channel heads tend to be located near the junction of unchanneled swales.

Timber management activities appear to have destabilized the soil pipe network and dramatically reduced the drainage area needed for channel initiation, thereby increasing the drainage density. Two aspects of management may have been particularly influential: the construction of roads (and skid trails) and the removal of vegetation. The increases in drainage density observed in these watersheds are greater than those found is areas where road-related impacts have been studied in the past (Montgomery, 1994; Wemple et al., 1996). The large increases at Elk River may be due in part to the extremely high density of skid trails present. Although skid trails generally support heavy equipment only briefly during a harvest cycle, skid trails have similar impacts as roads in that they intercept ground water, increase runoff due to ground compaction, and change drainage patterns. Skid trails were observed at many of the channel heads (Table 2-4). Field observations suggest that soil compaction on skid trails may play a role in tunnel scour and roof collapse in soil pipes, possibly by locally collapsing pipes, leading to tunnel scour as new flow paths are created.

The reduction in drainage area for the channel heads may have other contributing factors other than the presence and impacts of skid trails. Vegetation removal is likely to have reduced the drainage areas for channel heads through several mechanisms. Vegetation removal increases runoff due to reductions in transpiration and interception (Lewis et al., 2001). The increased runoff may destabilize the soil pipes and form gullies (Dewey, 2007).

Another factor that may contribute to destabilization of soil pipes is the reduction in root strength, which could decrease soil cohesion and resistance to erosion.

Drainage area-slope relationship

Unlike several studies (e.g. Montgomery and Dietrich, 1988; Montgomery and Dietrich, 1992), this study did not observe an inverse drainage area-slope relationship. Only when several potential outliers were removed was there a significant drainage area-slope relationship, but it was weak. One possible reason for the lack of this relationship may be the significant scatter in drainage area for a particular slope, thereby making it difficult to observe a trend (Jaeger et al., 2007). The large scatter in drainage areas is not unexpected. Montgomery and Dietrich (1988) attributed the large range in drainage areas partly to the variability in strength and saturated conductivity of soil which may vary considerably between locations.

Some of the variability may be attributed to measurement error. Although we estimate that errors in the measurement of drainage areas to be small for most channel heads due to the availability of the high resolution of the LIDAR DEM to measure the drainage area, estimating drainage areas on planar slopes with skid trails was difficult. However, only three channel heads were located on planar slopes where skid trails significantly affected the flow paths, so their influence on the overall slope-area relationship is small. Also, slope measurement at the channel heads was problematic at times, particularly when measuring the slope above road or skid trail cutbanks. Slope measurements were also equivocal at some old-growth forest sites because the swales axes typically had a series of meter-high steps above the channel heads instead of a smooth slope.

Jager et al. (2007) noted several other factors which might contribute to the lack of an area-slope relationship in their study, such as the sub-surface topography not aligning with surface topography, the error in 10-m DEM-generated drainage areas relative to more accurate GPS generated drainage areas, and the presence of a narrow range of slopes. Based on our observations during the field surveys, the subsurface impermeable layer appeared to parallel the surface. The high-resolution DEM used in this study improved measurement of the drainage area and therefore measurement errors should not be contributing to the lack of an area-slope relationship. However, it is possible that the range of slopes was too narrow to detect a slope-area relationship. Landslides, typically occurring on steep slopes, are present in these watersheds (Hart Crowser, Inc., 2005). However, only one channel head in these surveys was associated with a landslide. The lack of landsliding may be indicative that these watersheds lacked significant portions of steep slopes compared to other studies, which would diminish the ability to detect a drainage area-slope relationship.

The management activities in these watersheds may also be masking an area-slope relationship. A strong slope-area relation would be expected to show up at sites where channel and hillslope processes are more-or-less equilibrated. The channels in the managed watersheds may still be responding to changed conditions and may not have reached a new equilibrium. A stronger slope-area relation may be present in undisturbed channels than in those still responding to ongoing changes in hydrology and topography. One trend is clear regarding the drainage area-slope relationship. As the drainage areas have been reduced by management activities, channel heads have moved closer to ridgelines, where swale-axis slopes are steeper.

This trend is apparent in Figure 2.6 when comparing the relatively mild slopes above channels in the undisturbed portions of LSFER with the steeper slopes in the managed watersheds.

Sediment budgets and management implications

The increase in drainage density observed in these watersheds may be important to consider during construction of sediment budgets. An increase of drainage density suggests greater peak flows which could add to channel erosion and sediment yields. Furthermore, if a sediment budget used the existing drainage density to estimate the sediment delivery from soil creep, it would be overestimate the sediment delivery from this natural process.

Furthermore, it is clear that in the past large amounts of sediment have been delivered to the stream network due to the shift in location of the channel head (Pacific Watershed Associates, 1999). These relatively new channels, caused by management activities within the last hundred years, may still be unstable and are potentially chronic sediment sources due to continued headcutting and bank erosion occurring within the channels (Dewey, 2007).

In several catchments in Corrigan Creek that had recent timber harvesting operations, we observed the upslope migration of channel heads. These channels appeared to be intercepting groundwater flow from the skid trail used in the recent operations. However, these newer channel heads may only be temporary seeps that are due to the increased runoff associated with the harvest (Lewis et al., 2001). Also, since our surveys took place during a wetter than average year, the new channels may not become permanently established or become chronic sources of sediment.

Future research is needed to determine if the current channel-head locations in managed watersheds represent the minimum drainage areas needed to overcome erosion thresholds, or if future timber harvesting activities could cause channel heads to migrate even farther upslope. Although limited surveys after recent logging have not report renewed bank erosion and channel incision these headwater channels in the area (Pacific Watershed Associates, 1999; Hart Crowser, Inc., 2005), it was noted that the drainage areas for mature second-growth forest, 1.3 ha, was greater than recently harvested areas, 0.7 ha (O'Connor Environmental, Inc., 2005). The difference in drainage areas indicates that there is the potential for further upslope migration of the channel head and associated gully erosion, which could deliver more sediment to downstream receptors.

Given that water quality is impaired in the Elk River watershed and that it is extremely difficult to manage gully erosion once it has initiated, steps to prevent upslope migration of channel heads should be considered when developing plans to mitigate the impacts of future harvesting. Tractor operations and construction of new skid trails should be minimized, particularly in swales. Furthermore, to reduce the increases in peaks and loss of cohesion due to vegetation removal, partial-cuts should be considered in well-defined swales instead of clear-cutting.

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Table 2-1. Management history

	Road density km km^{-2}	Skid trail density km km^{-2}	Total km km^{-2}
South Branch North Fork Elk River	6.1	32.9	39.0
Corrigan Creek	5.6	31.4	36.9
Little South Fork Elk River	0.8	*	0.8

* A few short skids trails were created during the construction of the road in this watershed, but are not included it this table.

Table 2-2. Catchment size.

	All Catchments		Surveyed Catchments			
	Number	Area (km^2)	Number	Percent	Area (km^2)	Percent
South Branch North Fork Elk River	125	4.9	16	12.8%	0.7	14.6%
Corrigan Creek	117	4.4	17	14.5%	0.5	12.1%
Little South Fork Elk River	83	3.0	14	16.9%	0.4	14.4%
Total	325	12.3	47	14.5%	1.7	13.6%

Table 2-3. Number (and percentage) of catchments with channel heads and drainage area at channel head (area in hectares).

Watershed	Catchments with channel heads	Number of channel heads	Minimum	Maximum	Median	Average	Catchments without channel heads
South Branch North Fork Elk River	15 (94%)	22	0.07	2.69	0.42	0.69	1 (6%)
Corrigan Creek	11 (65%)	17	0.12	3.30	0.72	0.98	6 (35%)
Little South Fork Elk River (road)	2 (40%)	2	0.57	2.24	1.40	1.40	3 (60%)
Little South Fork Elk River (no-management)	4 (44%)	4	1.33	4.73	3.15	3.10	5 (66%)

Table 2-4. Management features and channel initiation processes. Channel heads are categorized in the cutbank category when seepage erosion and/or saturation overland flow appeared to be the channel forming processes.

	Management Feature					Total Management Features	Total Number of Channel Heads
	Road		Landing	Skid trail			
	Cutbank	Landslide	Tunnel Scour	Cutbank	Tunnel Scour		
South Branch North Fork Elk River	2	1	1	5	8	18	22
Corrigan Creek	1	-	-	4	2	7	17
Little South Fork Elk River	2	-	-	-	-	2	6

Table 2-5. Drainage density (km km^{-2}) using the median drainage area from the survey results to determine the potential impact of management activities on the stream network.

	Natural (Drainage Area = 4.22 ha)	Managed (Drainage Area = 0.52 ha)	Increase (X)
South Branch North Fork Elk River	3.9	11.7	3.0
Corrigan Creek	3.3	10.2	3.1
Little South Fork Elk River	3.3	8.8	2.7

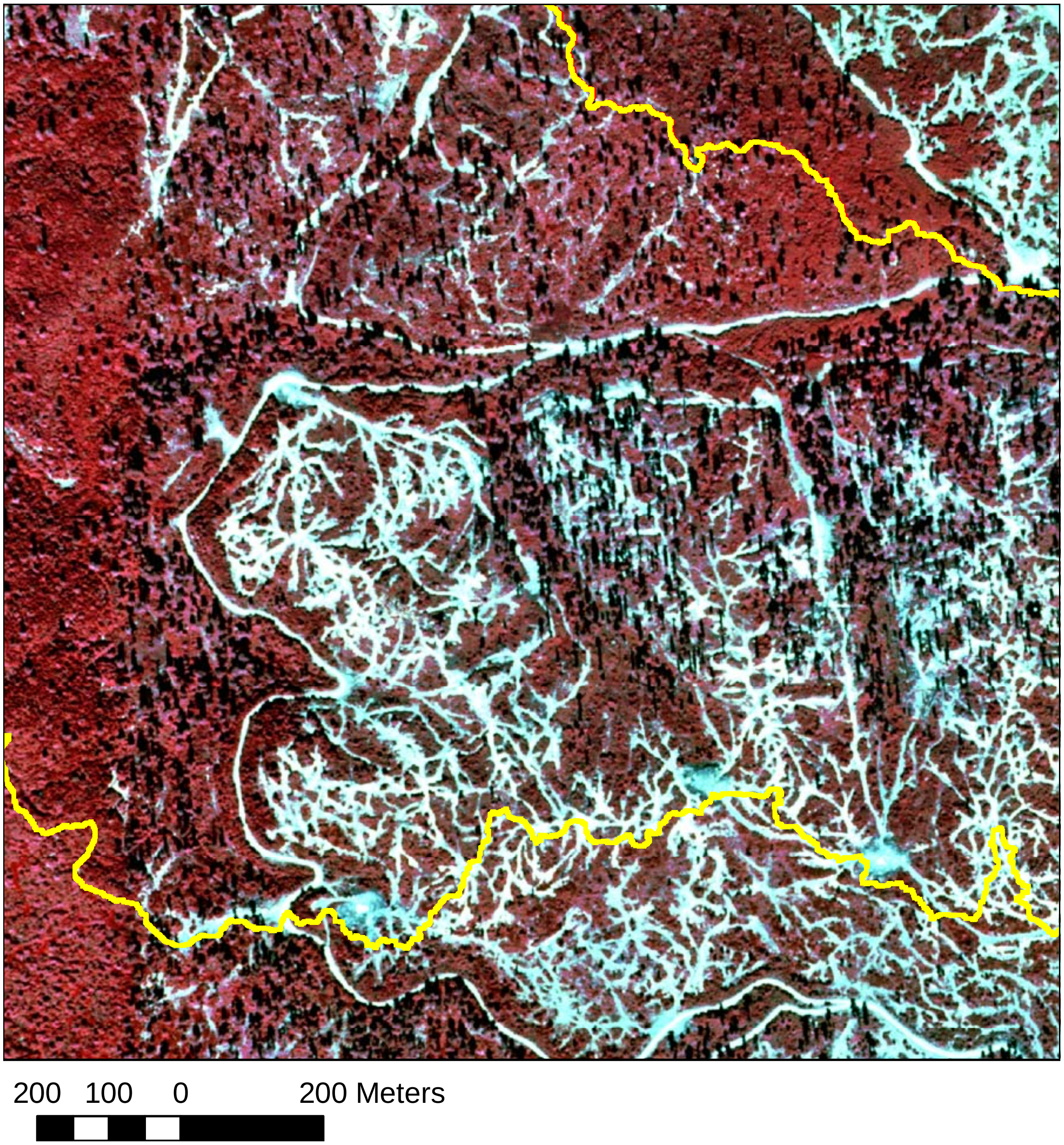

Figure 2.1. USGS infra-red digital orthophoto quadrangle "McWhinney Creek" showing the skid trail network in the middle portion Corrigan Creek showing (photo date 8/18/1988). The yellow lines represent the northern (top) and southern (bottom) watershed boundaries.

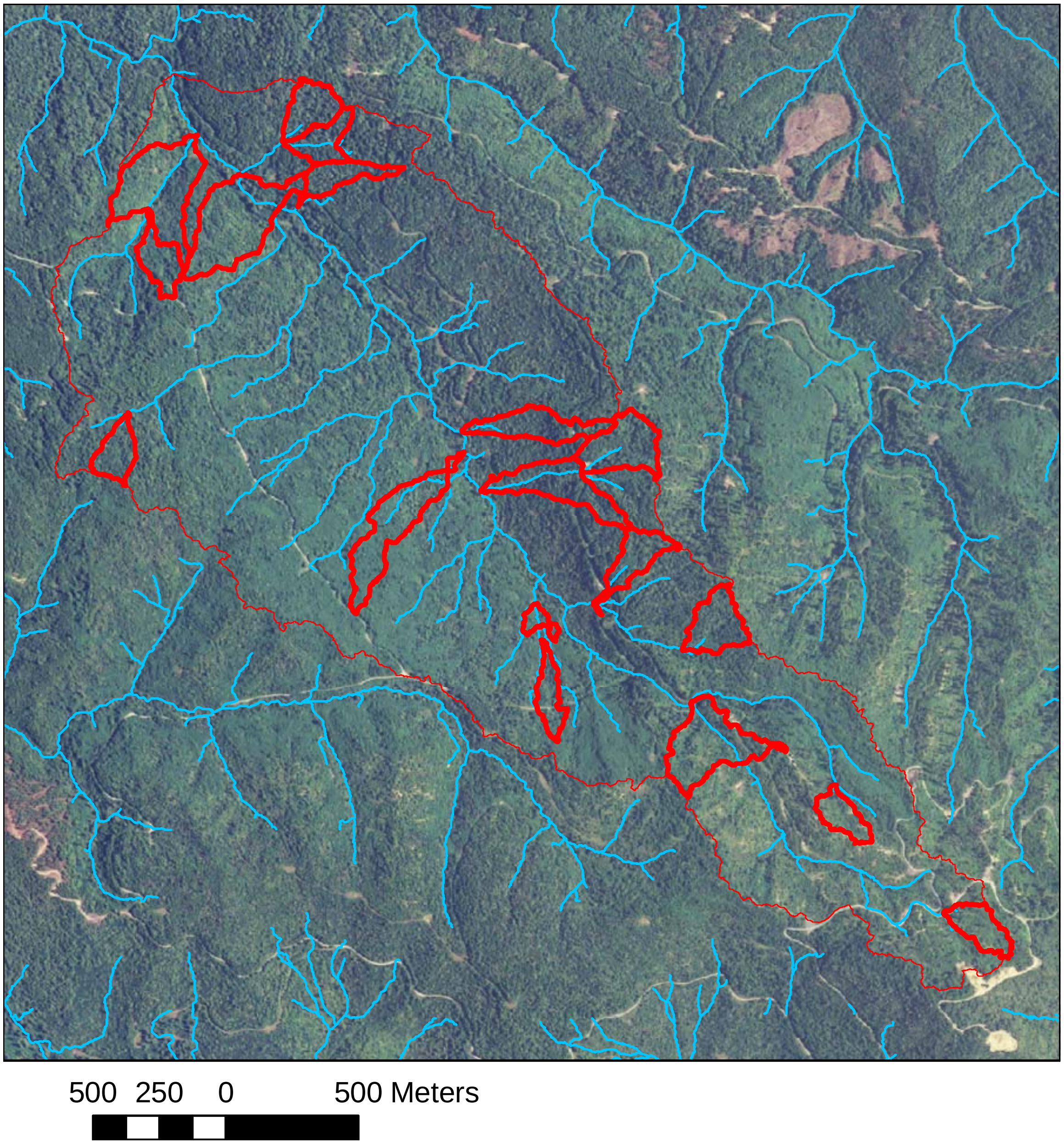

Figure 2.2. South Branch North Fork Elk River with randomly selected catchments highlighted. Streams, in blue, have an assumed 2-ha drainage area. 2005 air photo from National Agriculture Imagery Program (NAIP).

