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APPLICATIONS OF LONG-TERM WATERSHED RESEARCH TO FOREST MANAGEMENT IN CALIFORNIA: 50 YEARS OF LEARNING FROM THE CASPAR CREEK EXPERIMENTAL WATERSHEDS

California Forestry
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North Fork Caspar Creek weir, summer 2010

Retired USFS PSW Watershed Project Leaders for Caspar Creek Research

(not pictured: Bob Crouse and Sam Krammes)

Dr. Ray Rice
(retired 1989)

Dr. Bob Ziemer
(retired 2002)

Dr. Tom Lisle
(retired 2010)

Retired CDF/CAL FIRE Jackson Demonstration State Forest and Soil Erosion Studies Project Leaders

(not pictured: retired JDSF Forest Managers Jean Sindel and Hal Slack)

Dave Burns, JDSF Assistant Forest Manager 1962-1968 (left)
Forest Tilley, JDSF Forest Manager 1978-1992
Norm Henry, JDSF Research and Demonstration Program Manager 1973-2000

Marc Jameson
JDSF Forest Manager
1998-2009

John Munn
Soil Erosion Studies Project Manager
1984-2009

Executive Summary

For over 50 years, the Caspar Creek Experimental Watersheds, located in western Mendocino County, California, have been the site of long-term cooperative watershed research carried out by the U.S. Forest Service Pacific Southwest Research Station (PSW) and the California Department of Forestry and Fire Protection (CAL FIRE). Preliminary stream flow, suspended sediment, and rainfall measurements began on October 1, 1961. Monitoring has continued nearly uninterrupted since then, making the research site one of the few in the United States with hydrologic records spanning this length of time. This report summarizes results of the first 50 years of studies at Caspar Creek.

Two major watershed experiments have been carried out at Caspar Creek to study the hydrologic effects of second-growth harvesting of coast redwood and Douglas-fir forests. The first experiment focused on the 424-ha (1,048-ac) South Fork Caspar Creek watershed. After five years of pre-treatment monitoring to establish calibrations to the North Fork control watershed, a riparian road was constructed along the South Fork channel in 1967. The effects of road construction were monitored for four years before the watershed was selection logged and tractor-yarded during the early 1970's. The practices used were typical for that time, which was just before implementation of the modern California Forest Practice Rules.

The second experiment employed a different silvicultural strategy and a different experimental design. In this study, sub-watersheds within the 473 ha (1,169 ac) North Fork Caspar Creek watershed provided the controls, and pre-treatment monitoring was carried out between 1985 and 1989 at 13 gaging stations. Sub-watersheds in the North Fork were then clearcut from 1985 to 1992, predominantly using skyline cable yarding from roads located high on ridges.

Key findings from the South Fork and North Fork experiments address topics often of concern to California resource professionals, including the effects of logging on peak flows, summer low flows, annual water yields, sediment yields, surface erosion, channel erosion, gullies, landslides, hillslope hydrology, stream temperature, fog drip, nutrient cycling, and biological responses. Study results have quantified the effects of forest management activities on these watershed characteristics, and have allowed the influences of clearcutting and selection logging to be compared for many of them. Results have also shown how different kinds of influences can interact and contribute to cumulative watershed effects on downstream habitats. As a by-product, the studies have led to significant advances in monitoring technology, and turbidity monitoring procedures developed at Caspar Creek are now being used at sites throughout the world. Examples of key research findings include:

- Peak flows increased after both selection and clearcut logging.
- Low flows initially increased after both selection and clearcut logging, but summer flows rapidly declined after selection logging to below pretreatment levels while the decline after clearcutting was more gradual.
- Wood inputs to the North Fork channel increased after clearcutting due to blow-down in Watercourse and Lake Protection Zones (WLPZs; these are buffer strips designed to meet the standards of the California Forest Practice Rules).
- Increases in sediment load were greater after tractor-yarded selection logging in the South Fork than after cable-yarded clearcutting in the North Fork.

- After initial trends toward recovery in sediment load following logging, loads once again increased due to deterioration of old riparian roads in the South Fork and due to increased flows associated with pre-commercial thinning in the North Fork.
- After logging, the main sediment sources are large landslides and increased in-channel erosion caused by higher flows.
- Road construction across a headwater swale, followed by clearcutting, caused large increases in the pore pressure at and above the road.
- Reduced fog drip was not an important influence on stream flows after North Fork logging.
- Nitrate concentrations increased in streams after clearcutting, but fluxes were relatively low.
- The effects of old-growth logging of the late 1800's remain important: after North Fork logging, 29% of the sediment volume from streamside landslides originated from legacy sources, and old-growth logging appears to have produced lasting channel impacts.

Results from the Caspar Creek experiments have been applied to address numerous forestry-related issues in California and elsewhere. Registered Professional Foresters (RPFs) commonly use Caspar Creek results to aid in evaluating the potential impacts of Timber Harvesting Plans (THPs) and other types of projects that require approval by government agencies for commercial timber harvesting operations in the Coast Ranges of California.

This report concludes with a series of appendices that illustrate potential applications of Caspar Creek experimental results to specific topics often addressed in forestry-related plans. Appendix A describes a method that has been in use for over a decade for predicting changes in peak flows in second-growth coast redwood and Douglas-fir forests. Appendix B outlines an approach currently being developed for estimating the change in late summer flow that results from one or more selection logging entries. Appendix C shows how available suspended sediment data could be used to estimate logging-related changes in sediment inputs from in-channel sources such as bank erosion and channel incision. Appendix D illustrates how Caspar Creek data can be used to test the applicability of existing methods by using data from a North Fork tributary basin to evaluate flow estimation approaches commonly used for sizing watercourse crossings. Finally, Appendix E uses Caspar Creek flow data to calibrate and validate a specific flow prediction method.

Research at Caspar Creek continues. Preparation for a third major experiment in the South Fork began in 2000 with the establishment of 10 new gaging stations, and an initial road decommissioning treatment was completed in the fall of 2011. Future treatments will permit evaluation of interactions between the effects of watershed rehabilitation activities and impacts associated with modern timber operations. A 100-year Memorandum of Understanding was signed in 1999 by PSW and CAL FIRE, providing for continuation of the cooperative Caspar Creek project throughout this century and ensuring that the Caspar Creek Experimental Watersheds will continue to provide lessons for the benefit of all.

APPLICATIONS OF LONG-TERM WATERSHED RESEARCH TO FOREST MANAGEMENT IN CALIFORNIA: 50 YEARS OF LEARNING FROM THE CASPAR CREEK EXPERIMENTAL WATERSHEDS

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North Fork Caspar Creek watershed in 1991

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The original plan for the Caspar Creek study (presented by W. Hopkins and K.L. Bowden in the "First Progress Report, 1961-62, Cooperative Watershed Management Research in the Lower Conifer Zone of California"):

A STUDY OF LOGGING EFFECTS UPON
STREAMFLOW, SEDIMENTATION, FISH LIFE AND FISH HABITAT
IN THE NORTH COAST REDWOOD-DOUGLAS-FIR FOREST TYPE

JACKSON STATE FOREST, FORT BRAGG, CALIFORNIA
(STUDY N0. 2-1).

Two experimental watersheds in second growth Redwood-Douglas-fir forest type have been established on the Jackson State Forest which is under the intensive management of the California Division of Forestry.

Objectives

Essentially no quantitative data exist on the comparative performance of logged and unlogged watersheds in the North Coast Region. Fundamental to good management, answers are needed for such questions as:

1. What is the water and sediment production of North Coast watersheds which have been undisturbed for many years?
2. How are water yield, water quality, flood peaks, and stream sedimentation affected when road building and logging practices are designed to minimize excessive runoff and erosion?
3. What changes take place in the channel following logging and what effect do these changes have upon fish life and upon the stream as a habitat for fish?

I. INTRODUCTION

On October 1, 1961, preliminary measurements of stream flow, suspended sediment, and rainfall began at several sites in the Caspar Creek watershed, located in Jackson Demonstration State Forest (JDSF) in western Mendocino County. Gaging weirs were constructed the following summer, and measurements for a major watershed experiment formally began in the fall of 1962. Thus began a research partnership between the U.S. Forest Service Pacific Southwest Research Station (PSW) and the California Department of Forestry and Fire Protection (CAL FIRE) that has so far spanned 50 years. Two major watershed studies have now been carried out in the Caspar Creek Experimental Watersheds, and the initial stage of a third watershed-scale experiment is currently in progress. In each case, the goal has been to better understand interactions between forest management and watershed processes.

The Caspar Creek watersheds are the only long-term experimental watersheds in the coast redwood vegetation type, and are among the few throughout the United States with continuous records of streamflow and sediment that span half a century (Ziemer and Ryan 2000). The Caspar Creek experimental design includes maintenance of long-term control watersheds forested by untreated second-growth stands, an important attribute in an era when most forest management is focused on stands that have already sustained at least one prior logging entry. Additionally, Caspar Creek is one of the few sites that have provided flow and sediment data from a series of nested watersheds, allowing watershed responses to be observed at a progression of watershed scales (Ziemer 2004).

For all of these reasons, as well as for the kinds of questions addressed by the research, results from the Caspar Creek study continue to be of considerable interest to private landowners, state and federal land-management and regulatory agencies, non-governmental organizations (NGOs), and the public. Lessons learned from the Caspar Creek experiments have been applied to address numerous forestry-related issues in the Coast Ranges of California and elsewhere.

Four kinds of information from the Caspar Creek studies are regularly applied. First, long-term monitoring provides data that can be used to characterize flow, sediment, and temperature conditions in the region, facilitating such activities as design of in-stream flow requirements and sediment mitigations. Second, results of the watershed-scale experiments demonstrate the effects of tractor-yarded selection logging and cable-yarded clearcutting on a watershed's sediment yield and runoff, providing the kinds of data useful for designing and modifying California's forest practice rules and best management practices (BMPs). Third, process-based studies provide topical information that can be used to resolve particular problems or to understand the basis for certain kinds of environmental responses. Finally, monitoring technology designed and tested during the Caspar Creek study has now been employed at variety of other sites, reducing sediment monitoring costs and improving data quality. A bibliography of published research conducted at Caspar Creek and access to Caspar Creek data are available at the Caspar Creek website: http://www.fs.fed.us/psw/topics/water/caspar/.

The goals of this report are to (1) briefly summarize key results of Caspar Creek research from the past 50 years, and (2) describe how Registered Professional Foresters (RPFs) and other resource professionals can use Caspar Creek research results to aid planning of projects in the northern and central parts of the Coast Ranges of California. Examples of applications are provided in appendices.

II. THE CASPAR CREEK EXPERIMENTAL WATERSHEDS

Site Description

The Caspar Creek Experimental Watersheds (Figure 1) are located approximately 7 km (4 mi) inland from the Pacific Ocean and 10 km (6 mi) south of Fort Bragg, California. The Caspar Creek basin drains 2,170 ha (5,362 ac), of which 1,958 ha (4,838 ac) are located in the Jackson Demonstration State Forest and support watershed and silvicultural research. The study area includes two major gaged watersheds, the 473-ha (1,169 ac) North Fork (Figure 2) and 424-ha (1,048 ac) South Fork watersheds of Caspar Creek, each drained by a 4^{th}-order channel (Figure 3).

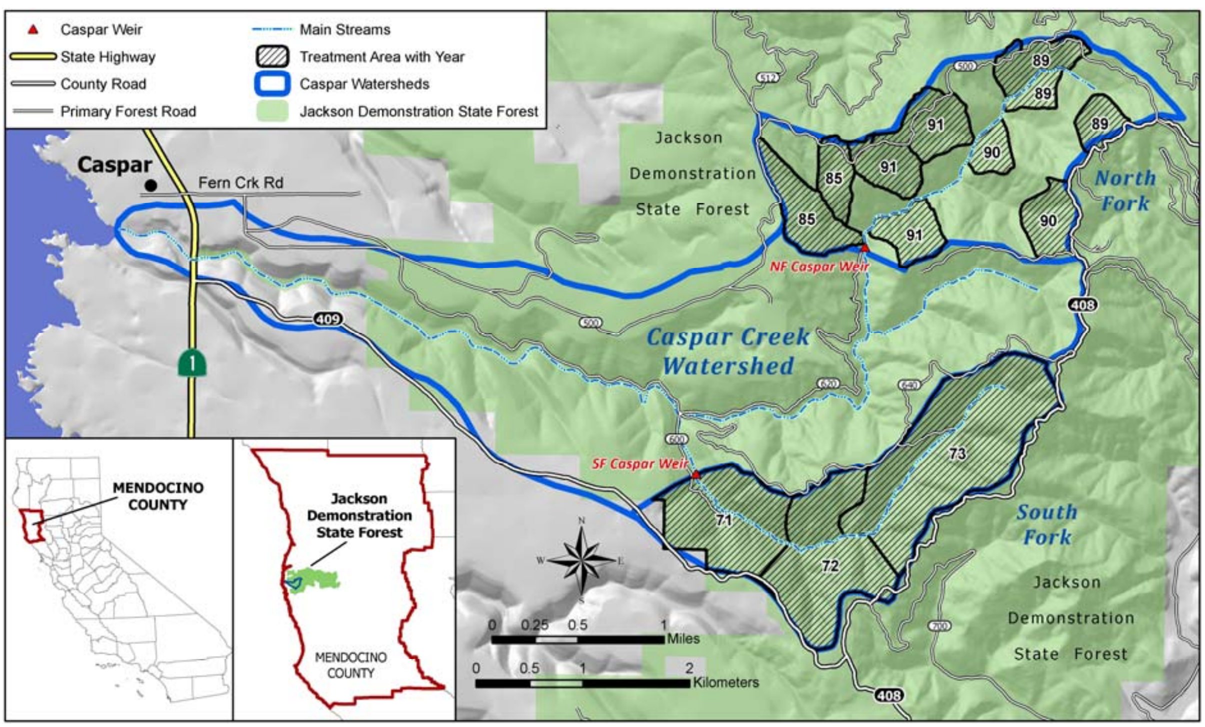

Figure 1. The Caspar Creek Experimental Watersheds. Numbers indicate the year when logging began. Logging and yarding continued into the following calendar year in some North Fork units.

The watersheds are underlain by marine sandstone and shale of late Cretaceous to early Cenozoic age and are incised into Pleistocene marine terraces; elevations range from 37 to 320 m (120 to 1,050 ft). Soils are 0.5 to 2 m (1.6 to 7 ft) deep and are well-drained, with textures ranging from loams and sandy loams to very gravelly loams (Rittiman and Thorson 2006).

Figure 2. View to the southeast across the North Fork Caspar Creek watershed in 2005 (tributary watersheds EAG and DOL are in the center of the view; CAR is in the foreground).

Figure 3. The South Fork Caspar Creek channel.

Winters are mild and snow is not hydrologically significant. Approximately 95% of the average annual precipitation of 1,170 mm (46 in) falls between October and April, and many tributaries stop flowing during the summer. About half of the incoming precipitation runs off as stream flow (Keppeler et al. 2009). During the summer, frequent coastal fog extends far enough inland to moderate air temperature in the watersheds.

Old-growth trees in the Caspar Creek watershed were logged from the mid-1860's to 1904. Boles were bucked on site and transported to a mill located at the mouth of Caspar Creek, first using oxen (Figure 4) and splash dams, and later steam donkeys and railroad inclines (Napolitano et al. 1989). The majority of the North Fork watershed was harvested approximately 15 years later than the South Fork. Other than some minor pole cutting that occurred during the World War II era, little or no disturbance occurred from 1905 to 1966 in either the North or South Fork (Tilley and Rice 1977).

The dominant conifer species present in the second- and third-growth stands (Figure 5) are coast redwood (*Sequoia sempervirens*) and Douglas-fir (*Pseudotsuga menziesii*), with lesser amounts of grand fir (*Abies grandis*) and western hemlock (*Tsuga heterophylla*), and a minor component of Bishop pine (*Pinus muricata*) near the coast. The main hardwood species present is tanoak (*Lithocarpus densiflorus*), with red alder (*Alnus rubrus*) found mainly in the South Fork riparian stand. Evergreen huckleberry (*Vaccinum ovatum*), Pacific rhododendron (*Rhododendron macrophyllum*), sword fern (*Polystichum munitum*), salal (*Gaultheria shallon),* blue blossom *(Ceanothus thyrsiflorus)*, Pacific wax myrtle (*Myrica californica*), and manzanita (*Arctostaphylos columbiana*) are common in the understory or forest openings (Woodward 1986, Henry 1998).

Figure 4. Logging with oxen "bull teams" in the Caspar Creek watershed in the 1870's. Photo courtesy of the Marian Koshland Bioscience and Natural Resources Library, University of California, Berkeley: lib.berkeley.edu/BIOS/.

Figure 5. Second-growth forest in the North Fork watershed (HEN tributary).

The South Fork Experiment, 1962-1985

The original Caspar Creek watershed experiment was designed as a traditional paired watershed study, in which one basin is treated and the second is held as a control. With this approach, an initial calibration period is used to develop a pre-treatment relationship between basins, and treatment effects can then be identified by comparing observed values with those predicted on the basis of the pre-treatment calibrations. As long as the condition of the control watershed does not change markedly during the duration of the experiment, the actual condition of the control watershed is not important—the control acts simply as a benchmark against which the treatment watershed can be compared.[3]

Stream gaging weirs were constructed on both the North and South Forks in 1962 (Figure 6), and streamflow and sediment data collection began at these stations (Table 1). Wooden fish ladders were constructed at the South Fork weir in November 1962 and the North Fork weir in August 1963. Until 1976, suspended sediment was sampled during rising flows at the weirs using fixed-stage samplers mounted on the weir faces; these would fill when the stage rose high enough to inundate the sampler nozzles. Additional samples were obtained using DH-48 hand samplers to check fixed-sampler results and to define sediment concentrations on falling limbs. Sediment accumulations in the South Fork and North Fork weir ponds have been surveyed annually since 1963.

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[3] Note that "control watershed" here does not denote pristine conditions, such as would occur at reference watersheds without anthropogenic impacts.

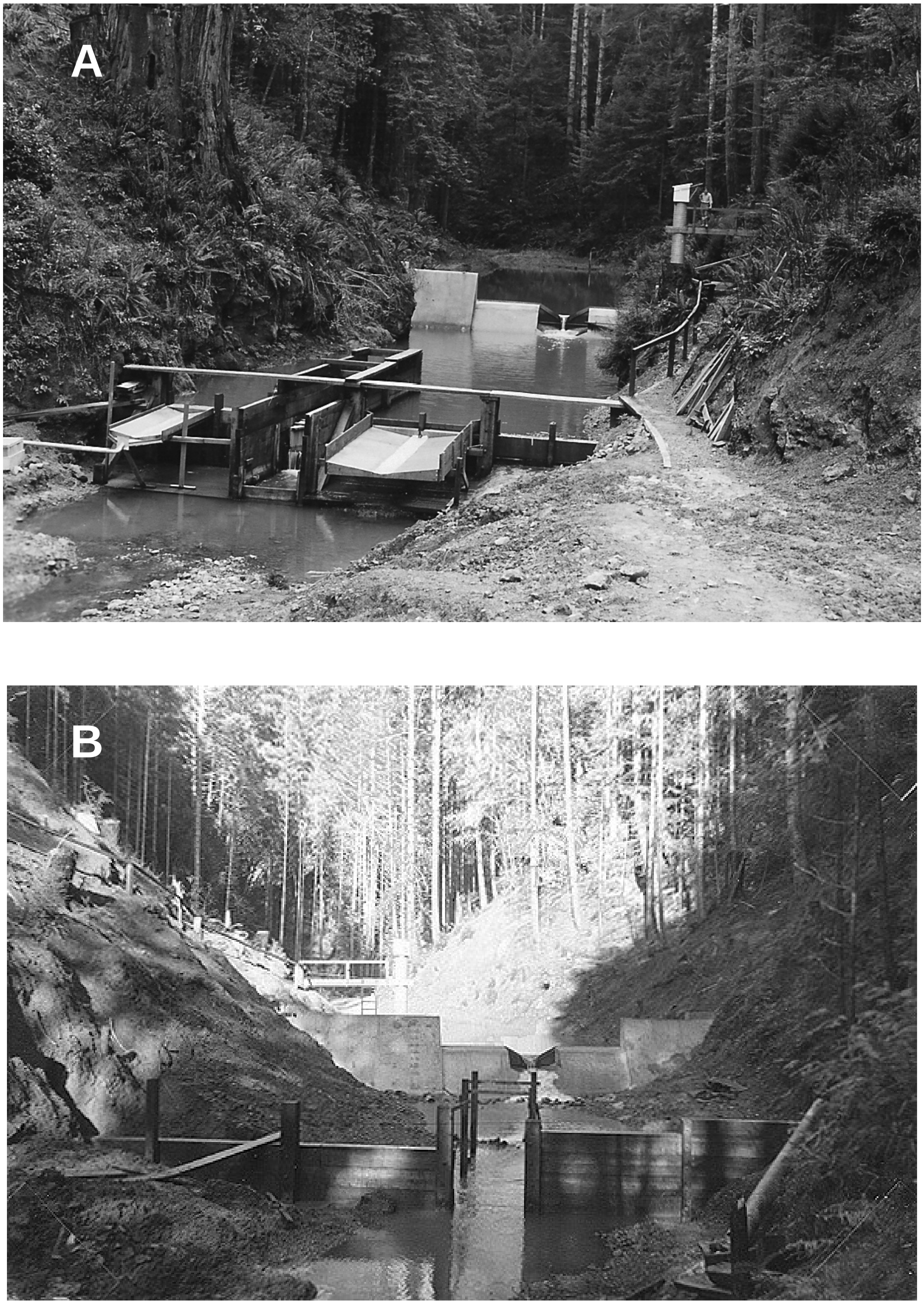

Figure 6. A. The South Fork gaging weir and fish ladder in 1964 (note person standing by the stilling well for scale), and B. the North Fork weir and fish ladder in 1964. The planks used to raise the water elevation between the fish ladders and the weirs were removed from the fish ladders during the summer low-flow period.

Table 1. Timing of treatments and major events during the Caspar Creek experiments. At Caspar Creek, water years (or “hydrologic years”) are defined to begin on August 1 of the preceding calendar year (for example, the December 1964 storm occurred in water year 1965).

Water year	Rain (mm)	South Fork events	North Fork events
1963	1132	Monitoring starts 11/62	Monitoring starts 11/62
1964	857		
1965	1228		
1966	978		
1967	1287	Road construction 5-9/67	
1968	962	South Fork splash dam failure 12/67	
1969	1434		
1970	1170		
1971	1242	Lower watershed logging begins 3/71	
1972	926	Middle watershed logging occurs	
1973	1280	Upper watershed logging occurs	
1974	1694		Major slide 3/74
1975	1200		
1976	762		
1977	305		
1978	1335	Road rehab; waterbars & gates installed	
1979	923		
1980	1252		
1981	874		
1982	1518		
1983	2008		
1984	1232		
1985	897		Y-Z logging begins 3/85
1986	1205		13 gages installed 10/85;Y-Z logging ends
1987	828		
1988	934		
1989	1088		Upper watershed logging begins 5/89
1990	979		Middle watershed logging begins 6/90
1991	716		
1992	919		Lower watershed logging begins 9/91, ends 1/92
1993	1511		
1994	841		Y-Z thinned
1995	1559		7 gages removed 5/95; major Z slide 1/95
1996	1252		Minor windthrow salvage 5/96-7/96
1997	1292		
1998	2202		
1999	1376	Main road decommissioned 8/98-9/98	0.3-ha (0.7-ac) Z wildfire ~9/98; K thinned 8/98
2000	1167		XYZ gage installed 11/99
2001	812	10 gages installed 10/00	
2002	1162		X, M gages 10/01; units thinned 9/01-1/02
2003	1499		
2004	1100		
2005	1223		
2006	1692	Major U slide, 3/06	Major E slide 12/05

Table 1. (continued)

Water year	Rain (mm)	South Fork events	North Fork events
2007	857		
2008	981		
2009	767	Fish ladder replaced 5/08-12/08	Fish ladder replaced 7/08-12/08
2010	1341		
2011	1344		
2012	957	Y-Z road decommissioned 10/11	

Following the 1962-1966 calibration period, 6.8 km (4.2 mi) of mainline (Figure 7) and spur roads were built in the South Fork watershed in 1967, four years prior to timber harvest. The standards for road construction were the same as those used elsewhere on JDSF at that time (D. Burns, CAL FIRE (retired), personal communication). An additional 1.1 km (0.7 mi) of spur road was built between 1971 and 1973 during timber harvest. Approximately 3.9 km (2.4 mi) of the mainline road and 2.1 km (1.3 mi) of spur road were constructed within 61 m (200 ft) of the main South Fork channel (Rice et al. 1979). Impacts associated with road construction were documented by Krammes and Burns (1973).

Figure 7. South Fork road construction in 1967. Note the tractor in the channel; about 110 m (360 ft) of streambed was disturbed by tractors operating directly in the channel (Krammes and Burns 1973).

The second-growth coast redwood and Douglas-fir forest in the South Fork watershed was selectively tractor-logged from 1971 through 1973 (Figure 1) using practices typical of the period immediately prior to implementation of the Z'Berg-Nejedly Forest Practice Act of 1973. Approximately 65% of the timber volume was harvested under three separate timber sales from 1971 to 1973 (Rice et al. 1979). Roughly 60% of the timber volume removed was coast redwood and 40% was Douglas-fir, grand fir, and hemlock (Woodward 1986). Approximately 15% of the watershed was compacted from construction of roads, skid trails (Figure 8), and landings (Rice et al. 1979). Although the practices used during South Fork logging were intended to be better than those generally used at the time, they were inadequate by today's standards: roads and landings were commonly located low on slopes near stream channels to facilitate downhill tractor yarding; roads were constructed with fills placed on steep slopes; inadequate watercourse crossings were installed along headwater channels; and buffer strips were not left along channels (Keppeler 2012). Rice et al. (1979) summarize results of the South Fork experiment through 1976.

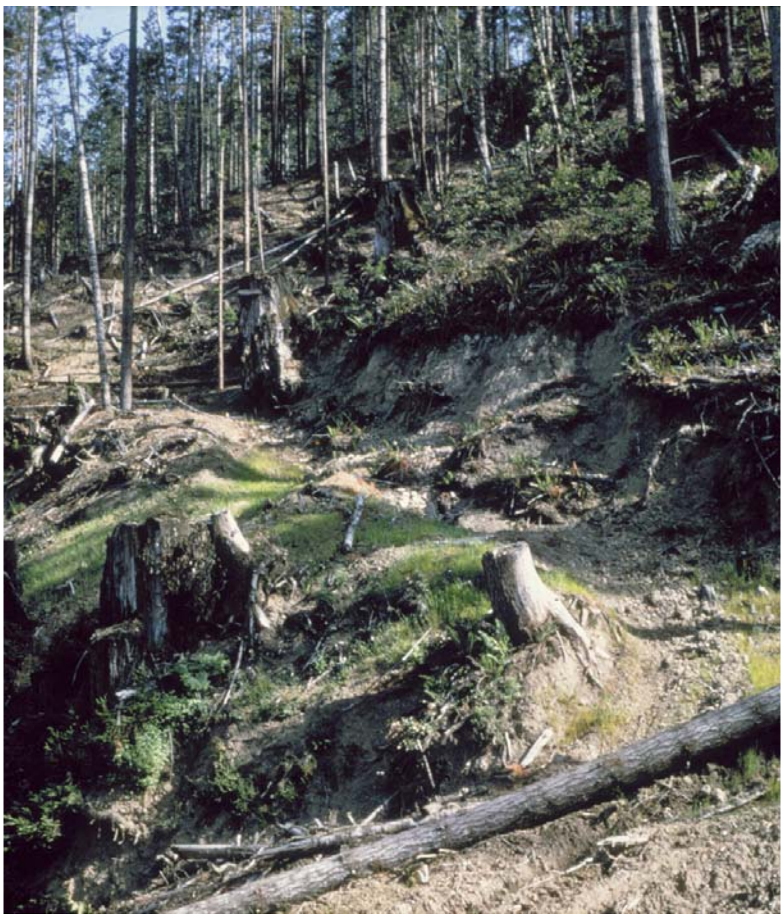

Figure 8. Tractor skid trail 10 years after selection harvest and tractor yarding in the South Fork watershed. Photograph taken in 1981.

A total of 4.6 km (2.8 mi) of the main South Fork road was decommissioned in 1998, and 26 watercourse crossings were removed (Keppeler et al. 2007). Watershed responses to South Fork logging and to the decommissioning project continue to be monitored. State-of-the-art concrete fish ladders were installed at both the South Fork and North Fork weirs in 2008, replacing the original wooden structures.

Table 2. The gaged watersheds at Caspar Creek. Locations are shown in Figure 9.

