Lee MacDonald
7 October 2021

Management-related and Long-term Erosion Rates in Two Intensively-managed Forested Watersheds in Northwestern California

ABSTRACT

Sediment inputs from timber management and roads are a major concern because of their potential adverse effects on water quality, aquatic habitat, and fisheries. The objectives of this study were to estimate and compare the relative magnitudes of legacy, current, and background sediment inputs for two 15 km^2 watersheds dominated by coast redwoods within the Little River watershed north of Eureka, California. Both watersheds are only used for timber production, and they are virtually identical other than the Lower South Fork (LSF) is long and narrow and the adjacent Upper South Fork (USF) is dendritic. Ninety-two percent of the old growth was harvested in each watershed from 1910-1929 using railroads and steam donkeys, and in the mid-1970s harvesting of the second-growth timber began using tractors and a rapidly-expanding road network. Streamflow and suspended sediment measurements began in 2004, and this roughly coincided with declining rates of timber harvest, upgrading of the road network, and a shift from mostly tractor to shovel and cable logging. Management-related sediment inputs are postulated to have peaked in the early, intensive tractor-logging period, and there is little current evidence for legacy sediment storage and inputs, or large inputs from current timber harvest, roads, or management-induced landslides and bank erosion. Long-term erosion rates using beryllium-10 are more than double the mean estimated total sediment yield, and we postulate that long-term sediment yields are dominated by periodic large inputs of sediments from shallow landslides following the combination of large earthquakes and high rainfall. Peak streamflows and annual suspended sediment yields are more than twice as high in the LSF than the USF, and different geologic controls are believed to cause these differences. Salmonid fish populations and outmigrant rates are about three times higher in the LSF than the USF despite the higher peak flows and suspended sediment yields, implying that these two factors are not a key control on fisheries.

ACKNOWLEDGMENTS

This report would not have been possible without the extensive collaboration of Green Diamond Resource Company (GDRCo), as they provided ready access to their lands and compiled most of the data. Matt House initiated and led much of the effort, and his leadership has been essential throughout this study. David Lamphear and Annie Fehrenbach did much of the heavy lifting to compile the complete harvest history in a GIS database. David Lamphear also compiled the railroad network, provided an overall characterization of the watersheds, and gathered historical photos. Jason (Woody) Woodward provided the geologic context and mass movement data. Jeremy Wright provided much of the road data, while Will Olsen and Drew Coe helped compile the road history. Several foresters with decades of experience in the watersheds, particularly Greg Templeton, provided a real-world historical perspective. Jonathan O'Connell compiled and helped with the streamflow, turbidity, and suspended sediment data. Dr. Ken Ferrier, now at the University of Wisconsin, took the lead on analyzing and calculating the long-term erosion rates using beryllium-10, and Dr. Patrick Belmont also helped with some of the sampling and initial assessment of the two watersheds. Dr. Sean Gallen has assisted with the LiDAR analyses and geologic interpretation, and Dr. Sharon Bywater-Reyes provided some initial comments and data for this manuscript. Eric Clark, a graduate student at Colorado State University, ran the GRAIP-Lite road sediment model and helped with the figures and tables. Financial support has been provided primarily by the California Department of Forestry and Fire Protection, and I am grateful to Pete Cafferata for his continuing support and sharing his extensive knowledge of forestry on the North Coast. The National Council for Air and Stream Improvement has also contributed some funding, including several visits to the GDRCo office in Blue Lake. I am grateful that by working on this project I have met, worked with, and learned from so many dedicated professionals that I can now consider as friends.

1. INTRODUCTION

1.1. Background

The effects of forest management activities on erosion rates have long been a concern due to the potential adverse effects of increased sediment loads on water quality, sedimentation and flooding, and aquatic habitat. These concerns are particularly acute in areas where salmon fisheries are of high economic and cultural importance. In northwestern California the coastal redwood forests areas are an important source of drinking water and provide much of the freshwater habitat for resident and anadromous salmonids, but they also are very important economically for producing high-value timber. The potential disturbance from timber management activities in this area is particularly great due to the large size of the trees, high annual rainfall, and relatively steep terrain.

The total impact of forest management activities is difficult to assess because these can affect a series of different hydrologic and geomorphic processes. Harvesting the trees reduces the forest canopy, which will increase net rainfall by reducing interception and evapotranspiration (Reid and Lewis, 2009). This can increase the size and frequency of peak flows, which can induce bank erosion and stream channel scour. The associated increase in soil moisture can lead to higher pore pressures, and this combined with the loss of root strength can increase landslide erosion rates (Sidle and Ochiai, 2006). The passage of machines to cut and transport the logs to a central area for loading onto trucks can cause soil compaction and removal of the protective understory plant and litter layers. Relatively dense road networks are built to access the areas to be cut and transport the logs to a sawmill for processing, and unpaved roads can induce surface erosion. Roads also alter the hillslope hydrologic pathways, and the concentration and diversion of flow can increase the size of peak flows and induce landslides. Road cuts and fill slopes in steeper areas also can induce slope instability by both hydrologic and physical mechanisms. Each of these different processes and erosion mechanisms must be addressed for a full assessment of the effects of forest management on erosion rates.

Any effort to assess the effects of forest management activities on erosion is further complicated by the fact that management practices have changed over time in order to reduce their impact on runoff and erosion. California was one of the first states to establish forest practice regulations beginning in 1973, and these have progressively evolved over time and are now arguably the strictest regulations in the U.S. These regulations govern all facets of forest management, including the size and density of timber harvest units, harvest and yarding practices (yarding refers to the means by which the timber is transported to a road) based on slopes and soils, road and skid trail layout, the design and use of roads and stream crossings, and forest regeneration. Prior to 1973 there was minimal regulation of forest management activities, and past practices may have caused much larger amounts of erosion and deposition that may have an enduring legacy effect. We can conduct studies to assess the effect of current practices, but it is far harder to conduct forensic studies to assess the possible impact of past management activities. In the coast redwood region most of the old growth was harvested in the latter part of the 1800s and the first decades of the 1900s, but the effects of this initial harvest are difficult to quantify. Similarly, much of the second growth was harvested in the mid- to latter part of the 1900s, and assessments of these effects also usually are based on a forensic and empirical approach.

From a management perspective, any evaluation of the changes in runoff and erosion due to current forest management must also be put into a long-term perspective. If current erosion rates or sediment yields are being increased by 20%, 50%, or maybe even an order of magnitude, is this a cause for concern? To answer this question managers, regulators and the public have to know how a given increase compares to the natural variations and long-term mean erosion rates and sediment yields. The problem is that erosion rates, long-term sediment yields, and annual peak flows typically follow a highly-skewed distribution where the mean is much greater than the median because of a few extreme events. Putting current rates into a broader context is critical to determining if a given increase is a problem or noise when viewed in a larger context.

The overall goal of this study is to determine the extent to which current forest management activities are affecting suspended sediment yields and fish populations relative to the possible legacy impacts of historic forest management and the long-term natural erosion rate. The study was conducted in two adjacent approximately 15 km^2 watersheds in the coastal redwood region of northwestern California that are entirely owned and managed by Green Diamond Resource Company (GDRCo) (Figure 1). These watersheds are ideally suited to this study because discharge, turbidity, suspended sediment concentrations and fish populations have been intensively monitored for 15-20 years, they are small enough and had historic timber harvest records so that we could compile a complete land use history, and we could quantify the long-term sediment yields using beryllium-10 (Be-10). The specific objectives of the study were to:

1) Quantify current sediment inputs from deep-seated earthflows, shallow rapid landslides, and bank erosion;
2) Estimate current and legacy management-related sediment inputs by compiling a complete history of forest harvest, management practices, and the transportation network;
3) Determine long-term denudation rates using beryllium-10;

4) Compare the runoff, sediment yields, and fish populations between the two watersheds, and determine the extent to which these differ due to management history and/or watershed conditions; and
5) Use the results to estimate the relative impacts of forest management over time and the implications for management.

While the results are specific to these two watersheds, the comparison of current to legacy forest management effects helps assess whether current regulations and forest practices are effective in minimizing erosion and adverse effects on fish populations. The comparison of current sediment yields to millennial-scale denudation rates provides a much broader context for evaluating the relative impact of intensive forest management activities. These comparisons will help guide the direction of future forest practice regulations from the State of California and Aquatic Habitat Conservation Plans under the Endangered Species Act. The results also will have broader implications for formulating sediment TMDLs in the redwood region by the North Coast Regional Water Quality Control Board.

2. METHODS

2.1. Characterization of the Study Watersheds

The two study watersheds are tributaries in the 117 km^2 Little River watershed that drains directly into the Pacific Ocean in northwestern California about 25 km north of Eureka, California. The two study watersheds are the Lower South Fork (LSF) and the Upper South Fork (USF), and they are northward-flowing tributaries with very similar characteristics and management history other than the LSF is relatively long and narrow while the USF is more dendritic (Figure 1). The area of the LSF is 13.8 km^2, while the area of the USF is slightly larger at 14.7 km^2 (Table 1). Both watersheds are entirely owned by Green Diamond Resource Company and have been used for industrial timber production since the early 1900s under a variety of timberland owners.

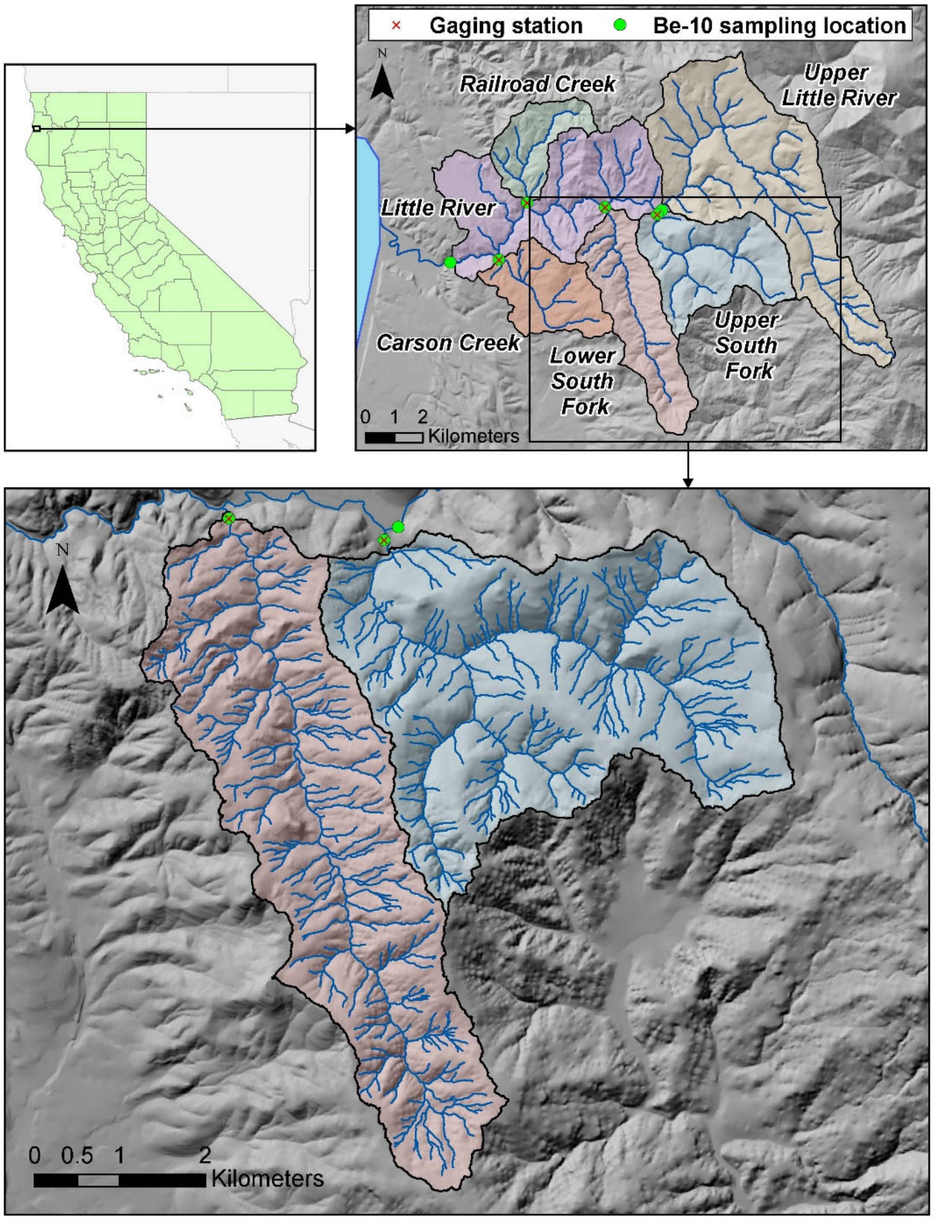


Figure 1. Location and map of the Little River watershed with the gaging stations and sampling sites for beryllium-10, and a more detailed map of the two study watersheds.

Table 1. Key characteristics for the Lower South Fork (LSF) and Upper South Fork (USF) watersheds, Little River, California.

	LSF	USF
Area (km^2)	13.8	14.7
Mean elevation and range (m)	309 (79-615)	360 (93-667)
Mean slope in percent (s.d.)	41 (23)	39 (24)
Mean annual precipitation (mm)	1570	1630
Stream length (km)/drainage density (km/km^2)	85.4/6.2	86.3/5.9

Class I (km)	9.1	7.6
Class II-1 (km)	19.1	25.1
Class II-2 (km)	21.7	27.4
Class III (km)	35.0	25.0
Watershed length/width ratio	4.0	1.4

The primary vegetation is coast redwood (*Sequoia sempervirens*), which is a fast-growing, high-value tree because the wood is naturally rot-resistant. Redwood is remarkable because of its fast growth rate, density, large size, longevity, and vigorous resprouting after harvest. With heights of up to 115 m and diameters of up to 9 m, old-growth coast redwood has by far the highest above-ground biomass of any forest on earth, with values exceeding 4000 Mg ha^{-1} (Sillett et al., 2020). Biomass accumulation rates can exceed 15 Mg ha^{-1} yr^{-1} (Sillett et al., 2020). The original old-growth stands would have been primarily redwood with relatively few understory trees due to the dense canopy, while the current second and third-growth stands can have 5-50% Douglas-fir (*Pseudotsuga menziesii*), which also is a valuable timber species, as well as tanoak (*Notholithocarpus densiflora*), red alder (*Alnus rubra*) and other conifers such as western hemlock (*Tsuga heterophylla*).

The Little River region is an area of active uplift and faulting. The estimated uplift rate of approximately 0.2 mm yr^{-1} (Balco et al., 2013) is primarily due to the subduction of the eastward-moving Gorda plate under the North American plate, but the area also is affected by the northern end of the San Andreas fault system. The active faulting has resulted in four earthquakes with a magnitude of seven or greater in the last 40 years (https://earthquaketrack.com/us-ca-eureka/recent?mag_filter=7). Both watersheds are relatively steep with nearly identical mean slopes of 41% for the LSF and 39% for the USF (Table 1). Total relief is also nearly identical and mean elevations are very similar, with the LSF being slightly lower at 535 m compared to 574 m for the USF (Table 1). The underlying bedrock is the central belt of Franciscan mélange, which is a matrix of clayey sheared argillite and intensely folded fine-grained sandstone, greywacke and siltstone (Kilbourne, 1985). Soils are primarily sandy loam, and there are numerous signs of dormant deep-seated landslides.