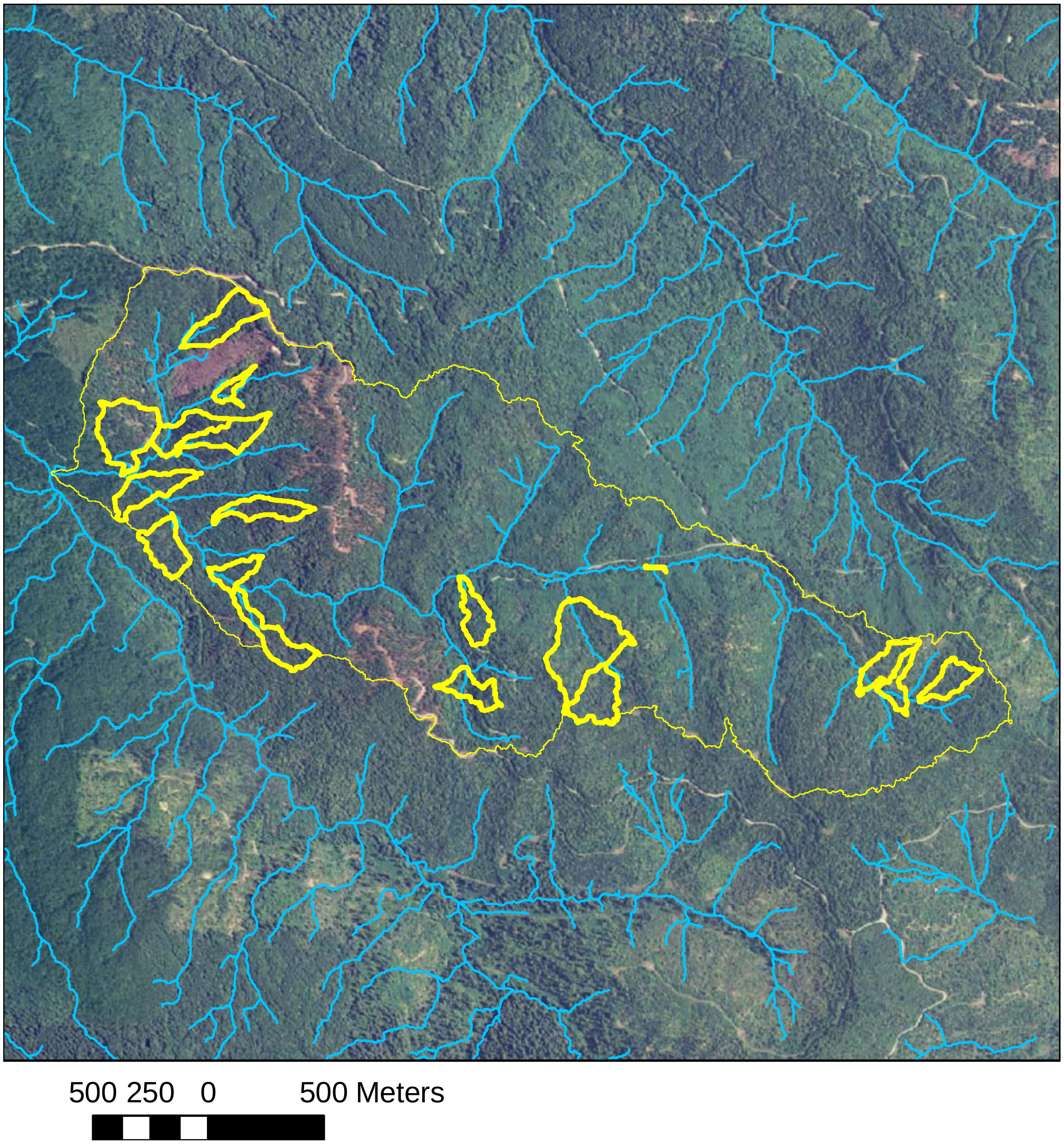

Figure 2.3. Corrigan Creek with randomly selected catchments highlighted. Streams, in blue, have an assumed 2-ha drainage area. 2005 air photo from NAIP.

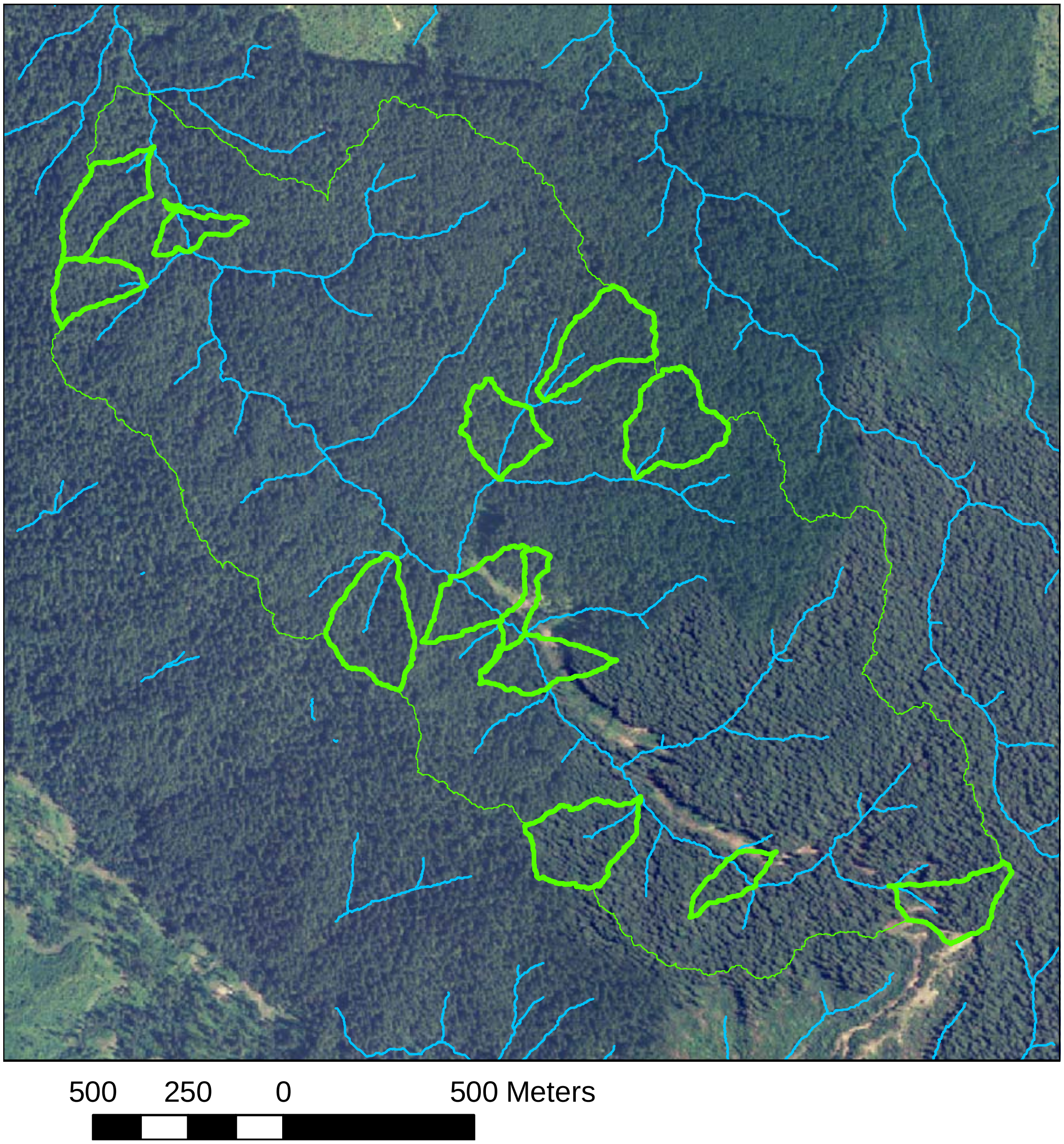

Figure 2.4. Little South Fork Elk River with randomly selected catchments highlighted. Streams, in blue, have an assumed 2-ha drainage area. 2005 air photo from NAIP.

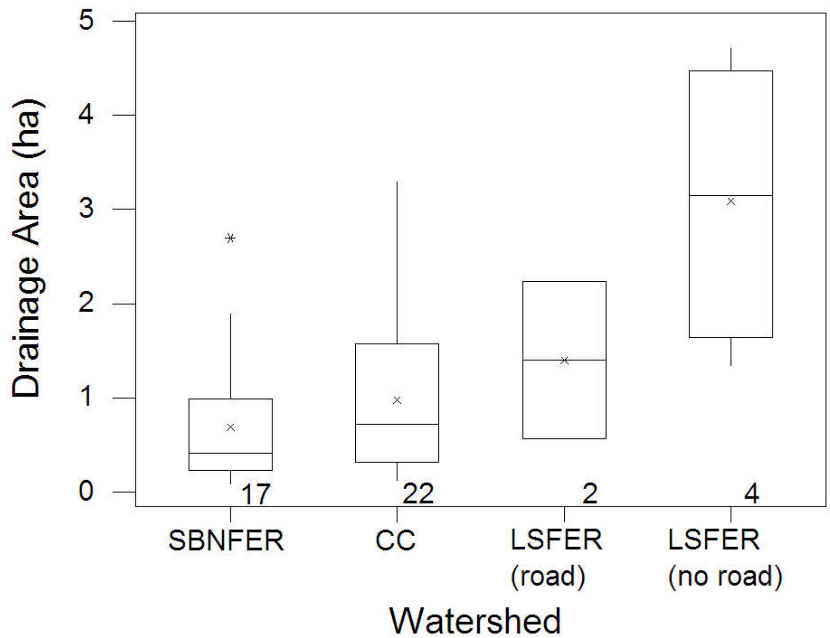

Figure 2.5. Box plot of drainage area of the channel heads. The number of channel heads in each group is shown above its name.

Note: the bottom and top of the box present first (25^{th} percentile) and third (75^{th} percentile) quartiles and contain, within the box, the middle 50% of the values. The median (50^{th} percentile) is marked by the center line within the box and the mean is shown as an X. The whiskers extend to the values that fall within 1.5 * IQR (interquartile range). Outliers are plotted with asterisks (*) when they fall outside of this range.

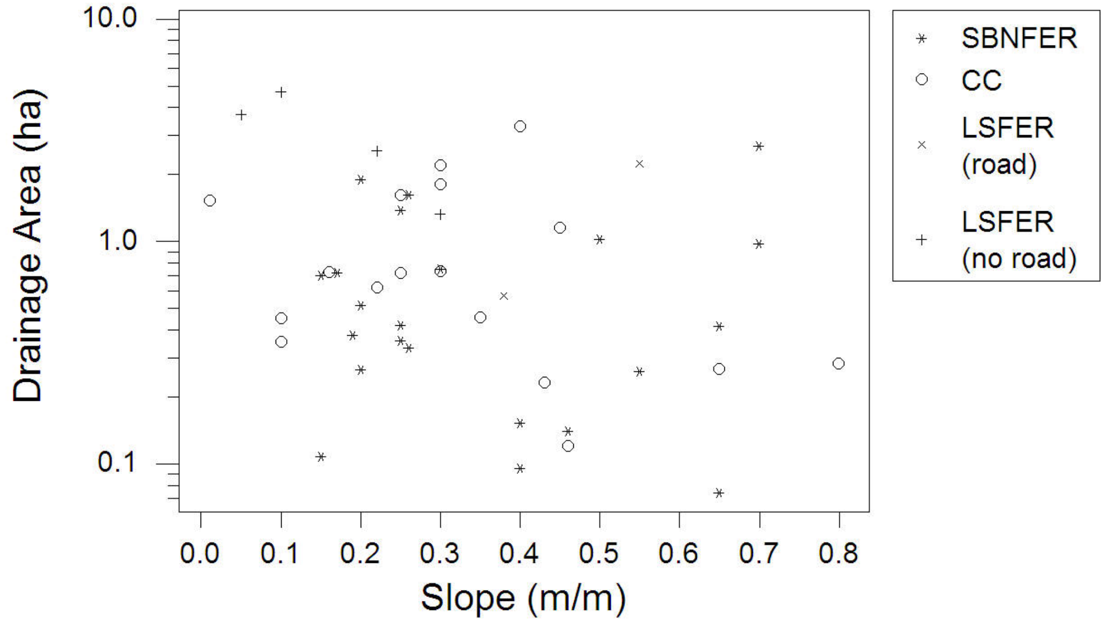

Figure 2.6. Drainage area versus local slope for channel heads.

Figure 2.7. A channel head formed by tunnel scour and roof collapse in the surface of a skid trail. This circular sinkhole was 2.75 m in diameter and had a depth of 1.5 meters.

CHAPTER 3

Comparison of Rapid Bank Erosion Survey Methodologies in Small Forested Watersheds

Abstract

Sediment budgets are used to assess impacts of management activities on water quality. However, time and fiscal constraints can limit the scope of sediment budgets and usually limit field investigations for sediment sources. Bank erosion is an important source of sediment in most watersheds, but it is a difficult process to evaluate. Recently, rapid field surveys have been used to estimate the amount of sediment delivery due to bank erosion. This study compares two rapid bank erosion methods for small forested watersheds. One approach measures the voids along a stream channel, while the other approach measures the volume of large wood that has entered the channel due to bank erosion. The bank erosion estimates from these two surveys are compared with suspended sediment loads measured at the mouths of these sub-basins. Estimating the volume of voids along the stream banks appears to quantify sediment delivery rates better than measuring bank-erosion-related wood. Although measuring channel wood has limited utility to estimate bank erosion rates in these small forested watersheds, wood inventories could be useful for other purposes such as identifying potential restoration opportunities.

Introduction

Sediment discharges from logging activities have impaired water quality in the majority of northern coastal Californian watersheds (CRWQCB, 2008). Under section 303(d) of the Clean Water Act (1972 amendments to the Federal Water Pollution Control Act), states must develop and implement Total Maximum Daily Loads (TMDLs) for impaired water bodies. A key component in developing TMDLs is the source assessment, which typically takes the form of a sediment budget. A sediment budget is an "accounting of the sources and disposition of sediment as it travels from its point of origin to its eventual exit from a drainage basin" (Reid and Dunne, 1996). Bank erosion is usually identified as an important sediment source, but it is a very difficult process to evaluate (Reid and Dunne, 1996).

Bank erosion is hard to evaluate because it can be highly variable in time and space. The factors involved in bank erosion that contribute to its variability include flow properties, bank material composition, climate, subsurface conditions, channel geometry and biology (Knighton, 1998). Bank erosion occurs by three categories of processes: subaerial processes, fluvial entrainment, and mass wasting (Lawler, 1992). Subaerial processes are climate-related and can reduce soil strength (e.g. freeze heave, soil desiccation; Thorne, 1982). Although subaerial processes can cause bank erosion (Prosser et al., 2000), it is generally considered a preparatory process since it increases soil erodibility (Wolman, 1959; Lawler, 1993a). Fluvial entrainment is the direct removal of soil by flowing water (Thorne, 1982), while mass wasting occurs when the weight of the bank is greater than the shear strength of the soil (Osman and Thorne, 1988). All processes are likely to be present in a watershed, although subaerial are likely to dominate in the upper portions of the watershed where temperatures are colder and where stream power and bank heights are relatively small. Downstream, where stream discharge increases along with bank heights, fluvial entrainment is likely to predominate. In the lowest reaches, mass wasting processes are likely to prevail since stream banks continue to increase in height, but stream power decreases with decreasing stream gradient (Wynn, 2004).

Three main sources of data are used to determine bank erosion rates: field measurements, maps and aerial photographs of different dates, and dateable sedimentary and biological evidence (Hooke, 1980). These measurement methodologies vary due to the large range of fluvial environments, the diverse spatial and temporal scales being investigated, and the varying disciplines of the investigators. The timing, financial and logistical constraints of the investigation also determine which methodology is employed (Lawler, 1993b).

Rapid bank erosion field surveys have been used to estimate bank erosion in small forested streams, where the canopy obscures the stream channels from aerial photographs and time constraints prevent using methods that would require multiple field trips (e.g. erosion pins or terrestrial photogrammetry). These bank erosion measurement methodologies are considered rapid because they rely on only one field survey in a given reach to measure bank erosion. There are two rapid field methods that have been recently used in northern coastal California.

Reid and Dunne (1996) describe a field method where bank heights are randomly measured along the channel to calculate a soil creep depth.   To estimate bank erosion delivery, an assumed soil creep rate based on creep rates for similar soils is multiplied by the creep depth and stream density. This method has been modified to measure the erosion-related voids along the banks (Pacific Watershed Associates, 1999; PALCO, 2007). Measuring bank voids as a field surrogate for bank erosion should have higher accuracy than applying an assumed soil creep rate determined at similar sites outside of the watershed (Reid and Dunne, 2003).

Another method appearing in recent literature relies on using wood budgeting methods to estimate bank erosion rates and, where appropriate, soil creep rates (Martin and Benda, 2001; Benda et al., 2002; Benda et al., 2003; Benda and Silas, 2003). In this methodology, stream surveys measure bank-erosion-related wood volume in the stream channel to estimate the annual wood flux, which is then used to calculate the bank erosion rate.

The main goal of this study is to conduct rapid bank erosion surveys in two managed and one old-growth forested watershed. The bank erosion rates for both field methods will be compared to each other and to suspended sediment discharges to test the reasonableness of these methodologies. These bank erosions rates are used to provide a check on the soil creep sediment delivery estimates in Chapter 4.

Methods

In Elk River watershed, located near Eureka, California, three subwatersheds were selected to conduct the rapid bank erosion surveys. The three watersheds share similar bedrock, which primarily consists of the sedimentary rocks of the mid-Tertiary to Quaternary-age deposits of the Wildcat Group, a poorly to moderately consolidated siltstone and fine-grained silty sandstone. The Late Cretaceous Yager terrane of the Coastal Belt of the

Franciscan Complex, a sheared and highly folded mudstone, is exposed in the deeper portions of the canyons of the watersheds (Marshall and Mendes, 2005). The three watersheds have average hillslope gradients of 23° to 24°. These watersheds experience a Mediterranean climate with dry summers and wet winters and with an average annual precipitation of 1650 mm. Snow rarely falls on these coastal watersheds (Hart Crowser, Inc., 2005). Forest stands in Elk River are dominated by redwood (*Sequoia sempervirens*) and Douglas-fir (*Pseudotsuga menziesii*) with grand fir (*Abies grandis*), Sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga heterophylla*), incense cedar (*Calocedrus decurrens*), western red cedar (*Thuja plicata*), and pacific madrone (*Arbutus menziesii*) present in some locations. Big leaf maple (*Acer macrophyllum*), willow (*Salix lasiandra*), and red alder (*Alnus rubra*) are the dominant deciduous tree species found in riparian zones and disturbed areas.

The primary difference between the three watersheds is their management history. Most of the South Branch North Fork Elk River (SBNFER) watershed was first logged in the 1970s, though small areas were harvested in the 1940s and 1960s as well. A second logging entry occurred throughout the entire watershed in the late 1980s and early 1990s, consisting of partial-cut and clear-cut harvests with tractor yarding. The western portion of the Corrigan Creek (CC) watershed was first logged in the 1950s and the eastern portion in the 1970s. The eastern portion experienced a second logging entry in the late 1980s and early 1990s, consisting of partial-cut and clear-cut harvests with tractor yarding (Manka, 2005). Recently, the western portion of CC was primarily commercially thinned and tractor-yarded, although portions were clear-cut units and cable-yarded. These managed watersheds are highly disturbed due to the harvesting and tractor yarding. Tractors would have been used to create layouts for felling the larger redwoods (to protect them from shattering upon ground impact) and to create skid trails to move the logs to the road network. The skid trail network is quite extensive in these watersheds. Air photo measurements indicate the skid trail network is 32.9 km km^{-2} in SBNFER and 31.4 km km^{-2} in CC.