Station	Area (ha)	Record begins	Record ends	Logging in catchment calendar years	% logged[a]
North Fork					
weir (NFC)	473	11/1962	on-going	1985-86,1989-92	50% C
ARF	384	10/1985	on-going	1989-92	46% C
BAN	10	10/1985	5/1995	1991	95% C
CAR	26	10/1985	on-going	1991-92	96% C
DOL	77	10/1985	on-going	1990-91	36% C
EAG	27	10/1985	on-going	1990-91	100% C
FLY	217	10/1985	5/1995	1989-91	45% C
GIB	20	10/1985	5/1995	1991	100% C
HEN	39	10/1985	on-going	control	0
IVE	21	10/1985	on-going	control	0
JOH	55	10/1985	5/1995	1989	30% C
KJE	15	10/1985	5/1995	1989	97% C
LAN	156	10/1985	5/1995	1989-90	32% C
MUN1	16	10/1985	5/1995	control	0
MUN2	16	10/2001	on-going	control	0
XYZ	77	11/1999	on-going	1985-86	78% C
XRAY	18	10/2001	on-going	control	0
South Fork					
weir (SFC)	424	11/1962	on-going	1971-73	65% S
OGI	19	10/2000	on-going	1971	60% S
POR	31	10/2000	on-going	1971	60% S
QUE	394	10/2000	on-going	1971-73	65% S
RIC	47	10/2000	on-going	1972	70% S
SEQ	17	10/2000	on-going	1972	70% S
TRE	14	10/2000	on-going	1972	70% S
UQL	13	10/2000	on-going	1973	65% S
WIL	26	10/2000	on-going	1973	65% S
YOK	53	10/2000	on-going	1973	65% S
ZIE	26	10/2000	on-going	1973	65% S

[a] C = clearcut; S = selection cut

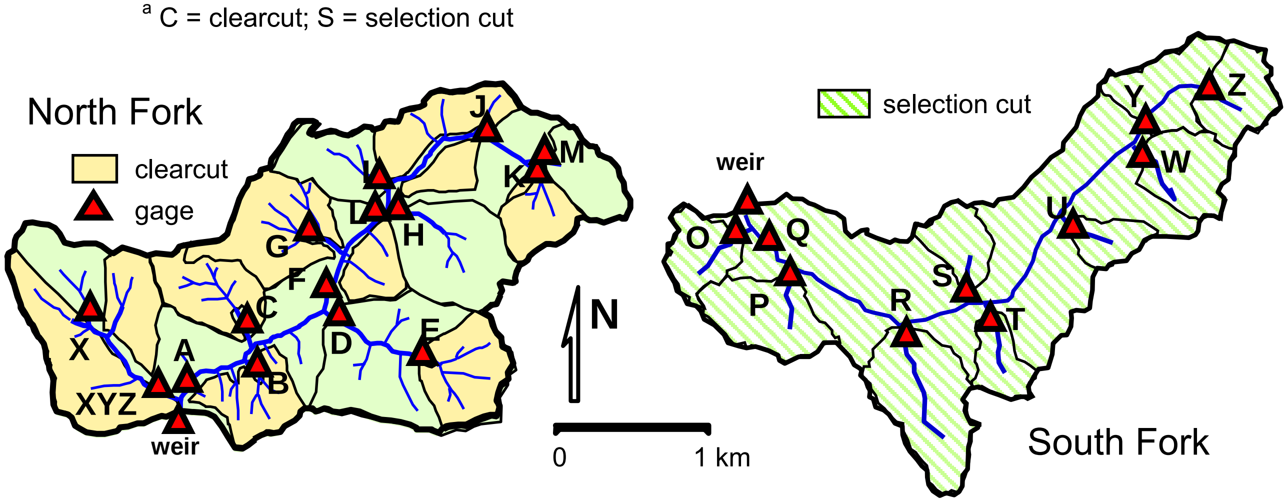

Figure 9. Gaging stations in the North and South Fork Caspar Creek watersheds. Stations are identified by initial.

The North Fork Experiment, 1985-Present

The North Fork experiment was designed to quantify the cumulative watershed effects (CWEs) of clearcutting on suspended sediment, storm runoff volume, and peak-flow discharges (Rice 1983). Thirteen gaging stations were installed in the North Fork watershed for the new study (Table 2, Figure 9), with eight placed in headwater catchments and the rest located downstream, allowing effects to be tracked through watersheds of increasing size. The downstream end of the experimental treatment area was the ARF gaging station, located upstream of XYZ tributary and having a drainage area of 384 ha (949 ac; Figure 9). The smallest headwater catchment (BAN) had a drainage area of 10 ha (25 ac). Three of the headwater catchments (HEN, IVE, and MUN) were designated as controls.

Monitoring for the North Fork study began in water year 1985. Measurements along the main channel were made at constructed cross sections with natural channel bottoms, where relationships between stage and discharge had been calibrated (i.e., rated sections). Wooden Parshall flumes were constructed for monitoring in smaller tributaries (Figure 10). Data loggers recorded stream depths in stilling wells at each gaging station, and pumping samplers collected water samples for analysis of suspended sediment concentrations. The initial second-growth harvesting in the North Fork watershed was not part of the experiment and took place in the XYZ tributary from 1985 to 1986 (Figure 9). About 13% of the watershed area above the weir was logged at this time (Figures 1 and 9).

Figure 10. Parshall flume in the North Fork watershed (DOL station).

Harvesting for the North Fork CWE experiment occurred from 1989 to 1992 with three timber sales (Figure 1). Approximately 46% of the area above station ARF was clearcut harvested for the experiment, with clearcuts occupying 30 to 99% of the area in the treated sub-watersheds (Henry 1998). Approximately 80% of the clearcut area was skyline cable yarded. The other 20% was located on flatter slopes near ridges, and these areas were logged using ground-based tractor yarding. In contrast to the road design and layout in the South Fork, the 8.4 km (5.2 mi) of new North Fork roads were constructed high on hillslopes, where the roads have little influence on watercourses. Logging and road building were conducted under the California Forest Practice Rules that pertained from 1989 to 1992, which required Watercourse and Lake Protection Zones (WLPZs; selection-logged buffer strips designed to meet the requirements of California Forest Practice Rules) both along perennial fish-bearing streams and along intermittent streams that provide habitat for other aquatic species. Four harvest blocks, amounting to 92 ha (227 ac), were broadcast burned after logging (Figure 11) and were later treated with herbicide to control broadleaf species (e.g., blue blossom) that compete with regrowing conifers (Lewis et al. 2001). The clearcut units were inter-planted with conifer seedlings to supplement natural redwood sprouting and conifer seeding from adjacent uncut units (Jameson and Robards 2007).

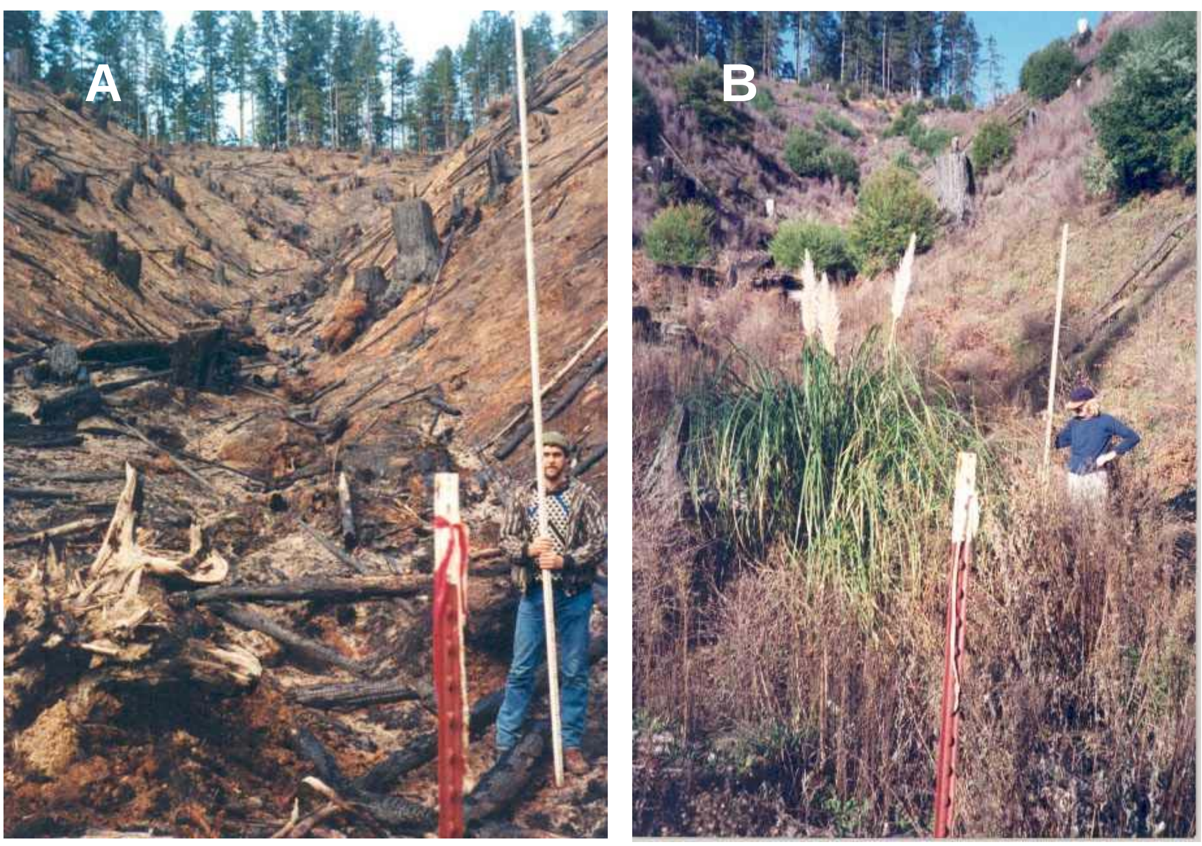

Figure 11. North Fork headwater tributary in logging unit J (located near monitoring station JOH). A. soon after clearcutting and burning in 1990, and B. in 1994, after four years of regrowth.

Seven of the 13 North Fork gaging stations were decommissioned in 1995, while monitoring has continued at the rest in order to quantify long-term recovery trends (Table 2). Between 1999 and 2004, fiberglass Montana flumes were installed to replace the wooden Parshall flumes at the remaining North Fork gaging stations. Limited pre-commercial thinning took place in 1995 and 1998, and most of the remaining units were thinned in 2001 (Figure 12). Pre-commercial thinning reduced basal area of the third-growth stands in treated units by an average of about 75% (Keppeler et al. 2009). Ziemer (1998a) summarized North Fork study results through 1998.

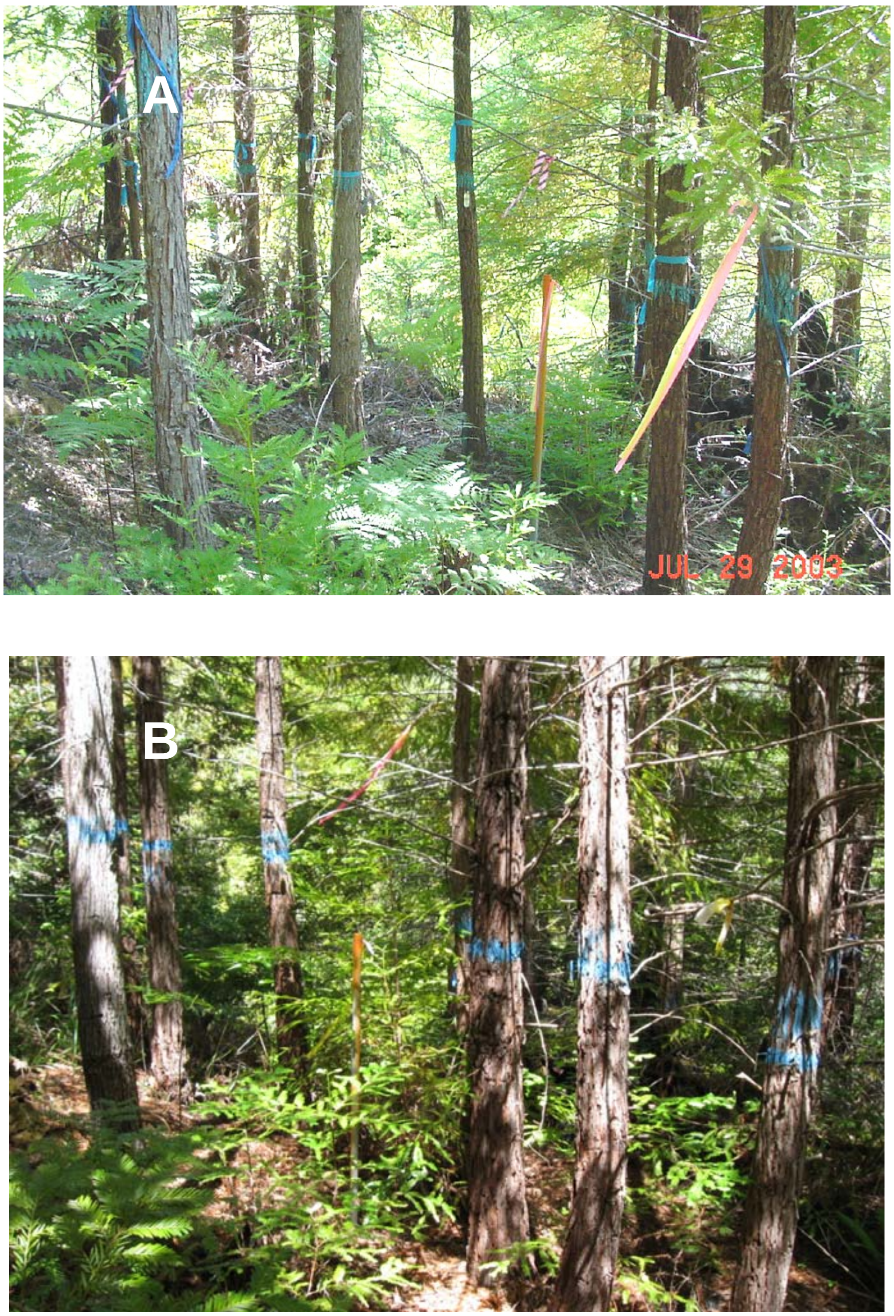

Figure 12. Experimental thinning plot installed in North Fork logging unit J in March-April 2001; A. photo taken in 2003. B. The same thinning plot in 2012.

III. KEY LESSONS LEARNED AND POTENTIAL APPLICATONS

The following sections summarize key findings from the South Fork and North Fork experiments for topics commonly addressed by California resource professionals during preparation of Timber Harvesting Plans (THPs), Nonindustrial Timber Management Plans (NTMPs), conversion permits, and other types of permit applications.

Peak Flows

Changes in instantaneous stream peak flows resulting from timber operations have been studied for more than 50 years in the Pacific Northwest, but conclusions remain controversial and conflicting results have been reported (Jones and Grant 1996, Thomas and Megahan 1998, Beschta et al. 2000, Grant et al. 2008, Alila et al. 2009, Lewis et al. 2010, Kuraś et al. 2012). Elevated peak flows can increase the frequency and magnitude of downstream overbank flooding, increase sediment transport, cause adverse impacts to fish habitat, contribute to streambank erosion, increase streamside landsliding, and trigger changes in channel morphology (Ziemer 1998b, MacDonald et al. 1991). Studies of the effects of logging on peak flows in the Pacific Coast ecoregion and the Pacific Northwest have been summarized by Ziemer and Lisle (1998) and Moore and Wondzell (2005), respectively. Ziemer and Lisle (1998) describe these effects to be more pronounced and easier to detect in small watersheds, greater in areas where rain-on-snow events occur, greater in the fall months, and greater for relatively small events that occur frequently.

Research at Caspar Creek has quantified the effect of timber harvesting on peak flows (Figure 13) in an area where hydrologic inputs are dominated by rainfall and where coast redwood and Douglas-fir represent major components of the native forest. Caspar Creek papers that address changes in peak flows include Ziemer (1981), Wright (1985), Wright et al. (1990), Ziemer (1998b), Lewis et al. (2001), Lewis and Keppeler (2007), Keppeler et al. (2009), and Reid (2012). The conclusions reached in this sequence of papers show an evolution of thought due to the increasing length and diversity of data sets available for analysis, the refinement of the temporal categories analyzed, and the increase in computing capabilities provided by new technologies. Interception studies conducted in the North Fork have helped explain why changes in peak flows occur following timber harvesting in the Coast Ranges of California (Reid and Lewis 2007). Several conclusions regarding the influence of logging on peak flows at Caspar Creek are now evident:

- The largest percentage increases for peak flows after timber harvest[4] are seen for small storms in the fall, when logged and unlogged watersheds are expected to show the greatest difference in soil moisture levels because of the extent of summer transpiration at unlogged sites (Ziemer 1981, Ziemer 1998b, Lewis et al. 2001).

[4] Increases are calculated by comparing observed values to those predicted on the basis of pre-treatment calibrations between peak flows in treatment and control watersheds.

Figure 13. The North Fork Caspar Creek weir at high flow.

- In winter, when differences in soil moisture levels between logged and unlogged areas are minimal, peak flows increase after clearcutting due primarily to reduced interception loss after logging, and secondarily to reduced winter transpiration (Reid and Lewis 2007, Reid 2012).
- The dense second-growth forest canopy characteristic of the Caspar Creek area intercepts and evaporates approximately 21% of incoming rainfall even during large storms (Reid and Lewis 2009). Evaporation often can proceed throughout a storm because air usually remains unsaturated even though humidity is high, and wetted foliage and bark expose a large water surface area to evaporation.
- The estimated peak flow having a 2-year recurrence interval increased 14% for the 8-year period following completion of selection logging in the South Fork (Keppeler et al. 2009).
- The 37% of the North Fork watershed logged between 1989 and 1992 produced an estimated 9% average increase in the 2-year peak flow at the North Fork weir for the 1989-1995 period (Ziemer 1998b).[5]

[5] Approximately 50% of the area above the North Fork weir was clearcut from 1985-1992, but pre-treatment peak-flow data included effects from 1985-1986 clearcutting in the XYZ tributary, complicating the analysis (i.e., the calibration period used a basin already 13% logged). The 37% of the watershed logged during the North Fork experiment (1989-1992) represents 46% of the watershed area above the ARF gaging station.

- The 2-year peak flow in clearcut North Fork sub-watersheds increased an average of 27% during the same period (Ziemer 1998b).
- Peak-flow responses in clearcut sub-watersheds neared pre-treatment levels about 10 years after North Fork logging, but then increased again after pre-commercial thinning (Keppeler et al. 2009) (Figure 14).
- Increases in peak flow from clearcutting in the North Fork watershed were greater with increasing proportion of the basin logged and became smaller with increasing antecedent wetness, storm size, and time after logging (Lewis et al. 2001, Rice et al. 2001).

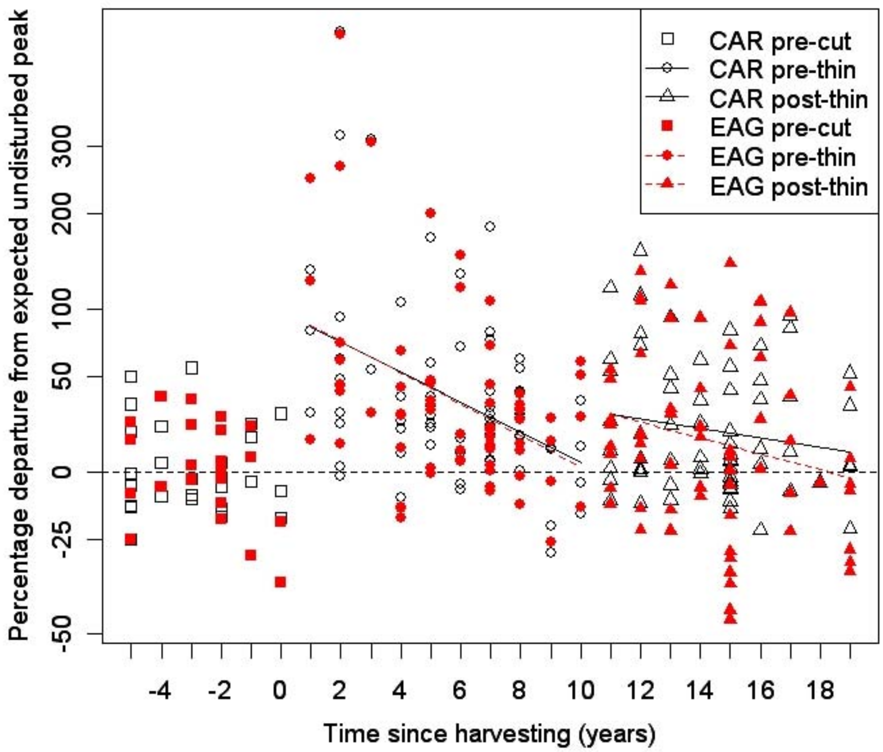

Figure 14. Peak-flow departures from those predicted for pre-treatment conditions in a 26-ha (64-ac), 96% clearcut sub-watershed (CAR, logged in 1991, thinned in 2001) and in a 27-ha (66-ac) clearcut and burned sub-watershed (EAG, logged in 1990-91, thinned in 2001).

Peak-flow results from Caspar Creek can be extended to other forested watersheds in rainfall-dominated portions of the California Coast Ranges. A regression equation has been developed using the North Fork dataset to predict changes in peak flow after logging (Lisle et al. 2000, Lewis et al. 2001). The equation can be inserted into a spreadsheet and used to make predictions about how a specific silvicultural prescription in a THP can be expected to change winter peak flows (Cafferata and Reid 2011). An example of this procedure is provided in Appendix A.

Caspar Creek peak-flow results can be used to help prepare the cumulative effects assessment required as part of a THP, and the Caspar Creek regression equation can be used to evaluate watershed response to proposed harvest levels. For example, Munn (2002) used a prediction of peak-flow changes to identify an acceptable rate of harvest in the Freshwater Creek and Elk River watersheds in Humboldt County, where increased peak flows were raised as an issue during public review of THPs and were determined to be a threat to public health and safety. On the basis of these peak-flow calculations, harvesting was limited to a rate that would not increase peak flows over existing levels in the short term.

Peak-flow data from Caspar Creek have been used (1) to predict changes for proposed harvesting in THPs and NTMPs by RPFs and CAL FIRE staff; (2) in THP Official Responses written by CAL FIRE staff; (3) in development of prescriptions for aquatic Habitat Conservation Plans (HCPs; e.g., Green Diamond Resource Company, Mendocino Redwood Company); (4) in the Environmental Impact Report (EIR) for the Jackson Demonstration State Forest Management Plan; (5) in EIRs for vineyard conversion projects; and (6) for watershed analyses (e.g., Freshwater Creek, Salminen 2003). In addition, Caspar Creek peak-flow data were used to validate methods for sizing of watercourse crossings (Cafferata et al. 2004; Appendices D and E).

Summer Low Flows and Annual Water Yield

Forest harvesting in mountainous watersheds in the Pacific Northwest has been shown to initially increase summer and early fall stream flows and annual water yields (Moore and Wondzell 2005). Soils are wetter in harvested areas than in unlogged areas during the growing season, when transpiration rates are ordinarily high, so summer groundwater levels and late-summer stream flow are correspondingly higher after logging (Chamberlin et al. 1991). Sufficient late-summer stream flow is critical for supporting juvenile salmonids, so dry-season flow increases have been reported to be a greater benefit for salmonids than increases in total annual flow (Botkin et al. 1994). Increased flows during the growing season also benefit downstream water users who rely on stream flow for irrigation or domestic use.

Although the initial post-harvest period generally shows increased summer flows, results of several longer-term studies in the Pacific Northwest suggest that dry-season flows may decrease to below their original levels as forest stands become reestablished on logged units (Hicks et al. 1991, Perry 2007). Such declines may reflect high rates of water use by rapidly growing young conifer stands (Moore et al. 2004) or by the establishment of young hardwood stands on hillslopes or in riparian zones (Hicks et al. 1991). The magnitudes of responses are expected to vary by vegetation type and climatic setting.

Research at Caspar Creek has produced a sequence of papers that address changes in low flows and annual water yield. Keppeler (1986), Keppeler and Ziemer (1990), and Keppeler (1998) documented increased minimum flows and annual water yields for both the South Fork and North Fork experiments. More recent papers (Reid and Lewis 2011, Reid 2012) have reported longer-term decreases in low flows in the South Fork. Conclusions from these hydrologic studies include the following:

- For 7 years after selection harvest in the South Fork, low flows were higher than expected for pre-treatment conditions[6] (Keppeler 1986, Keppeler and Ziemer 1990, Keppeler 1998). Flows then declined to below expected values for the next 20 years[7] (Reid and Lewis 2011, Reid 2012) (Figure 15); future monitoring will show whether flow has again stabilized at pre-treatment levels.
- Following clearcut logging in the North Fork, late-summer flows increased to nearly twice those expected[7] and then returned to pre-treatment levels after 16 years, with a recovery trajectory that suggests a further decline is likely (Reid and Lewis 2011, Reid 2012) (Figure 15).
- After North Fork logging, the period of higher summer flows increased the volume of aquatic summer rearing habitat (Keppeler 1998).
- Annual water yields increased 15% for at least 8 to 11 years after logging in both the South and North Forks (Keppeler 1998), with 90% of the South Fork increase occurring during the high-flow season (Keppeler and Ziemer 1990).

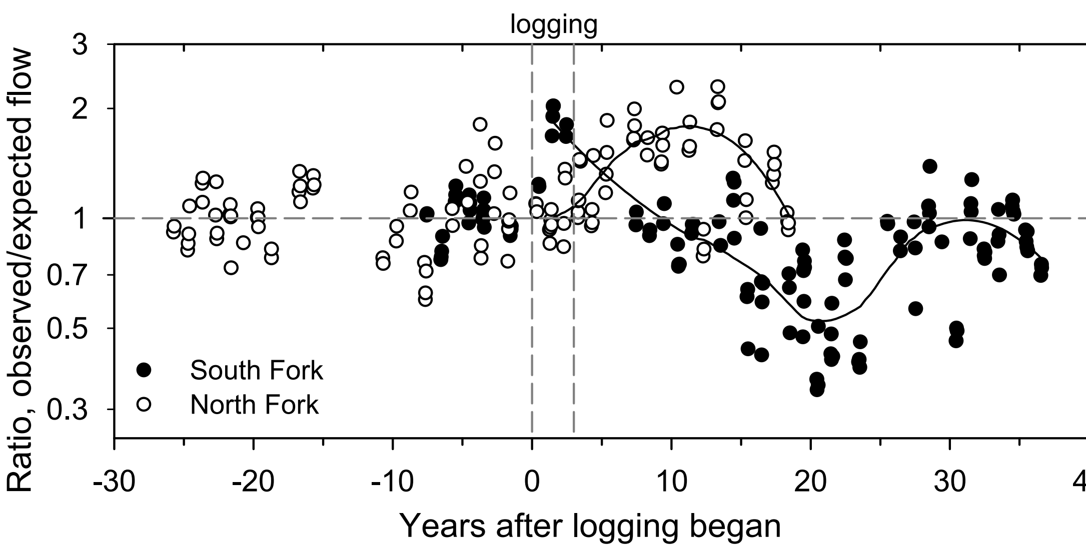

Figure 15. Ratio of observed late-summer flows to those expected for pre-treatment conditions at the South and North Fork Caspar Creek weirs as a function of years after logging began (from Reid 2012).

Low-flow results can be extended to other forested watersheds in rain-dominated portions of the California Coast Ranges. Low-flow data from Caspar Creek have been used to plan water drafting and in-stream flow requirements. In addition, data have been used in HCP development and vineyard conversion EIRs to evaluate potential impacts. An example of how Caspar Creek low-flow data can be used in a THP is provided in Appendix B.

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[6] As calculated on the basis of calibrations to the control watershed.

[7] After 1985, values expected for pre-treatment conditions were estimated for this study from relations between rainfall (in the form of "antecedent precipitation indices") and flow that were constructed from pre-treatment data (Reid 2012).

Hillslope Hydrology

Subsurface flow is the dominant route by which rainfall is transferred to stream channels in the coast redwood region (Keppeler and Brown 1998). As in forested areas of the Pacific Northwest, overland flow is uncommon except in areas that have been compacted by heavy equipment (e.g., roads, skid trails, and landings) or are seasonally saturated. Some subsurface flow travels slowly through the soil matrix, while some moves rapidly down hillslopes and unchannelled swales through subsurface soil pipes. Timber harvesting can modify transpiration and rainfall interception, increasing the amount of subsurface flow generated during storms; and road construction and heavy equipment use can compact soils and disrupt soil pipes. These kinds of changes can alter subsurface flow patterns and elevate pore water pressures during large storms, increasing landslide risk at some sites (LaHusen 1984, Montgomery et al. 2000).

During the North Fork experiment, arrays of piezometers and tensiometers were installed on two forested hillslopes that would later be clearcut (Figure 16). In addition, gages were constructed to monitor flow in soil pipes in a control watershed and in an adjacent watershed that would be logged (Figure 17). Keppeler et al. (1994) describe results of the piezometer/tensiometer study, and Brown (1995) uses the results to test a subsurface flow model. Ziemer and Albright (1987), Albright (1992), and Ziemer (1992) report on the pipeflow measurements. Keppeler and Brown (1998) summarize results from the entire suite of subsurface flow studies. Fisher (2000) used results from one of the piezometer arrays to model flow in an unchannelled swale crossed by a road, and Carr (2006) evaluated stream flow changes using a subsurface flow model. Results of the subsurface flow studies showed that:

- Pipeflow is an important delivery mechanism of water from hillslopes at Caspar Creek (Ziemer and Albright 1987, Albright 1992) (Figure 18).
- Following clearcut logging in the North Fork, peak piezometric levels and soil moisture contents rose, and subsurface pipeflow rates increased dramatically (Ziemer 1992, Keppeler et al. 1994, Keppeler and Brown 1998).
- Road construction across a headwater swale, followed by clearcutting above and below the road, resulted in large increases in the pore pressure response at and above the road (Keppeler and Brown 1998, Fisher 2000).

Results of the hillslope hydrology studies carried out in the North Fork Caspar Creek watershed are expected to be directly applicable to other watersheds in similar settings in rain-dominated portions of the California Coast Ranges, and the understanding of process mechanisms contributed by these studies is expected to be even more broadly applicable. Data from the studies have been used in evaluation of THPs in the Coast Ranges of California.

Figure 16. North Fork hillslope instrumented with piezometers and tensiometers, then logged. Ladders are used to prevent soil compaction during measurements. Photograph taken in 1991, two years after logging.

Figure 17. Gaging site for soil pipes in the North Fork watershed. Photograph taken in 1988.