The climate is cool moist Mediterranean, with a mean annual rainfall of about 1570 mm for the LSF and 1630 mm for the USF (http://prism.oregonstate.edu/normals/) (Table 1). Nearly all of the precipitation falls from October to May from frontal storms. Maximum short-term precipitation intensities are relatively low as the 1-hr, 100-yr rainfall is only about 36 mm, whereas the 1-day, 100-yr rainfall is about 220 mm (NOAA Atlas 14 https://hdsc.nws.noaa.gov/hdsc/pfds/). Temperatures are relatively cool and moderate, with mean monthly temperatures near the mouth of the study watersheds of 8.2^{o}C and 15.8^{o}C in January and July, respectively (http://prism.oregonstate.edu/normals/). This relatively small variation is due to the relatively constant cool ocean temperature, and the predominant wind from west to east. Especially in summer inland heating draws in the cool offshore air to create dense fogs, and the resulting fog drip from the redwood canopy is critical for sustaining the shallow-rooted redwoods during the otherwise dry summers (Dawson, 1998).

The fog also helps maintain cool stream temperatures, and both watersheds provide important habitat for threatened coho salmon (*Oncorhynchus kisutch*) and threatened and endangered steelhead (*Oncorhynchus mykiss*) populations. Stream densities are very similar at 6.2 km km^2 for the LSF and 5.9 km km^2 for the LSF (Table 1). The LSF does have a slightly higher percentage of fish-bearing or Class I streams (10.6% versus 8.8%, Table 1), and a substantially higher proportion of ephemeral first-order or Class III streams (41% vs. 28%, Table 1).

3.2. Ownership and Harvest History

Nearly all of the Little River watershed has been used for timber production since the first old-growth harvests began in the early 1900s. A 1911 ownership map shows a railroad extending up into the LSF and the two watersheds being split among about five owners (NRMC, 2000). In 1956 most of these properties were sold to Georgia-Pacific (GP), and in 1973 they were transferred to Louisiana-Pacific Corporation (LP) and the second growth began to be logged. In 1998 Simpson Timber Company (STC) acquired all of LP's timberlands in Humboldt County, causing over 90% of the Little River watershed and 100% of the two study watersheds to be under Simpson ownership (NRMC, 2000). STC changed their name to Green Diamond Resource Company (GDRCo) in 2004.

The location and timing of the old-growth harvests were tracked from 1910 to 1928 using the original timber company maps from the early 1900s. Given the non-systematic distortion in these maps they were tiled and recognizable map features georeferenced to the same features in the GDRCo LiDAR base data. No timber harvest occurred in the study watersheds from 1928 to 1954, and the harvest history from 1954 through the late 1900s was derived from digitizing timber harvest maps from the different companies, nine sets of aerial photos (1942, 1954, 1966, 1975, 1978, 1984, 1991, 1997, and 2004), and three sets of digital orthophoto quarter quadrangles (1980, 1988, and 1998). The digitized maps and aerial photos were scanned, orthorectified, and used to delineate the boundaries of each harvest unit, determine both the silvicultural system (clearcut or selection cut) and the logging system (cable or ground-based tractor yarding). More recent harvest data were available from the GDRCo GIS, and these data were supplemented as needed with 2006 imagery and images from the National Agriculture Imagery Program (NAIP) for 2005, 2009, 2010, 2012, 2014, and 2016. All of these data were integrated into a single polygon feature class for each harvest unit with attributes of subbasin name, depletion year, silvicultural system, logging system, and area.

The timing of the aerial photos meant that there were up to two years of uncertainty as to when a given harvest took place. The sum of harvested areas often exceeded 100% as units could be subjected to one or more selection cuts, sometimes followed by a final clearcut. Historical accounts and pictures, a review of the 1-m LiDAR data, and interviews with long-term foresters all helped to qualitatively assess sediment inputs from the railroad logging, and clarify the management practices and forest practice regulations used from 1974 to the present.

3.3. Transportation System

A map of the railroad lines in each basin was developed by scanning and digitizing the original paper maps from the early 1900s, and using the GDRCo LiDAR data to confirm old railroads because of their linear nature with relatively low, consistent gradients and a lack of sharp curves. In many cases the main haul logging roads followed the old railroad grades. The LiDAR data were visually inspected to identify inclines or steam donkey trails, which are linear features that can extend for several kilometers from a railroad. These were used to convey the old-growth logs to the railroad, and they could be either tracked or bare earth (Figure 2).

A detailed history of road construction and road condition from the early 1940s through 1997 was developed by inspecting aerial photos dating back to 1942 (PWA, 2001). As part of this report road condition, road-related sediment sources, and potential sediment inputs to streams were evaluated by walking more than 350 km of roads in the Little River watershed. Each of the nearly 1800 potential erosion or mass movement sites were inventoried and mapped, including nearly 1100 stream crossings, 350 potential slope failures (primarily from unstable sidecast material), and 350 sites with substantial amounts of road surface or inboard ditch erosion. This inventory also led to an estimate of the road length that was potentially connected to a stream. The hard copy maps from the 2001 PWA report were digitized to develop the road construction history, identify the roads within 30 m of a stream, and quantify the number of stream crossings from the early 1940s to 1997.

The road history from 1997 to 2018 was assembled from GDRCo road assessment data and the detailed timber harvest history. The timing of road rocking, drainage improvements, and decommissioning were assumed to occur when a given road was needed or included in a Timber Harvesting Plan (THP). In some cases the harvest did not take place for several years, so the timing of these changes may have occurred several years later than we assumed.

The current proportion of roads draining directly to a stream was estimated by field surveys of 18 road sections in the two study watersheds in 2014 and a smaller sample in January 2019 that together covered nearly 66 km or 47% of the active road network. For each surveyed road the field crews identified the lengths that drained directly to a road crossing or a drainage structure, such as a ditch relief culvert, rolling dip, or waterbar that drained to a stream as evidenced by a rill, gully, or sediment plume. Longer sections were chosen to increase the efficiency of the surveys, and an effort was made to select sections that were well distributed across the two study watersheds.

Road sediment production and delivery for the two study watersheds was estimated for 2005, 2010, 2015, and 2017 by running the GRAIP-Lite model (Nelson et al., 2016) for the complete road network. The default baseline erosion rate was 79 kg of sediment per meter of elevation loss, the surface factor was set to one for rocked roads and five for native surface roads, roads were classified as either open or closed (i.e., decommissioned), and we assumed low traffic given the current low levels of timber harvest.

3.4. Mass Movements

Sediment production and delivery rates were estimated for deep-seated landslides (DSL), shallow rapid landslides (SRL), and bank erosion in each basin. Deep-seated landslides (DSL) were delineated using the GDRCo 1-m bare earth LiDAR. DSLs within a THP were assessed in the field, and the combination of LiDAR data, aerial photos, and field assessments were used to classify each slide as currently active (approximately the last five years); active historic

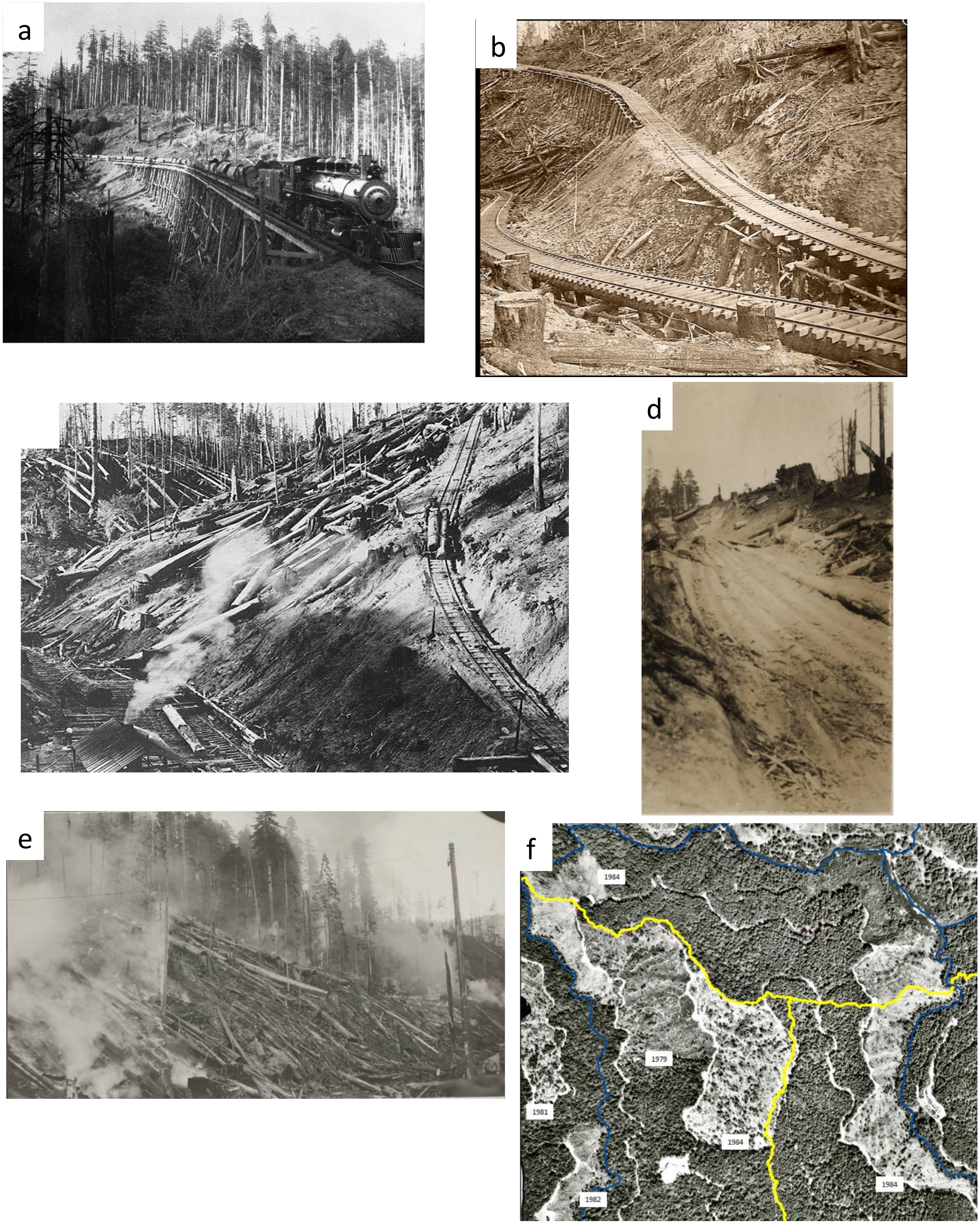

a
b
d
e
f
1984
1979
1981
1984
1984
1982

Figure 2. Photo of: a) railroad trestle crossing Little River; b) railroad trestles on a hillside with minimal cut and fill; c) tracked incline to bring logs down the main railway line (photo from Caspar Creek); d) dirt incline used in combination with steam donkeys to bring logs down to the main railway line; e) burning to reduce slash and facilitate the movement of the logs down to the railway; and f) 1984 aerial photo of a tractor-logged unit in the middle of the picture with the associated severe ground disturbance, and this can be compared to the adjacent unit tractor-logged in 1979 and several cable units logged from 1981 to 1984. Yellow lines are the watershed boundaries with the LSF in the lower left and USF in lower right.

(within the period of European settlement); dormant young; dormant mature; and dormant old (Wieczorek, 1984; Keaton and DeGraff, 1996). The area of each DSL polygon was summed and the total area for each DSL class was calculated for each watershed. The length of each DSL draining directly into a stream was estimated from the LiDAR data, and the bank height of the toes by stream type was determined from the bank erosion surveys. The annual rate of downslope movement by stream type was based on 12 movement rates from six different active DSLs in the adjacent Lindsay Creek watershed (GDRCo, 2016). The estimated sediment delivery from DSLs in each watershed was calculated by multiplying the toe lengths adjacent to each stream type times the bank height and the movement rate.

Shallow rapid landslides (SRL) in the two watersheds have been identified and mapped by several methods. First, one or more sets of aerial photographs for each decade were stereoscopically reviewed beginning with the first set of photos taken in 1942 and continuing through 2016. Since 1997 SRLs have been mapped from 1:24,000 orthophotos taken two to four years apart. The minimum size mapped ranged from about 30 m^2 to 160 m^2 (GDRCo, 2016). Second, a set of randomly selected stream segments totaling 6.6 km in the LSF and 5.7 km in the USF were surveyed along with their adjacent hillslopes, and all of the SRLs were identified and field mapped to estimate the volume of material displaced, the proportion of different size fractions following the Unified Soil Classification System (ASTM, 2011), and the proportion of displaced material delivered to a stream. Landslide age was estimated to the nearest decade by the age of the vegetation and the appearance of the scarp. These data were part of a much larger study of mass movements (GDRCo, 2016).

Third, any landslides encountered in the development of a THP were mapped and the volumes of displaced and delivered material were calculated from the field measurements. Proportions of material by size fraction were also estimated. Altogether 121 SRLs were delineated in the two watersheds and mapped into the 1-m LiDAR DEM. If the rupture volume was not available from field measurements, the rupture depth was calculated from the general relationship between SRL area and rupture depth derived from field measurements of more than 3300 SRLs on GDRCo lands in north coastal California (GDRCo, 2016). When percent delivered was not measured in the field, we applied the mean percent delivered by stream type that was obtained from the field surveys in each watershed. To the extent possible the causal mechanism/location for each SRL was classified as natural, induced by streambank erosion, DSL associated (located within a DSL), bedrock, road-related, harvest related (in an area that had been harvested in the last 20 years), or unspecified. The 20-year period for identifying harvest-induced landslides represents the approximate window of vulnerability due to the loss of root strength versus the growth of new roots (Sidle and Wu 2001; Imaizumi et al., 2007).).

Bank erosion that was not associated with DSLs and SRLs was assessed by a random survey of 3.2 km and 4.2 km of streams in the LSF and USF, respectively. The minimum size for mapping an erosion void was >0.6 m^3, and for each void the volume was estimated along with the percent delivered and age to the nearest decade. The volumes were stratified by stream type, normalized by stream length, and then extrapolated to the entire watershed according to the total length of each stream type. We assumed 100% delivery and that the particle-size proportions for bank erosion were the same as for the SRLs.

3.5. Runoff, Turbidity, and Suspended Sediment Yields

Discharge has been continuously measured by the US Geological Survey near the mouth of the Little River watershed since water year 1956 (USGS 11481200 Little River near Trinidad, CA). The gaging station is about 5 km above the mouth and the drainage area is 105 km^2.