The portion of Little South Fork Elk River (LSFER) surveyed in this study is primarily an old-growth redwood forest. In the early 1990s, a 2.3-kilometer road was constructed adjacent to the upstream portion of the stream channel. The maximum width of disturbance from the road construction and the adjacent concurrent logging was 61 m (Pacific Watershed Associates, 2007). This area of the Little South Fork watershed was included in the Federal purchase of the Headwaters Forest Reserve in 1999. The road was subsequently decommissioned. A complete slope restoration, including excavation of stream crossings and recontouring of hillslopes, was completed in 2003 (Manka, 2005).

The field inventory of bank erosion voids and bank-erosion-related wood was conducted on a random sample of tributary streams within the three subwatersheds. A stream network was created from a 1-m digital elevation map (DEM; Sanborn, 2005) derived from laser altimetry (known as LIDAR: Light Detection and Ranging). The stream network was developed for each subwatershed assuming a 0.8-ha drainage area defining the location of stream inception. This drainage area was chosen because it estimated the approximate drainage area needed to initiate streams in management areas based on timber harvest maps from the managed watersheds. However, assuming a small drainage area would likely misclassify several zero-order swales as stream channels in LSFER. This stream layer was used to designate the Strahler (1952) order of all tributary channels within the three study subwatersheds. Table 3-1 shows the stream lengths by order for the three watersheds.

A stratified random sample of stream reaches was selected for a total of approximately 3,000 m in each of the three study subwatersheds. Randomly selected stream reaches were selected to provide a uniform sample of 750 m in each order category: 1^{st}, 2^{nd}, 3^{rd} and 4^{th} order and higher. Since 1^{st} order streams have a higher density than higher stream orders, a uniform sample size in each category means that 1^{st} streams have a smaller proportion sampled relative to higher order streams. Because bank erosion rates generally increase with catchment size (Hooke, 1980) and hence with stream order, the uniform sampling was used to focus the surveys on higher order streams where bank erosion rates are likely to be higher. 4^{th} and 5^{th} order streams were combined into the same category because SBNERF had no 5^{th} order streams. Furthermore, even though the 4^{th} and 5^{th} order streams were combined into one category, this category has similar stream lengths as 3^{rd} order streams and the uniform selection would sample a relatively large portion of total stream length in this category compared to 1^{st} and 2^{nd} order streams. Table 3-2 summarizes the stream lengths by stream order, and their locations are shown in Figure 3.1 through Figure 3.3. The goal of uniform sampling by stream order was generally met. Stream reach characteristics are summarized in Table 3-3. Overall, 46 reaches were surveyed and the average reach length was 192 m.

Physical characteristics of the selected stream reach, such as channel slope gradient, channel width, and bank height, were measured at representative points along the reach. Dominant channel substrate and channel morphology were also noted. As expected, as stream order increased, drainage area, channel width, stream bank height and substrate diameter increased, while stream gradient decreased. Selected stream reaches were inventoried for bank erosion voids and wood deposited in the channel from bank erosion processes. For the purposes of this study, stream bank erosion is defined as erosion caused by lateral migration of stream flows (i.e. flow deflection or stream undercutting). Bank erosion did not include streamside hillslope failures (mass wasting), or stream channel incision (vertical down cutting) caused by fluvial processes. Surveys were conducted in the dry summer period between July and September in 2007.

Specific void attributes were collected on field data forms for bank erosion voids having sediment delivery volumes greater than about > 3.8 m^3, and these were mapped on 1:1200 shaded relief field maps constructed from the LIDAR DEM. Bank erosion attributes collected in the field included: field void measurements, age indicator, stream morphology, and causal mechanism. The locations of small bank erosion sites, voids < 3.8 $m^3$of sediment delivery, were flagged in the field and mapped on the field maps, but data forms were not filled out for these smaller features. Volume estimates for large erosion voids were estimated by measuring bank erosion height and root exposure depth along the length of eroded stream bank. The volume of bank erosion was computed as the product of bank erosion height, root exposure depth, and length of eroded channel. Small bank erosion sites were tallied by stream order, and erosion from these sites was estimated by multiplying the number of smaller voids by an assumed average delivery of 2 m^3 per site. Unit bank erosion (m^3 km^{-1}) was determined for stream order category based on the total estimate of field inventoried bank erosion (large and small voids combined) in each stream order. Unit sediment delivery was then extrapolated to the total length of stream in each of the three subwatersheds by each stream order. Age of the bank erosion for the large voids was estimated by the age of vegetation on or near the void scar to the closest decade (e.g., 1970s, 1980s, and 1990s). Annual volumetric rates were then calculated by dividing the unit sediment delivery by the median age of the bank erosion voids.

The bank erosion methods used to measure voids for this study were the same as previous studies (e.g. Pacific Watershed Associates, 1999) with two exceptions. The cutoff for separating large bank erosion voids from small voids was reduced, so more voids would have their attributes identified and collected for these small streams. Also, instead of estimating bank erosion rate for each decade, the median age of voids was used to estimate the annual bank erosion rate.

Bank-erosion-related wood was also inventoried and mapped along the sample stream reaches in the three study subwatersheds. To be considered bank-erosion-related wood, wood pieces must show evidence of roots connected to the stream bank, or a root wad in the channel with evidence of adjacent bank erosion (Benda et al., 2002). Wood from other sources (e.g., natural mortality, landslides, wind throw) was not inventoried. The minimum bank-erosion-related wood size identified as part of this project was approximately 8 cm in diameter and 1.8 m in length. Additional attributes that were collected for the bank-erosion-related wood included: total and in-stream wood volume measurements, tree species, and decay class. The volume of each piece of wood was calculated as a cylinder using measurements of the diameter at the midpoint and in-stream length of each inventoried wood piece. Decay class categories include needle or leaf, twig, branch, primary branch, nub, hard, or rotten (Hennon et al., 2002; Hennon and McClellan, 2003).

Bank erosion estimates using the wood budget method, as described by Benda et al., (2003) were calculated for all stream of 2nd order or larger and were also calculated separately for just the largest (4th and 5th order) streams. This method assumes steady state, which may be acceptable over short periods (years to a few decades) for most field studies (Benda et al., 2003). The basic equation used to calculate bank erosion rates is:

$$I_{be} = [B_L \cdot E \cdot P_{be}] \cdot N \qquad 3\text{-}1$$

where I_{be} is the annual wood flux to streams ($m^3\ m^{-1}\ yr^{-1}$), B_L is the volume of standing live biomass per unit area ($m^3\ m^{-2}$), E is the mean bank erosion rate ($m\ yr^{-1}$), P_{be} is the fraction of stem length of fallen trees that is deposited into the channel ($0 < P_{be} \leq 1.0$) and N is the number of banks (Benda et al., 2003). By rearranging equation 3-1, the bank erosion rate is:

$$E = \frac{I_{be}}{B_L \cdot P_{be} \cdot N} \qquad 3\text{-}2$$

For this study, bank erosion rate estimates were derived for both stream channel banks (N=2). The standing biomass densities for the three study subwatersheds were provided by the Pacific Lumber Company (PALCO) from previous stand inventories. The standing biomass density was based on the volume inside a 10-m buffer along streams that have aquatic vertebrate habitat or fish presence. LSFER standing biomass density data was derived from 1998 inventory information at the time this area was owned by PALCO.

The fraction of stem length of fallen trees that is deposited into the channel (P_{be}) is based on a random geometric tree fall model (Van Sickle and Gregory, 1990) and assumes a hypothetical uniform stand of trees within a designated distance normal to the stream bank (Lee Benda and Associates Inc., 2004a). Based on field observations, P_{be} assumes 100% fall probability towards the stream channel (Murphy and Koski, 1989; Martin and Benda, 2001). P_{be} is dependent on average stream width and average tree height and was calculated for each study subwatershed using a probability calculator provided by Paul Bigelow (Lee Benda and Associates, Inc.). Average stream width was derived from field observations and average tree height was estimated as 34 m for CC and SBNFER, and 80 m for the LSFER.

Annual wood supply to the stream from bank erosion (I_{be}) was calculated using the following equation:

$$I_{be} = \frac{V_{be}}{L \cdot \Delta T} \qquad 3\text{-}3$$

where V_{be} is the volume (m^3) of bank-erosion-recruited wood surveyed in the stream reach, L is the total stream reach length (m), and ΔT (yr) is the weighted mean age of bank-erosion-recruited wood.

The weighted mean average of bank erosion recruited wood (ΔT) was derived using the wood decay class and the recruitment age of bank-erosion-related wood from the following equation:

$$\Delta T = \sum_{i=1}^{n} a_i \, p_i \qquad 3\text{-}4$$

where a_i is the mean age of wood in decay class i and p_i is the proportion of wood in that decay class. ΔT is based on the number of trees in each decay class rather than volume to reduce its sensitivity to the sequence of tree recruitment. Furthermore, equation 3-4 will give more weight to trees that have been recruited longer ago to account for the assumed increasing loss of trees since recruitment due to decay (Murphy and Koski, 1989). The mean age of wood in the decay classes were taken from Lee Benda and Associates Inc. (2004b), which is a compilation of three studies conducted in the redwood region (Table 3-4).

The wood inventories used the same methods to determine bank erosion rates as previous studies (e.g. Benda et al., 2002), with one minor exception. After the field data was collected, it was discovered that in some cases, the age of the wood was recorded instead of its decay age. However, the decay class was collected for each piece of wood and the decay class data, along with the decay class ages from Lee Benda and Associates Inc. (2004b), was used to estimate annual bank erosion rates.

Volumetric rates were calculated as the product of erosion rates, bank height, bank number (2), and stream length. For these watersheds, bank height refers to the average "entrenched" bank height weighted by the stream lengths for each stream order. Based on field observations, stream channels in the Elk River watershed appeared to have incised as a result of uplift and stream down cutting. In higher order streams, this results in "entrenched" stream channels where the 2-year flow event appears to be below the point where the top of the stream bank intercepts the hillslope. The entrenched bank height was used to determine bank erosion estimates, because it is assumed that bank erosion will undercut the entire entrenched stream bank.

Results

A total of 58 large bank erosion sites were inventoried and field mapped along the 8.89 km of stream channel reaches in the three study subwatersheds (Table 3-5). In addition, 175 smaller bank erosion voids were mapped and tallied in the field. Of the 58 large bank erosion sites, 11 were identified as directly associated with management activities since the flow deflection responsible for the bank erosion was management related (e.g. streamflow deflected by cut wood or streamflow exiting culverts that was directed into the channel banks).

The two managed watersheds, SBNFER and CC, exhibited similar numbers of bank erosion sites. The highest unit sediment delivery for bank erosion (419 m^3 km^{-1}) was observed in the 4th and 5th order stream channels in the CC watershed, and the second highest unit bank erosion sediment delivery rate (349 m^3 km^{-1}) was observed in the 4th and 5th order stream channels in the SBNFER. As stream order increased, CC had increased volumes of bank erosion. However, SBNFER did not follow this trend and exhibited high unit bank erosion rates in lower order channels (1st and 2nd order). The bank erosion rate for 1st order streams in SBNFER was greatly influenced by one very large site (61 m^3). This large site, 12 m in length with 4.6 m banks and 1.1 m in depth, located immediately upstream of a culvert, had downcut and subsequently undermined the adjacent bank. If this site is considered and outlier and removed from the calculations, the unit sediment delivery rate for 1st order streams in SBNFER becomes 26 m^3 km^{-1}, which is similar to bank erosion rate for 1st order streams in CC.

While the numbers of smaller voids in LSFER were similar to the managed watersheds, only four large sites were identified in this watershed. Three small bank erosion voids were identified in 1st order stream reaches in LSFER resulting in a much smaller unit sediment delivery rate than the managed watersheds. This result was expected since most of the 1st order streams, as defined for this study, were actually zero-order swales containing subsurface soil pipes that rarely had surface exposure. 2nd and 3rd order streams in LSFER had similar erosion rates as those in the managed watersheds, while the erosion rate in 4th and 5th order streams was much smaller than in the managed watersheds.

Age estimates for the large voids had a wide range, from less than 5 years to greater than 80 years with the median age for the voids of approximately 35 years. Most of the large voids (43 out of 58) were estimated to have occurred in the 1970s or later (Figure 3.4). Although there was a limited sample of large voids in LSFER where age estimates were made, it appears that the bank erosion scars in the unmanaged watershed tended to be older than in the managed watershed.

Figure 3.5 shows the total bank erosion rates for the watersheds extrapolated from the unit sediment delivery rates. The overall median age of 35 years was used to determine the annual rates, because the age distribution was not normal (Anderson-Darling normality test, $p = 0.000$) and small sample size for LSFER prevented separating age by watershed. The 1st order streams in SBNFER had very large rates compared to other stream orders and watersheds (13.1 $m^3\ km^{-2}\ a^{-1}$), but as noted earlier, this rate was heavily influenced by one very large site. If this large site is excluded, the bank erosion rates drops to 0.7 $m^3\ km^{-2}\ a^{-1}$. The bank erosion rates for the managed watersheds (26.3 and 19.5 $m^3\ km^{-2}\ a^{-1}$ for SBNFER and CC respectively) are much higher than bank erosion for the unmanaged watershed LSFER (6.6 $m^3\ km^{-2}\ a^{-1}$). The bank erosion rates for SBNFER and CC are 298% and 200% greater than LSFER.

Table 3-6 shows the results of the bank-erosion-related wood inventory. A total of 26 pieces of bank-erosion-related wood were identified along the 8.89 km of field-inventoried sample reaches. Only four pieces were identified on 2nd order streams, while the rest were in 4th and 5th order streams. A total 169.7 m^3 of bank erosion recruited wood was indentified in the three study subwatersheds, with 3% from CC, 37% from LSFER, and 60% from SBNFER.

Twelve of the 15 pieces of wood identified in the SBNFER originated from two 4th order stream reaches. The high influx of bank-erosion-related wood in these reaches may be a result of channel morphologies; these reaches are located within bedrock cascade and high-gradient riffle sections of SBNFER's main stem. Higher stream velocities and complex channel morphology may have contributed to an increased influx of bank-erosion-related wood in these reaches.

Three deciduous hardwood and one conifer species were identified in the field inventory of bank-erosion-related wood: big leaf maple (*Acer macrophyllum*), willow (*Salix lasiandra*), red alder (*Alnus rubra*), and redwood (*Sequoia sempervirens*). All the wood recruited by bank erosion in LSFER was redwood, whereas SBNFER had a mixture of deciduous and redwood trees and CC was mostly deciduous.

Because it appears that bank erosion-recruited wood has a threshold that corresponds to stream order, Table 3-7 list the annual wood recruitment rate for two different scenarios. Only 4 pieces of wood were recruited in 2nd order streams, while first and third order channels did not have bank-erosion-related wood. While it seems clear that there is not enough stream power for wood recruitment to occur by bank erosion in first order streams, the limited amount of wood in 2nd and 3rd order streams makes it appear that these stream orders also have limited ability to recruit wood by bank erosion. Therefore, bank-erosion-related wood recruitment rates were calculated for streams 2nd order and higher and also for the largest streams (4th and 5th order).

Overall, SBNFER yielded the highest annual bank-erosion-related wood recruitment rate compared to the other subwatersheds (Table 3-7), while the other managed watershed, CC had the lowest bank-erosion-related wood recruitment rate. The bank erosion rates calculated using equation 3-2 are shown in Table 3-8 for the two stream order scenarios discussed above (i.e., ≥ 2nd order streams and ≥ 4th order streams). The standing biomass is an order of magnitude greater in the old-growth watershed, LSFER, than in the managed watersheds, SBNFER and CC. The fraction of stem length of fallen trees deposited in the channel in LSFER is less than half the fraction in SBNFER and CC due to the larger trees in LSFER. The watershed ranking for bank erosion rates has switched compared to wood input rates; while SBNFER has the highest rates for both wood-recruitment and bank erosion, while CC had the lowest wood recruitment rates and LSFER has the lowest bank erosion rates.

Discussion

Wood recruitment and bank erosion rates

Only 26 pieces of bank-erosion related wood were identified for nearly nine kilometers of streams that were surveyed and nearly half of the pieces came from the largest stream reaches in SBNFER. Due to the very small sample of identified wood and its concentration in one area, it is not surprising to find over an order of magnitude of variation in wood input rates between the watersheds. As noted earlier, the stream morphology may be contributing to the high wood recruitment rate for the main stem of SBNFER. The lower wood recruitment rate in the CC watershed may be due to a higher percentage of hardwood trees in the riparian zone as compared to redwoods. For example, within the 10-m buffer along streams within CC, the ratio of hardwood to conifer is 1:10. In comparison, the ratio of hardwood to conifer in the SBNFER is 1:38 and LSFER is 1:451. Hardwood trees decompose at much faster rates than redwood. As a result, hardwoods that may have been recruited into the stream system a decade or two ago may not be present, which would result in a lower annual bank-erosion-related wood recruitment rate.

The bank erosion wood inputs reported by Benda et al. (2002) for small watersheds (0.2 to 4.4 km^2) had less variation than the watersheds in this study and ranged from 1.2 to 7.8 $m^3\ km^{-1}\ a^{-1}$ (Benda et al.; Table 3). Comparing their results with these watersheds, the wood recruitment rates for CC and LSFER (0.3 to 1.9 $m^3\ km^{-1}\ a^{-1}$) are generally lower than reported by Benda et al. However, surveys conducted by Lee Benda and Associates Inc. (2004a) for three managed watersheds located 130 kilometers to the south had similar recruitment rates (0.3 to 1.6 $m^3\ km^{-1}\ a^{-1}$), which indicates that the results for LSFER and CC are not abnormally low.

Wood recruitment rates for 2nd order and higher streams in SBNFER (3.3 $m^3\ km^{-1}\ a^{-1}$) fall in the middle of Benda et al. (2002) recruitment rate range. However, the largest streams in SBNFER had the highest wood recruitment rate (10.3 $m^3\ km^{-1}\ a^{-1}$) reported in any study. This high recruitment rate may be attributed to the stream morphology, although it may also indicate that this stream reach is responding to the logging activities in the watershed.