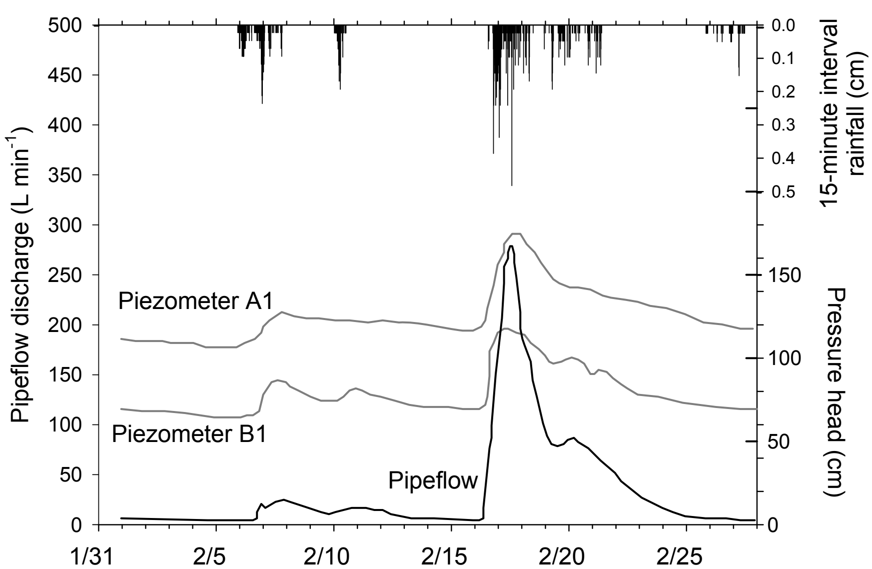

Figure 18. Pipeflow and piezometric response—at 2.3-m (A1) and 2.5-m (B1) depths—to a moderate winter storm in an untreated headwater swale of the North Fork (adapted from Keppeler and Brown 1998, rainfall data from Station n408).

Fog Drip

Past studies of fog drip in northern California and the Pacific Northwest have reported that fog can deliver significant amounts of moisture in areas that have a high frequency of advection fog, and that fog drip can be hydrologically important at certain locations (Kittredge 1948, Azevedo and Morgan 1974, Dawson 1998). Coast redwood is renowned for its association with the coastal fog belt, and the public has often raised concerns that harvest of second-growth redwood stands will reduce fog drip, resulting in reduced groundwater recharge, stream flow, and water yield. Even at sites where fog does not directly influence runoff, fog can supply water directly to foliage, reducing summer moisture stress (Ewing et al. 2009). Recent data from the central California coast suggest that fog precipitation may contribute an important input of mercury to coastal areas (Weiss-Penzias et al. 2012).

Precipitation gages were deployed in and around the Caspar Creek Experimental Watersheds in 1998 and 1999 to measure fog precipitation at forested and clearcut sites (Figure 19). Keppeler (2007) described the results of the fog-drip studies:

- Although rates varied greatly between sites, fog drip was greatest at the five ridge-top sites, averaging 39 mm (1.5 in) for June-September 1999; this is equivalent to 3% of the mean annual precipitation (Keppeler 2007).
- Fog-drip rates were considerably lower at mid-slope and valley-bottom sites, and rates in clearings were similar to those within forest stands at these sites (Keppeler 2007) (Figure 20).
- Annual water yield and dry-season flow initially increased following timber harvest in the South and North Forks of Caspar Creek, indicating that the effect of reduced rainfall interception and transpiration exceeded that of diminished fog drip (Keppeler 2007).

Figure 19. Installation for measuring fog drip and throughfall in a second-growth stand, North Fork watershed.

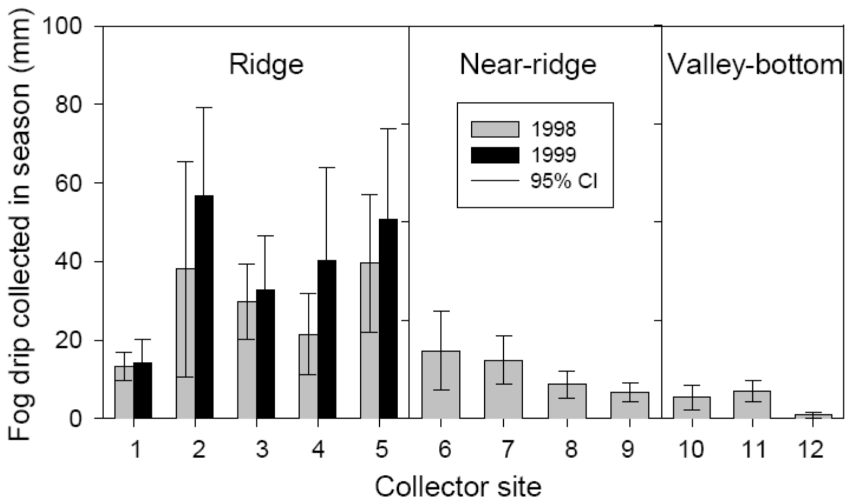

Figure 20. Seasonal fog-drip yields from 12 sites in the Caspar Creek Experimental Watersheds (from Keppeler 2007).

Along the California coast, the distribution and frequency of fog varies considerably with local topography and with distance from the coast, so fog-drip rates measured at Caspar Creek can be applied to other sites only with extreme caution. However, Caspar Creek information about inter-site variability and the importance of fog drip relative to other post-logging hydrologic changes provides a useful context for interpreting the potential influence of fog drip at other sites in similar settings. Fog-drip data from the Caspar Creek Experimental Watersheds have been used in THP reviews, the draft aquatic HCP for Mendocino Redwood Company, the EIR for the Jackson Demonstration State Forest Management Plan, and EIRs for planned vineyard conversions.

Sediment Yields

The effect of timber operations on hillslope erosion and sediment yield has received increased attention in the past 15 years due to growing concern over anadromous salmonids and water quality. Populations of coho salmon, Chinook salmon, and steelhead trout in the northern and central parts of the Coast Ranges have been listed as threatened or endangered by state and federal agencies, and the US EPA has listed most north-coast watersheds as sediment impaired under Section 303(d) of the federal Clean Water Act. High in-stream loads of fine sediment adversely impact spawning and rearing habitats for salmonids (Reiser and White 1988, Newcombe and Jensen 1996), and foraging efficiency of juvenile salmonids is reduced by high turbidity levels (Sigler et al. 1984, Madej et al. 2007).

Sediment studies have been an important component of Caspar Creek research since the project began. Krammes and Burns (1973), Tilley and Rice (1977), and Rice et al. (1979) described sediment yields from the South Fork experiment, while Lewis (1998), Lewis et al. (2001), Lewis and Keppeler (2007), and Keppeler et al.

(2009) evaluated sediment yields during the North Fork study. Conclusions from these studies include the following:

- Year-to-year variation in suspended sediment load is high and reflects the distribution and size of storms and the watershed treatments applied (Keppeler et al. 2007) (Figure 21).
- Lewis (1996) estimated that approximately two-thirds of the sediment load in the North Fork is transported as suspended sediment.
- During the six years after tractor logging, suspended sediment yield at the South Fork weir more than quadrupled relative to values expected for pre-treatment conditions (Figure 22; Keppeler et al. 2009).
- About two decades after logging ended, sediment production in the South Fork watershed again increased relative to expected values (Figure 22) largely due to deterioration of the road system (Cafferata and Spittler 1998, Keppeler and Lewis 2007, Keppeler 2012).
- Despite a major landslide in XYZ watershed in 1995 that contributed the equivalent of two years' suspended sediment at the North Fork weir, the increase in suspended sediment yield at the North Fork weir during the decade after treatment was only 25 to 45% of that observed after South Fork treatment, reflecting improvements in forest practices and in road network design[8] (Lewis 1998, Lewis et al. 2001).

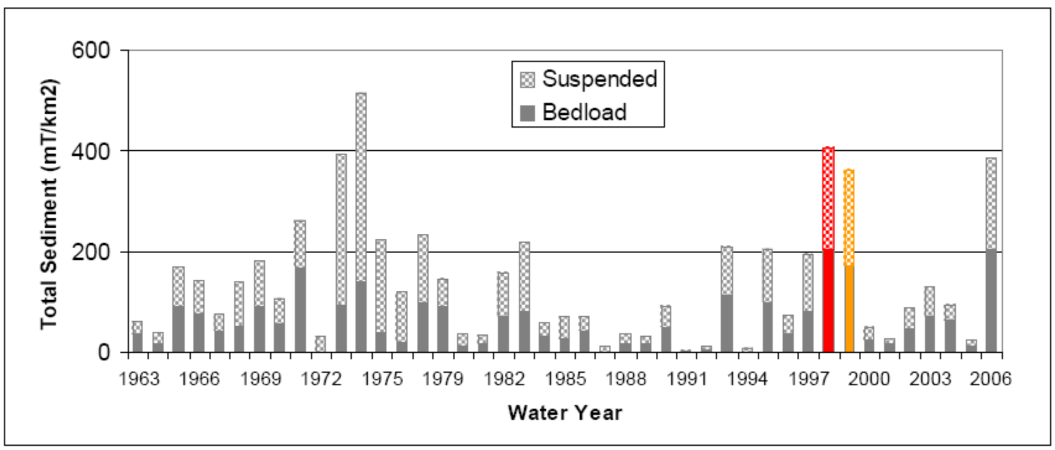

Figure 21. Total annual sediment yield for South Fork Caspar Creek, 1963-2006. Logging occurred in 1971-1973, and the main road was decommissioned in water year 1999 (shown in yellow). Major road-related landslides occurred in water years 1998 (shown in red), 1999, and 2006. The long-term average annual sediment yield at SFC was approximately 140 metric tons/km^2 (390 t/mi^2) through water year 2006 (from Keppeler et al. 2007). "Bedload" here refers to sediment accumulated in the weir pond, thus including some sediment that had been carried in suspension but had settled out before reaching the suspended sediment monitoring station at the weir.

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[8] Results are somewhat complicated because data from the North Fork weir reflect both the experimental treatment in the area harvested in 1989-92 above station ARF as well as 1985-86 logging in XYZ tributary (Figure 1). Because the calibration period includes data from a partially logged watershed in which sediment inputs were likely to be decreasing by the time of the later experimental logging, the actual treatment effect at the North Fork weir station may be slightly larger than reported.

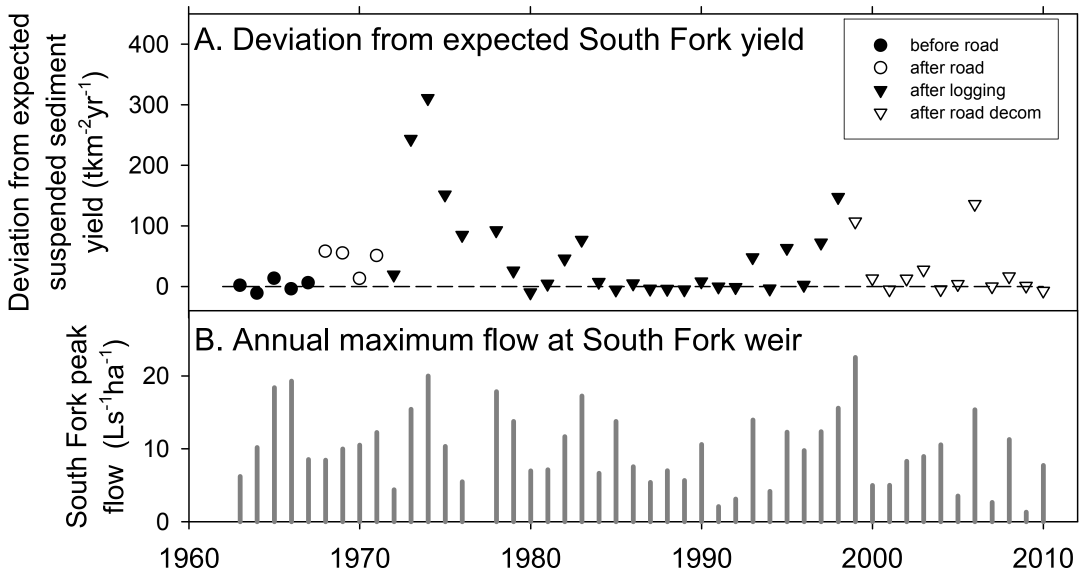

Figure 22. A. Deviations of annual suspended sediment yields from those expected for the South Fork of Caspar Creek, 1963-2010, and B. annual maximum peak flows at the South Fork weir. High deviations from 1973-1975 reflect tractor logging impacts in the South Fork watershed. Later high deviations reflect road-related landslides (1998, 1999, 2006) and road decommissioning work (1999) (adapted from Keppeler 2012).

- Reflecting contributions from both the XYZ tributary and the North Fork experimental area, suspended sediment load roughly doubled during the immediate post-harvest period at the North Fork weir[8] (Keppeler et al. 2009).
- The median increase in annual suspended sediment load between 1989 and 1995 was 109% in North Fork clearcut tributaries (Lewis 1998).
- Suspended sediment increases in gaged tributaries after North Fork logging were strongly correlated with increases in stormflow volumes (Lewis 1998, Lewis et al. 2001).
- Sediment loads in North Fork tributaries had substantially recovered by 10 years after timber harvesting, when pre-commercial thinning again increased peak flows and channel erosion (Figure 23A); sediment yields were also increased by a large landslide that occurred in a clearcut unit in December 2005 (Keppeler et al. 2009, Figure 24).
- For water years 1996 to 1999, the North Fork averaged 17 days (range 13-32) and the South Fork 19 days (range 5-34) each year with turbidities of over 40 NTUs at the weir station. Turbidity levels exceeded 100 NTUs in the North and South Forks an average of 3 (range 1-6) and 5 (range 1-9) days, respectively, over these four years (J. Lewis, USFS PSW (retired), unpublished memo dated March 31, 2000).[9]

[9] The durations cited are the sum of 10-minute periods with NTU values greater than the listed value. NTUs are Nephelometric Turbidity Units, which quantify the degree to which light traveling through a water column is scattered by suspended organic and inorganic particles.

The northern California Coast Range is an area of great geologic, topographic, and climatic diversity, so natural erosion rates are expected to have varied widely through the area. In an analysis of reservoir sedimentation rates in California, Minear and Kondolf (2009) provide data that show the ratio between maximum and minimum reservoir sedimentation rates within the Coast region to be larger than in any of the other five geomorphic regions evaluated. Such wide variations suggest that use of Caspar Creek sediment delivery rates as a basis for estimating rates at another site in the Coast Ranges is reasonable only if the processes and conditions that control erosion rates in the two areas are similar enough that results are likely to be meaningful.

By taking such concerns into account, it has been possible to use the 50-year record of sediment yields from the Caspar Creek watersheds to provide benchmarks for comparison with target sediment yields identified in Total Maximum Daily Load (TMDL) plans developed for nearby areas with similar geology (e.g., Garcia River watershed). Sediment data from Caspar Creek have been used in THP Official Responses, HCPs, EIRs, and other planning documents.

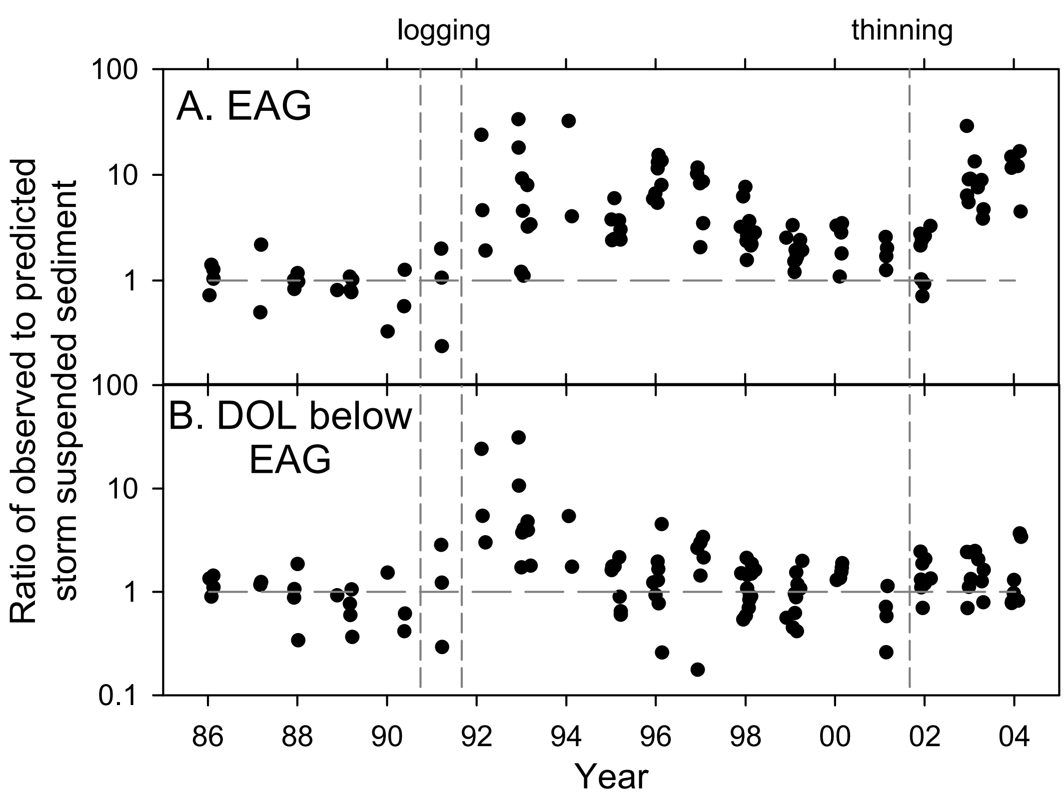

Figure 23. Deviations from expected suspended sediment load A. in the clearcut EAG sub-watershed and B. in the unlogged portion of the DOL sub-watershed downstream of the EAG gage (from Reid et al. 2010). Loads from the EAG sub-watershed were subtracted from those at DOL for these calculations, so the ratios plotted for DOL represent changes only within the unlogged portion of DOL.

Surface Erosion, Channel Erosion, Gullies, and Landslides

The relative contributions of sediment from legacy logging sources and current management practices remains a topic of debate, as does the role of modern activities in reactivating legacy sources.[10] Sediment budgets developed for impaired watersheds in northwest California generally report that road-surface erosion and road-related landslides are the dominant sources of sediment from recent forestland management activities. Many of these analyses, however, have relied primarily on aerial photographic analysis and digital terrain models and have incorporated only limited field measurements (Cafferata et al. 2007).

Research at Caspar Creek has included mapping and evaluation of sediment inputs from particular sediment sources, including landslides (Spittler and McKitterick 1995, Cafferata and Spittler 1998, Bawcom 2007, Reid and Keppeler 2012; Figure 24), gullies (Dewey 2007, Reid et al. 2010; Figure 25), road-related sources (Keppeler et al. 2007, Barrett et al. 2012; Figure 26), and surface erosion (Rice 1996). Napolitano (1996) constructed a sediment budget for the North Fork channel under pre-treatment conditions. Results of these studies provide information on the relative importance and characteristics of sediment production from a variety of sediment sources.

Figure 24 A. The North Fork Unit E slide scar, December 2005, and B. a downstream gaging flume under high flow following the Unit E slide.

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[10] Legacy sources are those attributed to logging operations that occurred prior to the most recent logging entry. On non-federal timberlands in California, “legacy” is often used to describe logging-related sources that originally developed before implementation of the modern California Forest Practice Rules. These rules resulted from the passage of the Z’Berg-Nejedly Forest Practice Act of 1973, but they were not enforced on the ground until 1975. The rules—and particularly those related to watershed protection—have been improved numerous times by the State Board of Forestry and Fire Protection since 1975.

Figure 25. Gully headcut in the South Fork watershed.

Figure 26. Excavating a road crossing during decommissioning of the main haul road in the South Fork watershed in 1998.

- After clearcut logging in the North Fork, in-channel erosion (i.e., gullying, channel incision, and bank erosion) appears to be the major sediment source during periods without large landslides, and sediment inputs increased significantly along an undisturbed channel reach downstream of a logged sub-watershed (Figure 23B) (Reid et al. 2010).
- The drainage density of small channels increased after North Fork logging even where roads were not present, likely due to increased runoff after logging. Comparison of channel-head locations in a sample of logged and unlogged catchments suggests that overall drainage density for channels in logged watersheds smaller than 30 ha (74 ac) increased by about 28% (Reid et al. 2010).
- Clearcut logging operations appear to have influenced landsliding primarily through an increase in the incidence of large landslides (some associated with roads and others not) and by destabilization of slopes adjacent to roads (Reid and Keppeler 2012).
- The largest landslides (>200 m^3 or 260 yd^3) did not occur until 9 to 14 years after North Fork logging and shortly after pre-commercial thinning, at a time when root strength is expected to be near its minimum value and hydrologic changes are once again important (Reid and Keppeler 2012).
- There was little field evidence of sediment delivery from the new spur roads located near ridges in the North Fork watershed during the immediate post-logging period (Lewis et al. 2001), but 14 years after logging such a road was associated with the largest landslide that has occurred in the watershed since the project began in 1961 (Reid and Keppeler 2012, Figure 24A).
- Measured total sediment production from four rocked road segments in the Caspar Creek watershed was less than 1 $kg/m^2/yr$ (1.8 $lb/yd^2/yr$) (Barrett et al. 2012); the net influence of this source in the North Fork is expected to be low since much of the displaced sediment from ridge-top roads is redeposited before reaching a stream channel.
- Significant channel adjustments were documented at several decommissioned South Fork road crossing locations; these inputs are reflected in increased annual sediment yields (Figure 22). Approximately 50% of the total eroded volume measured was produced by only three of the 26 decommissioned crossings (Keppeler et al. 2007). Of the crossings treated in 1998, 90% continued to erode at least 12 years after treatment (Keppeler 2012).
- Preliminary sediment budget calculations for the North Fork suggested that post-logging input of sediment, primarily from landslides and in-channel erosion, exceeded output values between 1991 and 1995, with sediment accumulating along the main North Fork channel (Lisle et al. 2009).

Northwest California's geologic, topographic, and climatic diversity influences the rates and relative importance of various erosion processes in different portions of the Coast Ranges, so erosion rates at Caspar Creek will not be typical of those at many Coast Range sites. However, even at sites where Caspar Creek data cannot be used directly to estimate sediment production rates, information provided by the studies often can be applied to evaluate how erosion sources are likely to be affected by forest management activities. For example, Caspar Creek studies showed that WLPZs and road repair work alone cannot prevent in-channel sediment increases because significant sediment inputs from in-channel sources can be generated by logging-related flow increases (Lisle et al. 2008, Reid et al. 2010). In-channel erosion data from Caspar Creek have been used to address rate-of-harvest issues in THPs from western Mendocino County. Sediment source information has been used in THP Official Responses and during preparation of HCPs, EIRs, and other planning documents. Appendix C illustrates how Caspar Creek data can be used to develop a method to predict logging-related changes in sediment production from in-channel sources.

Stream Temperature

Eleven North Coast watersheds have been listed as temperature-impaired under section 303(d) of the federal Clean Water Act. In the Coast Ranges, concern over the effects of logging on stream temperatures has centered on impacts to species of anadromous salmonids that have been listed as threatened or endangered, and coho salmon (*Oncorhynchus kisutch*) populations are the focus of particular concern (NMFS 2012). Field and laboratory studies show that high water temperatures increase the metabolic rate of salmonids, increase their susceptibility to pathogens, and decrease the amount of oxygen dissolved in water (McCullough 1999). Temperature increases can directly influence salmonid mortality, but they also can have indirect effects by contributing to decreased residence time of fry in gravels; earlier, less favorable timing of smolt migration to the sea (Holtby 1988); and modified abundance and diversity of food organisms. Timber operations may influence stream temperature by reducing streamside shading, changing channel morphology, and altering summer stream flows.

Stream temperatures have been monitored at Caspar Creek during several periods before 1989 and continuously since then. Kabel and German (1967) provide temperature data for the North and South Forks during 1963 and 1964. DeWitt (1967, 1968) describes temperature conditions before and after stream-side road construction along the South Fork of Caspar Creek, where operations were carried out prior to the implementation of modern forest practice rules (Figure 27). In the later North Fork experiment, selection-logged WLPZs were left along channels that support aquatic biota (Figure 28). Cafferata (1990a) and Nakamoto (1998) describe changes in North Fork stream temperatures after clearcutting. Results of these studies show that responses differed between the experiments:

- The road built in 1967 along the South Fork greatly reduced shading, and Hess (1969) reported that maximum summer water temperatures increased by as much as 11°C (20°F) at some sites after road construction.
- After road construction, maximum summer water temperatures in the South Fork frequently rose to near 21°C (70°F), and the highest value observed was 25.3°C (77.5°F) (DeWitt 1968).
- In contrast, maximum water temperatures increased little after North Fork logging (Figures 29, 30) and remained within the range found by Welsh et al. (2001) to be tolerable for coho salmon in another coastal California watershed (Cafferata 1990a, Nakamoto 1998).

Figure 27. South Fork shortly after road construction in 1967; note lack of shading along the channel.

Figure 28. WLPZ buffer strip following logging in the North Fork watershed (IVE tributary at lower left, MUN at upper right). Photograph taken in March 1990.

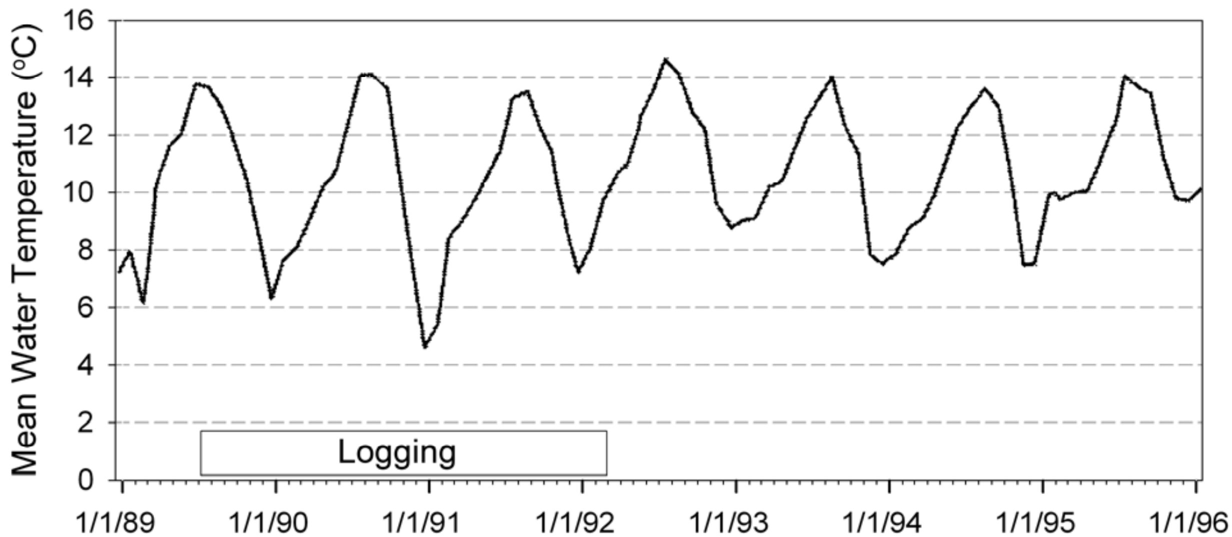

Figure 29. Variation in monthly mean water temperature (1989-1995) at Station ARF, just above the North Fork weir (redrafted from Bottorff and Knight 1996).

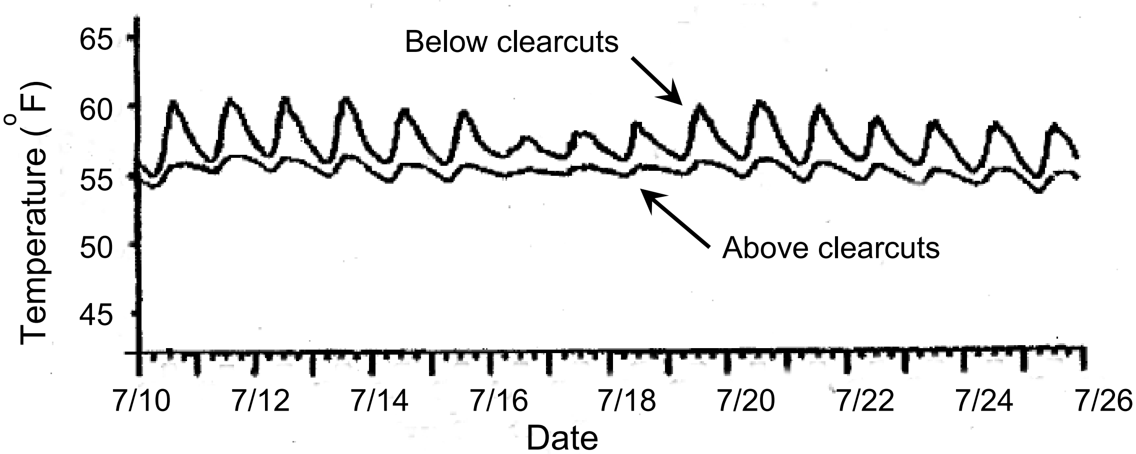

Figure 30. North Fork water temperature above and below clearcut units with a partially harvested WLPZ (Figure 28; maximum difference of approximately 2.2°C or 4.0°F), July 10-25, 1990 (redrafted from Cafferata 1990a).

The Caspar Creek Experimental Watersheds are located near enough to the coast that summer temperatures are moderated by coastal fog, so water temperatures at Caspar Creek have generally not been of as great a concern as those at sites located farther inland.[11] However, results from the South Fork study demonstrate that

[11] Lewis et al. (2000), for example, show that stream temperatures within a “zone of coastal influence” in California are significantly lower than those measured farther inland. Monitoring conducted in the South Fork below the weir, near the confluence with the main stem, showed that the Maximum Weekly Average Temperature (MWAT) ranged from 13.9-15.8 °C (57.0-60.4 °F) during 1996-1998, with an average of 14.6 °C (58.3 °F) (CAL FIRE 2005).

temperature changes can indeed be of concern even in coastal watersheds. Water temperature data from Caspar Creek have been used for validation of a reach-scale water temperature prediction model (Cafferata 1990a), which was used in an RPF guidebook for water temperature prediction that can be used throughout California (Cafferata 1990b). Additionally, Caspar Creek water temperature data have been used in THP Official Responses, the EIR for the Jackson Demonstration State Forest Management Plan, and other planning documents.