GDRCo began monitoring streamflow, turbidity, and suspended sediment concentrations at the outlets of the two study watersheds and two other Little River sub-watersheds, Carson Creek and Railroad Creek (Figure 1), in October 2003. Stage heights and turbidities are recorded at 10-minute intervals from 1 October to 1 June as flows, turbidity, and suspended sediment concentrations are negligible from June to September given the minimal summer rainfall. Suspended sediment samples are collected using automated pump samplers triggered by specified increases or decreases in turbidity following Lewis and Eads (2009). Each sample is analyzed for turbidity, and the lab-measured values are used to calibrate the field values as needed. Each sample is filtered using 1.0 µm glass fiber filters (Lewis and Eads, 2009; American Society for Testing and Materials, 2013) to determine the suspended sediment concentration (SSC). Each site is visited weekly, and manual discharge measurements are made approximately 5-10 times per year to check the stage-discharge rating curves, but the cross-sections generally are very stable.

Turbidity-SSC relationships are established for each major storm, but if less than four storm samples are taken the turbidity-suspended sediment relationship is based on the general rating curve developed from the approximately 100 samples taken each year at each station. The relationships are used to generate SSC values at 10-minute intervals; multiplying these by discharge and summing the results generates an annual suspended sediment yield (SSY).

3.6. Fish Habitat and Populations

Summer juvenile salmonid populations and the number of outmigrating smolts have been monitored in the two study watersheds since 1998. Summer populations are estimated by identifying the length of salmonid habitat and classifying the different habitat units into riffles, shallow pools (≤1 m residual depth), deep pools (>1 m residual depth), and other. Other includes complex habitats such as log jams that cannot be effectively surveyed, or dry sections of the stream. Fish populations in a random sample of shallow and deep pools are visually counted by snorkel surveys, and in riffles by electrofishing. These populations are adjusted by calibration against a subset of units that are subjected to more intensive monitoring, and the data are used to estimate salmonid abundance following Mohr and Hankin (2005).

The number of outmigrating coho, steelhead, and cutthroat trout are determined by funneling fish through a temporary weir into a live box, while a spillway allows for the passage of adult salmonids. The traps are installed in the spring after high flows and monitored at least daily until early summer when the number of migrating fish approaches zero. The length and weight of each fish is measured to calculate a condition index, and each day the first 20 fish of each species are marked and released upstream to calculate capture efficiencies. Outmigrant smolt population estimates and trap efficiencies are calculated with DARR v2.01 software (Bjorkstedt, 2005).

3.7. Long-term Denudation Rate using Beryllium-10

Samples of fluvially-deposited sand were collected from depositional bars in May 2015 at six locations in the Little River watershed (Figure 1). Each sample was processed at the PRIME Lab at Purdue University following standard procedures (Kohl and Nishiizumi, 1992), and the basin-averaged denudation rates were calculated using CAIRN (Mudd et al., 2016). We followed the standard assumptions that the analyzed quartz grains were exhumed at a steady rate from depth to the surface (Lal, 1991), and that the samples were a well-mixed representation of the sediment eroded upstream of the sample site (Bierman and Steig, 1996; Granger et al., 1996). In the Little River watershed vegetation shielding is much more likely to be important as the above-ground dry standing biomass for relatively similar sites in the same general region is nearly 4000 Mg ha^{-1} (Sillett et al., 2020). The wet mass is probably 2-3 times higher, particularly given the high rainfall and frequent summer fog (S. Sillett, pers. comm., 2020), so we assumed a value of 10^5 Mg ha^{-1} or 100 g cm^{-2}. This assumption decreased the estimated denudation rates by about 25% compared to a value of 40 g cm^{-2} (Ferrier et al., 2020).

3. RESULTS

3.1. Timber Harvest

Period 1, 1913-1928: Timber harvest in the two watersheds began in the 1910s with railroads running up the valley bottoms or along the ridgetops (Figure 3). The logs were typically 1-3.5 m in diameter and cut into 5-6 m lengths, and after felling broadcast burning was commonly used to eliminate most of the logging debris and facilitate the movement of the logs to the railroads (Figure 2). The logs were then hauled to the railroads, sometimes over a distance of several kilometers, by partial suspension using a high lead system, endlining (dragging) the logs to the railroad by cables using steam donkeys, or moving the logs along focused corridors that were either bare earth or temporary tracks (“inclines”) (Figures 2, 3). Old growth logging ceased by 1928 when 92% of each watershed had been harvested (Figure 4; Table 2).

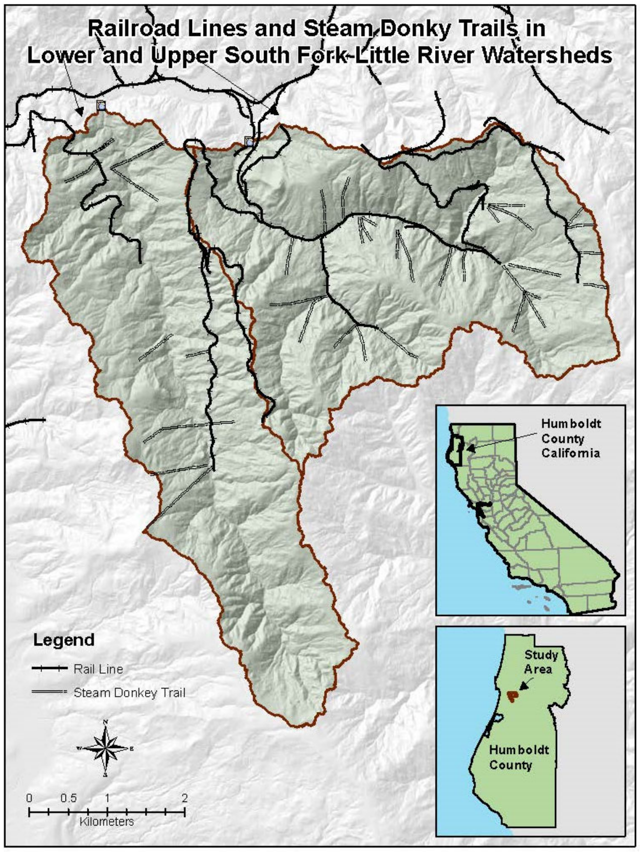


Figure 3. Map of the two study watersheds showing the railroad lines, steam donkey trails, and inclines that could be identified from historical maps and the 1-m bare earth LiDAR.

Table 2. Data by period for each watershed indicating area cut, percent of each watershed that was cut, percent cut by year, percent of harvested area that was clearcut, and percent of harvested area that was yarded using a ground-based system.

	Area cut (ha)		Percent of watershed that was cut		Percent of watershed cut by year		Percent of cut area that was clearcut		Percent ground based	
Period	**LSF**	**USF**	**LSF**	**USF**	**LSF**	**USF**	**LSF**	**USF**	**LSF**	**USF**
1913 - 1928	1270	1350	92	92	5.8	5.7	100	100	100	100
1954 - 1972	0	113	0	8	0.0	0.4	NA	96	NA	100
1975 - 1982	225	612	16	42	2.0	5.2	32	8	71	96
1983 - 1991	644	840	47	57	5.2	6.3	81	78	56	64
1992 - 2000	634	346	46	24	5.1	2.6	14	11	64	66
2001 - 2006	342	403	25	27	4.1	4.6	80	79	56	32
2007 - 2017	296	251	21	17	1.8	1.4	67	70	63	55
Total	2268	3915								

The lack of large earth-moving machinery meant that the railroads tended to use trestles to cross the streams and steep valleys, or to maintain a consistent grade across dissected slopes (Figure 2). Historical pictures indicate some localized areas of severe disturbance and sediment delivery due to the yarding of logs to the railroads, or the sidecast of sediment and channel infilling from railroad construction. However, there is little evidence that the inclines or other disturbances initiated gullies or substantially altered the channel network, and this can be attributed to limited areas subjected to severe compaction and soil disturbance and the rapid regrowth.

Period 2, 1928-1975: During this period only 108 ha of residual old growth was cut in the southeastern portion of the Upper South Fork (Figure 4; Table 2). This logging was done with tractors, and it seems that the logs were removed over the divide rather than being transported down through the watershed. There was no harvest in the Lower South Fork as the 8% of residual old growth had few merchantable trees. Some railroads were dismantled to salvage the steel, so this period can be characterized by regrowth and hydrologic recovery with minimal anthropogenic disturbance.

Period 3, 1975-1982: This period marked the start of the increasingly intensive harvest of the second-growth forest in the two watersheds, with nearly 42% of the USF being harvested versus only 16% of the LSF (Figure 4). The railroad lines were converted to main haul roads and an extensive road network began to be established, especially in the Upper South Fork (Figure 5a). Logging was primarily ground-based selection harvest using crawler tractors (Table 2). Forest practice rules began to be implemented in 1975 (Table 3), but these cool coastal watersheds were commonly exempted from the shade protection rules. Interviews with long-time foresters and regulators characterized this period as one of relatively severe ground disturbance by the tractor logging, as well as substantial erosion and sediment delivery from the largely native-surfaced road network with relatively minor changes being imposed by the forest practice rules. Broadcast burning and herbicide use could have increased or prolonged the surface erosion from logging, but the interviews suggested that neither of these practices resulted in large amounts of overland flow or surface erosion. The much lower amounts of logging in the LSF in this period would have resulted in substantially less management-induced erosion than in the USF.

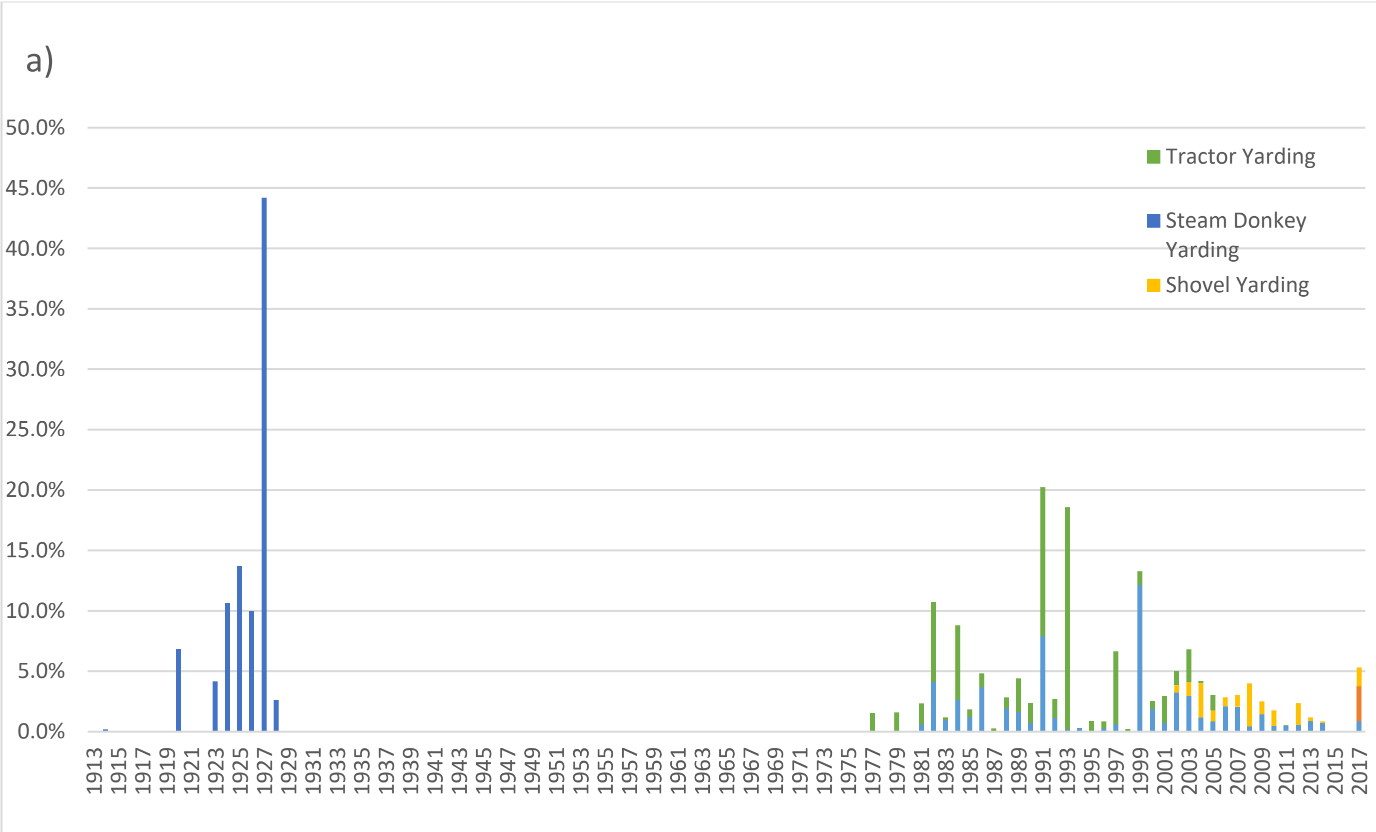
Period 4, 1983-1991: This was the most intensive period of second-growth harvest with 47% and 57% of the LSF and USF being harvested, respectively. Clearcutting was the dominant silvicultural system, and tractor yarding was used on about 60% of the harvested units (Figure 4; Table 2). Early in this period the road network was largely completed (Figure 5a). Slope-dependent buffer strips 15-61 m wide were required on the Class I fish-bearing streams with 50% overstory retention, whereas only 50% understory retention was required along the Class II streams (Table 3). Harvest units were commonly exempted from the shading requirements given the cool coastal climate. Improved road rules were implemented to reduce sediment inputs, but winter logging and hauling on native surface roads was still allowed.

Period 5, 1992-2000: During this nine-year period the focus of timber harvest shifted from the USF to the LSF, with 46% of the LSF being harvested as compared to just 24% of the USF (Table 2). There was a marked shift in the type of harvest, as less than 15% of the cut areas were clearcut, but ground disturbance was still relatively high since two-thirds of the cut areas were yarded using tractors rather than aerial systems (cable logging) (Table 2). This period marked the end of winter logging and hauling on unimproved roads, and the use of widespread broadcast burning after harvest to reduce slash and facilitate planting. Beginning in 1998 slope-dependent equipment limitation zones (ELZs) 8-15 m wide were required on the headwater (Class III) streams. Maximum clearcut size was reduced to 16 ha (Table 3), and herbicides continued to be used to facilitate tree growth.

Period 6, 2001-2006: Over this six-year period only about 25% of each watershed was harvested, with about 80% of this by clearcutting. Ground-based equipment was used on just over half of the harvested area in the LSF and less than one-third of the harvested area in the USF (Figure 4; Table 2), presumably because the more readily accessible timber had already been harvested. One major change was the extensive rocking and upgrading of the road network along with road decommissioning (see below). Canopy retention in the Class I buffer strips was increased to 65-85% (Table 3). The implication is that collectively these changes would have substantially decreased management-related sediment inputs.