To calculate bank erosion rates from wood recruitment rates, standing biomass and the fraction of stem length entering the streams (P_e) must also be estimated. For SBNFER and CC, both the standing biomass and stem-length fraction were lower than reported in Benda et al. (2002) and Lee Benda and Associates Inc. (2004a), which causes SBNFER and CC to have higher bank erosions relative to their wood recruitment rates compared to the other studies. While the bank erosion rate for CC (0.04 to 0.08 m a^{-1}) is within the range of bank erosion rates reported by Benda et al. and Lee Benda and Associates Inc. (0.017 to 0.21 m a^{-1}), the bank erosion rates for SBNFER (0.47 to 1.46 m a^{-1}) are much higher than the highest reported rate in those studies (0.21 m a^{-1}, Benda et al.; Figure 10), indicating the erosion rates for SBNFER are outliers and need to be verified before using them in a sediment budget.

Being an old-growth watershed, LSFER has higher biomass density than the managed watersheds studied by Benda et al. (2002) and Lee Benda and Associates Inc. (2004a), although the stem length fraction is much lower. It is surprising that the bank erosion rate based on the wood inventory for LSFER is only slightly less than CC and falls within the range of the managed watersheds surveyed by Benda et al. and Lee Benda and Associates Inc.

Comparison with soil creep rates and suspended sediment loads

Unlike the wood method discussed above, the void methodology was previously used in larger streams and therefore should not be directly compared to previous studies (e.g., Pacific Watershed Associates, 1999). Table 3-9 indicates that there is at an order of magnitude (or two orders for SBNFER) between the methods. To determine which method is reasonable for use in sediment budgets, the results are checked against soil creep rates and suspended sediment loads.

Soil creep rates can be used as on check for colluvial bank erosion rates (Reid and Dunne, 1996). Saunders and Young (1983) compiled natural soil creep measurements from around the world. The surface creep rates in temperate maritime climates predominantly ranged from 0.5 to 2 mm a^{-1}. To calculate the bank erosion rate for LSFER determined from the void surveys, the overall sediment delivery 6.6 m^3 km^{-1} a^{-1} is divided by the average bank height (0.66 m) and the number of banks (2), resulting in a bank erosion rate of 5 mm a^{-1}. The bank erosion rates determined from the wood methodology for LSFER is 45 mm a^{-1} for 2nd order and higher streams and 92 mm a^{-1} for the largest streams. Both methodologies have bank erosion rates which are higher than creep rates reported by Saunders and Young, although the bank erosion rates determined by wood methodology are over twenty times greater than the creep rates in Saunders and Young, while the void methodology is only 2.5 times greater.

Another way to test of the accuracy of the bank erosion estimates is to compare them with suspended sediment loads. Although the annual suspended sediment load for only one year will be used for this comparison, this comparison may provide a better test, because the suspended sediment loads can be fairly accurate and the suspended sediment loads are from the watersheds used in this study. Turbidity and suspended sediment concentrations were monitored at gauging stations for these three watersheds during the 2004 winter period (Manka, 2005). This water year (October 2003 through September 2004) had a nearly average rainfall year; 98.4 cm of precipitation were measured by the nearby rain gauge in Eureka, which has a long term average of 97.0 cm (California Data Exchange Center). However, the suspended sediment load measured in an average precipitation year should not be misconstrued as a long-term average suspended sediment load, because suspended sediment loads are disproportionally transported during high flow events (Rice et al., 1979). To provide a rough estimate of long-term annual load, the annual suspended yields for North Fork Caspar Creek data were examined from water years 1963 through 1989. The suspended sediment load for an average precipitation year in North Fork Caspar Creek is about half of the average annual suspended sediment load for this time period (Leslie Reid, personal communication).

The suspended sediment loads for the three watersheds used in this study are shown in Table 3-9. These annual loads were calculated from individual storm regressions between turbidity and suspended sediment. This method of calculating annual loads is expected to have greater accuracy than using the annual regression for turbidity and suspended sediment (Manka, 2005). The 95% confidence interval for annual loads was not calculated, but for individual storm events, the 95% confidence interval generally ranged from 5 to 10% of the calculated load.

The bank erosion volumes derived from the surveys were converted into metric tonnes by assuming a soil bulk density of 1.656 t m^{-3} (Stillwater Sciences, 2007). The bank erosion rates determined from the void methodology are lower than the suspended sediment loads for the managed watersheds, but higher for LSFER. The wood budget methodology generally calculates bank erosion as an order of magnitude greater than the suspended sediment loads. Considering the sources of sediment in these watersheds (e.g., landslides, roads), it seems unlikely that the bank erosion rates alone, as calculated by the wood budget methodology, could be an order of magnitude higher than suspended sediment loads.

It is recognized that both rapid methods of measuring bank erosion have their shortcomings. Identifying bank erosion voids in the field can be difficult. Bank erosion can be difficult to identify in long straight sections of stream banks, because scalloped voids that expose roots may not be present. These long banks may have re-vegetated with no evidence of past erosion, which could lead to an underestimation of bank erosion. Additionally, the depth of bank erosion into the bank can be difficult to determine if exposed roots are not present. For wood budgets, the assumption that wood attached to the stream banks has been recruited by bank erosion may not be valid. It is possible that mortality or wind throw could be the mechanism that places wood into the streams and still have its rootwad or be attached to the stream banks. This misidentification of the input mechanism could lead to an overestimation of bank erosion rates.

Additionally, both methods are limited by the qualitative age estimates used to derive annual rates and rely on estimating the age of vegetation regrowth on the disturbed soiled left by the void or the wood recruitment. There may be a time lag between the bank erosion the establishment of the vegetation which would lead to an overestimation of bank erosion rates. The wood budget method also relies on the decay age estimates, which could be much older for the primary, nub, hard and rotten decay categories for old-growth redwood.

Considering that the wood methodology bank erosion rates were much higher than the soil creep rates and suspended sediment loads, it appears that the wood budgeting method has limited utility for this study. However, valuable information was gathered during these wood budget surveys. For example, a relatively high amount of large wood has entered into the main stem of SBNFER through bank erosion. Also, the riparian stands in CC creek have large amounts of hardwood compared to the other watersheds, which may be limiting wood input into this watershed. This information can be very useful in prioritizing restoration projects (e.g., the hardwood in CC's riparian stands may need to be thinned to promote conifer growth). However, if field data for bank erosion rates for a sediment budget is desired without resorting to methods that require multiple field visits (e.g., erosion pins), the void methodology appears superior for smaller watersheds.

A greater concern is that the bank erosion rates estimated by the wood budget methodology for CC and LSFER are similar to results in other wood budgets studies conducted in the redwood region. Some of the assumptions used for the method may not be valid if this methodology consistently overestimates bank erosion rates. For example, steady-state may not be reached in managed watersheds, because wood inputs could be undergoing adjustments to their logging cycles. However, the bank erosion rates for the old-growth watershed, which presumably is in steady-state, were also much higher than the suspended sediment load. Therefore, it seems that this method has other invalid assumptions. Misidentifying bank-erosion-related wood or underestimating decay age would make the bank erosion estimates too high.

Further research

Clearly, it would be very beneficial for resource managers to establish long-term monitoring programs to measure bank erosion in both managed and natural watersheds to overcome the uncertainties in these rapid bank erosion methods. A combination of monitoring methods may be needed to verify bank erosion rates in these small streams.

Repeated surveys at established cross sections supplemented by installation of erosion pins may provide the needed measurements to establish long-term bank erosion rates.

Results from these surveys indicate that bank erosion rates are higher in managed watersheds. Other studies have shown that bank erosion rates can increase after logging. For example, Stott (2005) found that bank erosion increased after logging, although in the four years following logging, they decreased to levels that were lower than before the logging operations began. Although some recent logging has occurred in portions of CC, there has been at least a decade since logging in most of the area in the managed watersheds. Therefore, the time necessary for bank erosion rates to recover to natural levels in these watersheds has not been established. A long-term monitoring program is also needed to identify the factors related to the increases in bank erosion rates. Adaptive management could then be used to minimize this management-related source of sediment to help restore water quality in impaired watersheds like Elk River.

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Table 3-1. Stream lengths (km) and drainage density (DD) (km km^{-2}) by Strahler Order assuming 0.8 ha drainage area for channel initiation.

	Area (km^2)	Strahler order												All		
		1st			2nd			3rd			4th + 5th					
		Length	%	DD	Length	%	DD	Length	%	DD	Length	%	DD	Length	%	DD
South Branch North Fork Elk River	4.9	18.0	49%	3.7	11.3	31%	2.3	4.6	12%	0.9	2.9	8%	0.6	36.8	100%	7.5
Corrigan Creek	4.4	15.6	54%	3.6	6.6	23%	1.5	1.8	6%	0.4	4.9	17%	1.1	28.9	100%	6.6
Little South Fork Elk River	3.0	9.6	50%	3.2	4.5	23%	1.5	2.6	14%	0.9	2.3	12%	0.8	19.1	100%	6.3
Total	12.3	43.2	51%	3.5	22.5	26%	1.8	9.1	11%	0.7	10.1	12%	0.8	84.9	100%	6.9

Table 3-2. Surveyed stream lengths by stream order.

	Strahler order								All	
	1st		2nd		3rd		4th + 5th			
	km	Percent	km	Percent	km	Percent	km	Percent	km	Percent
South Fork North Fork Elk River	0.622	3%	0.752	7%	0.754	16%	0.757	26%	2.885	8%
Corrigan Creek	0.752	5%	0.752	11%	0.753	41%	0.756	16%	3.013	10%
Little South Fork Elk River	0.754	8%	.740	16%	0.748	28%	0.755	32%	2.997	16%
Total	2.129	5%	2.244	10%	2.255	25%	2.268	22%	8.895	10%

Table 3-3. Reach Description

Watershed	Order	Area (km^2)	Length (m)	Slope (%)	Width (m)	Substrate	Channel type
South Branch North Fork Elk River	1	0.020	142.9	36	NM	NM	SSF
	1	0.031	117.7	35	0.4	Sand	SSF
	1	0.059	268.6	15	0.7	Sand	HGR
	1	0.036	93.1	43	0.61	Sand	CAS
	2	0.114	149.2	26.9	1	Gravel	CAS/HGR
	2	0.252	150.8	26.4	0.8	Gravel	CAS
	2	0.125	136.9	16.9	1.2	Gravel	HGR/CAS
	2	0.070	150.8	31.3	0.6	Gravel	SSF/CAS
	2	0.301	164.4	10	0.9	Sand	HGR
	3	0.224	167.8	23	1.2	Gravel	CAS/HGR
	3	0.449	174.5	13.6	1	Gravel	CAS/LGR
	3	0.442	411.5	3	0.55	Sand	LGR
	4	1.705	150.2	12	3.4	Cobble	HGR/CAS
	4	2.237	307.5	6	3.4	Cobble	CAS/LGR/HGR
	4	3.386	299	3	4.1	Gravel	LGR
	1	0.017	162.5	39	0.58	Sand	CAS
	1	0.030	206.1	10	0.6	Sand	SSF
	1	0.020	113.2	38	0.6	Gravel	CAS
	1	0.016	128.1	30	NM	NM	SSF
	1	0.013	142.3	25	1.2	Gravel	CAS
	2	0.192	233.7	10.3	1.6	Sand	CAS / SSF / LGR
Corrigan Creek	2	0.193	518.1	5.3	0.68	Sand	LGR/CAS/HGR/STP
	3	0.170	273.1	27	0.9	Gravel	CAS
	3	0.328	72.4	5	1	Gravel	HGR
	3	0.288	298.6	3.2	0.88	Sand	SRN / LGR
	3	0.185	108.8	5.6	0.64	Gravel	HGR/SSF
	4	1.883	293.1	3.6	1.6	Sand	LGR
	4	0.428	155.3	2	0.76	Gravel	LGR
	5	4.107	307.4	3	6	Cobble	LGR

Table 3-3. Reach Description (Continued).

Watershed	Stream order	Drainage area (km^2)	Reach Length (m)	Slope (%)	Channel width (m)	Dominant substrate	Channel type
Little South Fork Elk River	1	0.020	141	32.9	0.3	Sand	SSF/CAS
	1	0.018	154.5	14.7	0.3	Sand	SSF
	1	0.042	238.8	20	0.5	Sand	SSF
	1	0.014	126.3	35	0.3	Sand	SSF
	1	0.028	93.3	18	0.4	Sand	SSF
	2	0.140	147.7	14	1	Cobble	SSF
	2	0.078	166.8	26.5	0.6	Sand	SSF/CAS
	2	0.047	119.8	14	0.6	Sand	SSF
	2	0.124	185.2	5.3	0.9	Sand	STP/Road excavation
	2	0.076	120.6	34.3	0.4	Sand	CAS/SSF
	3	0.260	300.9	15.8	0.6	Sand	SRN
	3	0.171	143.6	10	0.4	Sand	SRN
	3	0.451	303.3	8	1.2	Sand	SRN
	4	0.479	128.4	7	1	Sand	HGR
	4	1.249	254.6	2.1	0.89	Sand	LGR
	5	3.030	228.4	4	4	Gravel/Cobble	LGR
	5	1.748	143.9	2	2	Sand	LGR

Note: NM – Not measured, LGR – Low Gradient Riffle, HGR – High Gradient Riffle, CAS – Cascade, SSF – Subsurface Flow, STP – Step Pools, SRN – Step run.

Table 3-4. Decay class ages in years from Lee Benda and Associates, Inc. (2004a).

Conifers			
Class	Mean	Standard Deviation	Number
Needle[a]	1.0	-	-
Twig, Branch	5.0	2.4	25
Primary, Nub	17.9	15.1	30
Hard, Rotten	42.4	27.6	85
Deciduous			
Class	Mean	Standard Deviation	Number
Leaf[a]	1.0	-	-
Twig[b], Branch	4.4	1.8	19
Primary, Nub, Hard	11.2	6.4	13
Rotten	20.5	14.3	8

Notes:

[a] age of needle and leaf decay classes are assumed to be 1 year.

[b] twig decay class data was not available for deciduous tree, so conifer data was used.

Table 3-5. Bank erosion void measurements.

Watershed	Strahler Order	Small Voids (< 3.8 m^3)	Large Voids (> 3.8 m^3)		Total Volume (m^3)	Unit sediment delivery	
		Number	Number	Volume (m^3)		(m^3 km^{-1})	(m^3 km^{-1} a^{-1})
South Branch North Fork Elk River	1st	8	1	61	77	124	3.5
	2nd	22	4	27	71	94	2.7
	3rd	10	3	11	31	41	1.2
	4th & 5th	15	17	234	264	349	10.0
Corrigan Creek	1st	3	1	13	19	25	0.7
	2nd	11	2	22	44	59	1.7
	3rd	14	5	32	60	80	2.3
	4th & 5th	35	21	247	317	419	12.0
Little South Fork Elk River	1st	3	0	0	6	8	0.2
	2nd	23	2	17	63	85	2.4
	3rd	17	2	10	44	59	1.7
	4th & 5th	14	0	0	28	37	1.1

Table 3-6. Bank-erosion-related wood.

Watershed	Stream Order	Tree type	Midpoint Diameter (m)	Instream length (m)	Total length (m)	Decay Class[1]	Volume (m^3)
South Branch North Fork Elk River	2	Deciduous	0.09	4.9	9.8	2	1.39
	4	Deciduous	0.15	1.8	19.7	1	0.82
	4	Deciduous	0.27	1.5	12.2	1	1.23
	4	Deciduous	0.11	3.1	11.0	1	1.05
	4	Deciduous	0.20	1.8	13.1	1	1.12
	4	Conifer	0.14	1.8	8.0	1	0.79
	4	Conifer	0.19	5.4	7.5	1	3.22
	4	Deciduous	0.12	1.8	7.6	1	0.68
	4	Deciduous	0.25	2.9	17.0	2	2.28
	4	Conifer	0.10	12.0	12.0	5	3.77
	4	Conifer	0.45	7.0	29.0	6	9.90
	4	Conifer	0.27	8.0	13.0	6	6.79
	4	Conifer	0.61	4.9	4.9	6	9.39
	4	Conifer	1.20	14.0	14.0	6	52.78
	4	Conifer	0.58	3.7	4.7	7	6.74
Corrigan Creek	2	Conifer	0.20	1.5	11.0	1	0.94
	2	Deciduous	0.15	3.4	3.4	7	1.60
	4	Deciduous	0.10	2.0	12.0	5	0.63
	4	Deciduous	0.10	2.2	2.4	5	0.69
	4	Deciduous	0.20	1.7	9.5	6	1.07
Little South Fork Elk River	2	Conifer	5.00	0.0	0.0	5	15.71
	4	Conifer	0.85	1.8	16.1	6	4.81
	4	Conifer	0.75	1.8	5.9	5	4.24
	5	Conifer	1.00	4.7	4.7	5	14.77
	5	Conifer	2.90	2.4	30.5	6	21.87
	5	Conifer	0.30	1.5	6.7	7	1.41

[1] Decay class: 1 – leaves or needles, 2 – twigs, 3 – secondary branches, 4 – primary branches, 5 – partial primary branches (nubs), 6 - hard, and 7 – rotten.

Table 3-7. Annual wood recruitment rates due to bank erosion (I_{be}).

Watershed	Surveyed reach length (km)	Volume (m^3)		Weighted mean age (a)		I_{be} ($m^3\ km^{-1}\ a^{-1}$)		
		Conifer	Deciduous	Conifer	Deciduous	Conifer	Deciduous	Total
2nd order and higher								
South Branch North Fork Elk River	2.26	93.4	8.6	29.0	2.0	1.4	1.9	3.3
Corrigan Creek	2.26	0.9	4.0	1.0	13.5	0.4	0.1	0.5
Little South Fork Elk River	2.24	62.8	0.0	30.2	-	0.9	-	0.9
Large streams (4th & 5th order)								
South Branch North Fork Elk River	0.76	93.4	7.2	29.0	1.6	4.3	6.1	10.3
Corrigan Creek	0.76	0.0	2.4	-	11.2	-	0.3	0.3
Little South Fork Elk River	0.76	47.1	0.0	32.6	-	1.9	-	1.9

Table 3-8. Bank erosion rates estimated from wood budgeting methodology.