Nutrient Cycling

Water quality and long-term forest sustainability are major issues that must be considered when management activities are planned in California's forestlands. There is concern that nutrient losses associated with erosion and leaching after timber operations may compromise the long-term sustainability of forest ecosystems in some settings (Worrell and Hampson 1997, Johnson et al. 1988), and nutrients lost from hillslopes can modify stream chemistry (Dahlgren and Driscoll 1994). Increased nutrient levels in streams can increase algal growth, particularly where near-stream logging has raised stream temperatures and increased light to the water column (Bottorff and Knight 1996). Ewing et al. (2009) demonstrated the role that a redwood forest canopy can play in processing atmospheric nitrogen inputs by rainfall and fog. Sanderman et al. (2008) evaluated organic carbon fluxes in Caspar Creek soils and compared them with those from a coastal grassland, and Sanderman and Amundson (2010) extended the comparison to include CO_2 production.

The impacts of modern harvest practices on nutrient cycling processes have rarely been evaluated in coastal California forests. Kopperdahl et al. (1971) documented nutrient levels in the South Fork after road construction and compared them to those in the North Fork control watershed. Efforts to evaluate nutrient cycling were expanded during the North Fork study, and Dahlgren (1998a,b) measured inputs, storage, and outputs of several kinds of nutrients on forested and logged slopes and at downstream sites. The experimental design for the North Fork study allowed changes in nutrient loads to be tracked downstream through watersheds of increasing size.[12] Results showed:

- Nitrate concentrations increased in streams draining clearcut sub-watersheds, especially during storms with high discharge volumes. However, fluxes were relatively low compared to those reported from studies in other forest ecosystems, and they decreased substantially by the time flow reached downstream sampling points (Dahlgren 1998b) (Figure 31).
- Immobilization of nutrients by the rapid regrowth of stump sprouts appears to make coast redwood forests relatively resistant to nutrient losses from leaching after timber harvest (Dahlgren 1998b).

[12] Although water chemistry measurements were made in both broadcast burned and unburned sub-watersheds, the effects of broadcast burning were not directly evaluated in the North Fork. Limited data showed that major contrasts in response associated with burning were not evident.

- Physical removal of nitrogen, primarily in the harvested boles, resulted in an appreciable loss of nitrogen from the ecosystem (Dahlgren 1998b).
- Losses of nitrogen, phosphorous, and sulfur during and after logging are the nutrient losses of greatest concern for future productivity in this forest type (Dahlgren 1998a).

The work conducted in the Caspar Creek Experimental Watersheds in the mid to late 1990's added greatly to the understanding of nutrient cycling in the redwood region. These results are expected to apply in general terms to other watersheds that support second-growth coast redwood forests. Caspar Creek nutrient data were used to address the nutrient loss issue in the EIR prepared for the Jackson Demonstration State Forest Management Plan.

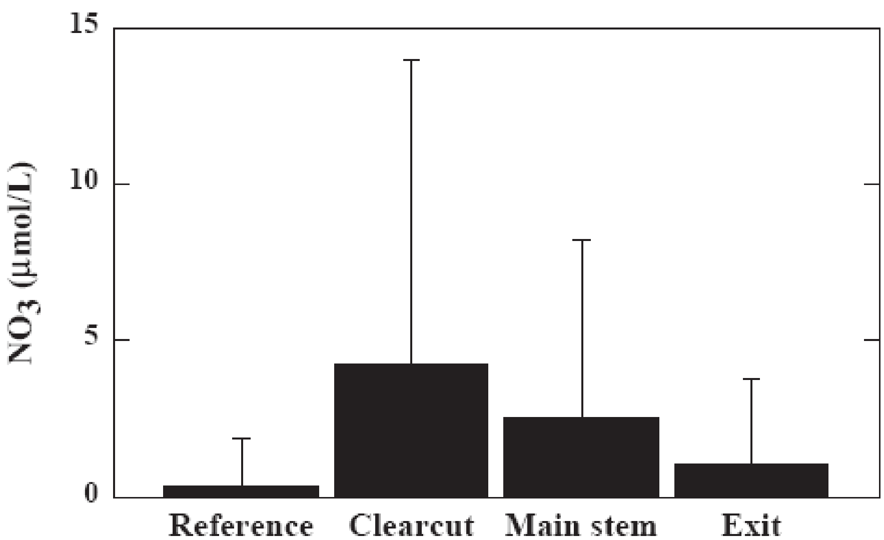

Figure 31. Nitrate concentrations (mean + standard deviation) in streams draining control and clearcut North Fork watersheds, at main-stem locations downstream from harvested basins, and at the ARF gaging station, the exit point for the study (from Dahlgren 1998b).

Inputs of Large Wood to Streams

Research conducted during the past three decades has increased the understanding of the biological importance of large wood in stream channels of the Pacific coastal ecoregion (e.g., Bilby and Bisson 1998), the sources of such wood (e.g., McDade et al. 1990, Benda et al. 2002), its influence on channel morphology (e.g., Keller et al. 1995), and its physical interaction with stream channels of various sizes (e.g., Gurnell et al. 2002, Hassan et al. 2005). Large wood in small coastal streams has been shown to be important for forming pools, providing cover for juvenile fish, storing sediment, and storing organic matter. Wood loading in most fish-bearing coastal streams is currently low due to historic logging practices, extensive stream clearance, and over-harvesting in riparian zones (Wooster and Hilton 2004). Sindel (1960) and Holman and Evans (1964) describe stream clearance plans implemented at sites near Caspar Creek.

Figure 32. Log jam at high flow, North Fork Caspar Creek. Photograph taken in 2003.

Studies at Caspar Creek have documented wood loads in the North (Figure 32) and South Fork channels (O'Connor and Ziemer 1989, Surfleet and Ziemer 1996), the distribution of wood jams in the North Fork (Napolitano 1996, 1998), the sources of in-channel wood (Reid and Hilton 1998, Hilton 2012), and its effects on channels in the North Fork watershed (Lisle and Napolitano 1998). Hilton (2012) describes changes in wood input, storage, and transport through time in the North and South Fork channels. The Caspar Creek studies show that:

- During a period when riparian stands were 80 to 100 years old, loading of large wood in North Fork Caspar Creek was approximately 20 to 30% of that measured in old-growth coast redwood watersheds (O'Connor and Ziemer 1989, Napolitano 1998, Lisle 2002), in part because of the removal of in-stream wood during old-growth logging (Napolitano 1996, 1998).
- Wood loading in the North Fork is similar to that documented by O'Connor Environmental (2000) and Wooster and Hilton (2004) in other streams in second-growth coast redwood forests.
- Primary input mechanisms for large wood volume in the North Fork are windthrow and bank erosion (O'Connor and Ziemer 1989, Surfleet and Ziemer 1996).
- Douglas-fir, grand fir, and alder trees provide the greatest input of large wood in Caspar Creek watersheds (O'Connor and Ziemer 1989, Surfleet and Ziemer 1996, Hilton 2012). Wood from these species decays more quickly than that from redwood.

- After clearcutting in the North Fork watershed, selection-logged buffer strips on inner gorge slopes experienced significantly greater windthrow rates during large storms than did similar unlogged second-growth stands not adjacent to clearcuts (Reid and Hilton 1998).
- Trees that had grown within one tree height of the channel (55 m or 180 ft) accounted for 96% of the wood inputs from fallen trees in buffer strips (WLPZs) (Figure 33), but 30% of these tree falls were triggered by trees falling from farther upslope (Reid and Hilton 1998).
- Post-logging wood inputs in the North Fork provided increased sediment storage and pool volume in the short term. However, decreased wood recruitment capacity and subsequent channel impacts are expected in the long-term (Lisle and Napolitano 1998).

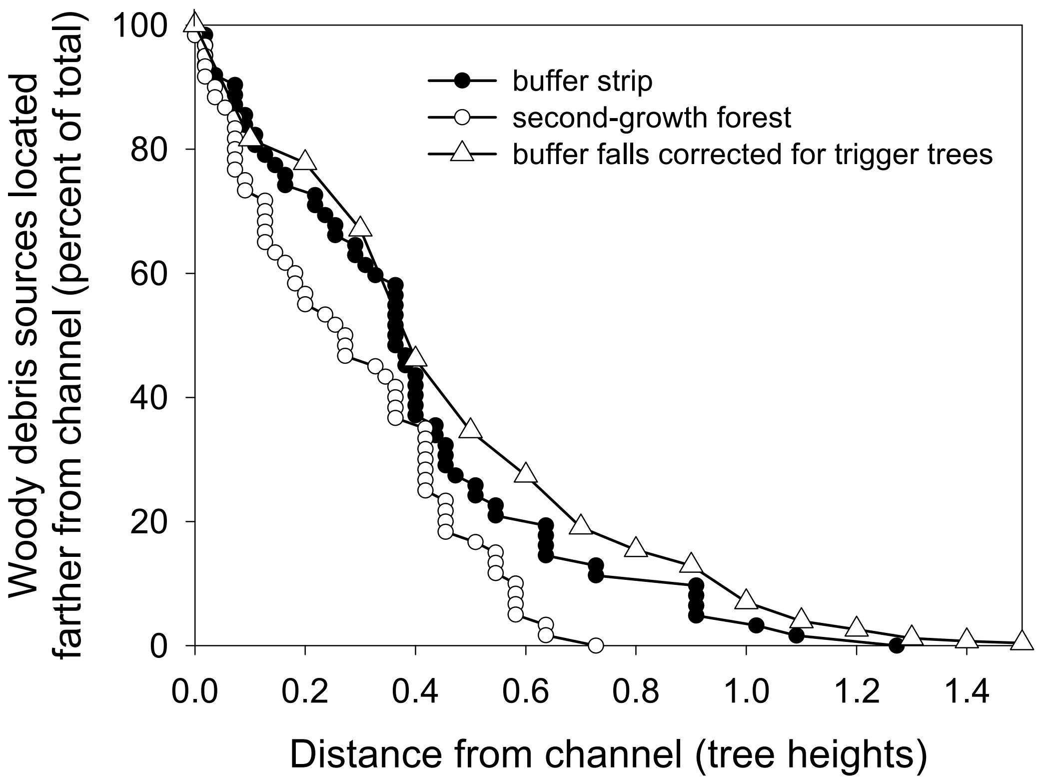

Figure 33. Comparison of large-wood inputs to the North Fork of Caspar Creek from selection-logged buffer strips and from 100-year-old second-growth forest. The curve labeled as “corrected for trigger trees” accounts for inputs from tree falls triggered by trees falling from farther upslope by plotting inputs according to the location of the triggering tree (from Reid and Hilton 1998).

Results of the wood studies at Caspar Creek are expected to apply to streams of similar size and geomorphic setting in the coast redwood region where the history of forest management has been similar. Wood recruitment data from Caspar Creek have been used to inform the design and management of WLPZs and in development of the 2009 Anadromous Salmonid Protection Forest Practice Rules. The wood data were also used during development of the draft aquatic HCP for the Mendocino Redwood Company.

Biological Changes Associated with Logging

The impact of timber harvest on aquatic ecosystems is of considerable concern in the Coast Ranges of California due to the rapid decline of anadromous salmonid species that have been listed as threatened or endangered. In particular, Central California Coast (CCC) coho salmon (Figure 34) are critically at risk of becoming extinct in the near future (NMFS 2012). CCC coho survival in their freshwater environment is poor due to impairment of the habitats needed for egg survival and emergence, juvenile summer and over-wintering rearing, and smolt out-migration. Habitat impairment has been shown to result from many different kinds of influences, including the effects of timber harvesting and roads (Ambrose 2008).

Figure 34. Coho salmon in North Fork Caspar Creek, December 2001.

The quality of in-stream habitat reflects the interacting influences of all the watershed characteristics discussed in previous sections: peak flows, low flows, water yield, hillslope hydrology, fog drip, sediment yield, sediment sources, water temperature, nutrient cycling, and large in-stream wood. Water, sediment, and organic material are routed along stream networks, and as they are transported they interact to modify the form of the channel through which they travel. These influences together form the physical aspects of aquatic habitat, and those, in turn, strongly influence the biological aspects of aquatic habitat. Not only are the biological responses of fish species altered when components of the system change, but the macroinvertebrate communities that supply food organisms for fish also change.

At Caspar Creek, the impacts of timber operations on aquatic biota and their habitat have been studied by researchers associated with federal agencies, state agencies, and universities. Biological studies for the South Fork experiment focused on quantifying the effects of road construction. Kabel and German (1967) studied salmonid populations in the area before experimental treatments began, and Burns (1971) described populations in the North Fork control watershed during 1967 and 1968. Burns (1972) then evaluated the effects of near-stream road construction on steelhead trout (*Oncorhynchus mykiss*) and coho salmon in the South Fork. Valentine et al. (2007) compared salmonid communities documented in 1967-1969 in the South Fork with those studied during 1993-2003. Burns (1970) evaluated changes in spawning gravel quality.

Macroinvertebrate communities provide an important food source for salmonids. DeWitt (1968) described changes in salmonid feeding after South Fork road construction, and Burns (1972) discussed results of a benthos study. Hess (1969) evaluated changes in inputs of macroinvertebrates from the riparian zone and provided some data on benthic macroinvertebrates before and after road construction.

During the North Fork study, biological research focused on evaluating the effects of logging along downstream reaches of the North Fork channel. Until a series of windstorms, the main channel and major tributaries had been well-insulated from the direct influences of clearcut logging by the presence of selection-logged WLPZ buffer strips of up to 61 m (200 ft) width on either side of the channel. Lau (1994) documented habitat usage by young salmonids in the North and South Forks before North Fork treatments began, and Lisle (1989) assessed the susceptibility of North Fork spawning redds to impacts from sediment deposition and scour. Nakamoto (1998) then evaluated the effects of North Fork timber operations on coho, steelhead, and Pacific giant salamanders (*Dicamptodon tenebrosus*). Cafferata et al. (1989) and Rodriguez and Jones (1993) described interim salmonid monitoring results, and Gallagher and Gallagher (2005) and Gallagher et al. (2010) estimated salmonid escapement for the system on the basis of redd counts. Harvey and Nakamoto (1996) evaluated interactions between coho and steelhead, and Wilzbach et al. (2009) described associations between sediment characteristics, salmonid feeding, and benthic communities. Bottorff and Knight (1996) described results from a study of changes in algal biomass, leaf decay, and macroinvertebrate density and diversity after North Fork logging. Several conclusions can be drawn from the biological studies as they relate to the effects of road-building and logging:

- Salmonid populations decreased immediately after road construction in the South Fork, but recovery began the following spring, and by the second spring, the salmonid biomass was only 20% lower than before disturbance (Burns 1972).
- Long-term fish monitoring in the South Fork showed lower variance in autumn salmonid densities during 1993-2003 compared to the three years following road construction, and revealed a shift from salmonid communities in which coho salmon and steelhead trout were both well-represented to ones dominated by single species (Valentine et al. 2007) (Figure 35).
- Riparian insect drop increased significantly after the riparian South Fork road was built (Hess 1969).
- North Fork logging did not induce significant changes in abundance of steelhead trout (Figure 36), coho salmon, or Pacific giant salamander (Nakamoto 1998).

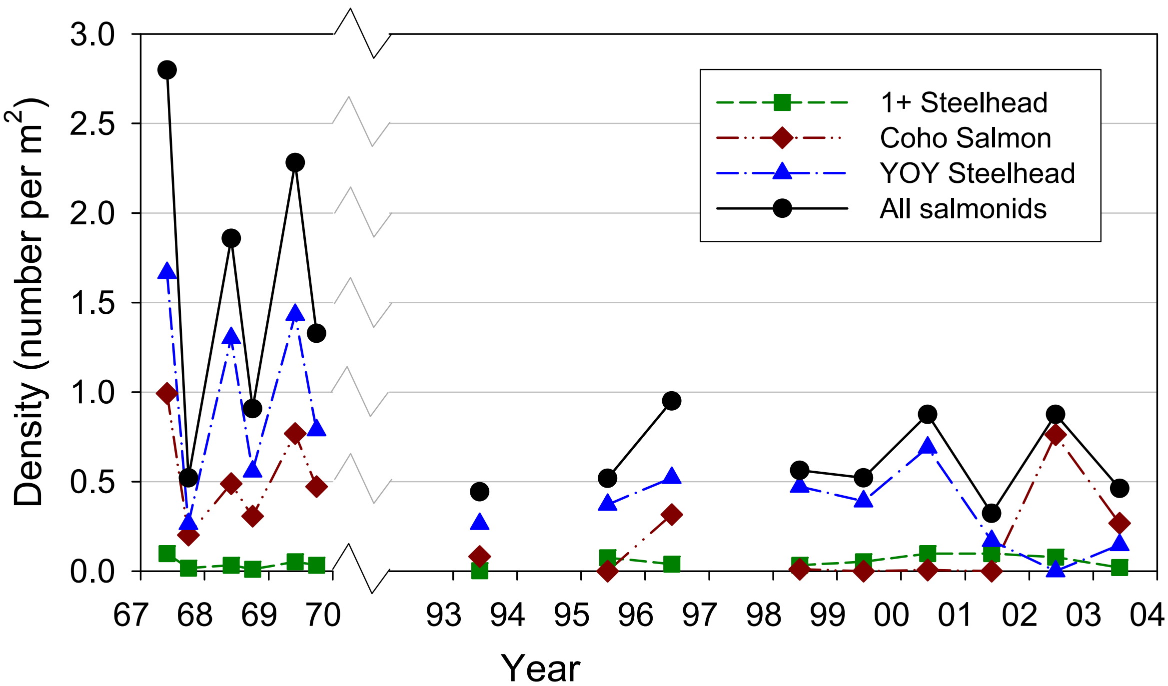

Figure 35. Density of salmonids in the South Fork, 1967 to 1969 and 1993 to 2003 (redrafted from Valentine et al. 2007).

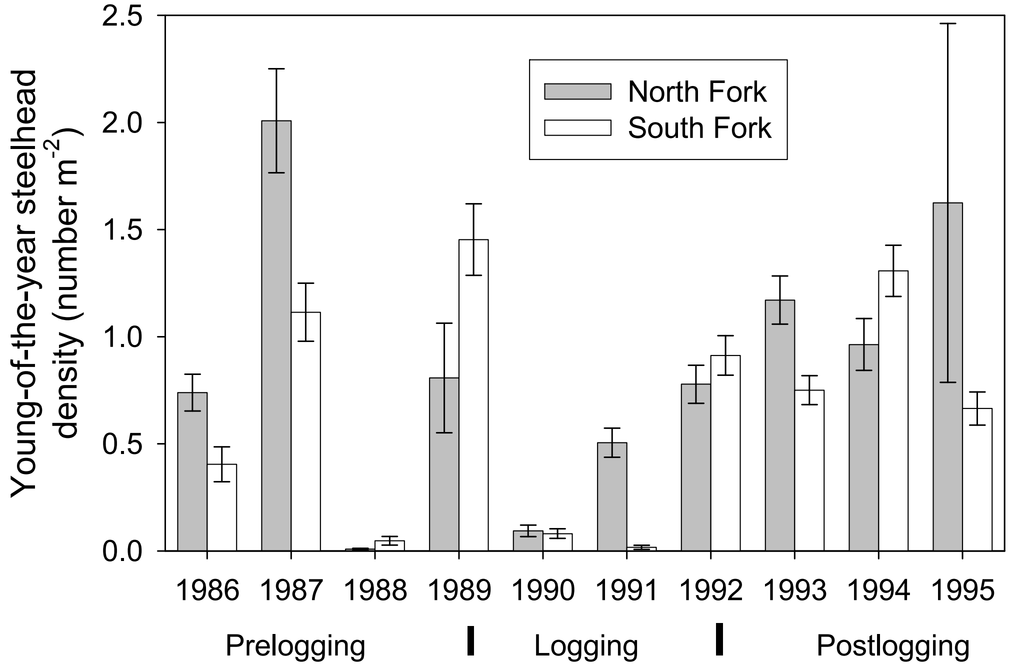

Figure 36. Mean and standard error for annual abundance of young-of-the-year steelhead in the North and South Forks (from Nakamoto 1998).

- North Fork logging was followed by increases in overall macroinvertebrate density and diversity and in the amount of stream algae; these changes likely reflect increased light, nutrient, and temperature levels (Bottorff and Knight 1996).
- Altered sediment loads along the main stem of the North Fork appear to have had little effect on macroinvertebrates, leaf decay rates, and algae (Bottorff and Knight 1996).

While general principles learned at Caspar Creek regarding changes in fisheries and macroinvertebrates can be applied elsewhere in the northern part of the Coast Ranges, extrapolation of specific data is not possible due to the importance of watershed-specific controlling factors such as flow regimes, the distribution and quality of local spawning and rearing habitat, and the distribution of migration barriers.[13] Caspar Creek biological data have been used to address aquatic biological issues in the EIR for the Jackson Demonstration State Forest Management Plan.

Cumulative Watershed Effects

The California Environmental Quality Act (CEQA) specifies that plans for projects requiring California state permits (including plans for commercial timber harvesting on non-federal timberlands) must address cumulative impacts. The key determination for CEQA cumulative impact analyses is whether project impacts, in combination with those of past and anticipated future projects, will accumulate over time or space to create significant impacts. The California Forest Practice Rules (FPRs) specify that the following subjects must be considered in a cumulative impacts assessment for a THP: watershed resources, soil productivity, biological resources, recreational resources, visual resources, and traffic impacts. Guidelines in FPR Technical Rule Addendum No. 2 for assessing cumulative impacts related to watershed resources state that RPFs must address the effects of proposed timber operations on sediment, water temperature, organic debris, chemical contamination, and peak flows. Causes of cumulative watershed effects (CWEs) in forested watersheds can include legacy effects (from early logging, road construction, and stream clearance practices), natural disturbances (e.g., wildfires, floods, earthquakes), timber operations, urbanization, wildfire control activities, fuel hazard reduction projects, grazing, mining, agriculture, water diversions, recreation, and off-highway vehicle use.

Analysis of CWEs is a complex task (Reid 1993). Effective assessment methods were not in wide use in California by 2001, when Dunne et al. (2001) reported that the commonly used methods were inadequate because information provided in THPs was too subjective to assess current resource conditions or the potential for additional impacts. Methods used by RPFs have changed little since then, so the problem still persists today. Reid (2010) described the kinds of analysis strategies available and summarized the shortcomings that have resulted in litigation over CWE

[13] Ocean conditions can also strongly influence coho populations utilizing watersheds in the California Coast Ranges (NMFS 2012), but in that case influences are experienced over broad areas.

analysis. Recent progress in California toward development of more effective methods for evaluating CWEs is taking place on several fronts: (1) new research provides a better understanding of how land-use activities affect watershed processes (e.g., Coe 2006, Reid and Lewis 2009, Reid et al. 2010); (2) studies are showing how different kinds of land-use-related changes can interact to affect resources or conditions of concern (e.g., Harvey and Railsback 2007, Cover et al. 2008, Wilzbach et al. 2009); and (3) methods are being developed that are capable of accounting for spatially distributed inputs (e.g., Carr 2006, Benda et al. 2007, Litschert 2009).

The North Fork Caspar Creek experiment was designed as a study of cumulative watershed effects. In a departure from earlier experimental watershed studies in the western US, an array of nested gages was deployed across the watershed to allow the hydrologic and sediment responses to logging to be tracked through watersheds of increasing size (Figure 9). Progressive downstream changes thus could be quantified as influences decreased, accumulated, or interacted along a sequence of increasingly large catchment areas.

The North Fork study design permitted new types of conclusions regarding the nature of CWEs. Study results compiled by Ziemer (1998a) summarize the short-term effects of North Fork timber operations on a variety of watershed responses, and Lewis et al. (2001) evaluated the influence of watershed scale on changes in flow and sediment loads. Reid (1998), Lewis et al. (2001), Carr (2006), Lisle et al. (2009), and Reid et al. (2010) describe pathways by which upslope forest management activities at Caspar Creek were found to induce downstream responses. These studies demonstrated multiple ways that logging-related influences interacted to affect the watershed responses:

- Post-logging changes in peak flow and storm flow varied with the proportion of each North Fork sub-watershed logged, irrespective of watershed size; these changes were effectively additive (Lewis 1998, Lewis et al. 2001).
- Sediment load increases were initially correlated with flow increases after logging (Lewis et al. 2001).
- Through time, sediment yields showed a wider variety of responses than did flow, reflecting both the distribution of particular sediment sources and the interactions among various kinds of local influences on sediment transport and storage (Lewis et al. 2001, Lisle et al. 2009, Reid et al. 2010).
- Logging-related influences induced different kinds of channel response in different parts of the channel system: (1) first-order channels grew headward due to increased flow, increasing the drainage density; (2) low-order channels incised and widened due to increased flow; and (3) higher-order channels aggraded due to the combined effect of increased sediment inputs from upstream sources and increased wood inputs from blowdown in the WLPZs (Lisle et al. 2009, Reid et al. 2010) (Figure 37).
- The two largest post-logging landslides occurred soon after pre-commercial thinning, suggesting that the effect of renewed hydrologic change combined with that of reduced root strength—which at that time would be near its minimum value after logging—to destabilize slopes (Reid and Keppeler 2012).

- Legacy sediment sources from old-growth logging remain important: after North Fork logging, 29% of the sediment volume from streamside landslides originated at skid roads or a splash dam dating from the 1800's (Reid and Keppeler 2012). Recent sediment production from landslides in the North Fork watershed thus reflects the cumulative influence of two logging entries.
- Old-growth logging activities of the 1800's appear to have produced lasting channel impacts, including channel incision, simplification of channel form, reduction in sediment storage capacity, and greatly diminished wood loading rates (Napolitano 1998). These legacy effects can influence the system's response to modern timber operations.
- Long-term responses to modern timber operations may ultimately be as important as short-term responses, but are difficult to predict (Ziemer et al. 1991). For example, unanticipated deterioration of the South Fork road network led to renewed sediment inputs more than a decade after sediment yields had returned to pre-treatment levels (Keppeler 2012).

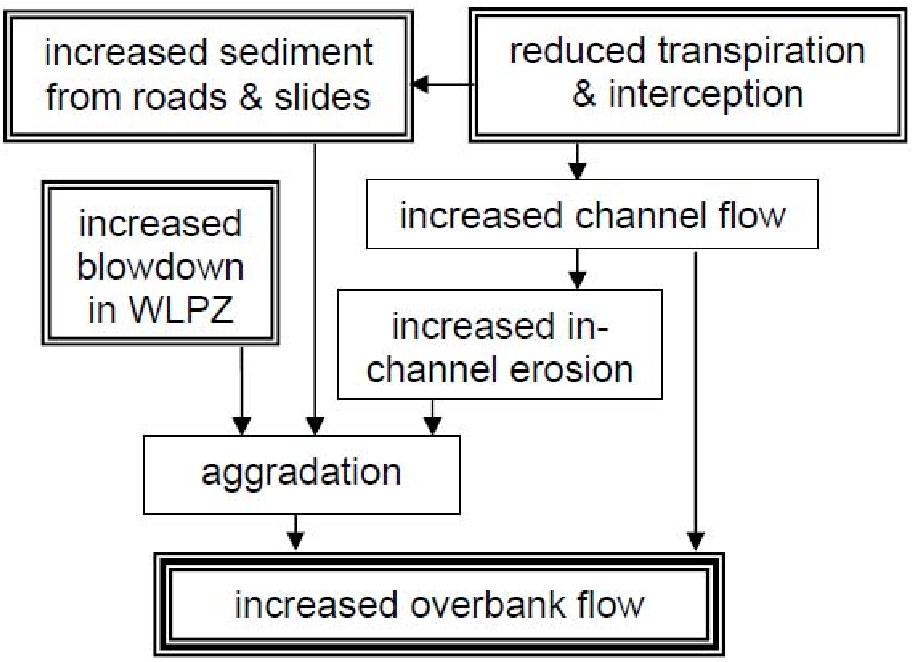

Figure 37. Some of the interactions among logging-related changes in hydrology, hillslope erosion processes, and clearcut-margin blowdown that can lead to altered regimes of overbank flow at downstream sites along the North Fork of Caspar Creek.

By revealing the kinds of interactions that can modify downstream responses to upslope activities, research conducted in the North Fork Caspar Creek watershed provides insight into how modern forest practices can be assessed for CWEs. The general principles learned at Caspar Creek regarding CWEs can be applied elsewhere in forested parts of the Coast Ranges, and some of the results can provide a basis for understanding effects in any temperate, rain-dominated forest. Caspar Creek CWE results have been used in the development of the EIR for the Jackson

Demonstration State Forest Management Plan and in assessment of THPs submitted for approval by CAL FIRE.

Development of New Monitoring Technology

Instrumentation for monitoring sediment, flow, and temperature at Caspar Creek has changed greatly over the past 50 years. During the first experiment, stream-flow stage was monitored with strip-chart recorders mounted on stilling wells, and sediment data was collected through 1975 primarily with fixed-stage samplers mounted on the upstream face of the concrete gaging weirs. Fixed-stage samplers can sample flow only during rising limbs of storm hydrographs. Automatic pumping samplers installed in 1976 expanded the sampling range by permitting sample collection during both rising and falling stages, allowing more accurate estimation of sediment loads. Several algorithms for triggering the pumping samplers were tested (Henry 1998), and by 1985 an efficient probability-based sampling protocol had been designed (Thomas 1985, 1989; Thomas and Lewis 1995). Station equipment was upgraded at the start of the North Fork experiment to implement the new protocol, which was based on an algorithm that increased the probability of sample collection at higher flows. The new equipment consisted of a portable computer, interface circuit board, pressure transducer for stage measurement (along with a strip chart recorder as back-up), and pumping sampler (Figure 38). Throughout both the South and North Fork studies, water samples collected using depth-integrating manual samplers (such as the DH-48) have supplemented those provided by automatic water samplers.