Period 7, 2007-2017: Timber harvest declined further in this period, with only about 20% of each watershed being harvested (Figure 4; Table 2). About two-thirds of the cut area was harvested by clearcutting, but there was a nearly complete shift away from tractor logging to shovel logging. With shovel logging the cut trees are picked up using a grapple hook on a caterpillar-tracked machine and moved towards a temporary, seasonal, or permanent road. Up to 3-4 swings are used to move the logs to a point where they can be loaded onto trucks. Since the machines are walking over a bed of slash rather than repeatedly traversing back and forth on skid trails, there is far less bare soil and soil compaction compared to traditional crawler tractor logging (Egan et al., 2002; House et al., 2012). Forest certification requirements and terrestrial wildlife plans also led to the use of "fuzzy clearcuts" where snags and some merchantable and smaller trees are left standing for habitat and visual impact purposes.

Figure 4. Percent of watershed area cut by year and silvicultural system for: a) Lower South Fork; and b) Upper South Fork.


a)
50.0%
45.0%
40.0%
35.0%
30.0%
25.0%
20.0%
15.0%
10.0%
5.0%
0.0%
Tractor Yarding
Steam Donkey Yarding
Shovel Yarding

b)

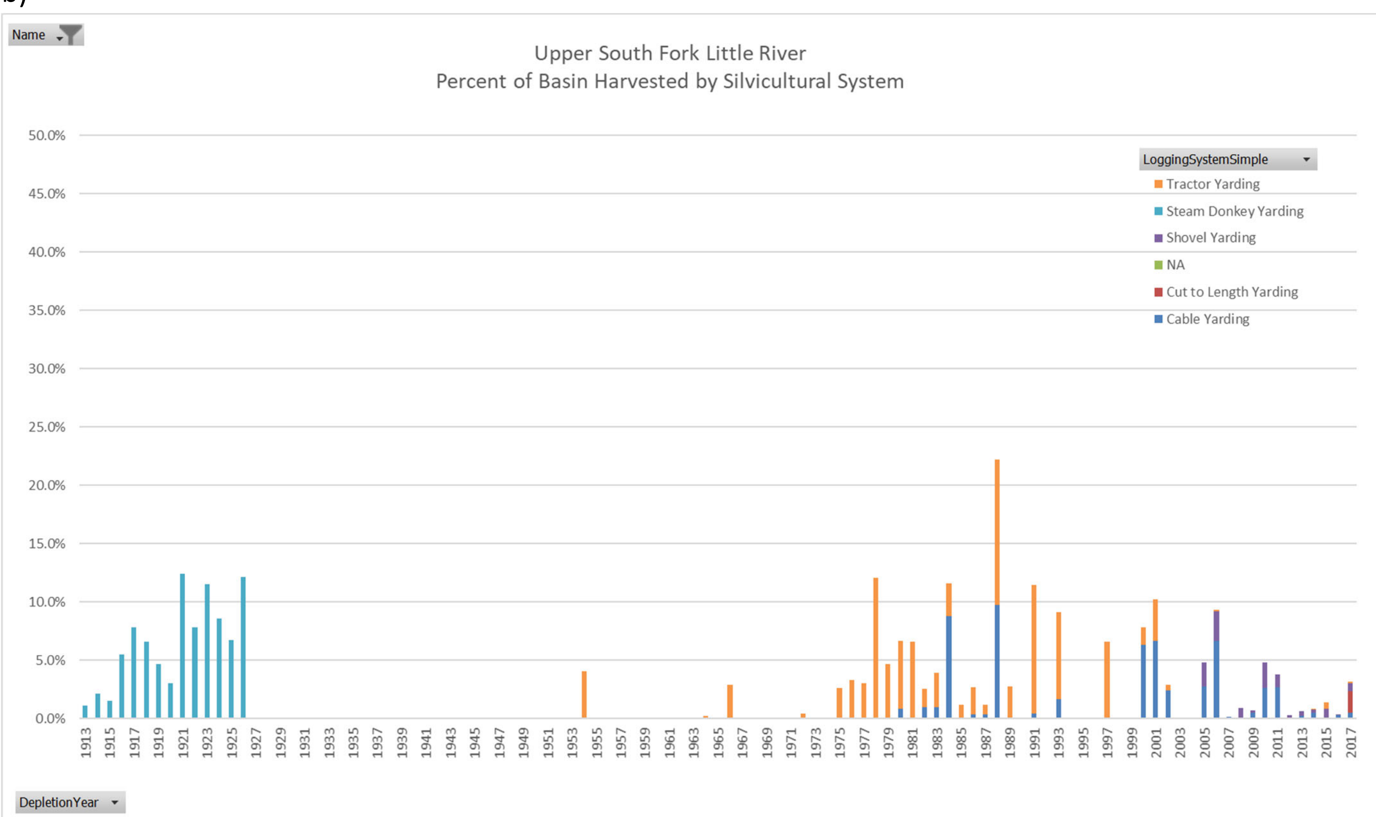

Name
Upper South Fork Little River
Percent of Basin Harvested by Silvicultural System
LoggingSystemSimple
Tractor Yarding
Steam Donkey Yarding
Shovel Yarding
NA
Cut to Length Yarding
Cable Yarding
DepletionYear

Table 3. Forest practices and key State regulations for each time period.

Period	Typical Operations and Forest Practice Rules
1913 - 1948	Railroad logging using steam donkeys, partial suspension cable logging, and inclines to move logs. No forest practice rules related to watershed protection.
1954 - 1972	Tractor logging introduced and rail lines converted to truck roads. No forest practice rules addressing stream protection, logging roads, or hillslope erosion.
1975 - 1982	Primarily tractor logging with 15-30 m buffers on USGS blue line streams, but shade exemption widely used; clearcuts up to 50 ha. Road construction and drainage requirements with crossings sized to 25-year flood; skid trail drainage rules.
1983 – 1991	Relatively intensive tractor logging, primarily clearcutting. Slope-dependent buffers 15-61 m wide with 50% retention of overstory shading for Class I (fish-bearing) streams, whereas only 50% understory retention in the 15-46 m for Class II streams; shade exemption was still widely used. Stricter road rules, and crossings sized to 50-year flood.
1992 – 2000	Primarily ground-based selection logging. 50% retention of the total canopy for Class II streams; from 1998 8-15 m slope-dependent equipment exclusion zones for Class III channels; maximum clearcut 16 ha. Reduced winter skidding and hauling; reduced post-harvest burning.
2001 – 2006	Primarily tractor-based clearcutting but reduced harvest rates. 65-85% canopy retention for Class I buffers; 8-15 m equipment exclusion zones for Class III channels. Crossings sized for 100-year flood. Aquatic HCP triggered extensive road upgrading.
2007 - 2017	Low harvest rates, mostly clearcutting and ground-based units all used shovel logging. Some canopy retention requirements for Class III channels.

3.2 Railroad and Road Development over Time

The LiDAR analysis identified 9.1 km and 20.2 km of railroads in the LSF and USF, respectively (Figure 3). Nearly 7 km of inclines were identified in the LSF and over 12 km in the USF (Figure 3), but these values are probably an underestimate as the subsequent tractor logging probably erased some of these features. Some inclines were more than a kilometer long and crossed over divides (Figure 3), so the much lower density of railroads in the LSF probably stems from the use of inclines to transport logs out of the relatively narrow LSF to the ridges and rail lines in the adjacent watersheds.

The development of the road network in the two study watersheds is closely related to when the second-growth timber was being harvested (Figures 4, 5a). In the LSF the absence of any timber harvest from 1929 to 1977 meant that there was less than 10 km of roads until 1974, whereas there was already 24 km of roads in the USF due to the earlier logging of the second growth (Figures 4a, 5a). From 1974 to 1987 nearly 50 km of roads were constructed in the LSF, and this represents 86% of the road network for which we have the dates of construction (PWA, 2001). Similarly, the road network in the USF nearly tripled from 1975 to 1987, which converts to an increase in road density from 1.6 to 4.7 km km^{-2}. Observationally, the 17-19% of roads with no construction date are primarily spur and connector roads.

In 1997 just under 25% of the road network was within 30 m of a stream, and there were 239 stream crossings in the LSF and 263 stream crossings in the USF, or a density of about 17 crossings per km^2. Stream crossings built prior to 2000 were not required to pass the 100-

year flow (Table 3), and most roads were insloped with ditches and relatively few cross drains. For the entire Little River watershed very few roads were rocked in 1997 and 74% of the roads were estimated to be connected to a stream (PWA, 2001).

Road improvements and decommissioning began in 1997 in the LSF, and sharply increased beginning in 2001 as a result of the GDRCo Aquatic Habitat Conservation Plan (AHCP) for sensitive aquatic species. From 2001-2005 roughly 33 km or 40% of the roads in the LSF were rocked and upgraded, while in the USF about 45 km or 51% of the roads were rocked and upgraded. By 2018 approximately 70% of the roads in both watersheds were rocked and had improved drainage (Figures 5b, 6).

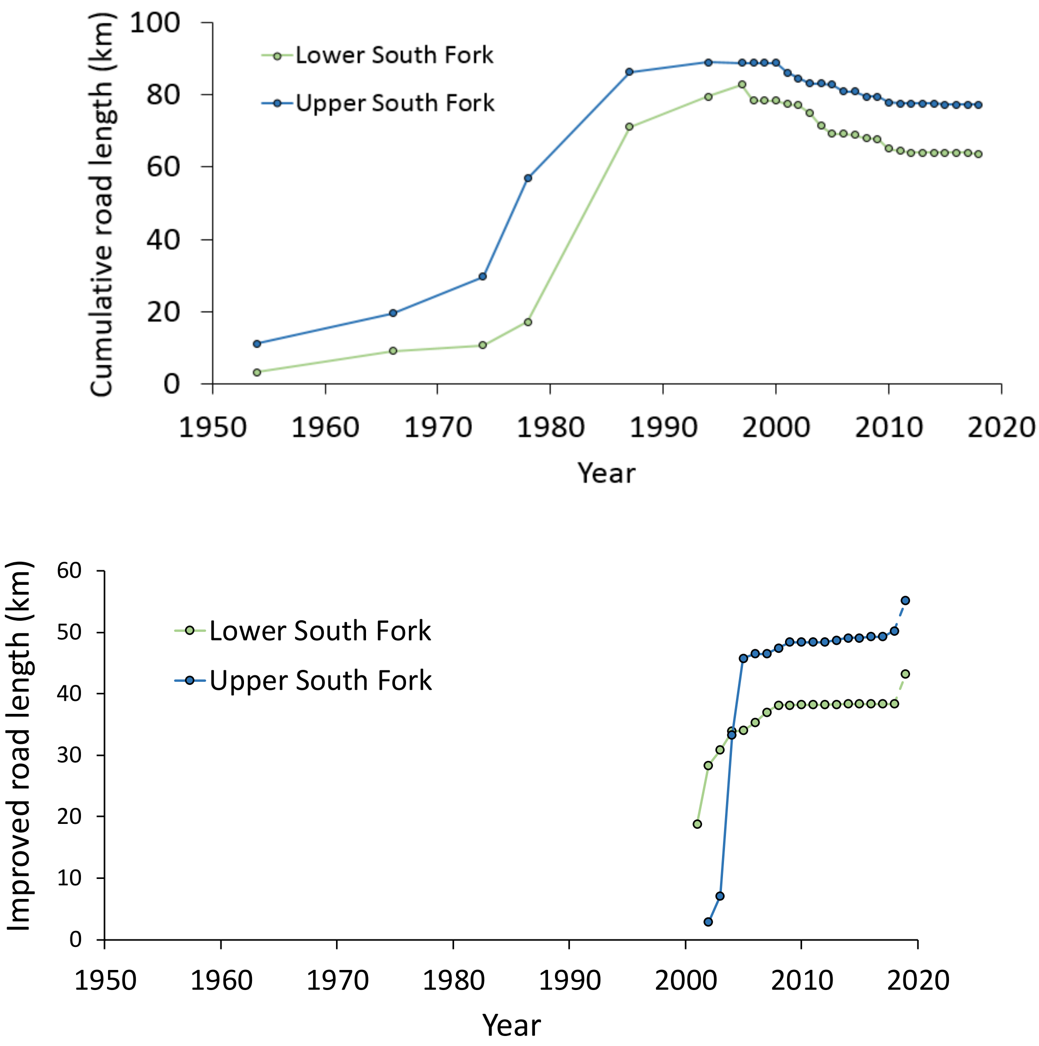


Figure 5. a) Development of the road network over time, and b) timing of road upgrading over time. Road upgrading typically is a combination of rocking and improved drainage. The dashed segments finishing at 2019 indicate the amount of road construction and upgrading for which we have no dates.

Figure 6. a) Photo of a primary road used for timber hauling in about 1990, and b) the same road in 2001 after upgrading by rocking and improved drainage.

The AHCP called for decommissioning those roads that were not essential for future operations, with priority being given to those roads that posed a greater threat to water quality. Decommissioning generally consisted of closing the road, removing the culverts, and pulling back the road fill that could erode into the stream. A total of 19 km of roads in the LSF and 12 km of road in the USF have been decommissioned, causing the total length of roads to decline to 63.5 km in the LSF and 77.2 km in the USF (Figure 5a). About 30% of the decommissioned roads were within 30 m of a stream channel, and road decommissioning has reduced the number of stream crossings by about 22-25%. The net result of the road improvements and decommissioning is that there are now only about 0.3 km km^{-2} of native surface roads within 30 m of a stream, which is an order of magnitude lower than in 1997.

The field survey of 66 km of roads in 2014 and 2015 showed that 14% of the road length was connected to a stream with no clear difference in percent connectivity between rocked and native surface roads. Slope position was important, as only 8% of the ridgetop roads were connected as compared to 18% of the roads in mid- and low slope positions.

The GRAIP-Lite modeling of the complete road network yielded nearly 200 road segments and drain points in each watershed. The total estimated road sediment production was 770 and 670 Mg yr^{-1} in the LSF and USF, respectively (1 Mg is 1000 kg or 1.1 English tons). About 16% of the road length was predicted to be delivering sediment to a stream, which is remarkably similar to the 14% value from the field survey. The total amount of road sediment being delivered to the watershed outlets was estimated to be 130 Mg yr^{-1} for the LSF and 100 Mg yr^{-1} for the USF, or about 10 and 7 Mg km^{-2} yr^{-1}, respectively (1.0 Mg km^{-2} is about 2.8 English tons mi^{-2}).

3.3. Mass Movements and Bank Erosion

Deep-seated landslides. Deep-seated landslides (DSL) are common in this region, and detailed mapping indicates that DSLs cover approximately 11% of the LSF and 9% of the USF, or roughly 150 and 130 ha, respectively. Nearly 90% of the DSL area was classified as dormant-mature, meaning that there is no evidence of active movement for at least several thousand years following Wieczorak (1984) and Keaton and DeGraff (1996). Eleven percent of the DSL area was classified as dormant-young, indicating some evidence of movement from about 100 to several thousand years before present. Only about 1 ha in the LSF and 2 ha in the USF were classified as dormant-historic, indicating some movement in the last hundred years or so. None of the DSL features were classified as active.