Watershed	Annual Wood recruitment (I_{be}) ($m^3\ km^{-1}\ a^{-1}$)	Standing Biomass (B_L) ($m^3\ ha^{-1}$)	P_{be}	Erosion rate ($m\ a^{-1}$)	Ave Bank height (m)	Drainage Density ($km\ km^{-2}$)	Bank Erosion ($m^3\ km^{-2}\ a^{-1}$)
2nd order and higher							
South Branch North Fork Elk River	3.34	272	0.13	0.473	0.88	3.86	3204
Corrigan Creek	0.55	262	0.13	0.080	0.92	3.07	452
Little South Fork Elk River	0.93	2075	0.05	0.045	0.66	3.12	183
Large Streams (4th & 5th order)							
South Branch North Fork Elk River	10.32	272	0.13	1.459	1.19	0.59	2047
Corrigan Creek	0.28	262	0.13	0.041	1.52	1.12	147
Little South Fork Elk River	1.91	2075	0.05	0.092	0.89	0.77	127

Table 3-9. Sediment delivery rates compared with suspended sediment loads (t km^{-2} a^{-1}).

Watershed	Void Methodology	Wood Budget Methodology		Suspended Sediment Loads[1]
		2^{nd} Order and higher	Large streams (4^{th} and 5^{th} Order)	
South Branch North Fork Elk River	44	5307	3390	122
Corrigan Creek	32	748	224	54
Little South Fork Elk River	11	303	211	6

[1] Data from Manka (2005).

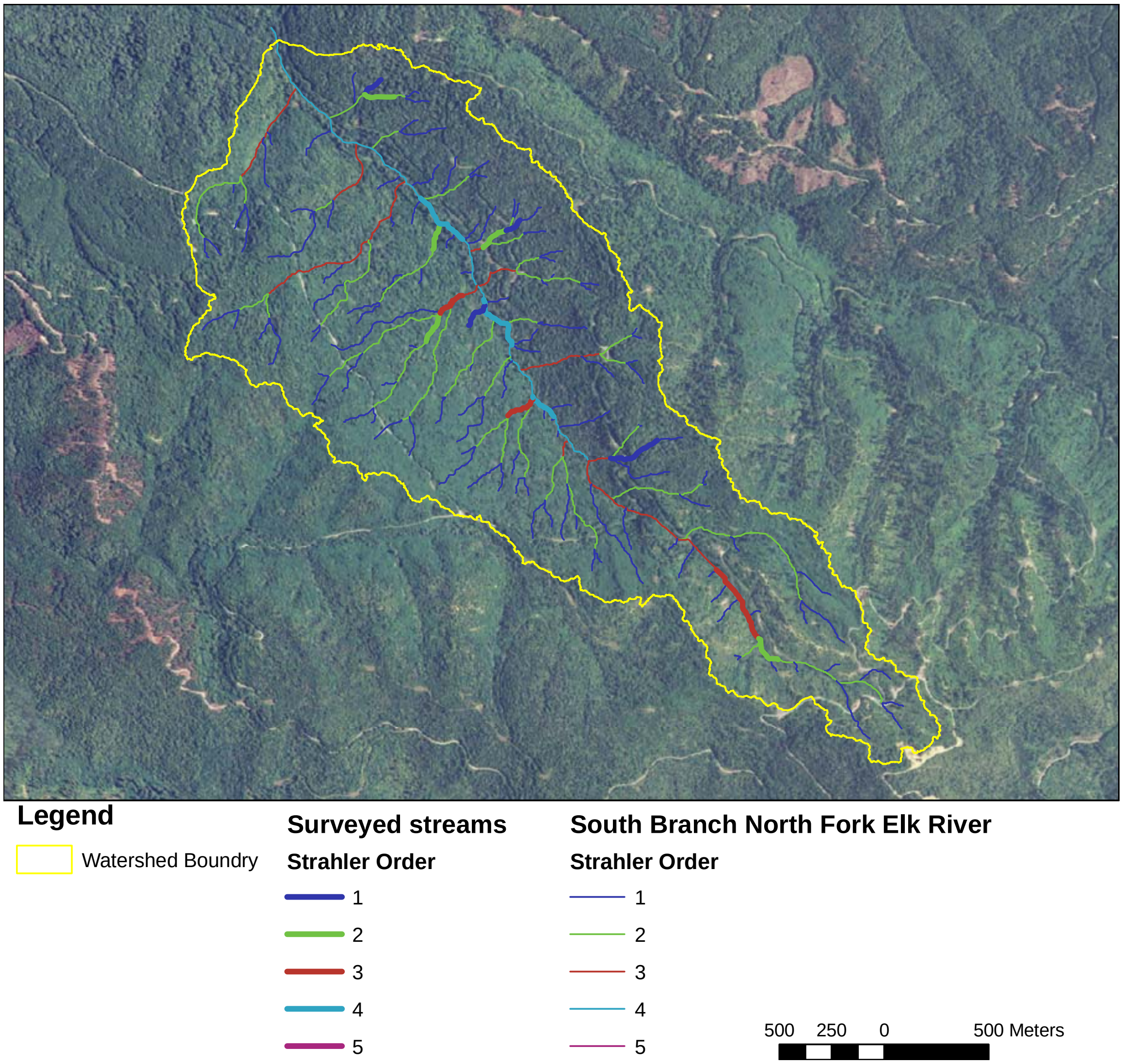

Figure 3.1. South Branch North Fork Elk River stream selection. 2005 air photo from National Agriculture Imagery Program (NAIP).

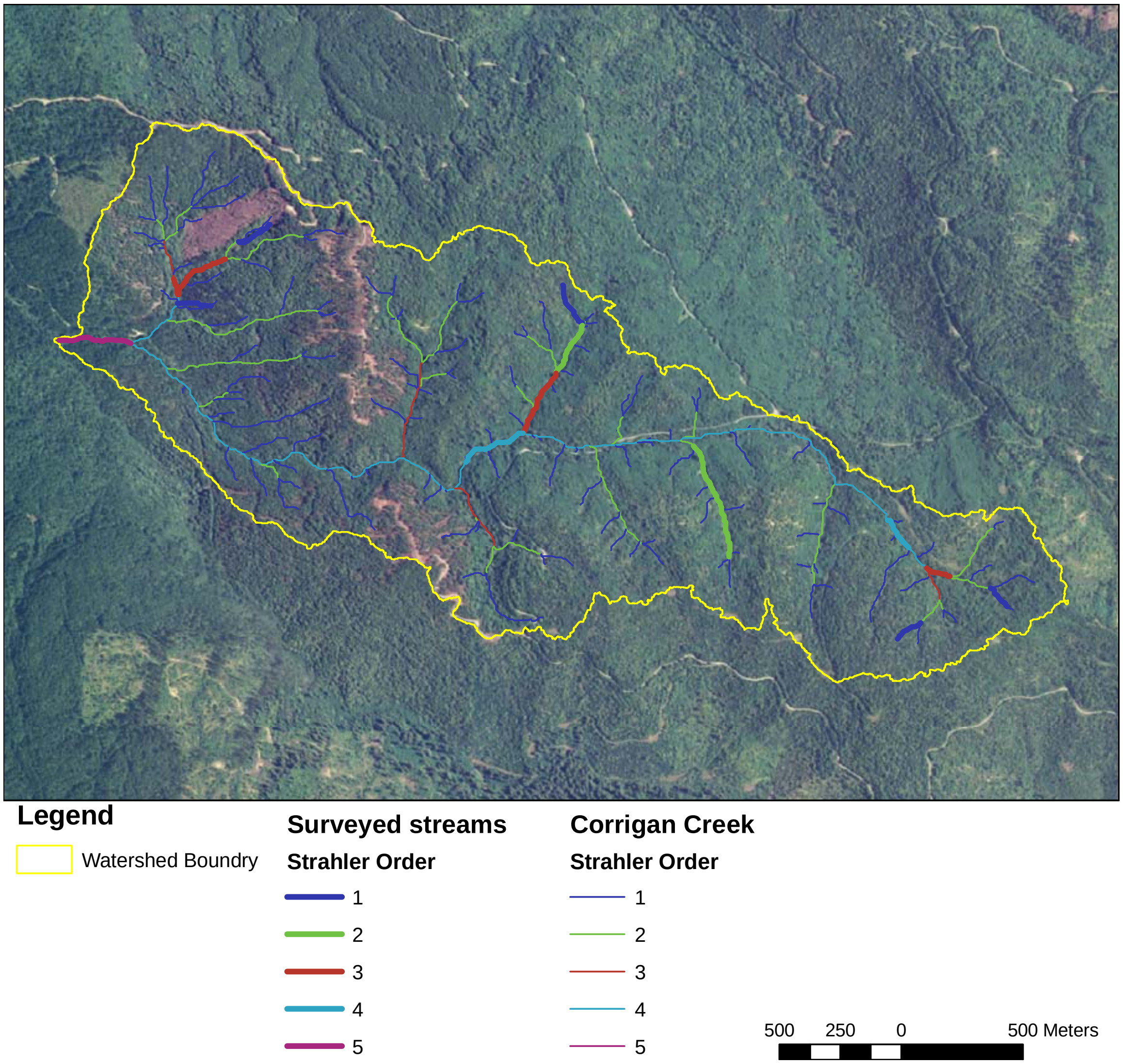

Figure 3.2. Corrigan Creek Stream Selection. 2005 air photo from NAIP.

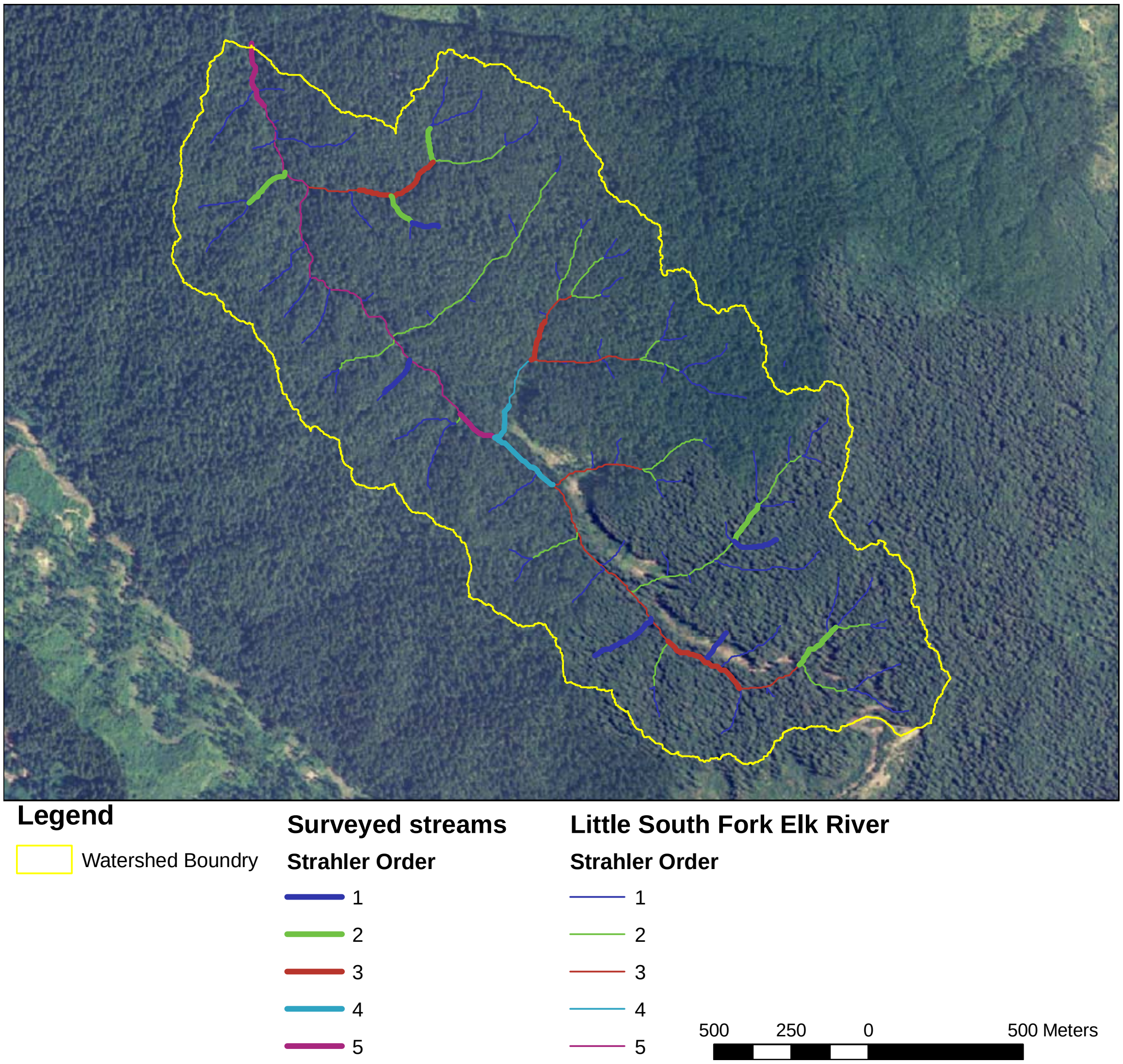

Figure 3.3. Little South Fork Elk River stream selection. 2005 air photo from NAIP.

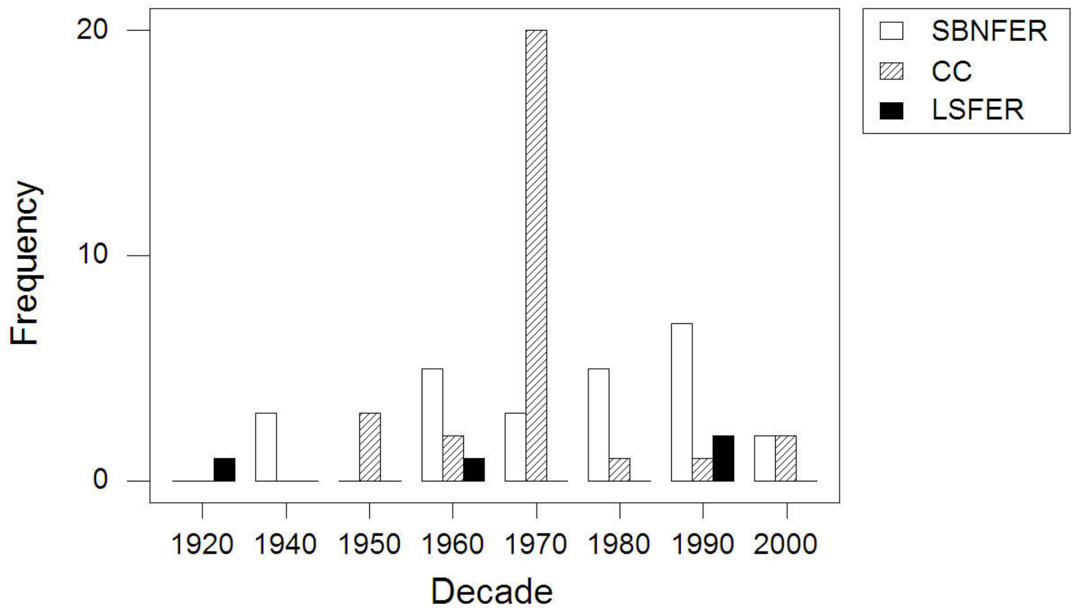

Figure 3.4. Age estimates for bank erosion voids.

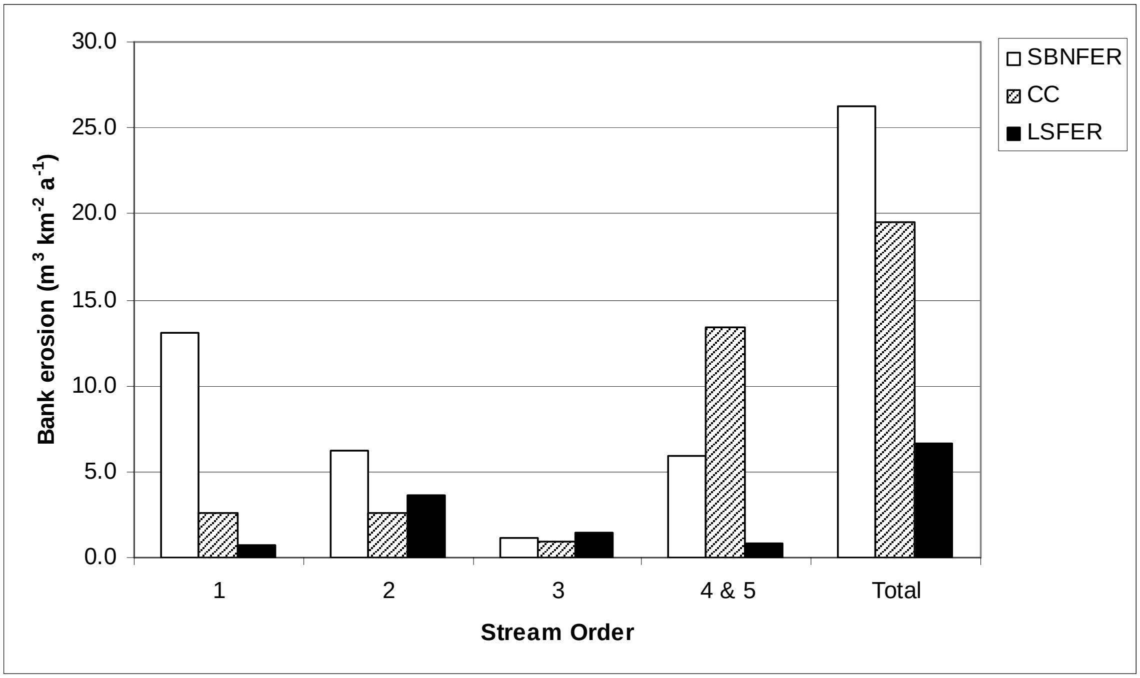

Figure 3.5. Bank erosion estimates from void methodology.

CHAPTER 4

Estimating Soil Creep Sediment Delivery

Abstract

Sediment budgets have become important tools for evaluating impacts to water quality. However, sediment budgets usually have large amounts of uncertainty and are difficult to verify. In this chapter, I review the methods used to estimate sediment delivery for one category that is typically included in sediment budgets developed for steep waterheds: natural sediment delivery due to soil creep. A review of the soil creep measurements and methods indicates that soil creep sediment delivery rates are expected to have low accuracy and can range over an order of magnitude. Example estimates for soil creep are developed for three small watersheds in Elk River; a watershed where water quality has been impaired by sediment discharges. Soil creep sediment delivery is compared with suspended sediment yields to determine reasonable delivery rates. Soil creep sediment delivery in the logged watersheds comprised only a small portion, < 1%, of the sediment budget. Since the uncertainty in soil creep rates and sediment delivery is not likely to be reduced by further research, future research should focus on measuring bank erosion rates for small streams. Further research should also focus on identifying practices that reduce logging-related increases in bank erosion.