The installation of recording turbidimeters allowed testing of new sediment sampling strategies and resulted in development of the Turbidity Threshold Sampling (TTS) method, with full deployment in water year 1996 at eight North Fork stations (Lewis 1998). The new method greatly improved sediment yield estimates while at the same time reducing the number of water samples necessary for accurate load estimation (Lewis 1996). TTS uses real-time turbidity and stream discharge data to trigger automatic collection of water samples, which are then used to construct storm-based calibrations between turbidity and suspended sediment concentration at each gaging station. Concentrations can then be estimated from the turbidity record, which provides data at 10-minute intervals. Required equipment consists of a programmable data logger, a recording in-stream turbidimeter (Figure 39), a pumping water sampler, and a pressure transducer for measuring water stage.

Development and implementation of the TTS method is described by Lewis and Eads (2001), Eads and Lewis (2003), and Lewis (1996). A comprehensive manual has also been prepared that describes required instrumentation, field procedures, software, data collection, laboratory methods, and data analysis (Lewis and Eads 2009). The TTS monitoring technology designed at Caspar Creek is being used by agencies, non-profit organizations, and private companies at an increasing number of sites in California (Harris et al. 2007) and elsewhere.

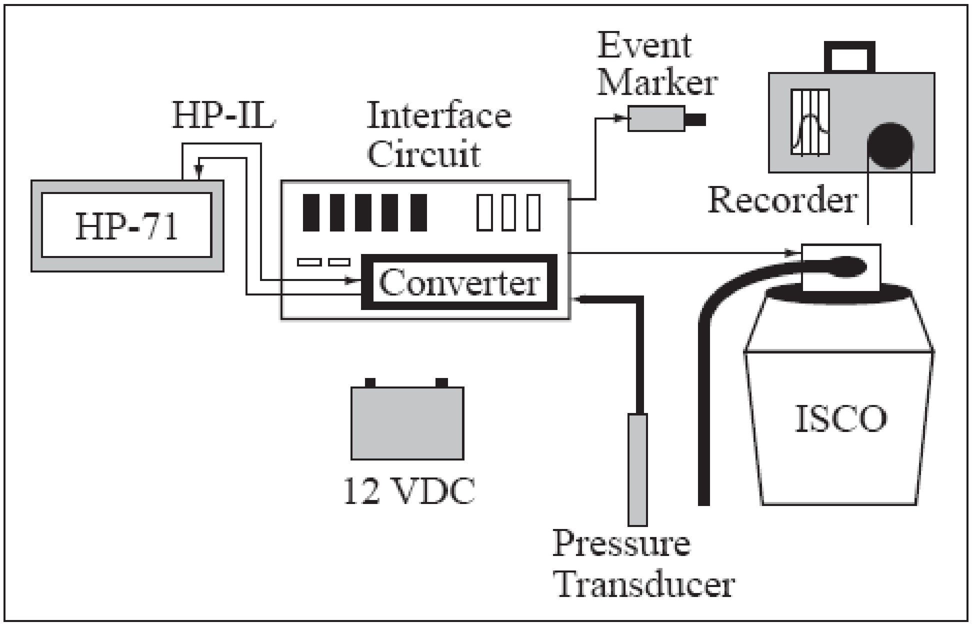

Figure 38. Equipment used at Caspar Creek at the beginning of the North Fork experiment in 1985 (from Henry 1998). The HP-71 is a portable calculator/computer, the HP-IL is an interface loop for device connections, the ISCO is an automatic pumping sampler, and the 12VDC is a 12-volt battery.

Figure 39. Turbidimeter on a cable-mounted boom, North Fork Caspar Creek (ARF gaging station).

IV. IMPLICATIONS FOR MANAGEMENT

Results of Caspar Creek research hold implications for many aspects of forest land management in northwest California and beyond. As the types of watershed response to management activities are documented and their causes understood, it becomes increasingly possible to design land-use activities to be compatible with other resource-based activities and values. Caspar Creek study results suggest possible management strategies that may reduce the potential for environmental conflicts (Table 3), particularly for areas with similar climatic, geomorphic, and ecological conditions.

Table 3. Potential management strategies to address implications of selected Caspar Creek study results.

Topic	Research Result	Potential Management Strategy
Peak Flows	Post-logging peak flows increase even during large storms due to reduced rainfall interception and transpiration.	Measures to reduce hydrologic change may include (1) planning forest management strategies at a watershed scale to maintain high enough interception and transpiration rates to limit peak-flow changes (see Appendix A); and (2) using silvicultural methods (such as single tree or group selection harvest) that maintain canopy.
Low Flows	An initial increase in summer flow after selection logging is followed by a longer-term reduction in summer flow as the forest regrows.	Use an appropriate mixture of silvicultural systems and timing of operations to avoid altering dry-season flows where possible. For example, new selection logging might be timed to superimpose the period of greatest flow increase on that of maximum flow reduction from earlier selection logging, reducing the overall impact on summer flows downstream.
Annual Runoff	Because most of the logging-related increase in annual water yield occurs during the storm season, little of the increase augments water supply during seasons of high water demand.	Use of logging to increase water supply for public consumptive use is not likely to be feasible in rain-dominated coastal watersheds without water storage facilities.
Hillslope Hydrology	Subsurface soil pipes and tunnels were found in many unchanneled headwater swales. These forms are vulnerable to collapse under loading, potentially connecting hillslope erosion sources more directly with the open channel network.	Minimize heavy-equipment use in unchanneled swales.
Hillslope Hydrology	Altered interception and transpiration can increase pore pressures on hillslopes after logging, thus influencing landslide incidence even when significant root cohesion is preserved in coast redwood forests.	The potential for logging-related increases in landsliding should be considered in coast redwood forests, and marginally stable areas should be evaluated by a qualified expert in slope stability where appropriate (see DMG 1999).[14]

[14] On state and private timberlands in California, the qualified expert would be a Professional Geologist licensed to practice geology in California.

Topic	Research Result	Potential Management Strategy
Fog Drip	At locations similar to Caspar Creek, reduction in fog drip after logging is not sufficient to offset large short-term increases in dry-season flow due to reduced interception and transpiration.	The potential for hydrologically significant altered fog drip varies with location, but may not be large away from coastal windy ridge locations.
Sediment Yield	Initial post-logging recovery of sediment yields can be followed by longer-term sediment increases as improperly located and poorly maintained roads deteriorate.	Provide adequate long-term road maintenance and upgrading; decommission unneeded roads.
Sediment Yield	Although useful for reducing long-term sediment inputs, road decommissioning can provoke temporary increases in sediment input as restructured channel crossings readjust.	Consider staging or sequencing sediment-producing activities to avoid superimposing multiple sediment inputs. Carefully inspect decommissioned crossings to ensure that prescribed excavation depths and widths are reached and streambanks are sloped back. For larger crossings, use grade control where appropriate.
Channel Erosion	In-channel erosion can be accelerated by logging-related increases in flow.	In-channel erosion cannot be adequately managed simply by maintaining riparian buffer strips, though these are important for reducing direct disturbance to channels and providing bank stability. Measures to control logging-related hydrologic change also contribute to control of in-channel erosion (see entry for "peak flows," above). Such erosion can also be reduced by placing equipment limitation zones (ELZs) around headwater streams and swales to ensure that subsurface drainage is not disrupted and that headwater channel extension does not encroach on disturbed areas.
Surface Erosion	An increase in drainage density that occurs as a result of increased flow after logging may extend surface flow into previously unchannelled swales, thereby establishing hydrologic connectivity between disturbed sites and the channel network.	Consider potential expansion of the drainage network following logging when designing equipment limitation zones (ELZs) intended to reduce sediment inputs from areas disturbed by timber operations.
Landslides	Landsliding may respond more to the combined influences of roading and logging than to either influence acting alone.	Marginally stable features along existing roads may become susceptible to landsliding when adjacent slopes are logged. Ensure that roads are properly drained away from potentially unstable features and that drainage controls are maintained; sites may need to be evaluated by a qualified expert in slope stability[14] (see DMG 1999).
Landslides	If pre-commercial thinning occurs at a time when root cohesion has reached a minimum after logging, the combined effects of increased wetness and decreased soil strength might reduce slope stability.	Consider this effect when planning pre-commercial thinning at marginally stable sites; sites may need to be evaluated by a qualified expert in slope stability[14] (see DMG 1999).

Topic	Research Result	Potential Management Strategy
Stream Temperature	Stream temperatures can increase to undesirable levels even in near-coastal zones, but maintenance of a well-stocked riparian buffer strip can help to prevent biologically significant increases.	Riparian buffer strips (WLPZs), as mandated by the California Forest Practice Rules, are important for stream temperature control even near the coast.
Large Wood	In second-growth redwood forests, streams that currently have low levels of large-wood loading are likely to remain deficient in wood for many decades due to the combined effects of past wood removal and young riparian stand ages.	Manage riparian stands with wood provision as one of the primary goals in coastal watersheds.[15] In areas with inadequate wood loading, active riparian management (e.g., thinning from below, planting, addition of large wood) should be considered if it will more rapidly improve aquatic habitat conditions.
Cumulative Watershed Effects	Changes in peak flows or water yield appear to be additive for watersheds of up to at least 500 ha (1,200 ac).	Likely peak-flow changes at these scales can be estimated from the proportion of the watershed logged and the silvicultural method used. The method described in Appendix A can be used to evaluate potential peak-flow changes in watersheds similar to Caspar Creek.
Cumulative Watershed Effects	Erosional features persisting from decades-old logging can remain important sources of sediment at the time of the next entry, and hydrologic changes caused by the modern logging may interact with these legacy features.	Correct significant existing and potential sediment sources to accelerate recovery and to offset impacts from new projects. Consider the rate and extent of recovery from earlier activities when planning the timing and intensity of new harvesting.

V. CONCLUSIONS

The Caspar Creek Experimental Watersheds have provided a wealth of data that have been used over the past 50 years to help evaluate and understand the environmental impacts associated with timber harvest activities in coastal forests of northern California and elsewhere. Results from Caspar Creek are used regularly by state and federal agencies charged with regulating forestry practices, particularly in regard to how practices impact aquatic habitat for state and federally listed fish species. Additionally, private consultants, timber companies, citizens' organizations, and university researchers routinely reference Caspar Creek research studies and utilize data from Caspar Creek (O'Connor 2003). The Caspar Creek Experimental Watersheds have provided the data needed for diverse studies carried out at regional, national, and international scales (e.g., Naranjo et al. 2012, Klein et al. 2012, Jones et al. 2012).

[15] Managing riparian zones for improved recruitment of wood from large conifers is usually an important objective, but this may not be the only goal associated with riparian management. Riparian forests containing a mixture of both conifer and hardwood species provide for multiple riparian functions, including large wood recruitment, stream shading, and inputs of leaf litter and nutrients. Past research suggests that, at appropriate locations, active riparian management that provides an appropriate mixture of conifers and hardwoods can enhance primary productivity that promotes fish production (Liquori et al. 2012).

Even as Caspar Creek research results are being applied to address forest management issues, research in the experimental watersheds continues. Monitoring is continuing to reveal new information about long-term responses to tractor-yarded selection logging of the early 1970's in the South Fork. We will soon know whether low-flow effects have recovered to pre-treatment conditions, and whether sediment yields have returned to background levels. Long-term peak-flow responses are now being evaluated by adapting the recently developed strategies for analyzing summer flows in the watershed. Past analyses have focused primarily on suspended sediment loads, but analysis of weir-pond sedimentation is now underway, and this will allow the eventual evaluation of long-term trends in total sediment load. On-going measurements of channel cross sections, pool volumes, fine sediment deposition (V*), and woody-debris distribution will permit evaluation of some of the long-term influences of the 1970's logging on aquatic habitat.

Monitoring also continues in the North Fork. Here, too, the long-term patterns of recovery are becoming evident, but in this case the effects of pre-commercial thinning are superimposed on responses to the 1989-1992 clearcutting. Over the next several years, analysis will focus on distinguishing between the effects of these two management activities on sediment and flow and on evaluating their cumulative effect. Analysis of weir pond sedimentation will be particularly informative in the North Fork, where it will be used to help complete an evaluation of spatially distributed sediment budgets for the watershed before and after logging.

Preparation for a third major experiment began in 2000 with installation of 10 gaging stations in the South Fork watershed. An initial treatment was carried out in fall of 2011 with rehabilitation of a mid-slope road in the upper part of the watershed. Future treatments will allow evaluation of interactions between rehabilitation activities and modern logging practices; and monitoring of erosion on hillslopes, along skid trails, and in tributary channels will provide information on interactions between the effects of new logging and the conditions produced by logging during the 1970's.

Although California's forest practice rules are modified every year, and preferred silvicultural strategies can undergo extreme shifts from decade to decade, the value of long-term research results transcends the shifting practices. At Caspar Creek, results of a 40-year-old experiment on selection logging in the South Fork now speak directly to today's emphasis on selection logging in most of the redwood region. Hydrologic recovery from the 1970's selection logging is now far enough along that today's measurements provide information needed to predict the long-term hydrologic effects of current selection logging plans. Much of the hydrologic response reflects the proportion of the canopy removed rather than the forest practices in use during logging. In addition, the basic understanding of runoff generation and sediment production processes that the Caspar Creek experiments have provided can be applied to better understand the likely outcomes of any suite of forest practices, even as practices are improved through time. When studies produce improved understanding of how effects occur, rather than simply quantifying the magnitude of effects, results can be applied to a range of problems, conditions, and locations far beyond those of the original study.

The Caspar Creek studies represent a long-term commitment between state and federal agencies to further the understanding of influences of forest management activities on watershed-based resources and downstream environments. CAL FIRE and the US Forest Service PSW Research Station have agreed to continue the cooperative Caspar Creek watershed study at least through 2099 under the aegis of a jointly signed 100-year Memorandum of Understanding (CAL FIRE and USFS PSW 1999). Long-term watershed records are critical for understanding rates of recovery and for identifying interactions between different kinds of short- and long-term environmental changes. As population pressures increase in California, sustainable forest management will increasingly rely on the strong scientific foundation provided by long-term field measurements in instrumented watersheds.

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VIII. APPENDICES

Appendix Tables

Appendix Figures

INTRODUCTION TO THE APPENDICES

Most of the applications we have described for information from Caspar Creek involve the direct use of results in support of planning for particular timber harvest operations in the northern and central parts of the California Coast Ranges. For example, results may be quoted in a discussion of the relative importance of fog drip, or low-flow data might be used to estimate likely minimum flows in a similar watershed. However, Caspar Creek data can also be used to aid in development of analytical tools that can be applied to address issues of concern across broad areas. These appendices present five such applications, each illustrating a different approach to use of Caspar Creek data.

Appendices A, B, and C together illustrate how Caspar Creek data and results at different stages of study completion can be used to develop assessment tools. Appendix A describes a method for estimating peak-flow change that has been in use for over a decade. This approach is based on a published analysis of a complete data set from North Fork Caspar Creek. In many cases, however, problems must be addressed before data collection is complete, and Appendix B illustrates how published interim results from the South Fork study might be used to estimate changes in summer flow after logging. Appendix C builds from an even earlier stage in study completion, showing how a preliminary method for estimating changes in in-channel sediment production can be developed directly from available data. Together, these three appendices demonstrate the potential for making use of the range of data and results available at any time from Caspar Creek studies.

Appendices A, B, and C first outline the conceptual basis for the method, then list the assumptions necessary for its valid application. A qualitative estimate of the strength of each of the assumptions is provided. The application method is then outlined, and an example of its use is shown.

Appendices D and E consider a different type of problem. Many kinds of methods have been developed at a variety of locations, and it is often desirable to adopt some of them for application at new sites. However, application of a method to a new site introduces uncertainty over how well the method actually performs under the new conditions. Appendix D illustrates the use of Caspar Creek data for testing the accuracy of several peak-flow estimation methods when applied under Coast Range conditions. Appendix E then shows how the data can be used to calibrate and then validate one of the models tested in Appendix D.

APPENDIX A. PEAK-FLOW CALCULATION

Where geologic and hydrologic conditions are similar, peak-flow results from the North Fork Caspar Creek study can be extended to other forested watersheds in rainfall-dominated portions of the California Coast Ranges. A regression equation was developed from the North Fork Caspar Creek dataset to predict changes in peak flow after logging (Lisle et al. 2000, Lewis et al. 2001) and has been used for over 10 years to make peak-flow assessments for THPs, watershed assessments (e.g., Salminen 2003), and other planning documents. In this appendix, we describe how this equation can be used to estimate changes in peak flows in coastal watersheds with conditions similar to those found at Caspar Creek.

Goal: Estimate the change in peak flows that would result from a logging entry (excluding changes associated with road, landing, and skid trail construction).

Suitable conditions for application: Rain-dominated coast redwood – Douglas-fir forests that have previously been logged. Applications are expected to be most reliable for watershed areas of 10 to 473 ha (25 to 1,169 ac), the range tested at Caspar Creek.

Assumptions:

1. Changes in peak flows can be predicted at the watershed of interest using the equation presented by Lewis et al. (2001) and applied by Lisle et al. (2000) *[strength of assumption: reasonable for the coast redwood belt, where vegetation and climate are similar to those at Caspar Creek].*
2. A watershed's peak-flow response to a partial harvest (e.g., single tree or group selection) is similar to that expected for a clearcut harvest with the same proportional canopy reduction in the watershed (Lewis and Ziemer 1999) *[strength: reasonable as an upper bound; a lower bound can be estimated by assuming the response for selection logging is about 60% of that expected for clearcutting (Reid 2012)].*
3. In clearcut watersheds, recovery occurs in approximately 11 years without subsequent treatments (e.g., pre-commercial thinning) *[strength: reasonable; data from Caspar Creek (Figure 14) suggest that by 11 years after logging, any residual peak-flow effect is expected to be less than about 15% of the initial response].*
4. Recovery rates for partial harvests are similar to those for clearcut harvests *[strength: reasonable on the basis of peak-flow results from the South Fork Caspar Creek experiment].*
5. Peak-flow changes from multiple units within a watershed are additive *[strength: reasonable on the basis of peak-flow results from the North Fork Caspar Creek experiment, although the equation presented by Lewis et al. (2001) shows a slight synergistic effect].*

Analysis Strategy:

1. Identify the analysis area.

2. Identify acreages and silvicultural systems for areas logged during the 12 years prior to the logging entry to be analyzed, and identify the area and silvicultural system planned for the proposed project.
3. Calculate equivalent canopy removal for each entry in the 12-year period, and for the entry to be analyzed.[16] The area of equivalent canopy removal for each THP can be estimated by assuming that 100% of the canopy is removed by clearcutting and rehabilitation cutting; 75% by seed-tree and shelterwood removal; and 10 to 50% by selection cutting and commercial thinning (i.e., 10% for a very light WLPZ selection, 30% for light selection, and 50% for typical selection harvest). These estimates can be refined if more detailed information is available for specific THPs based on canopy measurements made in previously harvested areas where similar logging has occurred.
4. Select the peak-flow recurrence interval to be analyzed (range of 1 year to 10 years).
5. Use a form of the regression equation presented by Lewis et al. (2001) to calculate the expected value for the change in peak flows of a given return interval:

$$E(r) = \exp\{[1 + B_2(t-1)]c[B_4 + B_5 \ln(y_c)] + B_6 \ln(w)\} \quad \text{(A1)}$$

where:

E(r)	The expected ratio between an observed peak flow of a given return interval and the flow expected without a logging effect
B_2	Logging recovery coefficient (-0.0771)
t	Number of summers since logging
c	Proportion of the watershed logged (calculated in terms of equivalent canopy removal)
B_4	Constant (1.1030)
B_5	Storm size coefficient (-0.0963)
y_c	Expected mean of peak discharges at control watersheds in Caspar Creek for a flow with the selected return interval (for a 2-yr return period, this is 0.0073 $m^3s^{-1}ha^{-1}$; other values are shown in Table A.1).
B_6	Watershed wetness coefficient (-0.2343)
w	Watershed wetness index (Caspar Creek data suggest that 50 is appropriate for dry soil conditions, 304 for average conditions, and 600 for wet conditions)

If a cumulative assessment is being conducted, carry out the calculation for each of the entries, using values for *t* that reflect the number of summers between an entry and the year for which the result is to be reported (e.g., if the answer is desired for the 2015-2016 winter and there was a prior entry in spring of 2011, *t* = 5 for that entry). Since the peak-flow change is caused in part by reduced

[16] If a cumulative impact assessment is being undertaken, consider the impacts of past harvesting going back 12 years. If there is only interest in determining the impact of the current project on peak flows, only the impacts expected from the canopy changes associated with the current logging entry are analyzed.

Table A.1. Mean of peak flows at North Fork control watersheds HEN and IVE for various return intervals.

Return interval (yr)	Mean of flows at HEN and IVE ($m^3s^{-1}ha^{-1}$)
10.0	0.01128
5.0	0.00985
3.0	0.00783
2.5	0.00755
2.0	0.00731
1.75	0.00672
1.5	0.00559
1.25	0.00497
1.0	0.00322

summer transpiration after logging, the equation slightly overestimates the initial response if calculations are made for a date before at least one post-logging summer has passed. It may be appropriate to select t = 0 to provide a reliable upper bound for the estimated response.

6. Sum the percentage changes from each of the entries to estimate the total percentage change expected in the target year, relative to background conditions expected in a coast redwood forest that is approximately 100 years old. The proportional change due to the proposed plan can then be reported both on the basis of its individual influence relative to background conditions and with respect to its contribution to changes already caused by previous recent entries, if desired.

Example

A Timber Harvesting Plan (THP) under review proposes to selectively harvest 204 acres of second-growth coast redwood forest in the 1,791 acre Lompico Creek watershed in Santa Cruz County (Figure A.1). The THP proposes a light selection harvest, with an average canopy reduction of 30% in the main harvest units and approximately 10% in the WLPZs (Cafferata 2001). In this case, we will first assume that no timber harvesting has occurred within the previous 12 years in the basin. We want to estimate the expected change in winter peak flows having a return interval of 2 years, and we will make the calculation for the 2001-2002 winter following logging in the spring of 2001.

1. Calculate the equivalent canopy removal for the THP area.

According to the plan, 15% of the THP is in Class I and II WLPZs (Figures A.1 and A.2), and 85% is in the main harvest unit, so

0.15 x 204 ac = 30.6 ac of the THP are in the WLPZ
0.85 x 204 ac = 173.4 ac are in the main harvest unit

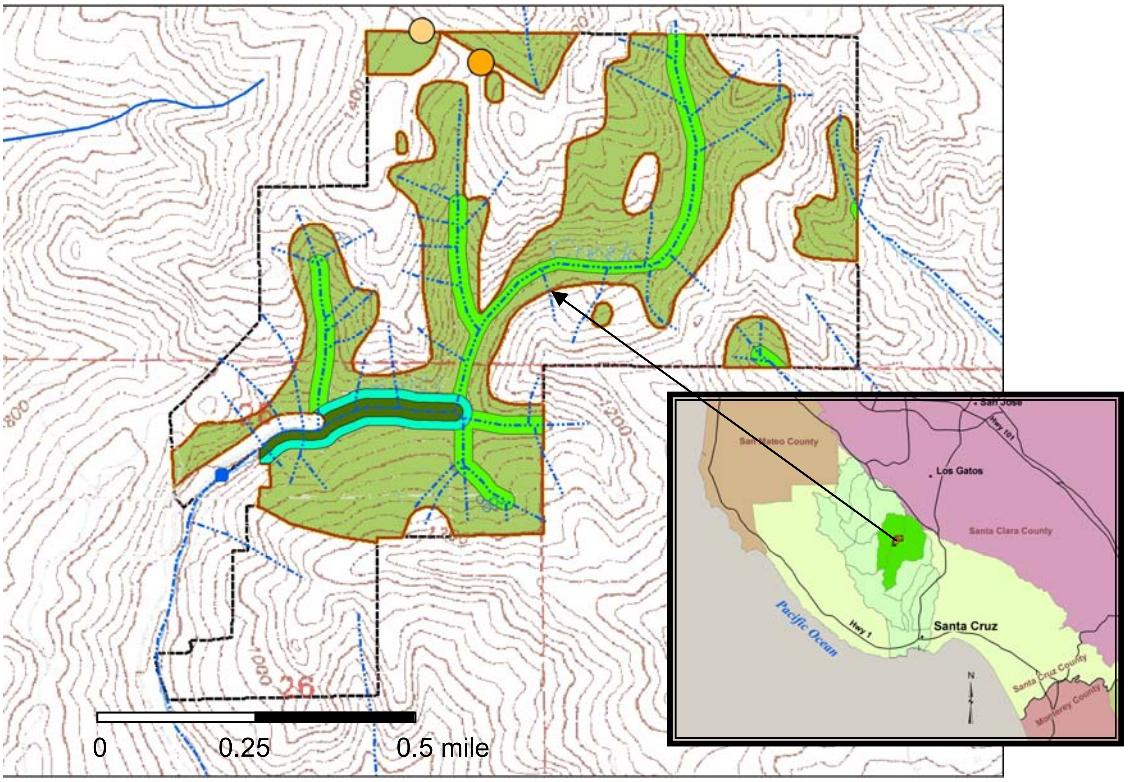

Figure A.1. Map of the proposed Lompico THP in Santa Cruz County. The property boundary is shown in black, the logging area in yellow-green, the Class I WLPZ in dark green and teal, the Class II WLPZ in bright green, and helicopter landings in orange and buff. (Figures produced by CAL FIRE Northern Region Forest Practice GIS.)

Given the selection harvest proportions of 0.10 for the WLPZ and 0.30 for the main units, there are 30.6 ac x 0.1 = 3.1 clearcut equivalent acres in the WLPZ and 173.4 ac x 0.3 = 52.0 clearcut equivalent acres in the main harvest unit, so the total equals 55.1 ac. For this calculation, this can be considered the equivalent of clearcutting 55.1 acres.

2. Insert the data and coefficients into a spreadsheet as indicated in Figure A.3.[17] Cells highlighted in yellow are entered by the user for each application, those in blue remain constant, those not highlighted contain the formulas used for calculations, and the green cell displays the result.

3. The canopy equivalent acres (cell **E19**) is the sum of cells **B19**, **C19**, and **D19**:

   =SUM(B19:D19)

   The proportion of the watershed logged (*c*) in cell **F19** is the clearcut equivalent acres logged (cell **E19**) divided by the total watershed acres (cell **D13**):

   =E19/D13

   or in this case, 55.1/1791 = 0.0308.

[17] A Microsoft Excel™ spreadsheet with the relevant equations is available from the authors.

Figure A.2. Class II watercourse and WLPZ in the Lompico THP area.

4. Use the following spreadsheet equation (cell **H19** in the spreadsheet) to estimate the ratio between observed and expected peak flows:

=EXP((1+($D$7*(G19-1)))*F19*($D$8+($D$9*LN($D$12))+($D$10*LN($D$11))))

Results are shown for a "dry watershed" with a wetness coefficient of 50. Results for other wetness conditions are calculated by entering 304 (for average conditions) or 600 (for wet conditions) into cell **D11**.

5. Calculate the expected percent peak-flow change (cell **J19**) using the equation:

=100*(H19-1)

For the first year after the 30% selection harvest, the peak-flow equations provide estimated peak-flow increases for a 2-year-return-interval storm of:

2.1% for dry soil conditions (wetness index of 50)
0.7% for average conditions (wetness index of 304)
0.2% for wet conditions (wetness index of 600)

Calculations for t = 0 would indicate 2.2%, 0.8%, and 0.3% increases for dry, average, and wet soil conditions, respectively; these values could be used to provide a slightly more conservative estimate of the likely effect.

6. The calculation in step 5 assumes that partial harvest generates the same response as that for a clearcut with the same proportional canopy removal in the watershed. This approximation provides an upper bound for the expected response. Data from Caspar Creek (Reid 2012) suggest that the response for

	A	B	C	D	E	F	G	H	I	J	K
1	**PEAK FLOW CALCULATION FOR THE LOMPICO THP**										
2											
3						*Notes and definitions*					
4	Flow recurrence Interval (yrs)			2							
5	Index logging year			2001		*Year of first summer after logging*					
6	Index calculation year			2002		*Year of January in the winter for which calculations will be made*					
7	Logging recovery coefficient (B_2)			-0.0771							
8	Constant (B_4)			1.103							
9	Storm size coefficient (B_5)			-0.0963							
10	Watershed wetness coef. (B_6)			-0.2343							
11	Watershed wetness index (w)			50		*50 for dry, 304 for medium, 600 for wet*					
12	Expected control peak (y_c)			0.00731		*Read value for specified recurrence interval (cell D4) from Table A.1*					
13	Watershed area (ac)			1791							
14											
15		Clearcut-equivalent canopy removal						Observed/		Estimated	
16		From	From	From	Canopy	Proportion	Summers	expected		peak flow	
17		clearcut	selection	ST or SW	equivalent	watershed	since	peak flow		increase	
18		(ac)	(ac)	(ac)	(ac)	logged (c)	logged (t)	ratio		(%)	
19		0	55.1	0	55.1	0.0308	1	1.021		**2.1**	

Figure A.3. Spreadsheet page used in the Lompico example. Information to be entered by the user for each application is highlighted in yellow; constants are highlighted in blue, and the result is highlighted in green.

single-tree selection logging may be about 60% of that for the equivalent canopy removal by clearcutting, so a second estimate can be calculated as 60% of the values estimated in step 5. Consequently, we can conclude that the 2-year peak flow under dry soil conditions will increase by no more than 2.2% and is likely to increase by only about 1.3%.

7. For comparison, we can redo the calculations for a different prescription. Before on-the-ground implementation of California's Forest Practice Rules in 1975, large areas could be clearcut without concern for adjacency requirements or streamside protection zones. We can estimate the effects on peak flows if the 204 acres included in the Lompico THP had instead been clearcut before the Forest Practice Rules were adopted:

   7.8% for dry soil conditions (wetness index of 50)
   2.7% for average conditions (wetness index of 304)
   0.9% for wet conditions (wetness index of 600)

8. Under the modern Forest Practice Rules, the scale of clearcutting evaluated above is not permitted on state and private forest lands in California, and in Santa Cruz County—the site of the Lompico THP—no clearcutting is permitted. For illustration, though, we can calculate the effects of a clearcutting prescription that might be carried out for an identical setting in coastal forests outside of Santa Cruz County.