The total toe length draining to streams was 10.5 km in the LSF and 9.3 km in the USF, or just over 10% of the total stream length. The distribution of DSL toe lengths by stream type was quite similar between the two study watersheds, with nearly half of the total DSL toe lengths draining to Class I or fish-bearing streams and most of the remaining DSL toes draining to Class II streams. Average bank heights at the toes were about 2 m, and the estimated rate of movement was 8 mm yr^{-1} in the Class 1 streams, 2.4-4 mm yr^{-1} for the different types of Class II streams, and less than 2 mm yr^{-1} for the Class III streams. The estimated sediment delivery from DSLs in each watershed was slightly over 11 Mg km^{-2} yr^{-1}. About one-third of the delivered sediment in the LSF and one-sixth of the delivered material in the USF was estimated to consist of particles smaller than 4.75 mm, which means that the amount of suspended sediment from DSLs would almost certainly be less than 3 Mg km^{-2} yr^{-1} in the LSF and 2 Mg km^{-2} yr^{-1} in the USF.

Shallow rapid landslides. One hundred and forty-one shallow rapid landslides (SRL) were identified in the two watersheds, with nearly all of these identified from the field surveys along the streams. The total displaced volume was estimated to be about 13,600 m^3 in the LSF and 16,800 m^3 in the USF, and about 35,000 and 162,000 m^3 respectively when extrapolated to the entire stream network. In the LSF nearly half of the SRL volume was identified as management-related, with about two-thirds of these being associated with harvest units and one-third with roads. In the USF only about 8% of the total SRL volume was attributed to management, with harvest units again having about twice as much displaced volume as road-related SRLs. Mean slope was 84% or 40 degrees, which is consistent with the slope stability threshold identified in other studies (Larsen and Montgomery, 2012). In volumetric terms, 86% of the SRLs in the LSF and 76% of the SRLS in the USF occurred in either concave or planar slope positions.

The majority of landslides do not have an associated date, but an extensive survey of GDRCo lands in northern California indicated a strong peak in SRL volumes in the 1960s and 1970s, a decline to about one-third of this rate in the 1980s and 1990s, and another sharp drop in the 2000s (GDRCo, 2016). Qualitatively, there was a paucity of recent SRLs in the study watersheds. The proportion of the displaced mass that was delivered to a stream varied by stream type, but the overall average was 53% for the LSF and 40% for the USF. Using the stream-specific delivery ratios, an assumed bulk density of 1.6 Mg m^{-3}, and an estimated sample period of 75 years yielded an estimated sediment delivery from SRLs of 68 Mg km^{-2} y^{-1} in the LSF and 110 Mg km^{-2} y^{-1} in the USF. About 34% of the delivered sediment in the LSF or 23 Mg km^{-2} y^{-1} was estimated to consist of particles smaller than 4.75 mm as compared to just 6%

or 7 Mg km^{-2} y^{-1} for the USF, and the much lower proportion in the USF is attributed to the greater competence of the rocks in the USF.

Bank erosion. The bank erosion features that were not at the toe of DSLs or SRLs were generally due to natural flow deflections and bank undercutting. The estimated bank erosion volume was just over 2300 m^3 in the LSF and about 6000 m^3 in the USF. One hundred percent of the bank erosion was assumed to be delivered into the stream channel. When divided by the estimated time period represented by the measured voids, the estimated sediment delivered from bank erosion was less than 3 Mg km^{-2} yr^{-1} in the LSF and just over 10 Mg km^{-2} yr^{-1} in the USF.

3.4. Runoff, Turbidity, and Suspended Sediment Yields

Peak flows. The Little River watershed has a mean annual maximum instantaneous peak flow of 1.32 m^3 s^{-1} km^{-2}, and this ranges from 0.19 m^3 s^{-1} km^{-2} in 1977 to a maximum of 2.65 m^3 s^{-1} km^{-2} yr^{-1} in 1975 (1.0 m^3 s^{-1} km^{-2} converts to 91 ft^3 s^{-1} mi^{-2}, so one can roughly convert by multiplying m^3 s^{-1} km^{-2} by 100) (Figure 7). While 2.65 m^3 s^{-1} km^{-2} yr^{-1} is a relatively large number, it is striking that the six highest flows are so tightly clustered at 2.38 to 2.65 m^3 s^{-1} km^{-2} yr^{-1}, or just 11%. This indicates a relatively flat upper end to the flood-frequency curve (Figure 8), which in turn reflects the predominantly maritime climate, the relatively low short-term maximum rainfall intensities, and the general lack of rain-on-snow floods.

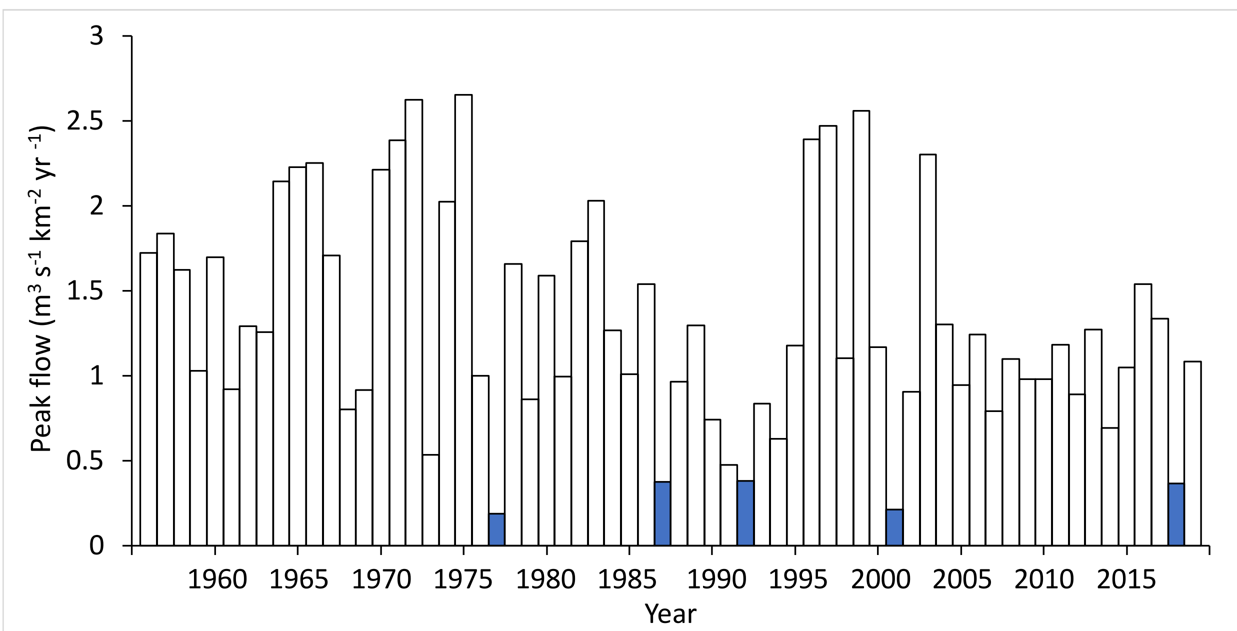


Figure 7. Instantaneous annual maximum peak flows for the USGS gaging station on Little River, 1956-2019.

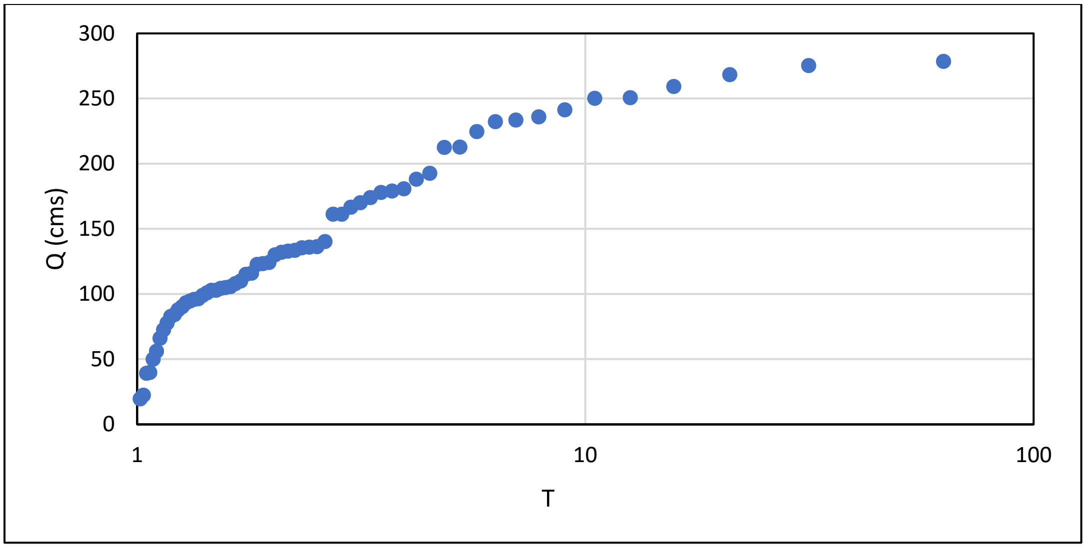


Figure 8. Flood frequency curve for the USGS gaging station on Little River, 1956-2019.

Mean annual runoff from the two study watersheds is relatively similar at just over 1000 mm for the LSF and 1080 mm for the slightly higher and wetter USF. Subtracting mean precipitation from mean runoff yields a mean annual evapotranspiration of about 550 mm, which is reasonable given the potentially large amounts of interception and transpiration in coast redwood forests (Reid and Lewis, 2009). Mean annual runoff between the two study watersheds is highly correlated (R^2=0.94).

Instantaneous annual maximum peak flows for the two watersheds are highly correlated (R^2=0.92), but the mean annual peak flow for the LSF of 1.30 (s.d.=0.40) $m^3 s^{-1} km^{-2}$ is 63% larger than the corresponding mean annual peak flow in the USF (Figure 9a). The largest instantaneous peak flow over the 14 years of record for the LSF is 2.20 $m^3 s^{-1} km^{-2}$ as compared to just 1.21 $m^3 s^{-1} km^{-2}$ for the USF, or a difference of more than 80% (Figures 7, 9). The regression slope of 0.45 indicates that the instantaneous annual maximum peak flows in the LSF are consistently more than double those in the USF, despite the similar amounts of total annual runoff. In both watersheds the three largest peak flows over the 14-year record occurred in 2013, 2016, and 2017.

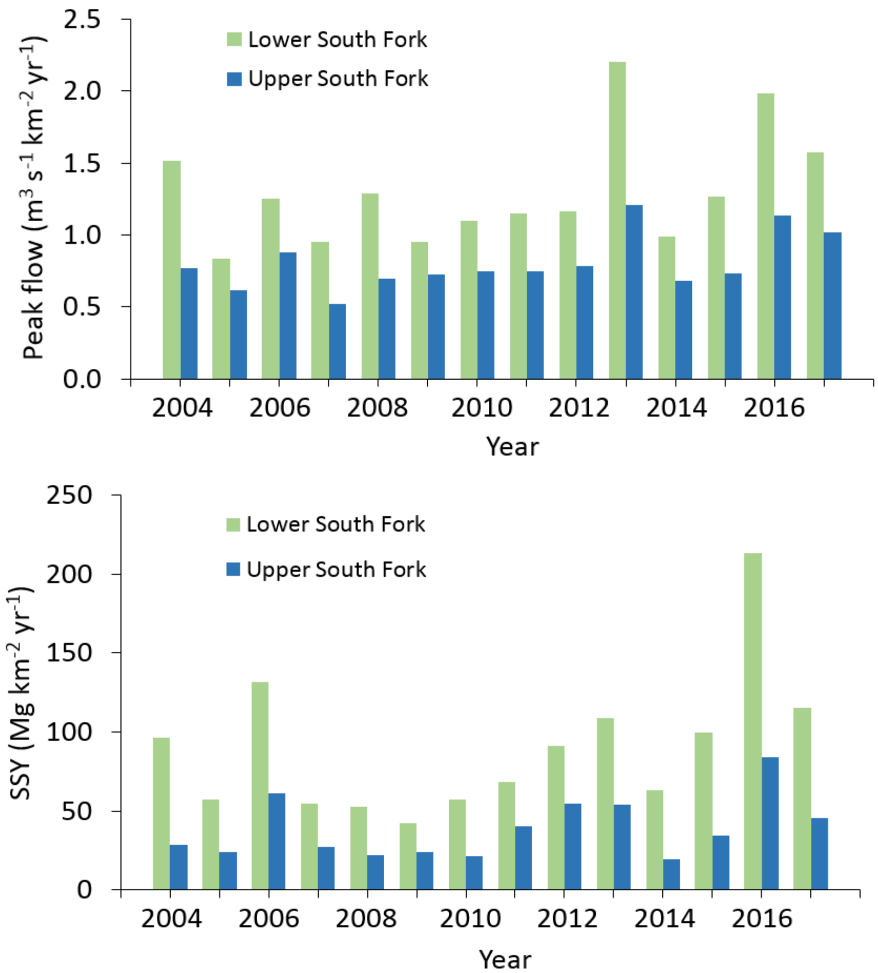


Figure 9. a) Instantaneous annual maximum peak flows and b) annual suspended sediment yields for the Lower South Fork and Upper South Fork, 2004-2017.

Peak flows in the two study watersheds have a surprisingly low correlation with the peak flows of the entire Little River watershed, as the R^2 values are just 0.59 for the LSF and 0.51 for the USF. In absolute terms the mean annual maximum peak flow in the LSF is about 36% larger than the corresponding peak flows for the entire Little River watershed, while the mean annual maximum peak flow in the USF is only about 63% of the value for the Little River watershed. This difference is consistent with the comparison of peak flows between the LSF and USF, and indicates that—relative to the entire Little River watershed—the LSF tends to have substantially higher peak flows and the USF tends to have substantially lower peak flows.

A comparison of the peak flows at the USGS station over the period of record to the peak flows over the 14-year period of record for the two study watersheds indicates an absence of large peak flows during the period of record for the LSF and USF (water years 2004-2017) (Figure 7). For these 14 years the mean annual peak flow at the USGS gaging station is only 83% of the long-term average, and the largest peak flow of 1.54 $m^3 s^{-1} km^{-2}$ has an estimated recurrence interval of less than five years. This comparison and the overall flood-frequency curve may be flawed as peak flows in the early years were probably over-estimated (USGS field technician, pers. comm., 2015).

Suspended sediment yields (SSY). Mean annual suspended sediment yields for the two study watersheds are 89 (s.d.=45) Mg km^{-2} y^{-1} in the LSF and just 39 (s.d.=19) Mg km^{-2} y^{-1} for the USF. On an annual basis the suspended sediment yields are relatively well correlated (R^2=0.83), and the regression slope of 0.39 confirms that SSY in the LSF are typically about 2.5 times higher than the USF.

The annual SSY are only moderately well correlated with the instantaneous annual maximum peak flows, as the R^2 values are just 0.54 for the LSF and 0.59 for the USF. For both watersheds the annual SSYs in 2016 were much higher than any other year (+62% for the LSF, and +38% for the USF). A closer review of the data indicates that in some years, such as 2013, most of the annual SSYs were due to a single storm, while years such as 2016, multiple storms collectively resulted in very high SSYs.