Introduction

Sediment budgets are used to provide information about sediment regimes, identify information needed to address particular questions, and assist in comparing conditions across catchments and displaying likely outcomes of management options (Reid and Dunne, 2003). For northern coastal California, sediment budgets have been used to establish Clean Water Act (Federal Water Pollution Control Act 1972 amendments) required Total Maximum Daily Loads (TMDLs) and as a tool in watershed analysis to identify impacts to endangered species as required by the Humboldt Redwood Company's (formerly Pacific Lumber Company) Habitat Conservation Plan (HCP). Aside from meeting regulatory requirements, sediment budgets are valuable in identifying measures necessary to reduce impacts from previous management activities and to restore water quality.

TMDL sediment budgets in northern coastal California indicate that total-to-natural sediment discharge ratios are currently too high (average = 228%, median = 177%, Table 1-1) and must be reduced to 125% of background to meet water quality standards. However, there is evidence that TMDL sediment budgets significantly underestimate this ratio. When comparing the measured suspended sediment discharge for two small watersheds that have undergone several logging cycles with one nearly pristine watershed in northern coastal California, Manka (2005) found the total sediment discharge in the managed watersheds was 10.2 and 22.0 times the background watershed's sediment discharge, i.e., 1,020% to 2,200% relative to background. Klein et al. (2008) compared turbidity, which is strongly correlated with suspended sediment concentrations, between 28 watersheds that had continuous turbidity and stage recording stations in northern coastal California. Comparing the nearly pristine old-growth watersheds to those with highest harvest levels, the ratio of total-to-natural turbidity was 717% (R. Klein, unpublished data). These studies indicate that the actual total-to-natural sediment discharge ratio could be much higher than those estimated in the TMDL studies. Underestimation of the total-to-natural sediment load ratio could result if the sediment budgets either are not accurately estimating the sources of sediment or are not categorizing the sediment sources correctly between management and natural. Ultimately, underestimating the total-to-natural sediment ratio could mean that the measures outlined in the TMDLs may not be adequate to meet water quality standards.

One reason TMDL sediment budgets may not be accurately estimating the total-to-natural sediment load ratio is that they could be overestimating natural sediment loads. Most TMDL studies assume no surface soil erosion and break the natural sediment delivery into two components: landsliding and soil creep. Sediment delivery estimates from landslides are usually derived by mapping and dating landslides using sequential aerial photographs. Field surveys are then conducted to confirm presence, volume and delivery to watercourses and to estimate smaller landslides hidden by trees on the aerial photographs (Reid and Dunne, 1996). Identifying landslide sediment delivery from these methods has a relatively high expected accuracy between 0.6 and 1.6 times the actual value (Reid and Dunne, 2003).

Soil creep is defined as the slow downslope movement of soil or rock debris which is usually imperceptible except to observations of long duration (Selby, 1993). Soil creep is related to landsliding because soil creep helps to refill landslide scars (Dietrich and Dunne, 1978). Other soil displacing processes, such as tree wind-throw and animal burrowing, are implicitly included in most soil creep rates used in sediment budgets (WDNR, 1997).

Colluvium from the hillslope is assumed to be supplied to the bank by soil creep and the rate of sediment supply to the bank is equal to the rate of erosion from that bank if equilibrium conditions are assumed (Reid and Dunne, 1996). As such, soil creep rates can be used to check estimates of colluvial bank erosion rates. Soil creep has been shown to be an important source of sediment in steep watersheds accounting for 30 to 50% of the sediment load in some pristine watersheds (Roberts and Church, 1986). Soil creep sediment delivery can be an important sediment source after logging.

However, soil creep is a difficult process to evaluate and generally has a low expected accuracy (less than 0.4 to more than 2.5 times the actual value). Many sediment budgets use an empirical soil creep formula to estimate the sediment delivery from this process. Relying on empirical formulae to estimate soil creep sediment delivery with little to no field evaluation could lead to large errors in its estimation. Soil creep can be evaluated by other process such as bank erosion and streambank landslides. Field studies for bank erosion and streambank landslides may improve delivery estimates to moderate accuracy (0.4 to 2.5 times the actual value) (Reid and Dunne, 2003).

In this chapter, I review soil creep rates measured in temperate forests that could to estimate soil creep sediment delivery in the redwood region along California's northern coast. Two general approaches for estimating sediment delivery by soil creep are reviewed as well as four estimates from sediment budgets derived in the Pacific Northwest. Based on the review of soil creep rates and methods, natural (i.e., background) sediment delivery rates due to soil creep are estimated for three subwatersheds in the Elk River watershed. Finally, soil creep sediment delivery estimates for the three subwatersheds are included as part of an example TMDL sediment budget.

Soil Creep Rates

Soil creep probably occurs by several mechanisms including pure shear, viscous laminar flow, expansion and contraction, and particulate diffusion (Selby, 1983). Bioturbation, or the churning and stirring of sediment by organisms, may also play important roles in the transport of soil downslope (Gabet et al., 2003). Although movement is generally downhill, soil creep is irregular in direction and rate, which makes it difficult to monitor and to test mechanisms (Selby, 1983).

Creep rates have been monitored by placing pins, or acrylic rods, in the walls of trenches which are then refilled; by inserting columns of beads, blocks, or tubes into the soil; by attaching cones to piano wire which is then led to the surface; by inserting sensitive tilt bars into the surface soil; or by using strain gauges (Selby, 1983). Most measurement methods seem comparable (Anderson and Cox, 1978). More recently, strain gauges that allow frequent monitoring without excavating the site have been used to correlate the observed soil movements with climatic events. For example, Auzet and Ambroise (1996) observed that the largest soil movements occurred with the slow freezing of very wet soil, while Yamada (1999) observed that the largest soil movements occurred when there was a large change in soil moisture associated with a summer rainfall event.

Saunders and Young (1983) compiled soil creep rate measurements from around the world and categorized them by climate. For the temperate maritime zone, surface movements were predominantly in the 0.5 to 2 mm a^{-1} range. Depths of appreciable movement typically extended to 25 cm. Temperate continental zones were occasionally as low as the maritime climates, but were more often higher, 2 to 10 mm a^{-1}. Although converting the linear surface creep rates to volumetric rates depends on the depth distribution of the movement, Saunders and Young reported that the conversion ranged from 0.5 to 3 for converting the linear rate (mm a^{-1}) to volumetric rate per width of slope (cm^3 cm^{-1} a^{-1}).

Creep rates for temperate forests, which includes the climate for the northern coastal California, are shown in Table 4-1. Matching the vegetation is important because creep rates can vary with vegetation type (Jahn, 1989). Lehre (1987) was included in this table even though most of the sites were on grasslands because this study location was in northern coastal California and is frequently referenced in TMDL sediment budgets for northern coastal California watersheds. Also, for consistency with other studies (e.g., Clarke et al. (1999)), the mean and median movement rates for Lehre (1987) were recalculated to include negative movement rates.

Table 4-1 shows that a variety of methods and devices have been used to measure creep rates including rods in trenches (known as Young pits after Young (1960)), pillars, plastic tubes, and strain gauges. Many of the sites were revisited only after the passage of several years, because long-term measurements are essential to distinguish creep rates from the short-term effects of disturbance from the initial installation (Clarke et al., 1999). Even though strain gauges have overall monitoring periods lasting less than a year, they allow frequent measurements that revealed the sporadic and reversible character of creep movements and their seasonal nature (Auzet and Ambroise, 1996; Yamada, 1999).

Creep rates show a wide range of values of at least an order of magnitude. For linear surface creep rates, the lower end of the range is at or near zero. Jahn (1989) reported no movement for the 5 sites located in mid-altitude forest and states that his results were not an artifact of measurement error because soil movement was detected at meadows located adjacent to the forest. Lehre (1987) measured small movements, which had a median value of 0.18 mm a^{-1}. The highest surface creep rate, 5.1 mm a^{-1} was reported by Auzet and Ambroise (1996) in the Vosges Mountains in France.

Volumetric creep rates varied over two orders of magnitude. Although several uphill movements were recorded by both Clark et al. (1999) and Lehre (1987), the lower end of the range appears to be near 0.14 to 0.43 cm^3 cm^{-1} a^{-1}. Creep rates estimated from the strain gauges and then correlated with climate to determine annual rates (Auzet and Ambroise, 1996; Yamada, 1999) ranged from 1.6 to 4.2 cm^3 cm^{-1} a^{-1}. The highest rate, 15 cm^3 cm^{-1} a^{-1}, was reported by Dedkov et al. (1978) for two sites located in Russia that had relativity deep freezing depths (0.89 m), although they acknowledge that the two sites make their measurements very limited.

The depth of observed movement tended to be shallow for most studies, usually near 0.5 meter in depth. However, Swanston et al. (1995) reported movements much deeper, ranging from 4 to 16 meters in the Redwood Creek watershed in northern California. Movements this deep are not consistent with the other studies in Table 4-1. However, Swanston et al. (1995) is frequently cited in northern California sediment budgets, because it offers one of the few estimates of soil creep for this region.

Because of its local importance and seemingly anomalous measurements, the soil creep rates from Swanston et al. (1995) require further scrutiny. From 1974 to 1976, PVC tubes were installed in eight sites ranging from 4.3 to 20.6 m in depth in the Redwood Creek watershed to measure the rates of soil movement (Swanston et al., 1995). Two tubes were installed at each site with a third tube installed in the eighth site. Tube deformation was measured twice a year with a mechanical pendulum with an electronic readout. This instrument could detect 2 mm displacements over the depth of the tubes. The surface movements through 1978, 1981, and 1982 were reported in Swanston (1981), Swanston et al. (1995), and Ziemer (1984) respectively.

The movements at the sites were separated into three categories: sites 1, 2 and 5 expressed creep deformation; sites 3, 4, and 7 were dominated by block-glide movement where most of the displacement was along a well-defined shear zone; and the rest of the sites had a combination of creep and block-glide movements (Swanston et al., 1995). Although Ziemer (1984) concluded that movements of tubes installed at sites 1, 2, and 5 were below the detection limits of the instrument and no consistent direction or rate of movement was detected, the movement rates of 1.0 to 2.5 mm a^{-1} for sites 1, 2, and 5 as reported by Swanston et al., (1995) have been used in several sediment budgets. The range of 1.0 to 2.5 mm a^{-1} given by Swanston et al., (1995) may overestimate creep rates, because two tubes were excluded from this range because the tubes weren't satisfactorily installed even though the movement rates for these two tubes were previously reported by Swanston (1981) to be less than 1.0 mm a^{-1}. Furthermore, movements were reported along the plane of maximum movement, which did not always coincide with the slope azimuth. Table 4-2 shows the annual movement rate for the tubes installed at sites 1, 2, and 5 (Swanston et al., 1995; Table 2) and the calculated downslope movement rates. The mean and median downslope movement rates, including the two excluded tubes which movements were assumed to be zero, are 0.44 and 0.19 mm a^{-1} respectively.

The soil creep measurements from Table 4-1 focus on mechanical creep which is often related with climatic cycles (e.g., freeze-thaw and wet-dry cycles). However, bioturbation could be contributing to these measured creep rates. Gabet et al. (2003) estimated soil movement rates for several processes including root growth and decay, tree throw, and excavation by fossorial mammals. Using the equation derived by Gabet et al., downslope soil transport by tree throw is estimated to be 22 cm^3 cm^{-1} a^{-1} for 25° slopes with a tree uprooting rate of 4 trees ha^{-1} a^{-1}, which is higher than the measured volumetric creep rates in Table 4-1. This indicates that tree throw sediment transport could be the most important process in moving the soil downslope in temperate forests. However, this estimate needs refinement for old-growth redwood forests, particularly the uprooting rate.

Gabet et al. (2003) also derived an equation for sediment transport by root growth and decay. To estimate a maximum transport rate, they assumed that soil is rigid and that none of the root growth strain is accommodated by changes in bulk density. For temperate forests on a 25° slope, the maximum soil transport would be 3.7 cm^3 cm^{-1} a^{-1}, which is similar to some of the volumetric creep rates in Table 4-1. Since this is a maximum estimate rate, it shows that root growth and decay likely contributes to soil creep, but it is not likely to be a primary mechanism.

Excavation by animals is another bioturbation process to consider in estimating downhill sediment transport, since redwood forests overlap with the range of mountain beavers (*Aplodontia rufa*). Mountain beavers forage above ground for food, so their tunnel activity is limited compared to gophers (Gabet et al., 2003). Mountain beaver tunnels are generally no deeper than 0.3 m and 3 to 30 m in length (Steele, 1989). Considering the limited burrowing activity and the low population densities of the mountain beaver, they are likely to be minor contributors to downhill soil movement.

Soil Creep Sediment Delivery

Two general methods for estimating sediment delivery by soil creep are proposed by Reid and Dunne (1996) and Washington Department of Natural Resources (WDNR, 1997). Reid and Dunne's method requires researching volumetric creep rates and depth of movement that are similar to your area of interest and determining the drainage densities for streams that flow through colluvium. "Creep depth" is used to estimate sediment delivery and has a maximum value that corresponds to the depth of creep movement. However, when the colluvial portion of streambank height is less than depth of creep movement, the volumetric rate should be reduced by the ratio colluvial bank height over depth of movement. This ratio is measured along the channel banks at randomly selected points. Multiplying the modified volumetric creep rate by the stream density will provide an estimate of sediment delivery.

If linear surface rates are known or can be estimated, but the movement depth distribution is not known, the volumetric rates of soil creep can be estimated by assuming how soil creep rate varies with depth. If soil creep is occurring by shearing at a constant depth and the soil mass is moving as a rigid body, then cross-sectional area will be rectangular and the volume transported can be estimated by:

$$S = C \cdot D \tag{4-1}$$

with S equal to the volume transported downslope, C is the surface creep rate and D is the depth of soil movement (Selby, 1993). Figure 4.1 shows examples of three different creep profiles: non-linear, linear, and constant. If the creep rate is assumed to vary linearly with depth, the equivalent depth used to calculate volumetric rate will be halved. However, the theories used to describe soil creep transport generally predict a non-linear depth relationship with the fastest movement rates at or near the surface which rapidly decrease with soil depth (Culling, 1963; Kirby, 1967; Roering, 2004). Furthermore, field measurements generally show a non-linear relationship with the fastest rates at or near the surface (Lehre, 1987; Auzet and Ambroise, 1996; Yamada, 1999). In such cases, an equivalent depth less than 0.5 should be considered for transforming surface rates to volumetric rates. The non-linear creep profile example in Figure 4.1 has an equivalent depth of 0.25.

WDNR (1997) approach is very similar to Reid and Dunne (1996) with the primary difference being that WNDR applies a linear creep rate to the soil depth while the example provided by Reid and Dunne uses a volumetric creep rate applied to a creep depth. The volume of sediment delivery is given by the following equation:

$$V = 2 \cdot L \cdot D \cdot C \tag{4-2}$$

where V is the annual erosion volume ($m^3 a^{-1}$), 2 represents the number of stream banks, L is the length of the channel (m), D is the soil depth (m) and C is the creep rate ($m a^{-1}$). WDNR acknowledges that there is relatively little research on soil creep rates, especially in forested mountain watersheds. Therefore, WDNR recommends using creep rates of 1.0 mm a^{-1} for slopes less than 30% and 2 mm a^{-1} for slopes are greater than 30%, unless the analyst has a better estimate of creep rates. For both methods, the erosion volume can be expressed as mass by multiplying it by the soil's bulk density.

One potential problem with WDNR method for estimating soil creep rates is that it does not specify if the linear creep rate used in the equation is the surface creep rate or if it is a depth-averaged creep rate for the soil profile. Most creep studies report either the surface creep rate or the volumetric creep rate. An analyst developing soil creep estimates will overestimate soil creep sediment delivery if they use surface creep rates and apply it to the soil depth to determine volumetric rates, because soil creep has a non-linear relationship with depth.

Four sediment budgets were chosen as examples to show how authors estimated soil creep sediment delivery. These studies and their approaches are summarized in Table 4-3. Creep rates were not measured for these sediment budgets; rather these studies referenced soil creep measurements from other sources.

Madej (1982) developed a sediment budget for lower Big Beef Creek in Washington to estimate sediment sources and transport rates to determine the impacts of logging and road construction on channel geometry. Roberts and Church (1986) developed sediment budgets for four watersheds in the Queen Charlotte Ranges, British Columbia to examine the sediment wedges that developed after logging had highly disturbed those drainages basins.

The soil creep calculation from CRWQCB (2001) is an example from one of the sediment budgets that have been developed for northern coastal California TMDLs. Not all TMDL sediment budgets have estimated soil creep sediment delivery, but this example is a typical estimate. However, CRWQCB combined soil creep estimates with earth flow sediment delivery estimates. The movement rates used in these combined estimates are much greater than areas without earth flows. I recalculated the combined soil creep and earth flow delivery estimate from CRWQCB (2001) to estimate only soil creep delivery using soil creep rates cited in the TMDL with the stream density and bank depth determined by the TMDL field surveys.

The soil creep delivery estimate by Hart Crowser, Inc. (2005) is an example from one of the sediment budgets developed during watershed analysis for the former Pacific Lumber Company (PALCO), now Humboldt Redwood Company, LLC, to satisfy the requirements of their HCP. Sediment budgets developed for the HCP are based on the WDNR methods. Although some of the other HCP sediment budgets have used higher creep rates, Hart Crowser, Inc. (2005) was chosen as an example, because their sediment budget includes portions of the Elk River watershed and the soil creep sediment delivery rates will be compared with other sediment sources estimates derived by Hart Crowser, Inc. Three soil creep sediment delivery estimates were developed by Hart Crowser, Inc: a lower-bound estimate based on the soil creep rates from Swanston et al. (1995), a moderate estimate based on WDNR (1997) recommended movement rates, and a upper-bound estimate based on block-glide movement rates from Swanston et al. (1995). For each estimate, a lower creep rate was applied to streams with adjacent hillslope gradients between 10% and 30%, while a higher creep rate was applied to streams with adjacent hillslope gradients greater than 30%.