   Again assume that 15% of the THP is in Class I and II WLPZs and 85% of the area is potentially available for clearcutting. Since the Forest Practice Rules applicable to counties in the northern part of the Coast Ranges (1) limit evenaged regeneration units to 20-30 acres, depending on the yarding system (with possible expansion to 40 acres in some situations), and (2) specify that regeneration units within an ownership must be separated by a logical logging unit that is at least as large as the area being harvested or 20 acres (whichever is less) and separated by at least 300 feet in all directions, we will assume that one-third of the remaining area can be clearcut in small blocks (partly due to the configuration of the plan area, Figure A.1). Therefore, there are 0.15 x 204 ac = 30.6 ac of WLPZ and 0.85 x 204 ac x 0.33 = 57.2 ac of main harvest units.

This evenaged prescription results in 30.6 ac x 0.1 = 3.1 clearcut equivalent acres in the WLPZ[18] and 57.2 ac x 1.0 = 57.2 clearcut equivalent acres in the main harvest unit, for a total clearcut equivalent area of 60.3 ac.

The first year after harvest, with 0% residual canopy cover remaining in the clearcut units, estimated peak-flow increases for a 2-year return-interval storm are:

2.2% for dry soil conditions (wetness index of 50)
0.8% for average conditions (wetness index of 304)
0.3% for wet conditions (wetness index of 600)

These values are nearly the same as those calculated in step #5 for logging proposed under selection silviculture.

9. If we are quantitatively evaluating cumulative peak-flow changes and there had been an earlier entry during the 12 years before the proposed plan was to be implemented, we would include an additional calculation for the effects of the previous entry. For example, if another 204 ac had been heavily (50%) selection logged (also with 15% WLPZ) in a THP in the autumn of 1996 and calculations are to be made for the 2001-02 winter season, five summers would have passed between the two dates, so $t = 5$. During the year following the proposed plan, the residual effect of the earlier logging by itself would amount to an increase of:

2.3% for dry soil conditions (wetness index of 50)
0.8% for average conditions (wetness index of 304)
0.3% for wet conditions (wetness index of 600)

For dry soil conditions, the combined change for the two entries (assuming the new plan is to use 30% selection silviculture, as described in steps 1-5, above) would then be 2.3% + 2.1% = 4.4%.

10. In each of these examples, the expected changes in peak flows are low in comparison to those documented in the clearcut tributaries of the North Fork Caspar Creek watershed. This difference is in part because calculations here are for the mouth of the 1791-acre planning watershed, and the entire 204-acre THP occupies only 11% of that watershed. Higher in the watershed, the proportional change would be greater. For example, calculations for the mouth of a 204-acre sub-watershed that had been 30% selection-logged the first year after logging ($t = 1$), also with 15% WLPZ, show an expected increase of:

---

[18] It is likely that the WLPZ total would be less with clearcutting, since the unit boundaries would impact a smaller percentage of the watercourses, but no correction for this is provided in this example.

19.5% for dry soil conditions (wetness index of 50)
6.6% for average conditions (wetness index of 304)
2.1% for wet conditions (wetness index of 600)

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APPENDIX B. USE OF LOW-FLOW DATA

Issues are frequently encountered that require the potential effects of an action to be estimated on the basis of the best information currently available. Often this need arises before formally tested analysis methods have been developed. In many cases, preliminary study results can be used in conjunction with a basic understanding of watershed processes to allow estimation of an outcome under the assumption that the area of interest will respond similarly to the area where measurements were made.

As an example, changes in summer low flows are of increasing concern at many sites in the California Coast Ranges, but no formal method is currently available for predicting the likely changes due to logging. Summer flows have been monitored at Caspar Creek since 1962, and data spanning three decades after selection logging have been used to describe the trajectory of post-logging flow changes in South Fork Caspar Creek (Reid 2012).

Here we illustrate how the existing data and published analyses can be used to estimate potential flow changes elsewhere by assuming that similar sites will respond to similar practices in a similar fashion. Low-flow data continue to be collected at Caspar Creek. This information will eventually allow an analogous method to be developed for clearcut logging and will also make it possible to test for longer-term influences of logging on low flows. Additional archived rainfall records are now being evaluated, and these will allow further refinement of the method in the future.

Goal**:** Estimate the proportional change in August and September flows that would result from a sequence of selection logging entries.

Suitable conditions for application**:** Coast redwood – Douglas-fir forests that have been managed primarily using unevenaged silvicultural methods. The study watershed, South Fork Caspar Creek, is 424 ha (1,047 ac) in area, and results are expected to be applicable to watersheds of about 300 to 800 ha (700 to 2,000 ac)—watersheds that support continuous summer flow but do not have extensive alluvial deposits.

Assumptions:

1. The flow effect is additive at the scale of the analysis watershed *[strength of assumption: generally good, as inferred from the nature of low-flow generation processes, but this assumption may be inappropriate in areas with extensive alluvial deposits or a patchy distribution of high-water-use riparian vegetation]*.
2. The effect is independent of the age of the trees logged *[strength: poor if old-growth is involved because the available data are from younger stands; expected to be good for forests of about 30 to 150 years]*.
3. The effect measured for a selection harvest of about 65% of the timber volume can be scaled proportionately to volume selections of < 80% *[strength: expected to be good as long as the remaining trees are spaced closely enough to use excess*

water. The level of confidence in the result is reduced as the selection rate diverges from that in the monitored watershed (about 65%)].

4. Recovery occurs at 32 years *[strength: reasonable; any further departures are likely to be small, although Figure B.1 suggests that full recovery may not yet be achieved; future data will allow testing of this assumption].*
5. Conditions at South Fork Caspar Creek are similar to those in the analysis area *[strength: depends on the site, but expected to be good for most coast redwood – Douglas-fir forests in watersheds of similar sizes because of the general similarity in setting across the region. Results may be less reliable in areas with deeply weathered, fine-grained bedrock, such as that characteristic of earthflow terrains; in areas with strong regrowth of red alder on logged hillslopes; or in watersheds without red alder or similar hardwood species in the riparian zone].*

Analysis Strategy:

1. Identify the analysis area.
2. Identify areas logged in the past and their associated percentages of volume removed by selection logging. Logging entries can be ignored if they occurred more than 32 years before the date of the logging plan that is to be evaluated.
3. Adjust the summer-flow curve from South Fork Caspar Creek (Figure B.1, Table B.1) for the selection intensities represented in the analysis watershed.

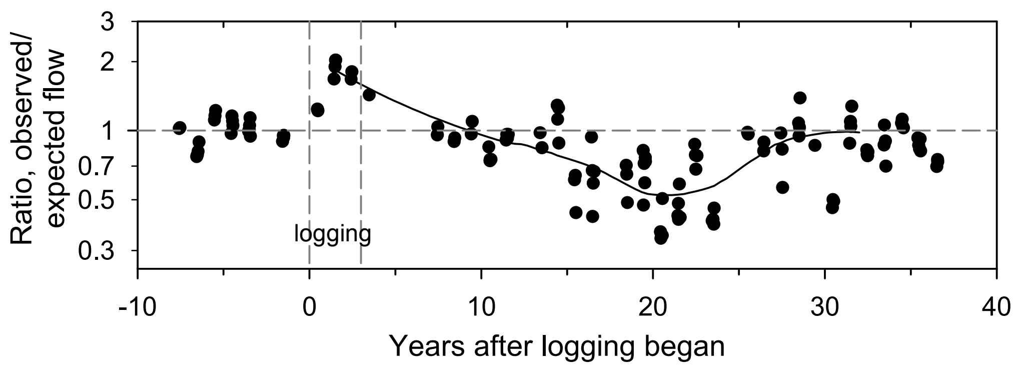

Figure B.1. Proportional change in summer flow, South Fork Caspar Creek. Curve is fitted using loess regression. The anomalous values in year 30 are due to an unusually large summer storm, and that year's data are not included in the regression (Reid 2012).

Table B.1. Proportional change by year after logging (from Figure B.1).

Year	Proportional change	Year	Proportional change	Year	Proportional change	Year	Proportional change
1	1.928	9	1.018	17	0.665	25	0.678
2	1.749	10	0.959	18	0.607	26	0.76
3	1.592	11	0.909	19	0.555	27	0.859
4	1.458	12	0.877	20	0.526	28	0.92
5	1.343	13	0.845	21	0.524	29	0.952
6	1.244	14	0.801	22	0.534	30	0.977
7	1.159	15	0.757	23	0.556	31	0.988
8	1.084	16	0.715	24	0.603	32	1

4. Offset the modified curves according to the timing of logging in each unit.
5. Calculate the incremental flow change associated with each unit and sum by year.
6. Calculate the proportional change for each year.

	A	B	C	D	E	F	G	H	I	J	K
1	Total area:	460									
2	Cut unit:	1	2		1	2					
3	Year logged:	2010	2012								Data to
4	% selection:	70	40						Total		paste into
5	ac logged:	90	150						proportional		columns
6		Proportion for			Proportion change			Excess	change		B & C
7	Year	65% cut			for actual % cut						
8	2009	1	1		0.00	0.00		0	1.00		1.93
9	2010	1.93	1		1.00	0.00		90	1.20		1.75
10	2011	1.75	1		0.81	0.00		73	1.16		1.59
11	2012	1.59	1.93		0.64	0.57		143	1.31		1.46
12	2013	1.46	1.75		0.50	0.46		114	1.25		1.34
13	2014	1.34	1.59		0.37	0.36		87	1.19		1.24
14	2015	1.24	1.46		0.26	0.28		66	1.14		1.16
15	2016	1.16	1.34		0.17	0.21		47	1.10		1.08
16	2017	1.08	1.24		0.09	0.15		30	1.07		1.02
17	2018	1.02	1.16		0.02	0.10		17	1.04		0.96
18	2019	0.96	1.08		-0.04	0.05		4	1.01		0.91
19	2020	0.91	1.02		-0.10	0.01		-7	0.99		0.88
20	2021	0.88	0.96		-0.13	-0.02		-15	0.97		0.85
21	2022	0.85	0.91		-0.16	-0.06		-23	0.95		0.8
22	2023	0.8	0.88		-0.22	-0.07		-30	0.93		0.76
23	2024	0.76	0.85		-0.26	-0.09		-37	0.92		0.72
24	2025	0.72	0.8		-0.30	-0.12		-46	0.90		0.67
25	2026	0.67	0.76		-0.36	-0.15		-54	0.88		0.61
26	2027	0.61	0.72		-0.42	-0.17		-64	0.86		0.56
27	2028	0.56	0.67		-0.47	-0.20		-73	0.84		0.53
28	2029	0.53	0.61		-0.51	-0.24		-82	0.82		0.52
29	2030	0.52	0.56		-0.52	-0.27		-87	0.81		0.53
30	2031	0.53	0.53		-0.51	-0.29		-89	0.81		0.56
31	2032	0.56	0.52		-0.47	-0.30		-87	0.81		0.6
32	2033	0.6	0.53		-0.43	-0.29		-82	0.82		0.68
33	2034	0.68	0.56		-0.34	-0.27		-72	0.84		0.76
34	2035	0.76	0.6		-0.26	-0.25		-60	0.87		0.86
35	2036	0.86	0.68		-0.15	-0.20		-43	0.91		0.92
36	2037	0.92	0.76		-0.09	-0.15		-30	0.93		0.95
37	2038	0.95	0.86		-0.05	-0.09		-18	0.96		0.98
38	2039	0.98	0.92		-0.02	-0.05		-9	0.98		0.99
39	2040	0.99	0.95		-0.01	-0.03		-6	0.99		1
40	2041	1	0.98		0.00	-0.01		-2	1.00		
41	2042	1	0.99		0.00	-0.01		-1	1.00		
42	2043	1	1		0.00	0.00		0	1.00		

Figure B.2. Spreadsheet used in the low-flow example. Information to be entered by the user is highlighted in yellow; results are highlighted in green.

This analysis is most easily carried out with the help of a spreadsheet, such as that shown in Figure B.2. In this figure, information entered by the user is highlighted in yellow and results are highlighted in green. Use of the spreadsheet can be demonstrated using a hypothetical example of a 186-ha (460-ac) second-growth watershed in which 36 ha (90 ac) was selection logged with 70% volume removal in 2010, and another 61 ha (150 ac) will be logged in 2012 at a 40% selection rate.

1. First, enter the watershed area in cell **B1**, and the information for each of the two logging entries in cells **B3-B5** and **C3-C5**.

2. In **column A**, enter the years for which the calculations will be made. This will span the period between a year before the first entry and 32 years after the second entry.
3. Copy cells **K8** through **K39** onto the clipboard; these values represent the data in Table B.1.
4. Paste the contents of the clipboard into **column B**, starting with the year shown in cell **B3**. Do the same in **column C**, this time starting with the year shown in cell **C3**.
5. Fill in any empty cells in **columns B** and **C** with "1." These columns now show the proportional change that would be expected if the entire watershed had been 65% selection logged in 2010 (**column B**) or 2012 (**column C**).
6. Paste the following formula into cell **E8**, and drag it down to cell **E42** to duplicate the formula through the rest of the column:

   =(B8-1)*B$4/65

   Do the same for cells **F8** through **F42** with the analogous formula:

   =(C8-1)*C$4/65

   (this can also be done by dragging the formula from cell **E8** into cell **F8**, and then dragging **F8** down to **F42**). **Columns E** and **F** now show the proportional changes as modified to reflect the actual selection intensity, now expressed as the proportional increase or decrease relative to a value of 1.0.
7. Paste the following formula into cell **H8**, and drag it down to cell **H42**:

   =SUMPRODUCT($B$5:$C$5,E8:F8)

   This interim result weights the sum of contributions from each entry for each year according to the area affected by each entry.
8. Finally, paste the following formula into cell **I8** and drag it down to **I42**:

   =(H8+$B$1)/$B$1

   Column I now contains the result: the proportional change expected for each year from the combined effects of the two logging entries. At this point, results can be shown in graphical form by plotting **column I** against the years listed in **column A**.

<u>Example</u>

We can further illustrate the method using an example of a hypothetical logging plan in Jackson Demonstration State Forest in Mendocino County. In this case, there are four relevant logging entries, so the spreadsheet must be modified to incorporate additional columns, and the relevant years span the period between 1988 and 2042.

We want to estimate the change in summer flow likely to be generated in South Fork Hare Creek (Figures B.3, B.4, B.5) by selectively removing 23% of the timber volume

Figure B.3. A typical stand in South Fork Hare Creek watershed in 2012.

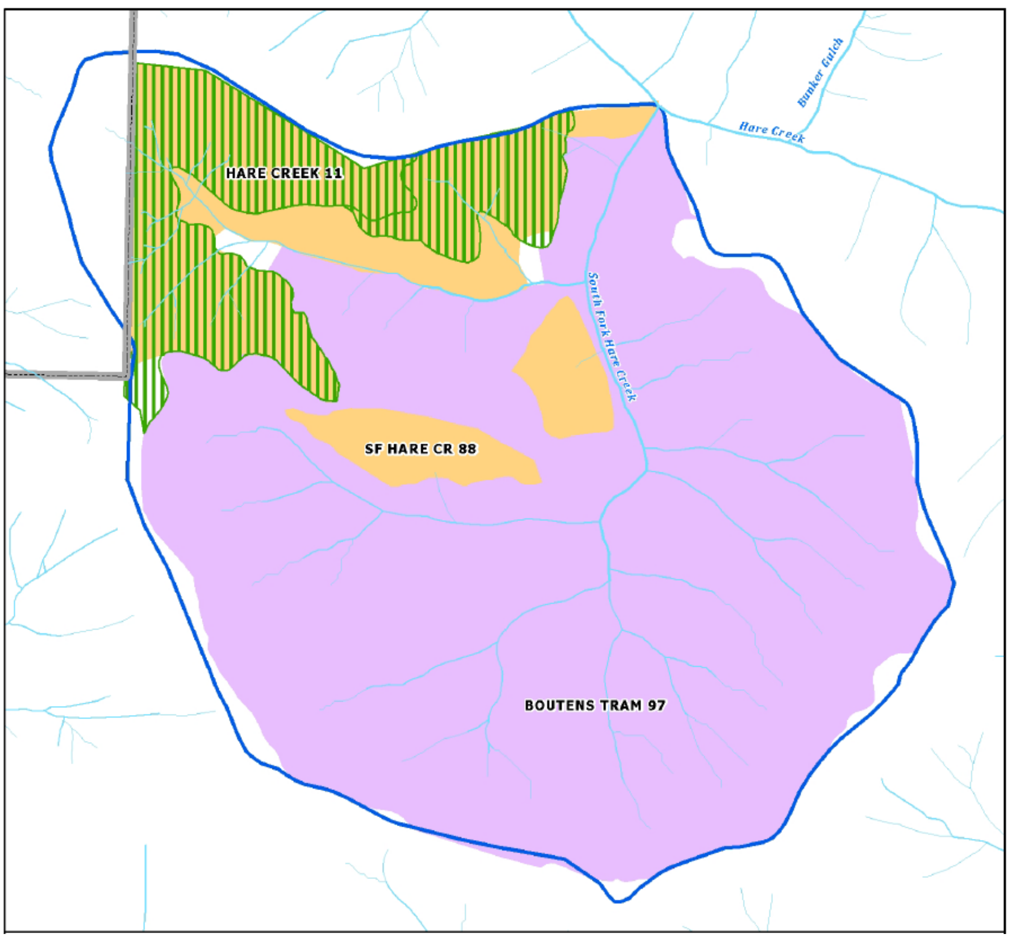

Figure B.4. South Fork Hare Creek harvest history (1988-2012).

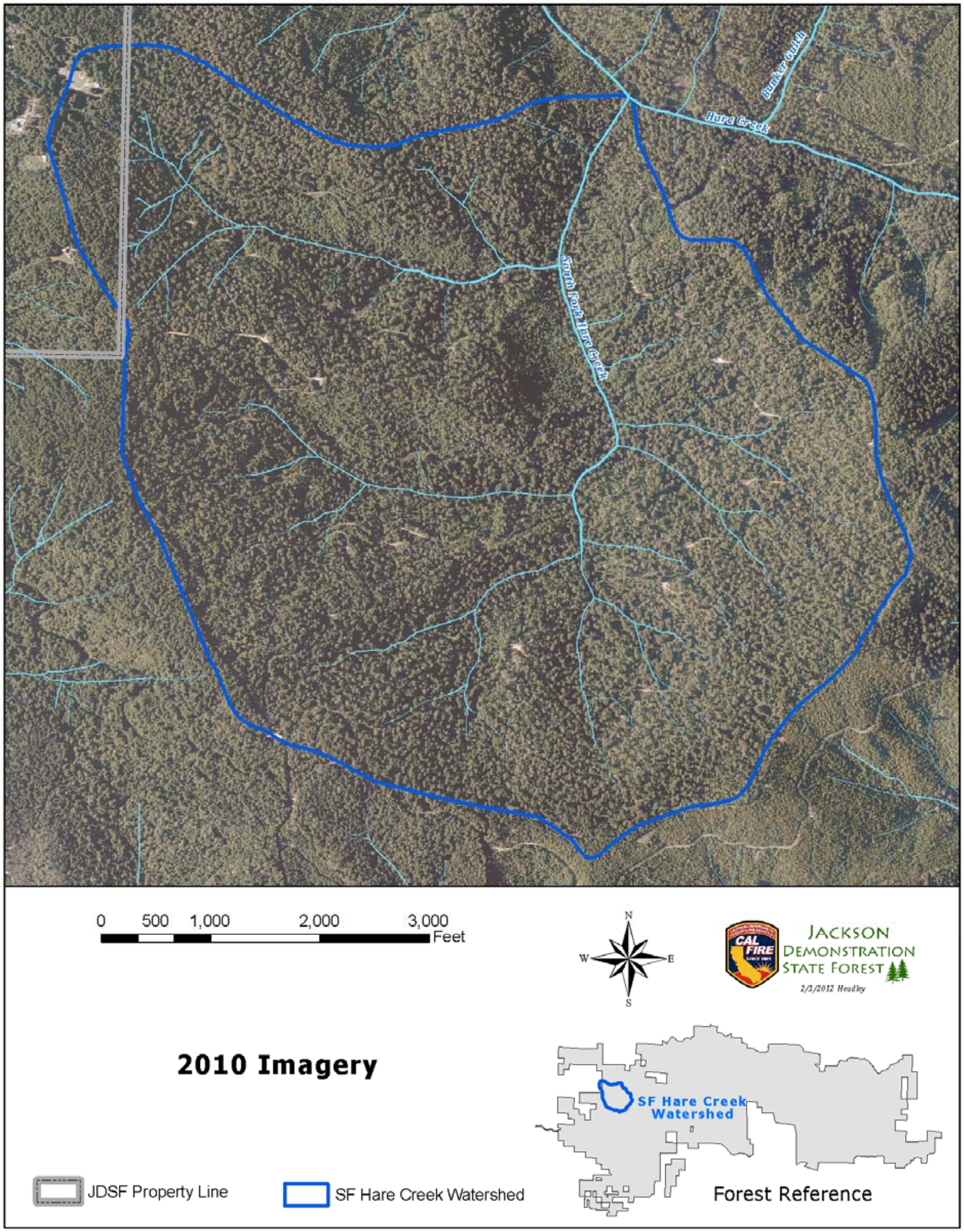

Figure B.5. Aerial view of South Fork Hare Creek, 2010.

covering 119 ac in the 865-ac watershed in 2011. Logging prior to 1979 can be disregarded because effects will have become inconsequential by 2011. Since 1979, the watershed has experienced two logging entries, one of which employed two silvicultural strategies (Figure B.4):

1988 30% selection of 113 ac
1988 clearcutting[19] of 48 ac
1997 51% selection of 640 ac

1. In the first column of the spreadsheet (Figure B.6), list years from the first year of logging within the 32 years preceding the date of interest (2011-32=1979 in this case) to 32 years after the date of the logging entry to be analyzed (2011+32=2043).

   Enter the watershed area in cell **B1** (note that areas can be listed in acres or hectares, as long as the units are used consistently throughout the calculation).

2. Establish a separate column for each year and type of logging within the defined period. At the top of each column, list the year of logging, the percent of the volume removed, and the area logged (select units of area to be consistent with that used in step 1).

3. In this case, we have a problem: the 1988 entry included 48 ac of "fuzzy" clearcutting,[19] but the Caspar Creek data currently apply only to selection logging. To determine whether this gap in understanding will invalidate our results, we will carry out the calculations with and without the clearcutting and compare results for the period we are interested in, 2011 to 2043 (Figure B.6 shows the calculation with the 1988 clearcut).

4. In each of the spreadsheet columns of step 2 (**columns B-E**), list the 32 values from Table B.1 (provided in **column O**), beginning with the year of each logging episode. Enter "1" for years outside the 32-yr range in each column.

5. Establish another column for each cut unit (**columns G-J**), and in each cell subtract 1.0 from the corresponding cell from step 4, then multiply the resulting value by the ratio between the percent logged and 65%, the average percent volume selection at Caspar Creek. The result is the proportional increase or decrease expected from each unit in each year. The formula in cell **G8**, for example, is

   =(B8-1)*B$4/65

   and that in **H9** is

   =(C9-1)*C$4/65

6. Establish a column for the combined effects (**column L**): for each logging entry, multiply the proportional change calculated in step 5 by the area logged in the unit, and sum these across the cut units for each year. The formula in cell **L8** is

   =SUMPRODUCT($B$5:$E$5,G8:J8)

---

[19] The harvest entry included two units covering 69 ac that were described as "70% clearcut," resulting in the clearcut equivalent of 48 ac. This kind of partial clearcut removal is referred to as "fuzzy" clearcutting.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	Total area:	865													
2	Cut unit:	1	2	3	4		1	2	3	4					
3	Year logged:	1988	1988	1997	2011										Data to
4	% selection:	30	100	51	23								Total		paste into
5	ac logged:	113	48	640	119								proportional		columns
6		Proportion for					Proportion change					Excess	change		B & C
7	Year	65% cut					for actual % cut								
8	1987	1	1	1	1		0.00	0.00	0.00	0.00		0	1.00		1.93
9	1988	1.93	1.93	1	1		0.43	1.43	0.00	0.00		117	1.14		1.75
10	1989	1.75	1.75	1	1		0.35	1.15	0.00	0.00		95	1.11		1.59
11	1990	1.59	1.59	1	1		0.27	0.91	0.00	0.00		74	1.09		1.46
12	1991	1.46	1.46	1	1		0.21	0.71	0.00	0.00		58	1.07		1.34
13	1992	1.34	1.34	1	1		0.16	0.52	0.00	0.00		43	1.05		1.24
14	1993	1.24	1.24	1	1		0.11	0.37	0.00	0.00		30	1.03		1.16
15	1994	1.16	1.16	1	1		0.07	0.25	0.00	0.00		20	1.02		1.08
16	1995	1.08	1.08	1	1		0.04	0.12	0.00	0.00		10	1.01		1.02
17	1996	1.02	1.02	1	1		0.01	0.03	0.00	0.00		3	1.00		0.96
18	1997	0.96	0.96	1.93	1		-0.02	-0.06	0.73	0.00		462	1.53		0.91
19	1998	0.91	0.91	1.75	1		-0.04	-0.14	0.59	0.00		365	1.42		0.88
20	1999	0.88	0.88	1.59	1		-0.06	-0.18	0.46	0.00		281	1.33		0.85
21	2000	0.85	0.85	1.46	1		-0.07	-0.23	0.36	0.00		212	1.25		0.8
22	...	...	...	...	...		...	...	...	...		...	...		0.76
23	...	...	...	...	...		...	...	...	...		...	...		0.72
24	2009	0.53	0.53	0.85	1		-0.22	-0.72	-0.12	0.00		-135	0.84		0.67
25	2010	0.56	0.56	0.8	1		-0.20	-0.68	-0.16	0.00		-156	0.82		0.61
26	2011	0.6	0.6	0.76	1.93		-0.18	-0.62	-0.19	0.33		-132	0.85		0.56
27	2012	0.68	0.68	0.72	1.75		-0.15	-0.49	-0.22	0.27		-149	0.83		0.53
28	2013	0.76	0.76	0.67	1.59		-0.11	-0.37	-0.26	0.21		-171	0.80		0.52
29	2014	0.86	0.86	0.61	1.46		-0.06	-0.22	-0.31	0.16		-194	0.78		0.53
30	2015	0.92	0.92	0.56	1.34		-0.04	-0.12	-0.35	0.12		-217	0.75		0.56
31	2016	0.95	0.95	0.53	1.24		-0.02	-0.08	-0.37	0.08		-232	0.73		0.6
32	2017	0.98	0.98	0.52	1.16		-0.01	-0.03	-0.38	0.06		-237	0.73		0.68
33	2018	0.99	0.99	0.53	1.08		0.00	-0.02	-0.37	0.03		-234	0.73		0.76
34	2019	1	1	0.56	1.02		0.00	0.00	-0.35	0.01		-220	0.75		0.86
35	2020	1	1	0.6	0.96		0.00	0.00	-0.31	-0.01		-203	0.77		0.92
36	...	...	...	...	...		...	...	...	...	...	...	...		0.95
37	...	...	...	...	...		...	...	...	...	...	...	...		0.98
38	2040	1	1	1	0.98		0.00	0.00	0.00	-0.01		-1	1.00		0.99
39	2041	1	1	1	0.99		0.00	0.00	0.00	0.00		0	1.00		1
40	2042	1	1	1	1		0.00	0.00	0.00	0.00		0	1.00		
41	2043	1	1	1	1		0.00	0.00	0.00	0.00		0	1.00		
42															

Figure B.6. Portions of the spreadsheet used in the South Fork Hare Creek example. Note that entries for years 2001-2008 and 2021-2039 have been left out in this image.

7. Establish a final column for the result (**column M**). Here, add each cell value from step 6 to the total watershed area and divide the sum by the watershed area. The formula in cell **M8** is

   =(L8+$B$1)/$B$1

8. The resulting tabulation in **column M** is a yearly estimate of the proportional change in August-September flows that would result from the combined influences of the logging units analyzed. When results are recalculated assuming that the 48 ac 1988 clearcut had not occurred (dashed red line in Figure B.7), the comparison shows little difference in the projected response from 2015 on, providing assurance that in this case the clearcutting was at a small enough scale and had occurred long enough ago that it will have little effect on our interpretation of the influences of the 2011 logging. Further, results recalculated without the 2011 logging (blue line in Figure B.7) show that the influence is expected to be small.

During 2011 through 2018 the initial increase in flow due to the new logging is likely to slightly offset the effects of the major logging of 1997, while during 2020 through 2037 flows are likely to be about 2% lower than would have been expected without the 2011 logging.

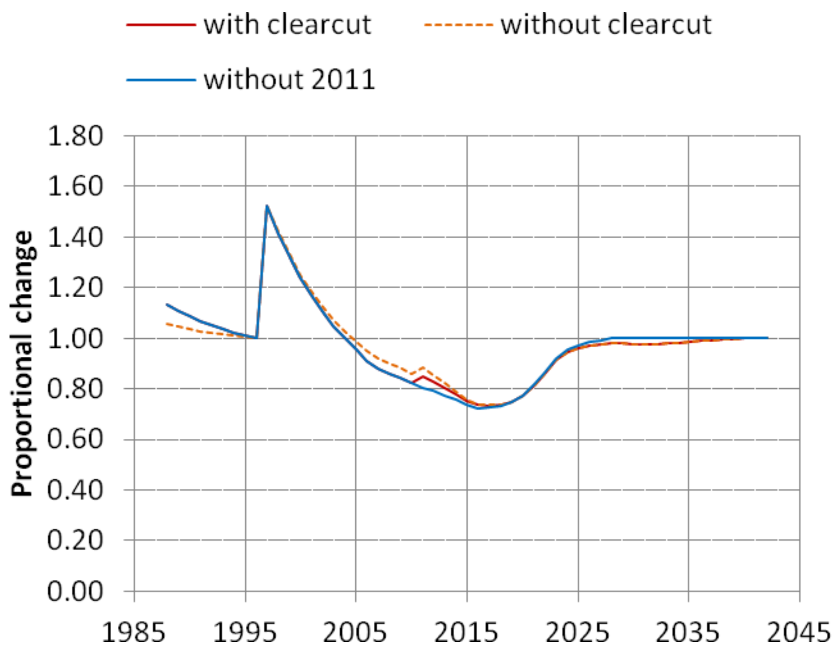

Figure B.7. Change through time for the example considered in Figures B.4 and B.6.