There is a much smaller difference in the frequency of a given turbidity value compared to the 2.5-fold difference in annual sediment yields. In general, a given turbidity value occurred 30-60% more frequently in the LSF than the USF. As one example, FNU values greater than 25 occurred about 570 hours per year in the LSF and 360 hours per year in the USF. Similarly, the mean 10% exceedance probability for the period of record averaged 22 FNU in the LSF and 16 FNU in the USF. In absolute terms turbidity levels are relatively low, as turbidities greater than 100 FNU only averaged about 50 hours per year in the LSF and 37 hours per year in the USF. The implication is turbidity levels in these two watersheds are likely to have minimal effect on salmonid sight feeding. Long-term employees of GDRCo note that the LSF and USF quickly clear after higher peak flows, while prior to 2000 the streams would remain turbid for a much longer period of time. These results indicate that the much greater SSY in the LSF are driven primarily by the large difference in peak flows rather than large differences in turbidities and suspended sediment concentrations.

The relatively short record for the two study watersheds and the large interannual variability means that there is no clear trend over time in the annual maximum peak flows, SSYs, or annual duration of hours above a given FNU threshold. Nor is there a clear trend in the slopes of the relationships between discharge and suspended sediment concentrations, either on an arithmetic or a log scale. The only relationship with a clear trend in both watersheds was a decrease over time in the slope of the regression between SSC values and turbidity on a log-log scale.

3.5. Fish Habitat, Summer Fish Populations, and Outmigration

The annual habitat surveys indicate that the mean length of anadromous fish habitat is about 3.6 km in the LSF and just under 3 km in the USF, with coho using about 97% and 86% of the available habitat in the LSF and USF, respectively (Table 4). The 20% greater length of habitat in the LSF is consistent with the 20% greater length of Class I streams, but migration barriers mean that salmon are present in less than 40% of the Class I streams in each watershed. Pools comprise 54% and 47% of the habitat in the LSF and USF, respectively, and the watersheds have very similar mean pool widths and residual depths (Table 4). The primary habitat difference is that the LSF has more than twice as much large woody debris (LWD) as the USF, with about 30% of the LWD being key pieces (Table 4).

There is a very large disparity in mean summer fish populations between the two watersheds, with more than 7200 juvenile salmonids in the LSF as compared to only 2400 in the USF. Coho account for about 97% and 87% of the salmonids in the LSF and USF, respectively, followed by much smaller numbers of steelhead and cutthroat (Table 5). There is no clear trend in the numbers of fish over time, and the detection of any trend is difficult given the interannual coefficient of variation of about 50% for coho (Figure 10) to 80-100% for steelhead and cutthroat.

The mean number of outmigrating fish was 1350 in the LSF and 475 in the USF, or about 20% of the estimated summer populations (Table 4). Again coho were predominant followed by steelhead and cutthroat, and interannual variability is high. The number of outmigrants compared to the summer juvenile populations indicate a mean overwinter survival rate of about 24%, with poorer survival rates following winters with higher peak flows and higher survival rates following winters with lower peak flows.

Table 4. Mean annual values for the habitat surveys, summer fish population by species, and number of outmigrating smolts by species in the Lower South Fork (LSF) and Upper South Fork (USF) from approximately 1998-2018. LWD is large woody debris.

Metric	LSF	USF
Distance surveyed (m)	3,580	2,980
Extent of coho use (m)	3,460	2,560
Number of habitat units	242	224
Proportion of pools (%)	54	47
Mean pool width (m)	3.3	3.2
Mean residual pool depth (m)	0.9	0.8
Mean number of pieces of LWD	1,676	775
LWD keyed in (%)	32	30
Mean number of coho	7050	2110
Mean number of steelhead	104	195
Mean of number of cutthroat	74	110
Mean outmigrating coho	1301	423
Mean outmigrating steelhead	33	38
Mean outmigrating cutthroat	17	14

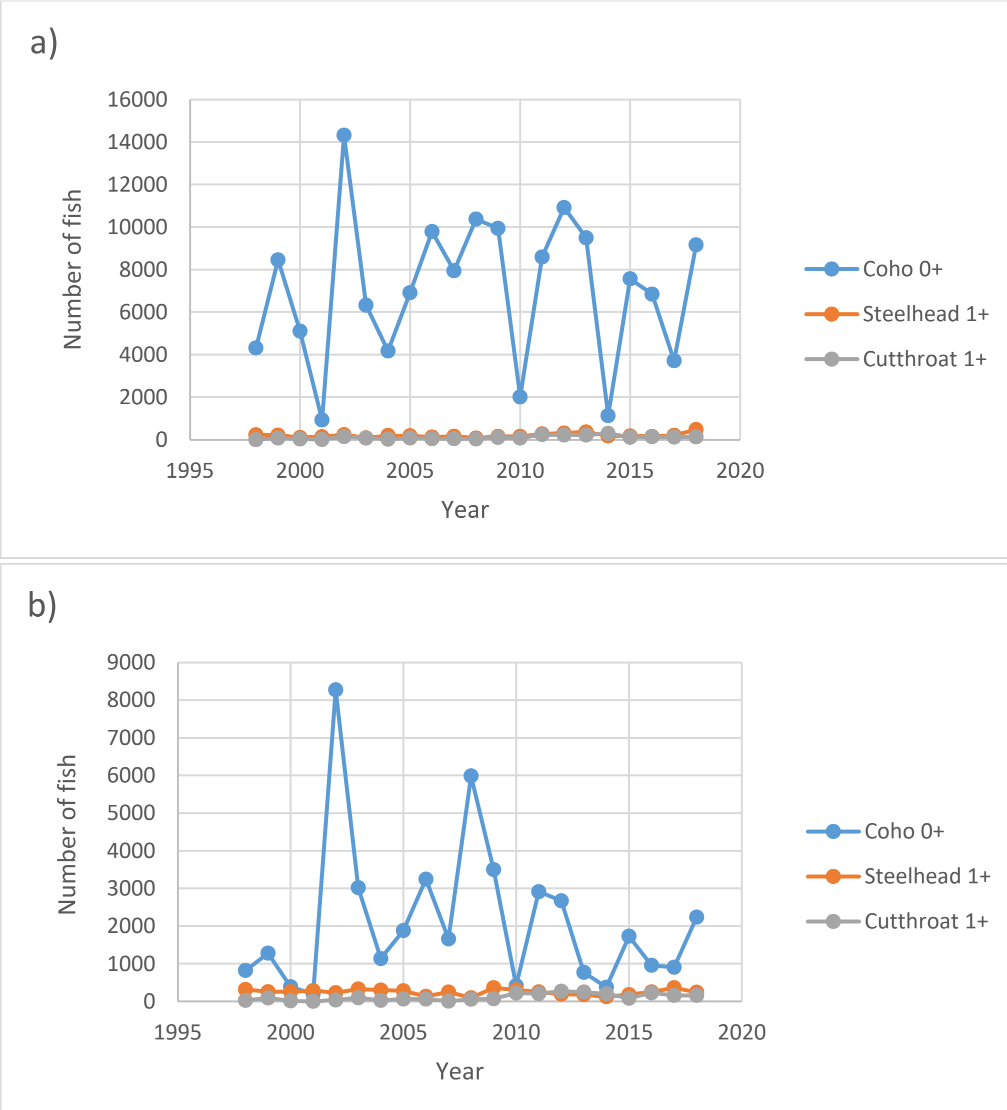


Figure 10. Summer populations of coho, steelhead, and cutthroat from 1998 to 2018 for: a) Lower South Fork; and b) Upper South Fork.

3.6. Long-term Denudation

The calculated long-term denudation rates using a wet weight for vegetative shielding of 100 g cm^{-2} (10,000 Mg ha^{-1}) are 260±76 Mg km^{-2} y^{-1} for the LSF and just 107±31 Mg km^{-2} y^{-1} for the USF (Ferrier et al., 2020). The 2.4-fold difference in long-term denudation rates between the LSF and the USF is nearly identical to the 2.3-fold difference in mean SSY. For both watersheds the long-term denudation rate is nearly three times the short-term mean annual suspended sediment load (89 and 39 Mg km^{-2} yr^{-1}, respectively) (Table 5). The relatively high vegetative shielding value is based on recent biomass data for comparable old-growth redwood forests (Sillett et al., 2020), and this increases the long-term denudation rate by about 35% compared to the value of 4000 Mg ha^{-1} used in Ferrier et al. (2005).

Table 5. Beryllium-10 sampling locations in the Little River watershed with the corresponding watershed areas, mean annual suspended sediment yields in Mg km^{-2} yr^{-1} with years of record in parentheses, and calculated denudation rates in Mg km^{-2} yr^{-1} assuming a vegetative shielding of 10,000 Mg ha^{-1}.

Location	Watershed area (km^2)	Mean annual suspended sediment yield (Mg km^{-2} yr^{-1})	Calculated ^{10}Be denudation rate (Mg km^{-2} yr^{-1})
Entire watershed	112.6	NA	200 ± 62
Carson Creek	9.5	31 (14)	95 ± 29
Railroad Creek	7.1	46 (11)	136 ± 40
Lower South Fork	13.8	89 (14)	260 ± 76
Upper South Fork	14.7	39 (14)	107 ± 31
Upper Basin	39.1	NA	181 ± 53

The long-term denudation rate in the LSF is higher than any of the other five locations in the Little River watershed, and about 30% higher than the calculated rate of 200±62 Mg km^{-2} y^{-1} for the entire watershed (Table 5). In contrast, the USF has a lower long-term denudation rate than most of the other sub-watersheds (Table 5). Mean annual SSY for the four gaged sub-watersheds are tightly related to the long-term denudation rates (Figure 11), and the strength of this relationship lends credence to the validity of the Be-10 values and measured SSYs.

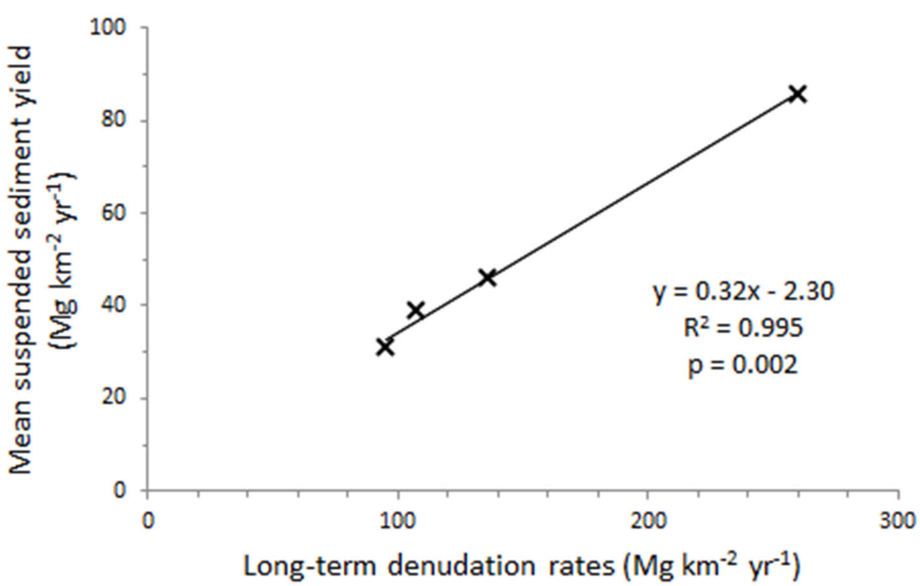


Figure 11. Plot of mean suspended sediment yields against the long-term denudation rates estimated using beryllium-10 for the four gaged Little River sub-watersheds.

4. DISCUSSION

4.1. Differences in Sediment Yields Between the Two Watersheds

It is striking that the mean annual SSY and Be-10 denudation rate in the Lower South Fork are each about 2.3 times the corresponding values in the USF despite their similarity in bedrock geology, soils, precipitation, vegetation, management history, and most topographic indices other than watershed shape. LiDAR analyses confirmed that the two watersheds have a nearly identical frequency distribution of slopes with a relatively steep-sided normal distribution peaking at just under 20 degrees. There is no evidence of either watershed encroaching on the other using chi analysis. Mean slope using a 250-m window indicates that the USF does have a slightly wider variation than the LSF, while the LSF has a slightly wider distribution of excess topography, but neither of these can explain the large differences in SSY and Be-10 denudation rates.

In terms of mass movements, both watersheds have very similar proportions of deep-seated landslides, but these are nearly all dormant-mature and contributing relatively small amounts of sediment. Even though the USF has much lower sediment yields, the USF appears to have substantially more sediment inputs from shallow landslides and bank erosion than the LSF, and this may be due to steeper streamside slopes, especially above the Class 2 streams. Otherwise there are no marked differences in the magnitude of the other sediment sources between the two watersheds.

The primary physiographic difference is watershed shape, as the length/width ratio is about 4 for the long and narrow LSF versus 1.4 for the more dendritic USF. The LSF also has a higher channel steepness index, which is the channel gradient normalized by drainage area, and this follows to some extent from the difference in watershed shape. More importantly, the channel steepness index is strongly correlated to the uplift rate, and uplift is a dominant control on landslide and long-term erosion rates (Larsen and Montgomery, 2012).

Instantaneous annual maximum peak flows in the LSF are about double those in the USF, even though one might expect a dendritic watershed to have a more uniform time of concentration and hence higher peak flows than a long, narrow watershed. This counter-intuitive observation may be explained by the long duration and relatively low intensity of the largest rainstorms in this area, which would allow the trellis shape of the LSF to more quickly and uniformly deliver runoff from all of the short tributaries to the main stem where transit times may well be shorter than in the USF due to the steep main channel and higher flow volumes. During high flows an estimated velocity of 1.5-2 m s^{-1} would allow the surface runoff to traverse the roughly seven kilometers from the top of the main stem in the LSF to the gaging station in only about 60-90 minutes.

The larger peak flows in the LSF could account for much of the difference in SSY, but the LSF also has higher turbidity values and a steeper increase in SSC values for a given turbidity. For FNU values of 25 to 500 the mean annual duration of turbidity levels in the LSF were 33% to nearly 60% higher than in the USF. In addition, the LSF tends to have higher SSC values for a given turbidity. These differences in peak flows, turbidity, and SSC can account for the much higher SSY in the LSF compared to the USF.

The more difficult issue is to provide a physically-based explanation as to why the LSF has much higher peak flows, higher turbidities, and higher SSC than the USF. The long narrow shape and orientation of the LSF strongly suggests that the main stem of the LSF follows an unmapped fault, especially since the northwest-southeast orientation is consistent with most local and regional faults. An unmapped fault along the mainstem of the LSF would cause weaker, more fractured rocks along the valley bottom, and this would increase the sediment yields in the LSF relative to the USF. Sampling of the bedrock along the main channels indicated about a one-class difference in rock strength following the Unified Rock Classification system (Williamson and Kuhn, 1988).