Ultimately, the lower-bound and moderate estimates were determined to be the most reasonable after they were compared with suspended sediment loads from an adjacent watershed. Furthermore, Hart Crowser, Inc. concluded that it was unlikely that the entire watershed was subject to block-glide movement with movement rates between 8 and 15 mm a^{-1}, so the upper-bound sediment delivery estimate of 487 m^3 km^{-2} a^{-1} is not included in Table 4-3.

Dietrich and Dunne (1978), a highly referenced sediment budget for the Rock Creek basin in the Oregon Coast Range, provides another example for soil creep sediment delivery. They used two creep rates, one for shallow soils (2.5 mm a^{-1}) and another for wedge soils found in colluvial hollows (10 mm a^{-1}), to estimate sediment delivery in that watershed. However, they later determined that the creep rate for wedge soils was a misinterpretation from other studies and that the high creep rate had not been reported in other studies (Dietrich et al., 1982) and so their approach is not used as an example here.

All the studies in Table 4-3 used a creep rate, which range from 1 to 5 mm a^{-1}, instead of using a volumetric rate. The linear creep rates cited by the studies in Table 4-3 have generally come from studies that reported surface creep rates. It is not clear if the studies in Table 4-3 intended to use surface creep rates or depth-averaged creep rates in their delivery estimates. By multiplying surface creep rate by depth, the authors are implicitly assuming that creep affects the soil as block with a defined slip plane instead of a deforming profile. As noted above, this approach to calculating the downhill sediment transport deviates from soil creep theory and field measurements and therefore these studies may have overestimated creep rates. Madej (1982) used an active creep depth of 0.5 m based on her observations in the watershed, while the other studies used either stream bank depth or soil depth, which tends to be near 1.0 m in depth.

Overall, the sediment delivery rates in Table 4-3 ranged about an order of magnitude. Madej (1982) had the lowest estimate of 6.25 $m^3\ km^{-2}\ a^{-1}$, which reflects the low values in depth and stream density used to estimate sediment delivery. Madej measured the stream density on aerial photographs, which may underestimate stream density because the canopy obscures small streams. The highest delivery estimates were estimated by Roberts and Church (1986) and Hart Crowser, Inc. (2005). Roberts and Church used the highest creep rates out of these examples, while Hart Crowser, Inc. had the highest soil depths and stream densities. Hart Crowser, Inc. used soil depths from soil surveys. Stream densities were based on streams identified during the development of timber harvest plans.

Soil Creep Estimates for Three Subwatersheds in Elk River

Several soil creep delivery estimates are derived using the general methods, Reid and Dunne (1996) and WDNR (1997), for three subwatersheds within Elk River. The soil creep estimates are compared with the estimates from Hart Crowser, Inc. (2005), the bank erosion estimates from Chapter 3, and the suspended sediment loads in a nearly pristine old-growth watershed.

The Elk River watershed is located near Eureka, California. The three subwatersheds for which soil creep delivery is estimated share similar bedrock, which primarily consists of the sedimentary rocks of the mid-Tertiary to Quaternary-age deposits of the Wildcat Group, a poorly to moderately consolidated siltstone and fine-grained silty sandstone. The Late

Cretaceous Yager terrane of the Coastal Belt of the Franciscan Complex, a sheared and highly folded mudstone, is exposed in the deeper portions of the canyons of the watersheds (Marshall and Mendes, 2005). The three watersheds have average hillslope gradients of 23° to 24°. These watersheds experience a Mediterranean climate with dry summers and wet winters and with an average annual precipitation of 1650 mm. Snow rarely falls on these coastal watersheds (Hart Crowser, Inc., 2005). Forest stands in Elk River are dominated by redwood (*Sequoia sempervirens*) and Douglas-fir (*Pseudotsuga menziesii*) with grand fir (*Abies grandis*), Sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga heterophylla*), incense cedar (*Calocedrus decurrens*), western red cedar (*Thuja plicata*), and pacific madrone (*Arbutus menziesii*) present in some locations. Big leaf maple (*Acer macrophyllum*), willow (*Salix lasiandra*), and red alder (*Alnus rubra*) are the dominant deciduous tree species found in riparian zones and disturbed areas (Manka, 2005).

The primary difference between the three watersheds is their management history. Most of the South Branch North Fork Elk River (SBNFER) watershed was first logged in the 1970s, though small areas were harvested in the 1940s and 1960s as well. A second logging entry occurred throughout the entire watershed in the late 1980s and early 1990s consisting of partial-cut and clear-cut harvests with tractor yarding. The western portion of the Corrigan Creek (CC) watershed was first logged in the 1950s and the eastern portion in the 1970s. The eastern portion experienced a second logging entry in the late 1980s and early 1990s consisting of partial-cut and clear-cut harvests with tractor yarding (Manka, 2005). Recently, the western portion of CC was primarily commercially thinned and tractor-yarded, although portions were clear-cut units and cable-yarded. These managed watersheds are highly disturbed due to the harvesting and tractor yarding. Tractors would have been used to create layouts for felling the larger redwoods (to protect them from shattering upon ground impact) and to create skid trails to move the logs to the road network. The skid trail network is quite extensive in these watersheds. Air photos measurements indicate the skid trail network is 32.9 km km^{-2} in SBNFER and 31.4 km km^{-2} in CC.

The portion Little South Fork Elk River (LSFER) surveyed in this study is primarily an old-growth redwood forest. In the early 1990s, a 2.3-kilometer road was constructed adjacent to the upstream portion of the stream channel. The maximum width of disturbance from the road construction and the adjacent logging was 61 m (Pacific Watershed Associates, 2007). This area of the Little South Fork watershed was included in the Federal purchase of the Headwaters Forest Reserve in 1999. The road was subsequently decommissioned. A complete slope restoration, including excavation of stream crossings and recontouring of hillslopes, was completed in 2003 (Manka, 2005).

Several approaches to calculating soil creep sediment delivery are shown in Table 4-4. Reid and Dunne (1996) suggest using a volumetric creep rate, adjusted for a creep depth when the stream banks are shallower than the creep depth, to determine sediment delivery. No volumetric estimates could be found for the redwood forests in California. However, Lehre (1987) estimated creep rates for the Lone Tree Creek watershed in Marin Co., which is located approximately 340 kilometers to the south of Elk River. Although seven of eight sites were located in grasslands, the study has volumetric creep rates nearest to the watersheds of interest. Lehre reports two rates in his study, a best estimate from the sites, which when recalculated to include negative values, averages 0.76 cm^3 cm^{-1} a^{-1} and has a median of 0.37 cm^3 cm^{-1} a^{-1}. Lehre also reports an upper-bound rate of a mean and median of 2.45 and 1.63 cm^3 cm^{-1} a^{-1} respectively. The median would be more appropriate for estimating soil creep since it appears from the limited sample size that the sample population is not normally distributed and therefore it is used for the estimates shown in Table 4-4.

The example in Reid and Dunne (1996) suggests surveying the stream banks to determine if they are smaller than the creep depth. For the streams in LSFER, colluvial bank heights were greater than 0.4 m, which is greater than the depth of movement indicated by Lehre (1987). Therefore no adjustment was made to volumetric creep rates.

The WDNR method recommends using better estimates when they are available. Lehre (1987) and Swanston et al. (1995) determined the surface creep rates that may be appropriate for Elk River. Once again, Lehre reports a best and an upper-bound movement rates of 0.18 and 0.49 mm a^{-1} respectively. Surface movements rates from Swanston et al. (1995) are adjusted to reflect downslope movements in Table 4-2. Combining these two studies, it appears that a good estimate for a local rate is the combination of the median "best" estimate from Lehre with the median value from Swanston et al. for 0.19 mm a^{-1}. An upper-bound movement rate is also used to estimate sediment delivery. The median from Lehre's upper-bound estimate is combined with the mean from Swanston et al. to approximate an upper-bound movement rate of 0.47 mm a^{-1} used in Table 4-4.

Soil creep sediment delivery was also estimated using recommended surface creep rates WDNR (1997). For these watersheds, the average slope gradient is approximately 43%, which is well above 30% threshold for the higher creep rate recommended by WDNR. Therefore the recommended movement rate of 2 mm a^{-1} is used to calculate sediment delivery.

WDNR (1997) uses soil depth to determine the volume of soil moving downslope, which implies a block-glide movement if surface creep rates are used in this method. In these three watersheds, soils consist of either the Hugo or Larabee series which range in soil depth from 0.76 to 1.78 m (Hart Crowser, Inc., 2005). For simplicity, the average depth, 1.27 m, was used to calculate the sediment delivery.

For all calculations, the stream density was determined by using a drainage area of 4.22 hectares for channel initiation, which represents the drainage area for channel initiation in old-growth forests (Chapter 2). The bulk density used in these calculations was 1,656 kg m^3 (Stillwater Sciences, 2007). For comparison, the soil creep delivery estimates from Hart Crowser, Inc. (2005) for SBNFER are included in Table 4-4. The calculated delivery rates in Table 4-4 range over two orders of magnitude. Lowest sediment delivery rates are from the local volumetric rates. The standard WDNR rate has the highest calculated rates. The sediment delivery rates by Hart Crowser, Inc. are also relatively high.

Creep rates can be used to check colluvial bank erosion rates (Reid and Dunne, 1996). Chapter 3 determined the bank erosion rates determined by measuring the bank erosion voids and wood inputs along the stream for the small old-growth watershed. Although the rates determined by the wood methodology appears to be unreliable, the bank erosion rates determine by measuring the voids along the stream banks is approximately 11 t km^{-2} a^{-1}.

The suspended sediment loads from LSFER, Table 4-5, also can be used to check for reasonableness on delivery rates although three years of data is not sufficient to establish long-term average, or median, annual sediment loads (Van Sickle, 1981). For the 26-year record of suspended sediment yields from North Fork Caspar Creek, a managed redwood forest in northern coastal California, the suspended sediment load in an average precipitation year is approximately half of the long-term average annual suspended sediment load (Leslie Reid, personal communication). Since the Elk River watershed shares similar climate and vegetation as North Fork Caspar, doubling the suspended sediment loads for LSFER provides a check for soil creep delivery rates. Assuming that all sediment delivery in LSFER is due soil creep, an upper bound for soil creep sediment delivery may be 10 t km^{-2} a^{-1}. Although this check on soil creep sediment delivery rates is limited by several assumptions, several of the methods used in Table 4-4 calculate higher delivery rates, which indicate that they may not be appropriate for TMDL sediment budgets.

Soil Creep Delivery Estimates for TMDL Sediment Budget

The Clean Water Act requires the establishment of a TMDL for water bodies that have been identified as not meeting water quality standards. "Such a load shall be established at a level necessary to implement the applicable water quality standards with seasonal variations and a margin of safety which takes into account any lack of knowledge concerning the relationship between effluent limitations and water quality" (Clean Water Act, §303(d)(1)(C)). The load allocations that are non-point pollution portion of a TMDL can be "reasonably accurate estimates to gross allotments, depending on the availability of data and appropriate techniques for predicting the loading" (40 Code of Federal Regulations, §130.2). It is anticipated that for many sediment TMDLs, the load allocations with be gross allotments due to the complexity and variability of sediment delivery and transport (USEPA, 1999).

A key requirement for TMDLs is the margin of safety. The margin of safety can be applied implicitly by making conservative assumptions about loading or the water quality response or explicitly accounted for during the load allocation (USEPA, 1999). Most northern coastal California sediment TMDLs have incorporated an implicit margin of safety by using conservative assumptions about the magnitude of natural sediment sources in the development of the TMDL. Sediment delivery estimates for soil creep need to be conservative if an implicit margin of safety will be used to meet legal requirements.

To estimate soil creep sediment delivery for these watersheds, Table 4-4 was evaluated for two criteria: 1) a method that produces a conservative estimate for soil creep to meet Clean Water Act requirements and 2) a method that matches theoretical mechanisms and local field measurements. It appears that using volumetric creep movement rates from Lehre (1987) fits these criteria the best, because it provides a conservative estimate, it uses rates where a depth profile is not assumed, and the measurement rates are from a location relatively close to Elk River.

The magnitude of sediment delivery by other source categories is derived from various sources with most of the data coming from PALCO's watershed analysis (Hart Crowser, Inc., 2005). Hart Crowser, Inc. derived three sediment delivery scenarios; a low, moderate, and high estimate for the sediment source categories. The low and moderate scenarios were determined to be most reasonable when compared with the suspended sediment discharge in a nearby watershed. The differences between the low and moderate estimates tended to be small with the exception of the small landslide category.

SBNFER was analyzed as its own subwatershed and the sediment delivery rates are taken directly from watershed analysis. CC was included as part of a larger sub-basin, South Fork Elk River. For this study, it is assumed that CC has the same sediment delivery rates as South Fork Elk River except for the bank erosion and deep-seated landslide categories, because these categories estimate sediment delivery along the main stem of South Fork Elk River and are not applicable to CC. LSFER was not included in watershed analysis, so sediment delivery rates for this nearly pristine watershed are developed here. Aerial photography analysis to estimate landslide sediment delivery was conducted by Pacific Watershed Associates (unpublished data). Field work was also conducted in LSFER to determine the sediment delivery rates of landslides too small to detect on air photographs (Pacific Watershed Associates, 2006).

The moderate estimates from Hart Crowser, Inc. (2005) are shown in Table 4-6 with one main exception. The small landslide category refers to landslides that are generally too small to be detected during the aerial photography inventory. Therefore, field surveys are conducted to determine the amount of sediment delivery for the small landslide category. However, the moderate sediment delivery estimates for the small landslides from Hart Crowser, Inc. are not included in this sediment budget for several reasons. First, the field surveys for this category were conducted outside of the three subwatersheds used in this study. Second, Hart Crowser, Inc. assigned this category to either road-related or natural sediment delivery. Given that the surveys were conducted in logged watersheds it seems unlikely that the portions of small landslides that aren't directly attributed to roads are solely due to natural sediment delivery. Finally, while the low delivery estimate for small landslides is approximately 10 t km^{-2} a^{-1}, the moderate delivery estimate is over five times greater (approximately 56 t km^{-2} a^{-1} for the entire watershed analysis). The moderate estimate is nearly ten times larger than the suspended sediments measured in LSFER, which indicates that this estimate is too high to be considered part of the natural sediment load.

The results from field surveys conducted by Pacific Watershed Associates (2006) in LSFER are used to account for the small landslides. Pacific Watershed Associates measured small landslides along 5.8 km of streams. Assuming a stream density of 3.3 km km^{-2} base on the results from Chapter 2, the sediment delivery for small landslide is 10.6 t km^{-2} a^{-1} for LSFER. This delivery rate is assumed to be same for SBNFER and CC.

The sediment budget for the three watersheds, Table 4-6, indicates that sediment creep is a minor category compared not only to categories of management-related sediment delivery, but also to other categories of natural sediment sources. This sediment budget shows that soil creep sediment delivery could be an order of magnitude lower than sediment delivery from natural landslides. Overall, soil creep accounts for less than 1% of the sediment delivery in the SBNFER and CC.

Discussion

A variety a tools and resources are used to create a sediment budget. The mixture of computer models, spreadsheet analysis, field surveys and professional judgments makes it hard to verify a sediment budget and, in some cases, may make the sediment budget unreliable (HWISRP, 2003). Because of complexity of sediment budgets, standard methods of error analysis are rarely applicable. Instead, results are tested by comparing estimated sediment delivery to measured sediment yields, assessing the reliability of each of the methods used in the creation of the sediment budget, or carrying out sensitivity analyses (Reid and Dunne, 2003).

Estimating soil creep sediment delivery is clearly a difficult task for the professional creating the sediment budget. The difficulty in measuring soil creep has resulted in very few published results and, for the studies that have been published, a wide range of creep rates have been estimated. Clearly, the sediment delivery rates are very sensitive to the assumed creep rate used in the delivery calculations. Compounding this problem, professionals must also determine an appropriate creep depth and natural stream density to determine sediment delivery estimates. Also, bioturbation processes like tree throw may be very important in the transport of soil downslope. All these factors give sediment delivery estimates for soil creep a low expected accuracy.

For watersheds used for this study, soil creep estimates could be bracketed and the sediment budget indicates that soil creep accounts for less than 1% of the sediment sources in the logged watersheds. Although the suspended sediment monitoring station in the old-growth forest has only been operational for a few years, it has provided enough information to provide an upper bound on delivery rates. Clean Water Act requirements also help to bracket the sediment delivery estimates because the required margin of safety necessitates that a low range of delivery estimates must be used. However, research into tree uprooting rates in old-growth forests could provide additional information soil transport rates.

Based on the data being produced from suspended sediment gauging stations, it appears the sediment budgets developed for TMDLs have not been accurate in estimating the current total-to-natural ratio of sediment sources. This ratio has been emphasized for determining compliance with water quality standards (USEPA, 2007). Although not directly applicable to other watersheds, the sediment delivery estimates for soil creep indicate that this category in previous TMDL sediment budgets has been overestimated.

Since the uncertainty in soil creep rates and sediment delivery is not likely to be reduced by further research, future research should focus on measuring bank erosion rates and stream incision for small streams. The bank erosion estimates developed in Chapter 3 indicate that logging has increased bank erosion rates and Chapter 2 indicated that streams have incised into previously unchanneled swales, although it is not clear which processes contributed to the stream incision or the increased bank erosion rates. Therefore, further research should also focus on identifying practices that will reduce these logging-related impacts.

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Table 4-1. Ranges of soil creep rates for temperate climates. Except for Lehre (1987), monitoring sites are located in forests.