Reference

Reid, L.M. 2012. Comparing hydrologic responses to tractor-yarded selection and cable-yarded clearcut logging in a coast redwood forest. Pp. 141-151 in: Standiford, R.B.; T.J. Weller, D.D. Piirto, and J.D. Stuart. (Technical coordinators). Proceedings of the Coast Redwood Forests in a Changing California: a Symposium for Scientists and Managers. General Technical Report PSW-GTR-238. USDA Forest Service, Pacific Southwest Research Station. Albany, CA. 675 p.

APPENDIX C. ESTIMATING SEDIMENT FROM IN-CHANNEL SOURCES

Previous appendices illustrate the use of published methods and preliminary published analyses from Caspar Creek studies to address forestry-related issues. It is also possible to use the original Caspar Creek data to address topical problems without relying on published analyses. As an example, questions have recently arisen concerning the effects of logging on sediment production from within channels, but no formally developed assessment method is yet available to address this issue. Both flow and sediment loads are monitored at Caspar Creek, and these data are currently available through 2004 on the Caspar Creek website. This appendix employs the available data to explore relations between flow and suspended sediment yield before and after logging at locations in the North Fork Caspar Creek watershed, and then uses basic geomorphological reasoning to apply the resulting relationships to estimate the effects of logging-related flow changes on sediment production from in-channel sources in the North Fork watershed.

Using Caspar Creek Data to Develop an Analysis Method

Work at Caspar Creek showed that recent clear-cut logging is associated with increased rates of gully and channel erosion in small headwater streams draining logged slopes (Reid et al. 2010). These in-channel erosion processes are controlled largely by stream flow, and Lewis et al. (2001) not only showed that logging had increased flow in the watersheds, but also demonstrated that increased suspended sediment loads after logging were correlated with observed increases in storm flow (i.e., the volume of stream flow that runs off during a defined storm). Unfortunately, rates of in-channel processes such as gully erosion, bank erosion, and incision are difficult to estimate over the short term using field measurements, and reliable methods for their prediction have not yet been developed. We would like to be able to predict the effects of logging on suspended sediment yields from in-channel sources in the Caspar Creek watersheds.

Strategy

Lewis et al. (2001) showed that logging-related changes in suspended sediment load at North Fork gaging stations were correlated with changes in stream flow, a result that was applicable across the range of watershed sizes and conditions present. If (1) we can estimate the flow changes expected from logging, and (2) we can define a relation between flow and sediment yield, we will be able to estimate the effects of logging on flow-related sediment inputs.

Pre-treatment data will be used to develop the relation between flow and sediment, so we will need to assume that this relation is not altered by logging. In effect, we will assume that if a particular flow causes characteristic rates of incision and bank erosion before logging, the same flow will remain capable of triggering similar erosion rates after logging, irrespective of how the flow was generated.

We will then need to interpret the result in terms of the information it provides about in-channel sediment sources. For this we will base our reasoning on several kinds of information: observations of logging-related disturbance along streams, observations of active sediment sources before and after logging, and correlations between sediment yields and the rates of erosion from various sediment sources. We know from basic geomorphologic principles that rates of in-channel erosion and sediment transport are strongly influenced by flow.

Assessing Flow Changes

We first need a method for estimating flow changes caused by logging. Although Lewis et al. (2001) found the relation with storm-flow change to best predict sediment change, we do not yet have a convenient way to estimate logging-related storm-flow changes, so we would like to use a different flow parameter as a predictor. At Caspar Creek, half to two-thirds of a storm's sediment load is usually transported during the 20% of a storm's duration with the highest flows, so we expect changes in sediment load also to be correlated with changes in peak flow. We can use the method described in Appendix A to estimate logging-related changes in peak flow, so we will base the analysis on peak-flow change rather than on storm-flow change.

Relating Sediment to Flow

Next, we need to estimate the effect of predicted peak-flow changes on suspended sediment loads. A plot of storm suspended sediment loads as a function of peak flows for North Fork tributaries during the pre-logging period (Figure C.1) shows strong relationships between the logarithms of the two variables ($0.70 < r^2 < 0.95$), and also shows that slopes of the relations are similar in different tributaries. Only in the case of watershed BAN is the slope significantly different from most others at the 0.01 level.

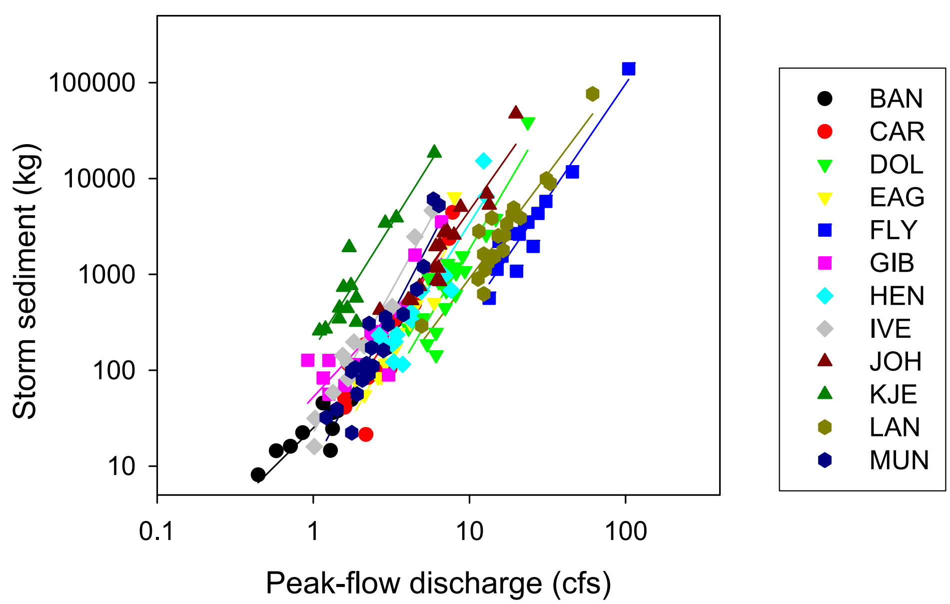

Figure C.1. Calibration relations between storm sediment load and peak flow for 12 gaged North Fork catchments.

Pairwise comparisons showed that most slopes in Figure C.1 are not significantly different from one another at the 0.05 level during the pre-treatment period. We used a linear mixed effects modeling procedure (J. Baldwin, PSW, personal communication 1/28/2012) to estimate the best-fit shared slope for all sites except BAN, resulting in a value of 2.44 ± 0.14 (95% confidence interval) for the shared slope. Comparison of results with and without slopes constrained to be equal to one another showed that the assumption of equality is appropriate for the data set. Since the slopes of the relation can be considered to be the same in different watersheds, all watersheds will experience the same percentage increase in suspended sediment if they have each undergone a given percentage increase in peak flow. The pooled slope can now be used to estimate the expected proportional change in sediment load (S_p) for a given proportional change in peak flow (F_p) after logging in any of the watersheds:

$$S_p = F_p{}^m \qquad \text{(C1)}$$

If changes are calculated as percentages (*S%* and *F%*) rather than proportions:

$$S\% = 100\left(1 + \frac{F\%}{100}\right)^m - 100 \qquad \text{(C2)}$$

In both cases, m is the slope of the relation between $\log_{10}$(peak flow) and $\log_{10}$(sediment). Note that a 20% increase in sediment or peak flow (*S%* or *F%* = 20) is equivalent to a proportional change of 1.20 (S_p or F_p = 1.20). Figure C.2 illustrates the relation described by equation C2 for m = 2.44, the pooled slope, and Table C.1 provides coordinates for points along the curve in Figure C.2.

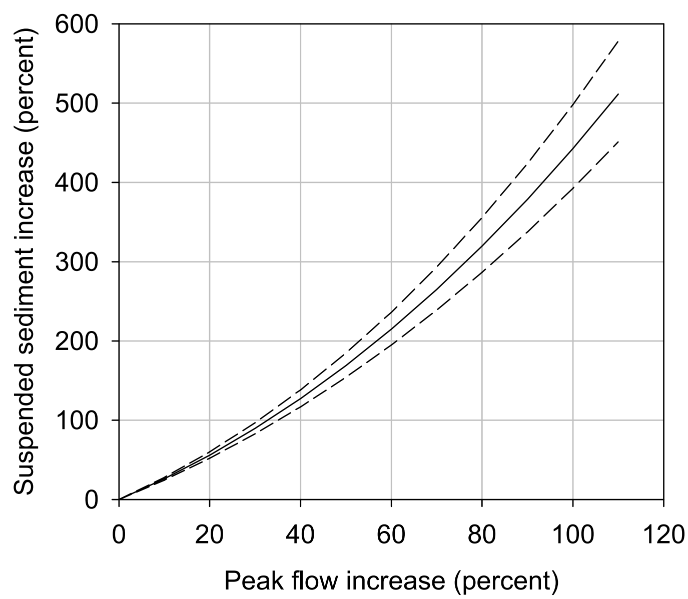

Figure C.2. Mean percentage increase in suspended sediment load per percentage increase in peak flow, as determined using the slope calculated for the pooled data sets. Dashed lines show the envelope calculated using the 95% confidence interval for the slope of the pooled relation.

Table C.1 Percentage change in suspended sediment load expected from a given percentage change in peak flow (from Figure C.2).

Percent peak flow change	Percent change, suspended sediment load	Percent peak flow change	Percent change, suspended sediment load	Percent peak flow change	Percent change, suspended sediment load
1	2	12	32	35	108
2	5	14	38	40	127
3	7	16	44	45	148
4	10	18	50	50	169
5	13	20	56	55	191
6	15	22	62	60	215
7	18	24	69	65	239
8	21	26	76	70	265
9	23	28	83	75	292
10	26	30	90	80	320

Table C.2. Comparison of observed and calculated changes in suspended sediment load after logging in seven gaged North Fork Caspar Creek watersheds of <100 ha, and in an equivalent period in three control watersheds.

	Area (ha)	Expected sediment (kg)	Observed sediment (kg)	Modeled sediment (kg)	Ratio: Observed / expected	Ratio: Modeled / expected
Treated watersheds:						
BAN	10	112	312	229	2.78	2.04
CAR	26	523	1044	1075	2.00	2.05
DOL	77	1850	5095	2734	2.75	1.48
EAG	27	829	2378	1548	2.87	1.87
GIB	20	501	1402	1502	2.80	3.00
Watersheds affected by KJE anomaly:						
KJE	15	5003	1896	11622	0.38	2.32
JOH	55	3015	2022	2604	0.67	0.86
Control watersheds:						
HEN	39	1075	1493	1065	1.39	0.99
IVE	21	446	318	503	0.71	1.13
MUN	16	1334	1058	1421	0.79	1.07

Column 3: Sum of sediment loads calculated for a suite of post-logging storms from the mean of HEN, IVE, and MUN loads for each storm using pre-treatment calibrations.

Column 4: Sum of suspended loads calculated from sediment data for the same suite of storms (those occurring within the first 4 years after the end of logging in each watershed).

Column 5: Sediment load predicted by 1) estimating the peak flow expected for each storm on the basis of calibrations to the controls; 2) calculating the ratio of observed to expected flow for each storm; 3) using the shared slope of 2.44 to estimate the corresponding percentage change expected for suspended sediment load; 4) calculating the corresponding kg of sediment relative to the expected sediment load for unlogged conditions (the components of the sums tabulated in column 3); and 5) summing these values for the same storms represented in columns 3 and 4.

Column 6: Column 4 divided by column 3.

Column 7: Column 5 divided by column 3

Sediment Sources

During the pre-treatment period, much of the sediment is expected to have been supplied from in-channel sources because few landslides occurred during the period and because other hillslope sediment sources (e.g., sheetwash erosion and dry ravel) are rarely seen under 80- to 100-yr-old second-growth forest at Caspar Creek. Furthermore, analysis by Reid et al. (2010) showed no significant dependence of sediment load on sediment inputs from small to moderate landslides that occurred in the gaged watersheds during the measurement period and only a weak relation to sheet erosion, even after logging. We thus assume that pre-treatment sediment is derived primarily from in-channel sources (including channel beds, stream banks, headcuts, and stored landslide debris); this assumption will overestimate the importance of these sources to the extent that other kinds of erosion processes are actively producing sediment during the pre-treatment period.

After logging, field observations indicated that a wider variety of sediment sources were active, including erosion from new haul roads and cable skid trails, and sheet and rill erosion on disturbed hillslope soils (Rice 1996). At the same time, observations suggested that higher-order channel banks were rarely disturbed during logging. WLPZ buffer strips protected most channels of second order or larger, and heavy equipment was rarely operated near first-order channels. However, some bank disturbance occurred through accelerated blowdown in WLPZs (Reid and Hilton 1998), and Lewis et al. (2001) described field evidence in the North Fork watershed indicating that unbuffered burned headwater channel reaches also became sediment sources. Reid et al. (2010) showed that even after logging, most sediment inputs were derived from in-channel sources.

If suspended sediment yields are estimated from modeled post-logging peak flows in treated watersheds, the resulting values should represent that portion of the post-logging sediment yield that is generated by processes analogous to those active before logging. As described earlier, if a given level of flow was capable of generating a particular sediment yield prior to logging, it is expected to be capable of generating the same amount of sediment after logging through interaction of the flow with those sediment sources most strongly influenced by flow—primarily the in-channel sources. Sediment loads greater than that amount are expected to result from more direct influences of timber operations on erosional processes, or through channel erosion at sites where logging activities triggered expansion of the drainage network.

Comparing Predicted and Measured Sediment Loads

To test the potential utility of equations C1 and C2, we can use Caspar Creek flow and sediment records to calculate the post-logging sediment changes predicted from observed flow changes and compare them to observed sediment changes after logging (Table C.2, Figure C.3). We restrict the analysis to the first four years after logging in each watershed, when the sediment response is likely to be greatest. Peak flows and sediment loads show little evidence of recovery during the first three years after logging (Figures 14 and 23), but begin to decline during the fourth year. Recovery trajectories are likely to begin to diverge at that point because sediment inputs from newly activated sources will take longer to recover than the hydrologic changes that triggered them. As trajectories diverge, calculations based on flow changes are likely to underestimate the corresponding sediment inputs.

Because the modeled response is expected to account primarily for the portion of the sediment increase contributed by in-channel erosion, we expect the average of modeled values to be less than the observed average, though variations are expected for individual watersheds. The variation observed at watershed KJE is particularly interesting. Here, pre-treatment sediment loads appear to have been recovering from an earlier erosion event, so the observed reduction in sediment after logging may simply reflect the progress of recovery from an earlier event. In any case, Lewis (1998) refers to this unusual response as the "KJE anomaly" and distinguishes KJE results from those in other watersheds; we do the same. Results from the JOH gage, located a few hundred meters downstream of KJE, also are strongly influenced by the KJE anomaly.

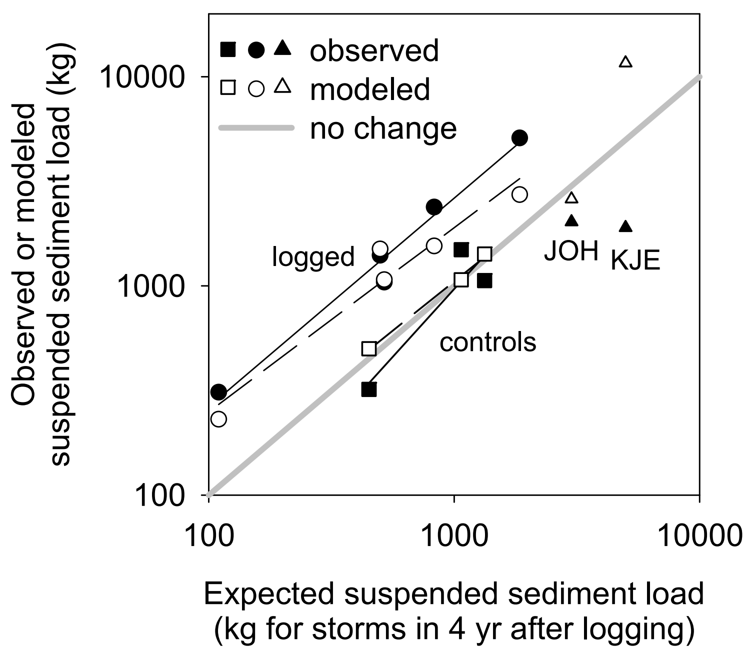

Figure C.3. Observed and modeled suspended sediment loads in <100-ha (247-ac) watersheds after logging at BAN, CAR, DOL, EAG, and GIB watersheds (circles); at control watersheds HEN, IVE, and MUN (squares); and at two watersheds influenced by the KJE anomaly (triangles).

The average modeled four-year sediment increase for the five gaged watersheds unaffected by the KJE anomaly is 70% of the average observed increase. If the pre-treatment sediment load is indeed largely contributed from in-channel sources, then about two-thirds to three-quarters of the initial increase in suspended sediment after logging could be explained by increased in-channel erosion. To the extent that other sediment sources contributed to the pre-treatment loads, the in-channel contribution would be less than that calculated. To the extent that logging has triggered new sources of in-channel erosion through blowdown and channel extension, the in-channel contribution would be greater. The actual relative importance of in-stream erosion in each watershed depends on the distribution of erosion processes such as landslides and gullies, so variations for individual watersheds are expected to be large, as they are indeed observed to be (Table C.2).

Identifying an Index Flow

The results in Table C.2 rely on information from individual storms in gaged watersheds, so we now need to modify the approach so that it can be used more easily and so that it can be applied in ungaged watersheds. Appendix A allows us to estimate changes in peak flow in ungaged watersheds, and we would like to be able to use that information to estimate sediment changes. If we can find a flow for which the percentage change in sediment load is equivalent to the average for the full distribution of flows that are likely to occur, we could use that flow as an index for estimating the overall average change likely for a typical distribution of storms in a four-year analysis period.

To identify an appropriate index flow, we used 18-year gaging records (including 115 storms) from control watersheds HEN and IVE to estimate flow return intervals for each storm in these watersheds (calculated from the partial duration series as described by Dunne and Leopold (1978)). We next calculated the expected peak flow for each storm before and after logging in each of the gaged watersheds, and we then used the relations shown in Figure C.1 to calculate the corresponding sediment loads for each storm. We summed expected sediment loads with and without logging for the 115 representative storms and compared the overall proportional change with that calculated for individual storms to identify the return interval for the storm that most closely predicts the overall proportional change.

Return intervals for the best predictor storms for individual watersheds ranged between 0.8 and 2.0 years, with a mean value of 1.24 ± 0.13 yr (95% confidence interval) for 100% logged watersheds and 1.31 ± 0.19 yr for 30% logged watersheds. A calculation carried out for an index storm with a return interval of 1.25 years is thus expected to provide a reasonable estimate of the change likely for an average distribution of storms in a four-year period, using the reasoning that the overall proportional change for the 115 storms occurring in an 18-year period provides a reasonably robust estimate of the proportional change likely for any 4-year period.

Summary

The result of these calculations is a method for estimating the likely proportional change in erosion attributable simply to an increase in flow after logging in sub-watersheds of the North Fork Caspar Creek watershed. Because most of the suspended sediment yield produced prior to logging is expected to have originated from in-channel sources, the post-logging yields calculated using this method are expected to primarily represent the portion of the post-logging load also generated from in-channel sources, with the calculated increases due solely to the increased erosive and transport capacities of the flow increases caused by logging. The method evaluates changes during only the first four years after logging. Sediment loads will likely remain elevated after that, but the relations between sediment and flow are expected to begin to change due to differences in recovery rates after logging.

Potential Applications: Estimating Changes Elsewhere

The approach described above was developed for sub-watersheds in the North Fork Caspar Creek watershed, but it is expected to be applicable to watersheds of similar size (10 to 80 ha, or 25 to 200 ac) at other Coast Range sites where erosion processes and runoff generation processes are similar to those at the North Fork. Runoff generation and erosion processes are influenced by topography, vegetation, geology, soil characteristics, stream-bank conditions, climate, and management history. Interactions between flow and sediment transport shift with increasing watershed size as deposition becomes important along low-gradient downstream reaches.

To test the applicability of the method elsewhere, we also evaluated relations between flow and sediment at gaged catchments in the South Fork Caspar Creek watershed, which was selection logged and tractor-yarded in the early 1970's. Pair-wise comparisons show that slopes of the relations at the South Fork sites are generally not significantly different at the 0.05 level from those in North Fork catchments. These results suggest that the approach may be fairly robust across a range of stand conditions, channel characteristics, and management histories within the larger Caspar Creek watershed.

Confidence in results from application of the approach to other Coast Range watersheds would be highest where gaging data are available for watersheds of appropriate sizes so that the slope of the sediment-flow equation can be defined for the particular application. If such information is not available, applications would be less reliable as conditions diverge from those in the North or South Fork Caspar Creek watersheds. It would be useful to compile relations between sediment yield and peak flow at other gaged sites to identify the range in conditions for which the sediment-flow relations are likely to be similar. Until such information is available, it may be appropriate to carry out calculations using a range of potential values for the slope of the relationships. This kind of calculation discloses how sensitive the result is to uncertainty in the value of the slope. Considerably more confidence can be placed in the result if it changes little over a wide range of slopes than if a small difference in slope causes a large change in the result.

Potential Applications: Estimating Sediment Input Rates

Although the method is designed to evaluate proportional changes in suspended sediment load, if estimates of existing sediment loads are available, the estimated change in load due to altered flow-related erosion can be calculated by applying the calculated proportional change to the portion of the estimated load associated with similar sources. Such calculations, however, will incorporate the kinds of uncertainties associated with any sediment budget calculations.

Assessing the Likely Impacts from Estimated Changes

Assessing the operational significance of a change in sediment yield is an entirely different problem than assessing the magnitude of a change, and the approach described above is not designed to assess the significance of sediment-related impacts. Unless there is a regulatory definition of a threshold impact level, the severity of an impact is determined by the effects of a change on particular resources or values. An estimate of the likely magnitude of a change is only the first step in an impact assessment.

For example, if interest focuses on impacts to anadromous salmonids, several aspects of stream sediment loads would need to be evaluated in addition to simply assessing suspended sediment yields from tributary watersheds. These would include evaluating the effects of altered tributary sediment loads on conditions both within the tributaries and at downstream sites, and, in particular, assessing how the altered load might affect pool sedimentation, spawning gravel sedimentation, turbidity, and the health and condition of the salmonids. Existing levels of impact would need to be evaluated to determine if the predicted changes in sediment load would contribute to an existing impact. Analysis of the significance of a change for other kinds of resources would require consideration of other kinds of effects.

Preliminary Method for Estimating Changes in In-channel Sediment Production

Goal: Estimate the likely proportional change in suspended sediment inputs from in-channel sources (such as bank erosion and channel incision) during the first four years following logging.

Suitable conditions for application: Watersheds supporting coast redwood and Douglas-fir on sandstone and shale bedrock in areas of moderate terrain. The method was developed using data from 10- to 80-ha (25- to 200-ac) watersheds, so results are expected to apply most reliably to watersheds within this size range.

Assumptions:

1. Suspended sediment inputs from the in-channel sources in question are a function of flow increases *[strength: good, as suggested by results of Lewis et al. (2001)]*.
2. Estimates are applicable only during the four years following logging; longer-term sediment inputs from these sources eventually may become decoupled from flow increases due to differences in recovery trajectories.
3. Peak-flow increases are a function of proportional canopy change *[strength: good for clearcutting, but changes for selection logging are expected to be lower; Reid (2012), for example, found that selection logging in the South Fork watershed generated a peak-flow increase of about 60% that expected for an equivalent canopy change due to clearcutting]*.
4. The slope of the relation between flow and sediment characteristic of the analysis area is similar to those measured in the North Fork Caspar Creek watershed

(Figure C.1) *[strength: unknown; until additional data are available it will be useful to carry out the calculations for a range of potential slopes]*.

Analysis strategy:

1. Identify the analysis area.
2. Use the method described in Appendix A to estimate changes in the 1.25-year peak flow (under average wetness conditions). Appendix A provides for calculation of the change in a 2-yr flow, and to modify the calculations to estimate flow changes for other return intervals, it is necessary to substitute in other values for y_c, the expected average of flows in HEN and IVE (as listed in Table A.1). For a 1.25-year flow, a value of 0.00497 $m^3s^{-1}ha^{-1}$ would be used in place of the value of 0.0073 $m^3s^{-1}ha^{-1}$ described in Appendix A for the 2-yr flow.
3. Estimate the corresponding change in suspended sediment load using equation C1 or C2. Until more is known of the regional variation in the pooled slope, *m*, it would be useful to calculate changes with $m = 2$, $m = 2.44$, and $m = 3$ in order to evaluate the sensitivity of results to uncertainty in this value at the site of interest. We selected this range to encompass about three-quarters of the values measured at the North Fork and South Fork sub-watersheds. Another approach for selecting a range might be to identify the 90% prediction interval from the measured values, resulting in a range of about 1.7 to 3.2. These ranges are clearly wider than the 95% confidence interval calculated for the mean in the North Fork (2.30 to 2.58), and are selected to be broad enough to test the stability of the result when the value of *m* has not been measured at the location of interest. If a small change in *m* produces a large change in the result, little confidence would be placed in the result until a more accurate estimate of *m* can be made.
4. If the area is to be selection logged, the calculated value is likely to represent a maximum potential change. It would be useful to recalculate the results assuming a peak-flow change equivalent to 60% of that calculated in step 2.
5. The resulting values represent estimates of the proportional change in suspended sediment load for a storm with a 1.25-yr return interval, and this value is expected to be similar to the overall proportional change from the actual distribution of storms likely to occur during the analysis period.
6. The method is designed to evaluate proportional changes in suspended sediment load due to in-channel erosion, but the magnitude of the change can also be estimated if the existing sediment load is known. In this case, the estimated change in load can be calculated by applying the calculated proportional change to the portion of the estimated load associated with similar sources.[20] For a watershed that has not been disturbed for several decades and shows low rates of landsliding and road-surface erosion, the load from similar sources might be

[20] TMDL sediment estimates are available for several watersheds in the northern part of the California Coast Ranges (see: http://www.waterboards.ca.gov/northcoast/water_issues/programs/tmdls/). Additional sediment information is available in North Coast Watershed Assessment Program (NCWAP) Reports (see: http://coastalwatersheds.ca.gov/Home/tabid/54/Default.aspx). Individual watershed studies may also be available (e.g., Resource Conservation District (RCD) watershed assessments, Habitat Conservation Program (HCP) documentation, and graduate student theses).

estimated as the total suspended sediment load. Estimation is more complicated for watersheds with more recent disturbances or recent large landslides because landslide debris deposited along channels is susceptible to accelerated erosion from heightened flows. In such cases, the component of landslide sediment immediately transported out of the watershed would be subtracted from the suspended sediment load, along with any suspended sediment from road-surface erosion.

Example

A 30-ac clearcut of second-growth coast redwood and Douglas-fir is planned for an 86-ac watershed that was last entered about 65 years ago. The landowner wants to estimate the magnitude of sediment load changes that may result from peak-flow changes. The site has terrain and bedrock geology similar to those at Caspar Creek, and an existing TMDL for a nearby 24,230-ac watershed indicates that sediment loads in the area are expected to be about 400 to 800 t/mi^2/yr, but this rate reflects both recent disturbances and inputs from large landslides. Data from a 130-ac watershed at Caspar Creek that was last entered 40 years ago shows an average annual suspended sediment load of about 230 t/mi^2/yr. If about a third of the total load is transported as bedload (i.e., *total* = *suspended* + 1/3 * *total*), total sediment load for the watershed would be about 350 t/mi^2/yr, a value near the lower bound of estimates for the TMDL watershed and similar to the 43-year average of sediment loads at the South Fork weir (390 t/mi^2/yr). On this basis we decide to use a value of 350 t/mi^2/yr as our estimate for the pre-treatment total sediment load.

1. Estimate the likely peak-flow change after one summer following logging for a 1.25-year flow (0.00497 $m^3 s^{-1} ha^{-1}$) using the method described in Appendix A. Results show an expected 10.0% increase under average wetness conditions.
2. Calculate associated changes in suspended sediment load using equation C2:

$$S\% = 100\left(1+\frac{10.0}{100}\right)^{2.44} - 100 = 26\% \qquad \text{(C2)}$$

3. To evaluate the sensitivity of the result, recalculate *S* using *m* = 2 (resulting in an estimated 21% increase) and *m* = 3 (resulting in a 33% increase).
4. Because results are calculated for a 1.25-year flow under average wetness conditions, they represent an *index* of likely change rather than an estimate of change. However, results for North Fork watersheds indicated that this index provides a value similar to that calculated using an actual distribution of storms. We thus conclude that the increase in suspended sediment load due to elevated in-channel erosion is likely to be about 26% ± 7% for the range of *m* values tested. In this case, the variation in the result over the tested range of *m* is small enough that we decide that the calculation is useful for the application intended.
5. Although this method calculates proportional changes in suspended load, the eroding materials also include sediment of sizes likely to be carried as bedload. Because the in-channel erosion processes do not preferentially contribute fine sediments and because these sources are likely to have provided much of the

bedload-sized sediment in the past, the proportional increase in coarse sediment input is likely to be similar to that for suspended load. Our estimated annual pre-treatment sediment load is about 350 t/mi^2, so a 26% increase in the 86-ac watershed would amount to an increase of about 12.2 t/yr, or about 49 t over a four-year period. If sediment bulk densities in the area are about 1.3 t/yd^3, this would be equivalent to a volume of about 38 yd^3, a 26% increase over the 145 yd^3 expected for a four-year period before the planned logging. Sediment loads are likely to decrease after the first four years, but to remain elevated above pre-harvest levels for several additional years.