Another possible explanation is that the LSF is in a transient state of adjustment as it has breached an antiform and is now incising into a weaker bedrock layer. This hypothesis is supported by the presence of a knickpoint about halfway up the mainstem, and the highly unusual presence of a very linear ridge immediately to the south of the LSF that is directly in line with the LSF mainstem (Figure 12). We conclude that the differences in geologic conditions and peak flows, which are exemplified by the difference in watershed shape, are the most likely cause of the difference in short- and long-term mean sediment yields.

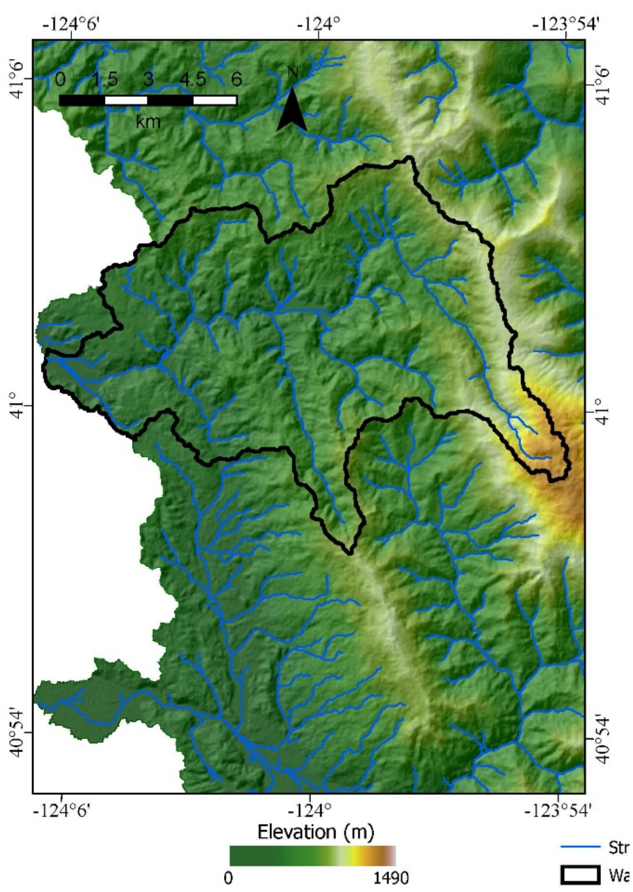


Figure 12. Topographic map of the Little River watershed and areas to the south showing the linear ridge extending south-southeast from the LSF watershed that is directly in line with the mainstem and presumed fault in the LSF.

4.2. Differences Between Short- and Long-term Sediment Yields

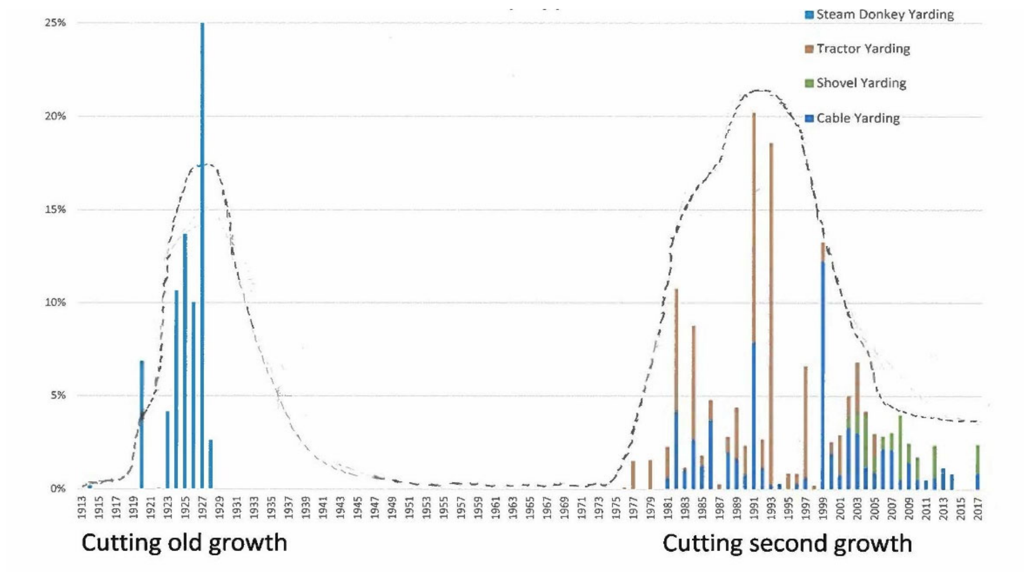
Mean annual suspended sediment yields in each watershed are only about 35% of the calculated long-term denudation rates. This discrepancy is smaller than it initially appears, as the measured SSYs do not include bedload or dissolved load. Bedload can be a substantial portion of the total sediment yields (Andrews and Antweiler, 2011), and at Caspar Creek, which is an analogous set of steep, redwood-dominated experimental watersheds to the south, data from weir ponds indicates that bedload is about 30% of the total suspended sediment load (Richardson et al., 2020). Dissolved load is typically less than 5% of the total mass being lost from a watershed (e.g., Lehre, 1982), so adding estimated bedload and dissolved loads would increase the measured sediment yields to around 120 and 50 Mg ha^{-1} yr^{-1} for the LSF and USF, respectively, or a little under one half of the long-term mean denudation rates.

The validity of using Be-10 concentrations to estimate long-term denudation rates has been questioned, but the Be-10 data for the Little River watershed are believed to be relatively valid for several reasons. First, the relative proportions of the measured SSYs to the Be-10 values are remarkably consistent for each of the four sub-watersheds in Little River despite the nearly three-fold variation in both SSYs and long-term denudation rates (Table 5). When the measured SSYs in the other two gaged Little River watersheds (Figure 1) are adjusted for bedload and dissolved load, the estimated total annual loss is about 45% of the estimated long-term denudation rate of 95±29 Mg km^{-2} y^{-1} for the relatively flat Carson Creek watershed and 45% of the denudation rate of 136±40 Mg km^{-2} y^{-1} for the Railroad Creek watershed (Table 5; Figure 11). Second, the estimated denudation rate for the Upper Basin (Figure 1) of 200±62 Mg km^{-2} y^{-1} is comparable to the values from the four sub-watersheds. Third, the area-weighted denudation rate for these four watersheds, when extrapolated to the entire watershed, is nearly 170 Mg km^{-2} y^{-1}, which is well within the uncertainty of the 200±62 Mg km^{-2} y^{-1} value for the entire watershed. Fourth, a denudation rate of 0.225±0.044 mm y^{-1} was reported for Panther Creek (Ferrier, 2005), which is just east of Little River. Assuming a bedrock bulk density of 2.6 Mg m^{-3} and a vegetative shielding factor of 10,000 Mg ha^{-1}, the long-term denudation rate for Panther Creek is nearly 400±80 Mg km^{-2} y^{-1}, which is within the margin of error for the LSF denudation rate and only moderately outside of the range for the entire Little River watershed.

The final and possibly most important indication of the validity of the Be-10 denudation rates is that the expected uplift rate is around 0.1-0.2 mm y^{-1} (Balco et al., 2013; Fisher et al., 2020). Mean slopes are already close to the expected slope threshold for landslides (Larsen and Montgomery, 2012), so much of the Little River watershed is probably more or less in equilibrium with the uplift rate. Assuming a bedrock density of 2.5 Mg m^{-3}, an uplift rate of 0.1 mm y^{-1} would convert to about 250 Mg km^{-2} y^{-1}, which matches up with the estimated denudation rate of 200±62 Mg km^{-2} y^{-1} for the entire Little River watershed (Table 5).

4.3. Management Implications

The historical data on timber harvest rates, roads, mass movements, management practices, and forest practice rules can be integrated to infer the relative magnitude of sediment inputs over time (Figure 13). The overall pattern of sediment inputs over time for the LSF and USF should be very similar given their comparable management history, with minor differences in the first part of the 1900s due to the later start and more concentrated harvest of old growth in the LSF, and the slightly later intensive road construction and second-growth harvesting in the LSF compared to the USF (Figure 13).



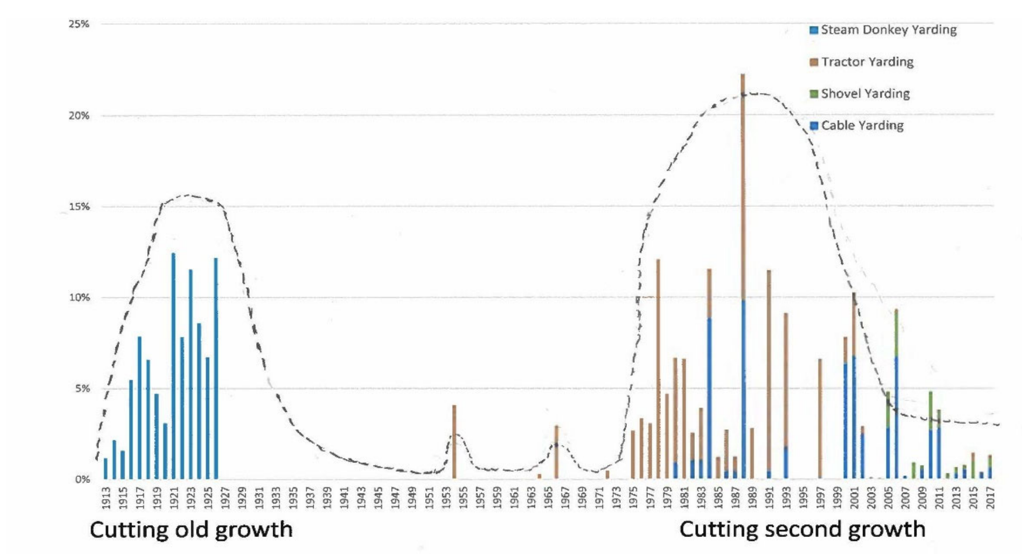


Figure 13. Timber harvest and hypothesized management-related sediment inputs over time for the LSF (above) and USF (below). No scale is provided for the estimated sediment inputs as they are on more of a relative than absolute scale.

Little information is available on the effects of the old growth harvesting in Little River, but in Redwood Creek sediment inputs from old growth logging are believed to be less than the sediment inputs from the tractor logging and extensive road network in the 1960s and early

1970s (e.g., Janda et al., 1975; Weaver et al., 1995). In contrast to Redwood Creek, rapid second growth logging only started in about 1975 in the USF and 1982 in the LSF, and this was when forest practice rules began to be implemented. Discussions with long-term foresters suggest that initially these rules did not greatly affect forest management operations, in part because these cool coastal watersheds could claim an exemption from the streamside shade retention requirements (G. Templeton, GDRCo, pers. comm.).

From 1983-1991 about 80% of each watershed was harvested, with about 60% of this being tractor logging and 40% cable logging (Table 2). From 1983 there were progressively more restrictions on logging in buffer strips, and road crossings were more regularly rocked (Table 3). The timing of the second-growth harvest and road construction, when combined with the extent of cable logging, would suggest lower sediment inputs in the two study watersheds compared to the relatively severe erosion and sedimentation in Redwood Creek in the 1960s and 1970s. This would be especially true in the LSF where the intensive second growth harvesting began about seven years later than in the USF, and peak second-growth harvest occurred in 1991-93 as compared to 1988 in the USF (Figure 13).

In the late 1990s the amount of ground-based logging dropped off, there were more stringent buffer strips and other forest practice rules, and rapid improvements began to be made to the road network in terms of extensive rocking, increasing culvert sizes, improving road drainage to disconnect the roads from the streams, decommissioning unneeded road sections, and restricting winter hauling (Section 3.2, Table 3). By the time stream gaging began in October 2003 timber harvest rates had declined, much of the logging was being done with either shovel logging or cable yarding, and the majority of the road network had been improved. From 2007-2017 only about 20% of each watershed was harvested, and this was done with shovel and cable logging rather than tractor logging.

These data lead us to hypothesize a relatively sharp decline in management related-sediment inputs in the 1990s, and declines in sediment yields over time also have been reported for Redwood Creek (Klein and Anderson, 2012). The gaging station data from the LSF and USF do not show a decline in suspended sediment yields as harvest rates continued to decline through 2017, indicating the lack of a legacy effect and that the improved practices have largely decoupled a direct linkage between harvest rates and suspended sediment yields. Field observations, the LiDAR data, and aerial photos all indicate that sediment inputs from current management are very low. Harvest units have minimal amounts of bare or disturbed soil, and there is virtually no evidence of surface flow paths from harvest units to streams. Results from GRAIP-Lite modeling indicate that roads are projected to contribute less than 10% and 25% of the mean measured SSYs in the LSF and USF, respectively. As mentioned earlier, the streams clear rapidly after a rainstorm, indicating no persistent bank, channel, or road erosion. There also is no trend in fish populations. The bed material particle sizes and channel cross-sections in the main stem of Little River above and below the study watersheds show no trends in time or space, suggesting no larger-scale legacy effects or sediment deposition. The implication is that large amounts of sediment were not deposited in the valley bottoms, contrary to other watersheds like Redwood Creek (Janda et al., 1975; Weaver et al., 1995) or Railroad Gulch in the Elk River watershed (Stubblefield et al., 2021). A larger-scale assessment of forest management effects on GDRCo lands noted that streams are generally downcutting and becoming narrower, indicating reduced sediment inputs over time as forest practices have changed (House et al., 2012). For the LSF and USF the roughly two-fold gap between the long-term and estimated total current sediment yields further indicate that management activities are not causing large amounts of erosion or high suspended sediment yields.

A key issue is the importance of shallow rapid landslides (SRL) as both a natural and management-related sediment source. SRLs are by far the largest sediment source identified in this study, but field observations, aerial photos, and the LiDAR data all indicate very few recent SRLs. The timing of the second-growth harvest shows a sharp peak from around 1980-2000, and timber harvest can increase SRLs from about 3-15 years after harvest due to the loss of root strength and wetter soils due to decreased evapotranspiration (Sidle and Ochiai, 2006). The high rates of clearcutting in 1983-1991 would have made both watersheds particularly susceptible to SRLs from the late 1990s through about 2010, and to a lesser extent after 2010. Flow data from the mouth of Little River show that four of the seven highest flows over the 64-year record in the Little River watershed occurred in water years 1996, 1997, 1999, and 2003, which is close to the minimum root strength postulated for other timber species (Sidle and Wu, 2001). The first three of these flows also occurred before most of the roads had been upgraded, yet there is no indication that these wet years induced large numbers or volumes of management-related landslides.

Most of the SRLs in the two study watersheds were not related to roads or harvest units, indicating that the relatively high sediment inputs from SRLs are primarily due to natural causes. Annual sediment yields typically follow a strongly log-normal distribution, so the mode is far less than the mean and most years are relatively benign in terms of sediment inputs (e.g., Kirchner et al., 2001) and by inference the number of SRLs. The study area is clearly subject to periodic magnitude eight or larger earthquakes as well as exceptionally wet periods driven by atmospheric rivers, and the mean slopes are relatively high. Hence our working hypothesis is that the long-term uplift in the study area, when combined with large earthquakes and wet years, leads to very sporadic occurrences of large numbers of SRLs as documented in other tectonically active regions like the Himalayas, Chile, and Taiwan (e.g., Larsen and Montgomery, 2012). Rare but extreme inputs of sediment from SRLs can explain the large gap between the measured landslide rates and suspended sediment loads compared to the much larger long-term denudation rates as indicated by the Be-10 data.