Source	Location	Geology	Method	Sites	Surface creep rate (mm a^{-1})	Volumetric Rate (cm^3 cm^{-1} a^{-1})	Slopes (degrees)	Depth of movement (m)	Time (a)
Dedkov et al., 1978	Volgaland, USSR	-	Young pits	2	-	15	24 to 28	1 to 1.2	2 to 5
Swanston, et al., 1995	Redwood Creek, CA	schist	PVC tubes	4[1]	0.12 - 2.5	-	-	4 to 16	6
Jahn, 1989	Sudetes Mountains, Poland	sandstone	pillars	2	0.0	-	20 to 30	-	12
		schist and gneiss	pillars	3	0.0	-	20 to 30	-	11
Lehre, 1987[2]	Lone Tree Creek, Marin Co., CA	greywacke melange	pillars	8	-0.07 to 1.52 Mean = 0.34 Median = 0.18	-0.32 to 1.93 Mean = 0.76 Median = 0.37	12 to 29	0.4 to 0.6	2 to 12
Auzet and Ambroise, 1996[3]	Vosges Mountains, France	granite	strain gauge	1	5.1	2 to 3	20	0.4	0.58
		granite	Anderson tubes	4	2.4 to 4.3	-	-	-	0.58
Yamada, 1999[4]	Hokkaido, Japan	-	strain gauges	3	-	1.6 to 4.2 Mean = 3.1 Median = 3.4	-	0.4	0.33 to 0.92
Clarke et al., 1999	New South Wales, Aus.	sandstone	Young pits	11	-	-4.08 to 1.95 Mean = -0.13 Median = 0.43	3 to 21	~0.6	8.65
		granite	Young pits	15	-	-1.36 to 3.03 Ave. = 0.37 Median = 0.14	4 to 13	~0.6	8.65

Notes: [1] Rates are for the four tubes dominated by creep. Rates are measured along the plane of maximum movement.

[2] Seven of the sites located in grassland, while the eighth site located in forest. Rates are from the author's best estimate. The maximum, or upper bound, volumetric rates range from -0.21 to 8.93 cm^3 cm^{-1} a^{-1} with a mean and median of 2.45 and 1.63 cm^3 cm^{-1} a^{-1} respectively. Mean and median were recalculated without changing negative values to zero.

[3] Volumetric creep rates calculated from relationship with climatic conditions.

[4] Creep rate calculated from relationship with climatic conditions.

Table 4-2. Creep rates for Redwood Creek, California.

Tubes	Movement along the Plane of Maximum Movement (PMM) (mm a^{-1})	PPM angle (degrees)	Slope azimuth (degrees)	Downslope movement rate (mm a^{-1})
1A	0.59	55	45	0.58
1B	0.12	275	45	-0.08
2A	NR		45	NR
2B	0.37	45	45	0.37
5A	2.52	90	45	1.78
5B	NR		45	NR
			Mean	0.44
			Median	0.19

Notes: NR - Not Reported, but considered zero for the calculation of the mean and median.

Table 4-3. Examples of soil creep sediment delivery estimates. Values of parameters used in the estimates are given in parentheses.

Source	Location	Creep rate (mm a^{-1})	Depth determined by (m)	Stream density determined by (km km^{-2})	Annual Volume (m^3 km^{-2} a^{-1})	Bulk density (t m^{-3})	Annual load (t km^{-2} a^{-1})
Madej, 1982	Big Beef Creek, WA	2.5	Creep depth (0.5)	Air photos[1] (2.5)	6.25	1.7	10.6
Roberts and Church, 1986	Mountain Creek, Queen Charlotte Ranges, BC	2 5	Soil depth (1.0)	Air photos[2]	19 47	-	-
CRWQCB, 2001[3]	Gualala River, CA	1.6	Bank height (0.9 to 1.9)	Field survey	12.2	1.76	21
Hart Crowser, Inc., 2005[4]	Elk River & Salmon Creek, CA	0.5 & 2.5 1.0 & 2.0	Soil depth	Field survey	11.5 15.2	1.42	16.4 21.7

Notes: [a] Creep rate explicitly includes 1.0 mm a^{-1} of soil movement due to wind throw.

[1] Stream density was determined on 1:12,000 scale air photographs and includes 1st through 4th order streams.

[2] Stream density was determined on 1:10,000 scale air photographs and includes stream channels flanked by steep, soil-covered hillslopes. The stream density used for estimating soil creep was approximately 4 to 5 km km^{-2}.

[3] Original calculations were for earth flows and soil creep combined. Annual sediment loads recalculated for soil creep delivery only. Loads were calculated for 1st through 3rd order streams. Soil heights along the banks averaged 0.9, 1.1 and 1.9 m for 1st, 2nd, and 3rd order streams. Total stream density used to calculate soil creep sediment delivery was 3.5 km km^{-2}

[4] Sediment delivery estimates for two scenarios: a lower bound based on creep rates from Swanston et al. (1995), and a "standard" WDNR (1997) estimate. A third estimate based on block-glide movement rates from Swanston et al. (1995) was determined to be unreasonable in the report and therefore is not included in this table. For each scenario, the lower value was applied to streams with adjacent hillslope gradients between 10% and 30%, while the higher value was applied to streams with adjacent hillslope gradients greater than 30%. Although the actual soil depth and stream densities used to calculate soil creep were not given, soil depths range from 0.76 to 1.78 m and the overall stream density for PALCO lands in Elk River is 5.9 km km^{-2}.

Table 4-4. Creep delivery estimates for the Elk River subwatersheds. For comparison, delivery rates from other studies are shown in gray.

Watershed	Method	Creep rate (mm a^{-1}) or (cm^3 cm^{-1} a^{-1})	Depth (m)	Stream density (km km^{-2})	Sediment Load (t km^{-2} a^{-1})
South Branch North Fork Elk River	Volumetric (local rate)	0.37[a]	-	3.94	0.5
	Volumetric (upper bound)	1.63[a]	-	3.94	2.1
	Linear (local rate)	0.19	1.27	3.94	3.1
	Linear (local upper bound)	0.47	1.27	3.94	7.8
	Linear (standard rate)	2	1.27	3.94	33.1
	Hart Crowser, Inc. (low estimate)	-	-	-	17.3
	Hart Crowser, Inc. (moderate estimate)	-	-	-	24.5
Corrigan Creek	Volumetric (local rate)	0.37[a]	-	3.32	0.4
	Volumetric (upper bound)	1.63[a]	-	3.32	1.8
	Linear (local rate)	0.19	1.27	3.32	2.6
	WDNR (local upper bound)	0.47	1.27	3.32	6.6
	WDNR (standard rate)	2	1.27	3.32	24.5
Little South Fork Elk River	Volumetric (local rate)	0.37[a]	-	3.30	0.4
	Volumetric (upper bound)	1.63[a]	-	3.30	1.8
	Linear (local rate)	0.19	1.27	3.30	2.6
	Linear (local upper bound)	0.47	1.27	3.30	6.5
	Linear (standard rate)	2	1.27	3.30	27.8
	Bank Erosion Void Estimate (Chapter 3)	-	-	-	10.9
	Bank Erosion Wood Estimate (Chapter 3)	-	-	-	210.6
	Suspended Sediment Loads (Table 4.5)	-	-	-	5.9

Note: [a] Volumetric creep rate.

Table 4-5. Suspended sediment loads (t km^{-2} a^{-1}).

Water year	Rainfall (percent of normal)	South Branch North Fork Elk River	Corrigan Creek	Little South Fork Elk River
2004	101%	122	54	5.9
2005	114%	-	-	-
2006	154%	-	-	-
2007	97%	234	55	1.6
2008	87%	396	85	9.9
Average		250	65	5.8
Median		234	55	5.9

Notes:

2004 water year data is from Manka (2005). 2007 and 2008 water year data from Kate Sullivan (Humboldt Redwood Company, LLC).

Table 4-6. Sediment budget for three Elk River watersheds from 1988-2000 (t km^{-2} a^{-1}).

	South Branch North Fork Elk River	Corrigan Creek	Little South Fork Elk River
Natural Sediment Delivery			
Soil Creep	0.5	0.4	0.4
Natural Landslides	0.0	6.6	13.1
Small Landslides	10.6	10.6	10.6
Management-related Sediment Delivery			
Harvest Surface Erosion	6.3	1.4	
Harvest Landslides	0.0	14.0	
Road Surface Erosion	13.8	10.3	
Road Landslides	0.0	15.9	0.5
Road Stream-side landslides	30.2	29.6	
Road Gullies	52.2	4.7	
Total Sediment Delivery (Natural + Management)	113.6	93.6	24.6
Total Sediment Delivery over Background	1022%	530%	102%
Median Annual Suspended Sediment Loads	233.8	55.1	5.9
Suspended Sediment Load over LSFER	3,947%	931%	100%

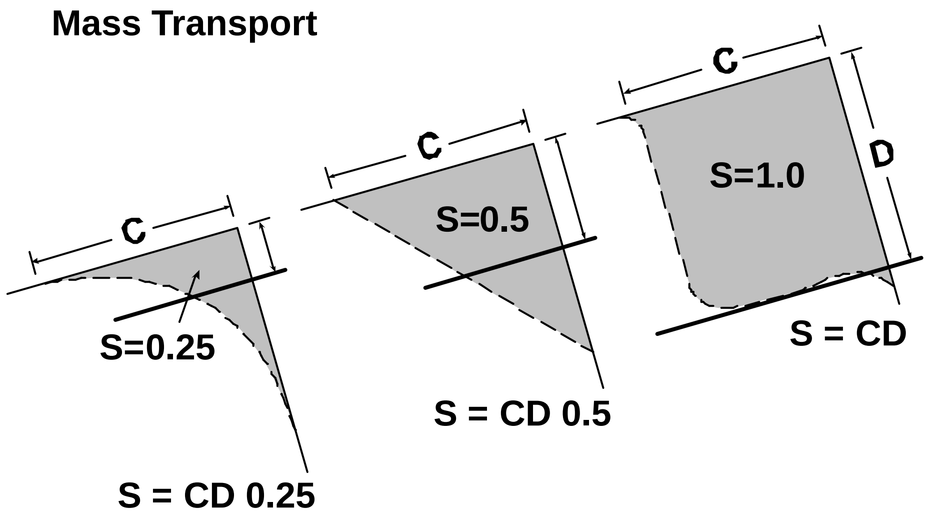

Figure 4.1. Mass transport of soil per unit contour, S, calculated in accordance with the observed creep profiles for non-linear, linear, and constant depth distributions (adapted from Selby, 1993 and Jahn, 1981).

CHAPTER 5

Conclusions

Like many other northern coastal California watersheds, water quality in the Elk River watershed has been impaired by sediment discharges. Sediment budgets are key to understanding sources of sediment and prioritizing watershed restoration even though they can be difficult to construct and verify. Due to court-mandated deadlines, the Regional Water Quality Control Board and US Environmental Protection Agency were forced to evaluate sediment discharges quickly for most Total Maximum Daily Load (TMDL) sediment budgets. To expedite TMDL development, the sediment budgets relied on remote sensing (e.g., landslides on aerial photographs) and modeling (e.g., road surface erosion) to estimate sediment sources. Field surveys conducted for the TMDLs tended to be limited in scope. As turbidity and suspended sediment data becomes available, it is not surprising to find a large discrepancy in the allocation of management and natural sediment sources between TMDL sediment budgets and the turbidity and suspended sediment data. For example, TMDL sediment budgets indicate the current loading is two times greater than background (Table 1-1), while Klein et al., (2008) indicate turbidity in logged watersheds is seven times greater than background.

The overall goal of this study was to examine one portion of a sediment budget, natural sediment delivery due to soil creep, to determine reasonable estimates of sediment delivery for this source. I also identified other potential causes of the discrepancy between suspended sediment loads and sediment budgets regarding the allocations of management and natural sediment sources during this investigation.

Most sediment budgets use an empirical formula to estimate creep that depends on soil creep rates, soil depth and stream length to determine sediment delivery. However, relying on empirical formulae with little to no field evaluation could lead to large errors in estimating sediment delivery.

I reviewed and evaluated soil creep rates and methods used to estimate its sediment delivery. Likely related to the difficultly in measuring soil creep rates, only a few creep measurements could be found for temperate forests. These creep rates also had substantial variation that made identification of reasonable creep rates for the redwood region difficult. Delivery estimates for other sediment budgets have used surface creep rates ranging over an order of magnitude (from 0.5 to 5 mm a^{-1}). Methods for estimating soil creep sediment delivery assume the creep rate is constant for the entire soil profile. However, this assumption is not consistent with creep theory or with the limited field measurements. Using the entire soil profile to determine the volumetric rates in this manner could lead to an overestimation of sediment delivery by soil creep.

Stream length is one of the parameters used to estimate delivery rates for soil creep. It is well documented that stream density in forested watersheds is usually underestimated unless field studies are conducted to verify stream lengths. However, management activities have the potential to increase stream length, so using the current stream length in managed watersheds could lead to an overestimate of soil creep. We found drainage areas for stream initiation decreased dramatically in logged watersheds compared to an old-growth watershed and drainage densities were much larger in managed watersheds. Therefore, when determining the stream length in other similarly managed watersheds, it is necessary to conduct surveys in an undisturbed watershed to get an accurate estimate of the natural stream density.

Bank erosion rates can be compared to soil creep sediment delivery rates to verify their reasonableness. We conducted field surveys to estimate bank erosion rates. The surveys used two rapid field methods allowing bank erosion rates to be estimated with only one field visit. Based on a comparison with suspended sediment loads, measuring the volume of bank erosion voids provides an adequate check on sediment delivery rates.

The Clean Water Act requires a margin of safety be incorporated into the TMDL. One approach to satisfy this requirement is to use conservative estimates in determining natural sediment loads. When a conservative approach is used to estimate creep rates, the soil creep delivery estimates are very small, less than one percent, compared to other components of the sediment budget in logged watersheds. Soil creep delivery estimates may be overestimated in other TMDL sediment budgets.

Management Impacts on Soil Creep Rates

I did not investigate the effects of management activities on soil creep rates. However, logging has the potential to increase creep rates due to root decay and regrowth. Also, creep rates may be increased by the loss of root cohesion or soil moisture increases from decreased transpiration (Reid, 1993). It is also possible tree uprooting rates increase along logging unit boundaries due to increased wind throw, which would result in an increased downhill soil transport rate.

Direct evidence for management activities affecting creep rates is extremely limited. Jahn (1989) indicated that creep rates tripled in cultivated meadows and doubled in high meadows affected by tourists and skiing. Jahn also noted depth of movement was twice as thick in the management areas and the volumetric rates between natural movement and man's activities were approximately 1:6 to 1:10. For forested environments, Swanston (1981) compared before and after logging movement rates in Oregon. Swanston found creep rates at least doubled due to the logging operations.

If logging activities accelerate creep rates, the assumed equilibrium between soil creep and bank erosion will be out of balance. Accelerated creep rates may increase soil accumulations along channel margins and increase bank erosion rates (Reid, 1993). The overall bank erosion rates determined by the void measurements (Chapter 3) in the managed watersheds were three to four times the bank erosion rates in the old-growth watershed. Rather than trying to attribute increases in bank erosion to a particular process, like soil creep, without direct evidence, further research should focus on monitoring bank erosion rates.

Monitoring Recommendations

Continued monitoring and research is vital, because it is evident some sources of sediment have not been identified and quantified in northern coastal California sediment budgets. Enhancing current monitoring programs and establishing a new one will improve the understanding of sediment generation and could lead to reprioritizing watershed restoration efforts. The importance of two monitoring programs is highlighted here: turbidity and suspended sediment gauging stations, and stream incision and bank erosion monitoring for small streams.

Klein et al. (2008) reported turbidity monitoring results for 28 continuous turbidity and stage monitoring stations located in northern coastal California that are maintained by a variety of non-profit organizations, private timber companies and governmental organizations. Thirty watershed variables were analyzed to identify the most important variable for explaining variation in turbidity duration among the watersheds for the 2005 water year. Regression analyses showed the average annual logging rate explained the greatest amount of variability. Drainage area was also a significant explanatory variable. This type of monitoring and analysis is essential to improve our understanding of sediment impacts to the watersheds.

Many of the stations used in Klein et al. (2008) also collect suspended sediment concentrations, which can be used to derive annual suspended sediment loads. Similar to the way suspended sediment loads were used in this study, sediment loading data provide an important method to test the accuracy of sediment budgets (Reid and Dunne, 2003). Although monitoring continues at many of the stations used in the Klein et al. study, currently no organizations or agencies are analyzing these monitoring data. Furthermore, several large timber companies turned down a request to have their monitoring data included in the Klein et al. study. Including the data from private timber companies and U.S. Geological Survey gauging stations would create a more robust dataset that can be analyzed to determine which watershed variables are related to the annual suspended sediment loads. Although financial resources need to be committed to analyze the turbidity and suspended monitoring data, this information is crucial for auditing sediment budgets, establishing long-term trends and establishing the loading capacities (i.e., the TMDL) in these watersheds.

This study found, compared to old-growth watersheds, bank erosion rates are much higher and stream incision has occurred in logged watersheds. However, management-related bank erosion has not been quantified in previous TMDL sediment budgets. A long-term monitoring program is needed to study bank erosion and stream incision for small channels to determine its magnitude compared to other sediment sources. Two monitoring methods would be very effective in meeting these monitoring goals: repeated surveys and erosion pins. An example for each method is provided below.

By using repeated instrument surveys and cross-sections measurements over three years with some additional measurements made for another two years, Dewey (2007) was able to establish that gullies are significant sources of sediment in a managed redwood forest watershed. Headcut retreat was bimodal; most retreat rates were gradual (0 to 15 cm a^{-1}), while a few were very dramatic (> 1 m a^{-1}). High bank erosion rates, which averaged 1.8 cm a^{-1}, were associated with the headcuts propagating through the gullies. These gullies, which appear to be created over a hundred years ago after the first-cycle logging, still had active portions that were discharging sediment.

Stott (2005) used 230 erosion pins to measure bank erosion rates before and after harvesting. He found bank erosion rates increased for the four year period after logging and then decreased to lower than pre-logging levels. The recovery was attributed to vegetation colonization along the banks.

Although a combination of these two methods would establish the importance of sediment delivery from these small channels, a program to determine which erosion control measures are the most effective at reducing the sediment discharges in these steep forested watersheds is also critical. Gully erosion can be minimized through a variety of actions: dewatering and diverting flow, establishing vegetation, or installing grade control. A combination of these erosion control measures may be necessary to reduce sediment discharges from small channels.

If we are to recover the endangered salmonid species, we must continue to use sediment budgets to help prioritize watershed restoration activities. We need to improve our understanding of sediment delivery and transport and the complex relationship it has on water quality. As our understanding improves, we can continue to adapt strategies to provide maximum benefit for the resources we utilize to restore water quality.

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