Another potential management-related sediment input is the bank erosion and channel scour resulting from an increase in the size and frequency of peak flows (Cafferata and Reid, 2013). In the absence of a detectable legacy effect, the question is whether current management is substantially increasing the size of peak flows and hence channel scour and sediment transport. Over the first several years of stream gaging the mean annual harvest averaged over 4% per year (Table 2). From 2007-2017 the total harvested area was only about 20% of each watershed or less than 2% per year. Data from western Oregon and other areas have shown that about 30% of a watershed needs to be harvested over just a couple of years in order to trigger a detectable increase on the size and frequency of peak flows (e.g., Grant et al., 2008). The relatively low rate of road-stream connectivity and limited amounts of timber harvest since 2007 suggest that current management is having a non-detectable effect on the size and frequency of peak flows. Bank erosion is the second largest sediment source in the USF but a much smaller source in the LSF, but field observations indicate that most of the bank erosion is occurring at the toes of DSL or flow deflections by LWD. The implication is that bank erosion is resulting from natural processes and part of the background sediment inputs rather than being induced by management.

A repeated measures analysis could be conducted to try and determine the relationships between key independent variables such as harvest rates, estimated precipitation, and changes in the road network with different dependent variables relating to turbidity, SS concentrations, SSYs, fish numbers, and fish condition. The problem with this approach is that there is only a relatively small range of management activities and projected impacts for the period with measured streamflow and sediment yields, and the limited variability in the dependent variables will limit the power and reliability of a repeated measures analysis.

It should be noted that the relative absence of legacy and current management effects in the LSF and USF may not necessarily be true for other watersheds in the redwood region that have been subjected to intensive forest management. The Little River Hydrographic Planning Area (HPA) has the lowest landslide erosion rate relative to the other nine HPAs identified by GDRCo (GDRCo, 2016). This lower rate may be attributed to a more competent geology, suggesting that the two study watersheds may be less susceptible to management-induced landslides than watersheds with less competent geology or higher uplift rates. In theory the lower rate of landslides in the study watersheds should make it easier to detect increased sediment inputs from surface erosion sources, such as roads and harvest units. In watersheds with less competent rock types and higher rates of landsliding there would be a greater potential for management-induced increases in SRLs, but this might make it more difficult to extract out the signal from increased surface erosion. Large legacy effects have been postulated for Redwood Creek and the Railroad Gulch sub-watersheds in the Elk River (Stubblefield et al., 2021), which could result in a very different pattern over time in management-related sediment inputs than those postulated in Figure 13.

5. CONCLUSIONS

The primary goal of this study was to compare long-term denudation rates derived from beryllium-10 concentrations to erosion and sediment yields from historic logging and current forest management activities. The study was conducted in two adjacent watersheds in the coast redwood region in northwestern California that have been managed for timber production. The two watersheds are very similar in their characteristics and management history except the 13.8 km^2 Lower South Fork (LSF) is long and narrow and the 14.7 km^2 Upper South Fork (USF) is more dendritic. Ninety-two percent of the old growth in each watershed was harvested from 1913-1928 using railroads and steam donkeys. Road construction and second growth logging—primarily by tractors—commenced in the 1970s. The most intensive logging took place from the late 1970s through the 1990s, which coincided with the development of increasingly strict forest practice regulations governing clearcut size, the extent and protection of buffer strips, and road design and management. Stream gaging began in the early 2000s as tractor logging was largely eliminated in favor of cable and shovel logging, and logging rates dropped to less than 2% of the watershed area per year. The early tractor logging is believed to have generated the highest erosion rates, but there is no evidence of either the old growth or second growth logging causing persistent legacy effects in terms of sediment deposition in the stream channels or valley bottoms. Mean annual suspended sediment yields are 89 and 39 Mg km^{-2} yr^{-1} in the LSF and USF, respectively, and there is no trend in the size of peak flows or annual sediment yields, which again indicates the lack of any legacy effect from past logging.

Shallow rapid landslides are the predominant sediment source, delivering an estimated 70 and 110 Mg km^{-2} yr^{-1} to the stream network in the LSF and USF, respectively. Most of this material is relatively coarse, so the delivery of particles smaller than fine gravel is estimated to be only 23 and 7 Mg km^{-2} yr^{-1} in the LSF and USF, respectively. Aerial photos and field surveys indicate that no more than one-third of the landslides can be related to timber harvest units or roads. Deep-seated landslides occupy about 10% of the watershed area but are almost entirely dormant-young, and the estimated sediment input from these is just over 10 Mg km^{-2} yr^{-1}. There is no visual evidence of surface erosion or sediment transport to streams from harvest units, whereas roads are estimated to deliver 7-10 Mg km^{-2} yr^{-1} to the streams and watershed outlets. Bank erosion is estimated to be less than 3 Mg km^{-2} yr^{-1} in the LSF and about 10 Mg km^{-2} yr^{-1} in the USF.

Long-term denudation rates are 260±76 Mg km^{-2} yr^{-1} in the LSF and 107±31 Mg km^{-2} yr^{-1} in the USF, or more than double the estimated total sediment yields. This large difference helps confirm that current management activities are not greatly increasing sediment yields. The much higher long-term and suspended sediment yields in the LSF compared to the USF are attributed to higher peak flows, a higher channel steepness index, and incision into weaker bedrock along an unmapped fault running the length of the LSF. The lack of any apparent legacy effects of past management and the relatively low sediment yields in these two watersheds may not apply to watersheds that have higher uplift rates, less competent geologies, and were subjected to intensive tractor logging prior to the implementation of forest practice rules.

6. REFERENCES

ASTM, 2011. Standard classification of soils for engineering purposes (unified soil classification system). In *Annual Book of ASTM Standards* 4: 206-215. American Society for Testing and Materials.

Andrews, E.D. and R.C. Antweiler, 2012. Sediment fluxes from California coastal rivers: The influences of climate, geology, and topography. *The Journal of Geology* 120(4): 349-366.

Balco, G., N. Finnegan, A. Gendaszek, J.O.H. Stone, and N. Thompson, 2013. Erosional response to northward-propagating crustal thickening in the coastal ranges of the U.S. Pacific Northwest. *American Journal of Science* 313: 790-806.

Bierman, P. and E. Steig, 1996. Estimating rates of denudation using cosmogenic isotope abundances in sediment. *Earth Surface Processes and Landforms* 21: 125 – 139.

Bjorkstedt, E.P., 2005. DARR 2.0: updated software for estimating abundance from stratified mark-recapture data. NOAA Technical Memorandum NMFS-SWFSC-368. 13 p.

Cafferata, P.H. and L.M. Reid, 2013. Applications of long-term watershed research to forest management in California: 50 years of learning from the Caspar Creek experimental watersheds. California Forestry Report No. 5, Dept. of Forestry & Fire Protection, State of California, 110 pp.

Dawson, T. 1998. Fog in the California redwood forest: ecosystem inputs and use by plants. *Oecologia* 117: 476–485. https://doi.org/10.1007/s004420050683

Egan, A., R. Hicks, and J. Skousen. 2002. Effects of shovel logging and rubber-tired skidding on surface soil attributes in a selectively harvested central hardwood stand. *International Journal of Forest Engineering* 13(1): 27-32.

Ferrier, K.L., J.W. Kirchner, and R.C. Finkel, 2005. Erosion rates over millennial and decadal timescales at Caspar Creek and Redwood Creek, Northern California Coast Ranges. *Earth Surface Processes and Landforms* 30: 1025 – 1038. DOI: 10.1002/esp.1260

Ferrier, K.L., L.H. MacDonald, P. Belmont, and K.Hu, 2020. 10 Be concentrations in stream sediment and inferred denudation rates in the Little River and Elk River basins, northern California Coast Ranges. *Hydrosphere*.

Fisher, A., P. Belmont, B.P. Murphy, L. MacDonald, K.L. Ferrier, and K. Hu, 2020. Natural and anthropogenic controls on sediment rating curves in Northern California coastal watersheds. *Earth Surface Processes and Landforms*.

GDRCo, 2016. Preliminary mass wasting assessment submitted to National Marine Fisheries Service and United States Fish and Wildlife Surface. 39 pp.

Granger, D.E., J.W. Kirchner, and R. Finkel, 1996. Spatially averaged long-term erosion rates measured from in situ-produced cosmogenic isotopes. *J. of Geology* 104(3): 249-257.

Grant, G.E., S.L. Lewis, F. J. Swanson, J.H. Cissel, and J.J. McDonnell, 2008. Effects of forest practices on peak flows and consequent channel response: a state-of-the-science report for western Oregon and Washington. General Technical Report PNW-GTR-760, USDA Forest Service, 59 pp.

House, M., R. Bourque, and D. Lamphear, 2012. Review of Green Diamond Resource Company's timber harvest operations and forest management activities as they relate to rate of harvest and cumulative watershed effects. Green Diamond Resource Company Final Report, Blue Lake, CA. 66 p.

Imaizumi, F., R.C. Sidle, and R. Kamei, 2008. Effects of forest harvesting on the occurrence of landslides and debris flows in steep terrain of central Japan. *Earth Surface Processes and Landforms* 33(6): 827-840.

Janda, R.J., K. Nolan, D.R. Harden, and S.M. Colman, 1975. Watershed conditions in the drainage basin of Redwood Creek, Humboldt County, California. USGS Open-File Report 75-568, 243 pp.

Keaton, J. R. and J. V. DeGraff. 1996. "Surface Observation and Geologic Mapping," in Transportation Research Board Special Report 247: Landslides. Investigation and Mitigation. pp. 178-228. Washington D.C.: National Academy Press.

Kelsey, Harvey M., 1978. Earthflows in Franciscan melange, Van Duzen River basin, California. *Geology* 6.6: 361-364.

Kilbourne, R. 1985. Geology and Geomorphic Features Related to Landsliding, McWhinney Creek 7.5-Minute Quadrangle, Humboldt County, California. (OFR 85-3 SF). NR: CDMG

Kirchner, J.W., R.C. Finkel, C.S. Riebe, D.E. Granger, J.L. Clayton, J.G. King, and W.F. Megahan, 2001. Mountain erosion over 10 yr, 10 ky, and 10 my time scales. *Geology* 29(7): 591-594.

Klein, R.D., and J.K. Anderson, 2012. Declining sediment loads from Redwood Creek and the Klamath River, north coastal California. In *Proceedings of coast redwood forests in a changing California: A symposium for scientists and managers.* USDA Forest Service Gen. Tech. Rep. PSW-GTR-238, Pacific Southwest Research Station, Albany, CA, pp. 79-88.

Lal, D., 1991. Cosmic ray labeling of erosion surfaces: in situ nuclide production rates and erosion models. *Earth and Planetary Science Letters* 104(2-4): 424 – 439. https://doi.org/10.1016/0012-821X(91)90220-C

Larsen, I.J. and Montgomery, D.R., 2012. Landslide erosion coupled to tectonics and river incision. *Nature Geoscience* 5(7): 468-473.

Lehre, A.K. 1982. Sediment budget of a small coast range drainage basin in north-central California. Pp. 67-77 in: F.J. Swanson, R.J. Janda, T. Dunne, D.N. Swanston, tech. eds. Workshop on Sediment Budgets and Routing in Forested Drainage Basins: Proceedings. Gen. Tech. Rep. PNW-141. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station.

Lewis, J., and R. Eads, 2009. Implementation guide for turbidity threshold sampling: principles, procedures, and analysis. General Technical Report PSW-GTR-212, U.S. Dept. of Agriculture Forest Service, Albany, CA. 551 pp.

Mohr, M.S. and D.G. Hankin, 2005. Two-phase survey designs for estimation of fish abundance in small streams. Unpublished report, Department of Fisheries Biology, Humboldt State University, Arcata, CA.

Mudd, S.M., M.A. Harel, M.D. Hurst, S.W. Grieve, and S.M. Marrero, 2016. The CAIRN method: automated, reproducible calculation of catchment-averaged denudation rates from cosmogenic nuclide concentrations. *Earth Surface Dynamics* 4(3): 655-674.

Nelson, N., C. Luce, and T. Black, 2019. GRAIP_Lite: A system for road impact assessment. U.S. Dept. of Agriculture, Forest Service, Rocky Mountain Research Station, Boise, ID. 145 pp.

NRMC, 2000. A retrospective of the Little River watershed. Report prepared by the Natural Resource Management Corporation, Eureka, CA. 136 pp. plus appendices.

PWA, 2001. Summary report: 2000 S.B. 271 watershed assessment and erosion prevention planning project for the Little River Watershed, Humboldt County, California. Pacific Watershed Associates, Arcata, CA.

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

Richardson, P.W., Wagenbrenner, J.W., Sutherland, D.G. and Lisle, T.E., 2020. Measuring and modeling gravel transport at Caspar Creek, CA, to detect changes in sediment supply, storage, and transport efficiency. *Water Resources Research* 56(6), p.e2019WR026389.

Roering, J.J., et al., 2015. Beyond the angle of repose: A review and synthesis of landslide processes in response to rapid uplift, Eel River, Northern California. *Geomorphology* 236: 109-131.

Sidle, R.C., and H. Ochiai, 2006. Landslides: processes, prediction, and land use. Water Resources Monograph 18, American Geophysical Union, Washington, D.C., 312 pp.

Sidle, R.C., and W. Wu, 2001. Evaluation of the temporal and spatial impacts of timber harvesting on landslide occurrence. Pp. 179-193 in M.S. Wigmosta and S.J. Burges (eds.) *Land Use and Watersheds: Human Influence on Hydrology and Geomorphology in Urban and Forest Areas*. Water Science and Application Volume 2, American Geophysical Union, Washington, D.C.

Sillett, S.C., R. Van Pelt, A. L. Carroll, J. Campbell-Spickler, and M.E. Antoine, 2020. Aboveground biomass dynamics and growth efficiency of *Sequoia sempervirens* forests. *Forest Ecology and Management* 458: 117740.

Weaver, W.E., D.K. Hagans, and J.H. Popenoe. 1995. Magnitude and causes of gully erosion in the lower Redwood Creek basin, northwestern California. Pp. 1-21 in: Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin, Northwestern California. K.M. Nolan, H.M. Kelsey, an D.C. Marron, eds., U.S. Geological Survey Professional Paper 1454. Washington, DC: US Government Printing Office. http://www.krisweb.com/biblio/redwood_usgs_weaveretal_1995_1454i.pdf

Wieczorek, G.F., 1984. Preparing a detailed landslide-inventory map for hazard evaluation and reduction. *Environmental and Engineering Geoscience* 21 (3): 337–342. https://doi.org/10.2113/gseegeosci.xxi.3.337

Williamson, D.A., and C.R. Kuhn, 1988. The Unified Rock Classification System. In *Rock Classification Systems for Engineering Purposes*, American Society for Testing Materials, pp. 7-16.