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APPENDIX D. COMPARING FLOW MODELS

The examples of applications described in previous appendices employ methods developed using data and understanding gained from watershed research at Caspar Creek. However, Caspar Creek data have also proved to be useful even when they are not directly involved in method development. Many analysis methods are available that were developed using information from regions with climates, vegetation, and bedrock that differ from those found in the California Coast Ranges. When such methods are adopted for application at a new site, there is often considerable uncertainty about the reliability of the outcome in the new setting, and in some cases the methods require calibration to assure their utility. Caspar Creek data have been used to address these problems, providing data sets used for both testing and calibrating existing methods.

Figure D.1. The HEN channel in North Fork Caspar Creek watershed.

As an example, Cafferata et al. (2004) used data from a gaged control watershed at Caspar Creek (Table D.1, Figures D.1 and D.2) to evaluate the relative effectiveness of three flow estimation methods commonly used for designing watercourse crossings along logging roads. Appropriate sizing of culverts and other drainage structures provides a challenge for forestland managers because crossings must have large-enough capacities to pass flood flows, woody debris, and fish, while at the same time being small enough to be affordable. Current California forest practice rules specify that new or reconstructed permanent watercourse crossings must be designed to pass the estimated 100-year flood flow, along with the debris and sediment transported to the crossing inlet. Also, they must allow for unrestricted passage of all life stages of fish that may be present.

This appendix describes and expands on the analysis of 10-year flows carried out by Cafferata et al. (2004) to illustrate how Caspar Creek data can be used to evaluate the applicability of a variety of existing methods to estimate peak flows of given return intervals. We carry out the calculations for 10-year flows instead of 100-year flows because the largest flow yet documented in the HEN watershed has a return interval of about 17 years.

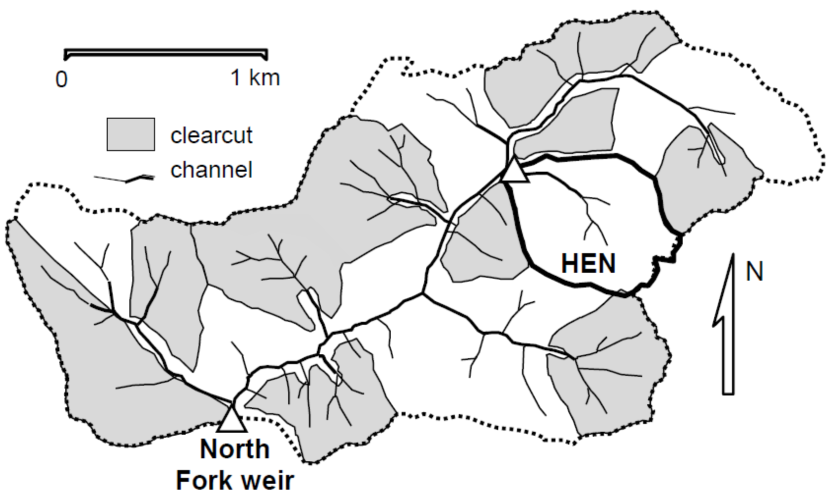

Figure D.2. Location of the HEN and North Fork gages.

Table D.1. Characteristics of the HEN watershed, and definition of selected variables used in Appendix D equations.[21]

Variable	Description	Value
A	Drainage area	96 acres or 0.149 mi^2
$I_{10,15}$	10-yr 15 min rainfall intensity	2.16 in/hr (Goodridge 2000)[22]
$I_{10,30}$	10-yr 30 minute rainfall intensity	1.46 in/hr (Goodridge 2000)
L	Flow path length	2800 ft (ridge to gage)
S	Mean watershed slope	580/2800 = 0.207
--	Soil	loam
P	Annual rainfall	46.85 in/yr (Henry 1998)

[21] Following Cafferata et al. (2004), we use English units in this appendix. Values for watershed attributes and peak flow discharges differ slightly from those used by Cafferata et al. (2004) because more detailed maps are now available.
[22] California rainfall depth-duration-frequency data are now available online at the DWR Climate webpage: http://www.water.ca.gov/floodmgmt/hafoo/csc/climate_data/# [accessed 5/01/2013].

Flow Frequency Analysis

First, for comparison, we need an estimate of the actual 10-year flow, calculated on the basis of monitoring data. This value is estimated from the annual maximum peak flow series (Table D.2). The recurrence interval for each of the measured annual peaks is calculated by dividing the rank of the flow into [1 + the number of years represented], or 19 in this case. Using the method described by Linsley et al. (1982), we find an estimated peak discharge of 17 cfs for a recurrence interval of 10 years. This value is similar to that which would have been estimated by linear interpolation from the measured values (Figure D.3), but does not exactly agree because recurrence intervals are not well defined for the most infrequent of the measured flows. The method described by Linsley et al. (1982) avoids this problem by assuming that the data should be fitted by a theoretical distribution that has been shown to be characteristic for extreme values. This method is most easily applied using the USGS PeakFQ software, available for download at http://water.usgs.gov/software/PeakFQ/ [accessed 4/12/2013].

Table D.2. Annual maximum discharges at the HEN control gage, 1986-2003.

Water year	Annual peak Q (cfs)	Rank	Water year	Annual peak Q (cfs)	Rank	Water year	Annual peak Q (cfs)	Rank
1986	12.7	6	1992	4.3	15	1998	13.0	5
1987	4.2	16	1993	17.0	1	1999	16.5	2
1988	7.6	11	1994	4.0	17	2000	6.6	12
1989	4.9	14	1995	14.7	4	2001	5.8	13
1990	12.2	7	1996	11.4	8	2002	10.0	10
1991	1.6	18	1997	15.6	3	2003	11.3	9

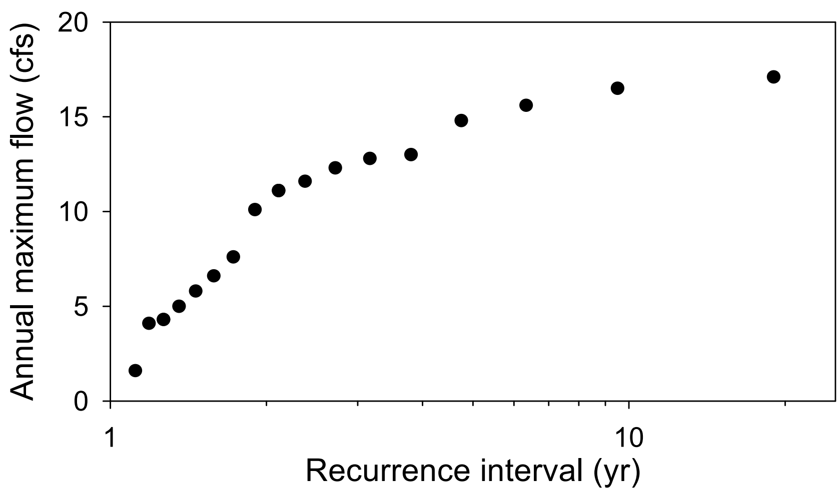

Figure D.3. Annual peaks at HEN plotted against their calculated recurrence intervals.

Rational Method

The rational runoff method is frequently used for flood analyses in urban watersheds, where much of the storm flow travels as overland flow on impermeable surfaces. Although the method is less appropriate for undeveloped watersheds, it is often used in such settings, and it may be particularly appropriate where tractors have compacted soils enough to generate widespread overland flow. Guidelines suggest that the method should not be used for watersheds larger than about 200 ac (Dunne and Leopold 1978).

The rational method incorporates the assumption that a 10-year flow is generated by a 10-year rain intensity calculated for a duration equivalent to the time required for all parts of the watershed to contribute runoff during a uniform-intensity storm (the "time of concentration" for the watershed). A 10-year recurrence-interval peak flow is calculated using the rational runoff equation (for English units):[23]

$$Q_{10} = C\, I_{10} A \qquad \text{(D1)}$$

where:

- Q_{10} Annual maximum discharge having a 10-yr return interval (cfs)
- C Rational runoff coefficient (= 0.3 for loam soil under woodland [Dunne and Leopold 1978], as expected for HEN)
- I_{10} An estimate of the rainfall intensity associated with a 10-yr flow (in/hr), for a rain duration selected to be equivalent to the time of concentration for the watershed
- A Watershed area (acres) (= 96 ac for HEN)

For a forestland application, the primary challenge is in defining the time of concentration for an ungaged watershed so that I_{10} can be estimated. Two methods are frequently used, and a third can be used as a check on the other two.

Calculations Using the Kirpich Equation for t_c

A version of the Kirpich equation (California Division of Highways 1944) provides the result:

$$t_c = \frac{0.00013\, L^{0.77}}{S^{0.385}} = \frac{0.00013\left(2800^{0.77}\right)}{0.207^{0.385}} = 0.108 \text{ hr or } 6.5 \text{ min} \qquad \text{(D2)}$$

where:

- t_c Time of concentration (hours)
- L Flow length from the ridge to the point of interest (feet) = 2800 ft
- S Average slope along the flow path (elevation difference/flow length) = 0.207

The 10-year recurrence-interval rainfall intensity for a 6.5-minute duration storm is required, but for t_c < 10 min, a 10-min duration intensity has been found to be more

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[23] When used with metric units, a coefficient of 0.278 is included, and Q has units of m^3/s, I of mm/hr, and A of km^2. The runoff coefficient represents the estimated proportion of rainfall that runs off and so is dimensionless. No proportionality constant is needed when the rational runoff equation is used with English units because one acre-inch/hour of precipitation is equal to 1.008 cfs.

appropriate (Yee 1994). In this case, the minimum duration for which frequencies of different rainfall intensities have been evaluated at a nearby weather station is 15 minutes (Goodridge 2000), and we will use the 10-yr 15-minute rainfall intensity of 2.16 in/hr. This value is lower than the 10-minute intensity (which extrapolation of the data suggests may be as high as 2.56 in/hr), so the calculated result will provide an underestimate.

We can now use the rational runoff equation to estimate the 10-year flow:

$$Q_{10} = C\, I_{10} A = 0.3 \text{ x } 2.16 \text{ in/hr x } 96 \text{ ac} = 62 \text{ cfs} \qquad \text{(D3)}$$

The time of concentration of 6.5 minutes is clearly shorter than expected for a half-mile-long forested watershed—this value would suggest that the average water velocity is more than 7 feet per second, which is not reasonable. Even a t_c of 15 minutes seems unlikely given the characteristic lengths of unchannelled hillslopes in the watershed, on which flow velocities will be quite low. The 10-year discharge estimated using this method is correspondingly high.

Calculations Using the Airport Drainage Equation for t_c

A second approach for estimating time of concentration employs the airport drainage equation (FAA 1970):[24]

$$t_c = \frac{1.8\,(1.1 - C) L^{0.5}}{(100\,S)^{0.33}} = \frac{1.8 \times (1.1 - 0.3) \times 2800^{0.5}}{(100 \times 0.207)^{0.33}} = 28 \text{ min} \qquad \text{(D4)}$$

where:

- t_c Time of concentration, this time in minutes
- C Rational runoff coefficient = 0.3 for loam soil under woodland
- L Maximum flow distance (feet) = 2800 ft
- S Slope = 0.207

We thus need the 10-year recurrence-interval rainfall intensity for a 28-minute storm, which will be similar to the 1.46 in/hr value noted by Goodridge (2000) for a 30-minute storm. Using the 30-minute value, the rational runoff equation now provides a second estimate for the 10-year flow:

$$Q_{10} = C\, I_{10} A = 0.3 \text{ x } 1.46 \text{ in/hr x } 96 \text{ ac} = 42 \text{ cfs} \qquad \text{(D5)}$$

The corresponding value for a 28-minute t_c would be slightly greater.

Calculations Using Estimated Travel Times for t_c

The times of concentration estimated using the Kirpich and airport drainage methods are shorter than those expected, given the observed rise-times for HEN hydrographs. Typical lag times between the centroid of rainfall and the hydrograph peak at HEN are several hours, suggesting that more than an hour is actually required before the entire watershed area contributes flow to the mouth of the watershed. Because most hillslopes in the watershed contribute to runoff through subsurface flow and

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[24] Although the airport drainage equation has been used in many settings, it was designed to be applied at sites with a maximum gradient of 7%.

saturation overland flow, both of which respond more slowly than Horton overland flow,[25] methods that assume that runoff is generated primarily by Horton overland flow are likely to underestimate flow times and so overestimate peak discharges.

Times of concentration can be roughly estimated using information about flow-path lengths and likely flow velocities for various segments of the flow path (Dunne and Leopold 1978). Dunne and Leopold (1978) suggest that maximum flow velocities for saturation overland flow on unchannelled hillslopes and for flow in small channels would be no more than about 0.1 and 6 ft/sec, respectively. Given the typical hillslope lengths of 300 to 500 ft in the HEN watershed, minimum travel times of 66.7 min (400 ft / 0.1 ft/s) on hillslopes and 6.7 min (2400 ft / 6 ft/s) in channels would provide an estimated total minimum t_c of about 73 minutes.

For the rational runoff method, we now need a 10-year rainfall intensity for a 73-min-duration rainfall, which we can estimate by interpolating values provided by Goodridge (2000), resulting in an estimated intensity of 0.94 in/hr.

A second source of uncertainty in the use of the rational runoff equation is the estimate of the rational runoff coefficient, *C*. Dunne and Leopold (1978) provide an estimate of 0.3 for loam soils in woodlands, but many of Caspar Creek's loams have high gravel contents. Dunne and Leopold (1978) suggest values of 0.10 for gravelly soils in woodlands and 0.10 to 0.30 for unimproved urban areas irrespective of soil type. These potential ranges of reasonable values suggest that the assumed value for *C* can carry a large uncertainty, and that calculations might usefully be carried out for a range of *C*-values. We will calculate results for *C* = 0.20 ± 0.10 (see Appendix E for further evaluation of the *C* factor; those results suggest that a *C*-value of 0.13 would indeed be most appropriate for this application in calculating the 10-year flow).

We can now use the rational runoff equation to estimate the peak discharge using the 10-yr, 73-minute storm and a range of *C*-values:

$$Q_{10} = C\, I_{10} A = [0.20 \pm 0.10] \text{ x } 0.94 \text{ in/hr x } 96 \text{ ac} = 18 \pm 9 \text{ cfs} \qquad \text{(D6)}$$

This result provides a range of predicted values that encompasses the measured value. The range in predicted values obtained using reasonable assumptions in equations D3, D5, and D6 illustrates the level of uncertainty associated with application of the rational runoff method in forested settings.

USGS Magnitude and Frequency Method

Examination of relations between mean annual rainfall and peak discharge frequencies has shown that different regions in California have different characteristic flow distributions, and these patterns have been used to estimate peak discharges from annual rainfall (Waananen and Crippen 1977).[26] While these equations are easy

[25] Horton overland flow is surface flow that occurs when rainfall intensity is greater than a soil's infiltration rate.
[26] These calculations are automated by the USGS's National Streamflow Statistics Program (available at http://water.usgs.gov/osw/programs/nss/ [accessed 4/12/2013]). Also, an automated spreadsheet

to use, they have not been updated since 1977 and do not incorporate data from more recent large flood events. In addition, they generalize vast areas of the state into six regions, resulting in overestimation in some parts of California and underestimation in other areas (Cafferata et al. 2004).

For HEN, the equation developed for 10-year flows in the North Coast region produces an estimated 10-yr discharge of

$$Q_{10} = 6.21\, A^{0.88}\, P^{0.93}\, H^{-0.27} = 6.21 \text{ x } (0.149 \text{ mi}^2)^{0.88} \text{ x } (46.85 \text{ in/yr})^{0.93} \text{ x } 1.0^{-0.27} = 42 \text{ cfs} \quad \text{(D7)}$$

where:

A 0.15 miles^2
P 46.85 inches/year (Henry 1998)
H Average channel elevation (ft)/1000 = 1.0 (for the North Coast region, a value of 1.0 is assigned if *H* is calculated to be < 1.0, as here).

Flow Transference Method

Waananen and Crippen (1977) showed that long-term flow-frequency data from a watershed can be used to estimate flow frequencies at locations within the watershed or in nearby watersheds. We will employ this method in three forms: (1) using a 42-year record of discharge data from the North Fork Caspar Creek gage, located downstream of the HEN gage; (2) using the 1986-2004 record from the North Fork gage; and (3) using a 61-year record from the more distant Noyo River gage. Each of these data sets will incorporate extra variance (relative to records from undisturbed watersheds) due to the on-going sequence of management activities that can affect runoff within the watersheds.

Gage Record: North Fork Caspar Creek, 1962-2003

The gaging weir for North Fork Caspar Creek is located downstream of the HEN watershed and, as of 2004, had a 42-year record of annual peak discharges (Figure D.2). This long record provides an estimated 10-year flow of 232 cfs for the 1168-ac North Fork watershed (Cafferata et al. 2004). We can use this information to estimate the 10-year flow at HEN by applying the equation provided by Waananen and Crippen (1977):

$$Q_{10} = Q_{10\text{gaged}}\, (A_u/A_g)^b = 232 \text{ x } (96/1168)^{0.88} = 26 \text{ cfs} \quad \text{(D8)}$$

where:

A_u Area of ungaged watershed (HEN) = 96 ac
A_g Area of the gaged watershed (North Fork) = 1168 ac
$Q_{10gaged}$ 10-yr discharge at the gaged watershed = 232 cfs
b Exponent for drainage area from Equation D7 = 0.88

for both the USGS regression equations and the Rational Method and is available at: http://calfire.ca.gov/resource_mgt/resource_mgt_forestpractice_pubsmemos_pubs.php [accessed 5/02/2013].

Gage Record: North Fork Caspar Creek, 1986-2003

Many large storms occurred during the first 20 years of gaging at the North Fork, including those that generated the three largest recorded annual peak flows. Because monitoring at HEN postdates this period, the 10-year flow estimated from the 1986-2003 record is likely to be lower than that which would have been estimated from a 42-year record. To evaluate the influence of the storm history, we can use the flow transference method to estimate the 10-year flow based only on the 1986-2003 record from North Fork Caspar Creek.

During this period, the estimated 10-year flow at the North Fork weir was 222 cfs, as calculated using the method described by Linsley et al. (1982, p.361), so the estimated 10-year flow at HEN is:

$$Q_{10} = Q_{10\text{gaged}} (A_u/A_g)^b = 222 \text{ x } (96/1168)^{0.88} = 25 \text{ cfs} \quad \text{(D9)}$$

The difference between this value and that calculated using the 42-year record (equation D8) is inconsequential, indicating that the outcome is not particularly sensitive to the details of the storm history over these lengths of record.

Gage Record: Noyo River, 1952-2012

For most forestland applications, the nearest gaged watershed is located farther from the site of interest than is the case at Caspar Creek, and the gaged watershed is often much larger than the watershed of interest. The accuracy of predictions declines as these differences increase, and Sumioka et al. (1998) advise that the flow transference method is most appropriate where the drainage area for the ungaged site is between 50% and 150% of that for the gaged site. Use of data from the North Fork gage, representing a watershed 13 times the size of the HEN watershed, still provided a reasonable estimate (equation D9), but often the only available information is from a US Geological Survey gage located in an even larger watershed.

As an example, we can redo the flow transference analysis using the 61-year record from the nearest USGS gaging station, which has a drainage area of 69,760 ac and is located on the Noyo River, four miles north of the HEN gage. Using the USGS PeakFQ software program for the Noyo River, a 10-yr discharge of 14,910 cfs for the watershed is obtained, allowing estimation of Q_{10} for HEN:

$$Q_{10} = Q_{10\text{gaged}} (A_u/A_g)^b = 14910 \text{ x } (96/69760)^{0.88} = 46 \text{ cfs} \quad \text{(D10)}$$

where:

A_u	Area of ungaged watershed (HEN) = 96 ac
A_g	Area of the gaged watershed (Noyo River) = 69,760 ac
$Q_{10\text{gaged}}$	10-yr discharge at the gaged watershed = 14,910 cfs
b	Exponent for drainage area from equation D7 = 0.88

As expected, the accuracy of the prediction is considerably lower than that calculated using records from the North Fork Caspar Creek gage. Such differences may arise because of climatic differences between the sites (particularly at higher elevations within the larger watershed) or because of differences in runoff generation processes in watersheds of different sizes.

Direct Flow Transference Method

Skaugset and Pyles (1991) found that the flow transference method can be simplified if the gaged and ungaged watersheds are near one another, are hydrologically similar, and have sizes within an order of magnitude of one another. In this case, the exponent in the flow transference equation is set to 1.0, providing the simplified equation:

$$Q_{10} = Q_{10gaged}\ (A_u/A_g) = 232 \text{ x } (96/1168) = 19 \text{ cfs} \qquad \text{(D11)}$$

where:

A_u	Area of ungaged watershed (HEN) = 96 ac
A_g	Area of the gaged watershed (North Fork) = 1168 ac
$Q_{10gaged}$	10-yr discharge at the gaged watershed = 232 cfs

Conclusions

Of the approaches tested, the flow transference methods that use data from nearby gages generally provided the most reliable results (Table D.3). Use of flow transference with a data set from a significantly larger watershed, however, produced a poor estimate, indicating the importance of selecting a data set from a site that matches as closely as possible the conditions in the target watershed.

Although the rational runoff method is capable of producing results that are consistent with observed values, it is just as capable of producing results that differ greatly. Appropriate use of this method depends strongly on having good estimates both of the time of concentration for a watershed and of *C*, the rational runoff coefficient. Because this coefficient is poorly defined for forested lands, calculations might usefully be carried out for the range of potential values. If possible, the appropriate *C*-value should be estimated on the basis of measured peak-flow values, as illustrated for Caspar Creek in Appendix E.

The calculations presented in this Appendix simply test the ability of the selected flow models to accurately estimate the 10-year flow at HEN. When these models are used to estimate flood flows for designing permanent watercourse crossings, a variety of other factors must be considered. First, 100-year flows must be estimated instead of 10-year flows, and the calculations presented here do not directly test the equations' utility for 100-year flows. However, it is probably safe to assume that if a method does not adequately characterize a 10-year flow, it is not likely to work well for larger flows, either. Second, passage of sediment, debris, and fish must also be considered, so many other kinds of information are needed before an adequate design can be developed—sizing for 100-year flood flows alone does not ensure adequate capacity for wood, sediment, and fish (Cafferata et al. 2004). Finally, results should always be checked against field observations.

Table D.3. Comparison of 10-yr annual peaks predicted for HEN station, listed in order of accuracy.

Method	Predicted 10-yr RI discharge (cfs)
***Observed value** (HEN flow frequency analysis)*	***17***
Rational runoff method—Travel time estimate	18 ± 9
Direct flow transference (42-yr N Fork Caspar Cr.)	19
Flow transference (18-yr N Fork Caspar Cr.)	25
Flow transference (42-yr N Fork Caspar Cr.)	26
Rational runoff method—airport drainage equation	42
USGS magnitude and frequency	42
Flow transference (61-yr Noyo R.)	46
Rational runoff method—Kirpich equation	62

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APPENDIX E. CALIBRATING AND VALIDATING A FLOW MODEL

As we saw in Appendix D, Caspar Creek data can be used to test the applicability of existing models as they are commonly employed. Results of the comparison described in Appendix D showed that one of the widely used models—the Rational Method—can provide widely disparate results due to uncertainty in estimating a value for *C*, the empirically-based rational runoff coefficient. Here we illustrate three additional applications of Caspar Creek data: (1) a long record of flow data from one of the gaged Caspar Creek watersheds can be used to calibrate the runoff coefficient for use in this type of setting; (2) flow data from other Caspar Creek watersheds can be used to test the validity and applicability of the resulting calibrated model; and (3) the flow data can be used to test a hypothesis regarding the runoff coefficient.

Calibrating the Model

The HEN watershed record was selected to use for calibration because it is one of the three North Fork watersheds that were not logged during the period of record; it is one of the two control watersheds with more than 12 years of record as of 2004; and of those two, it is the one with a hydrologic response typical of most other gaged watersheds in the area. We will work with annual maximum peak-flow data from HEN watershed (Figure D.2) to estimate an appropriate value of the rational runoff coefficient, *C*, such that use of the airport drainage method (FAA 1970) for estimation of the time of concentration, t_c, along with the rational runoff equation (Dunne and Leopold 1978), will provide an accurate estimate of the HEN peak flow observed to have a 10-year recurrence interval, 17.0 cfs. It should be noted that the physical basis for this application is weak: the airport drainage equation was developed for sites with a maximum gradient of 7% or less, and is generally used in watersheds with a high proportion of impermeable surfaces. Similarly, the rational runoff method was developed for use in urban watersheds, where a significant portion of the watershed is impermeable. We thus do not expect values of t_c or *C* estimated for this application to be physically meaningful. Instead, we consider the calculated values to be empirically based indices that calibrate the equations in such a way that they provide useful estimates of the 10-year flow.

We first use analyses of North Fork Caspar Creek rainfall data presented by Goodridge (2000) to develop a relation between rainfall intensity for 10-year rainfalls and rainfall duration (Figure E.1). We can use the resulting relation to calculate the 10-year rainfall intensity for any rainfall duration, and the duration we will need for the rational runoff equation is that equivalent to the time of concentration for the watershed, t_c:

$$\log (I_{10}) = 0.908 - 0.501 \log (t_c) \qquad \text{(E1)}$$

We do not yet know t_c, however. We will use the airport drainage equation to provide an expression for t_c:

$$t_c = \frac{1.8\,(1.1 - C) L^{0.5}}{(100\ \ S)^{0.33}} = \frac{1.8 \times (1.1 - C) \times 2800^{0.5}}{(100 \times 0.207)^{0.33}} = 35.04\,(1.1 - C) \qquad \text{(E2)}$$

and the rational runoff equation to calculate C:

$$Q_{10} = CI_{10}A, \text{ so } C = \frac{17.0}{96\ I_{10}} = \frac{0.177}{I_{10}} \qquad \text{(E3)}$$

where:

Q_{10}	10-yr return interval annual peak flow (cfs) = 17.0 cfs
C	Rational runoff coefficient
I_{10}	A measure of the rain intensity associated with a 10-year flow
A	Watershed area (acres) = 96 ac
t_c	Time of concentration for the watershed (minutes)
L	Maximum flow distance (feet) = 2800 ft
S	Slope = 0.207

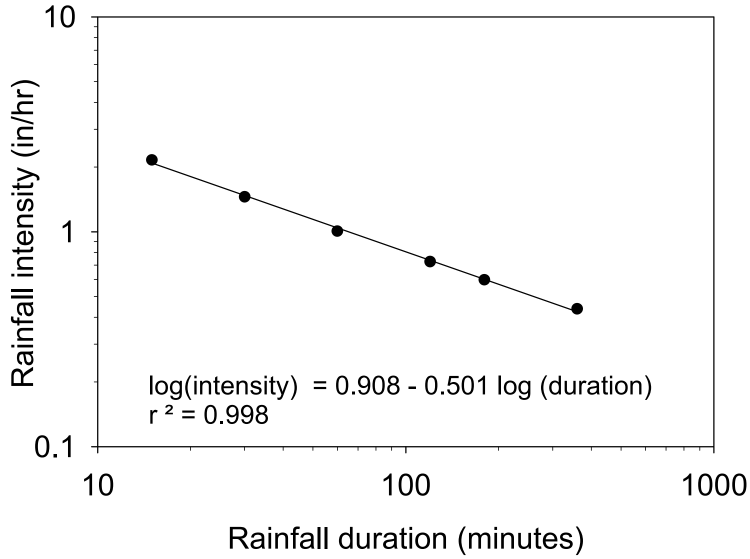

Figure E.1. 10-year rainfall intensities for storms of various durations.

We now have three equations and three unknowns, I_{10}, t_c, and C; we have the information we need to solve the problem. Although this solution might be derived algebraically, it is considerably easier to use equation E1 to calculate a value of I_{10} for each of a sequence of t_c values, use equation E3 to calculate C for each value of I_{10}, and then use equation E2 to recalculate t_c from each of those C values. Each recalculated t_c value can then be compared with the t_c value used at the start of its calculation sequence. The desired value of C is the one for which the original and recalculated values of t_c agree. This procedure results in an estimate of C=0.129 to produce the expected 10-year flow.

To check our calculated result for C, we see that the resulting estimate of Q_{10} agrees well with our expected 10-year flow of 17.0 cfs:

$$t_c = \frac{1.8\,(1.1-C)L^{0.5}}{(100\ S)^{0.33}} = \frac{1.8\times(1.1-C)\times 2800^{0.5}}{(100\times 0.207)^{0.33}} = 35.04\,(1.1-0.129) = 34.0\,\text{min} \qquad \text{(E2)}$$

$$\log(I_{10}) = 0.908 - 0.501 \log(34.0) = 0.140, \text{ so } I_{10} = 1.38 \text{ in/hr} \quad \text{(E1)}$$

$$Q_{10} = CI_{10}A = 0.129 \times 1.38 \text{ in/hr} \times 96 \text{ ac} = 17.1 \text{ cfs} \quad \text{(E3)}$$

Testing the Validity of the Calibration

We now have a value for *C* that produces the expected value for the 10-year annual peak flow at HEN, but we do not know if this value is applicable elsewhere. To test it, we use the calculated value of *C* with equations E1, E2, and E3 to estimate the 10-year discharge at other gaged North Fork watersheds (Figure E.2), and we then compare the predicted values to those calculated from existing flow records (Table E.1, Figure E.3) using the method described by Linsley et al. (1982, p. 361).

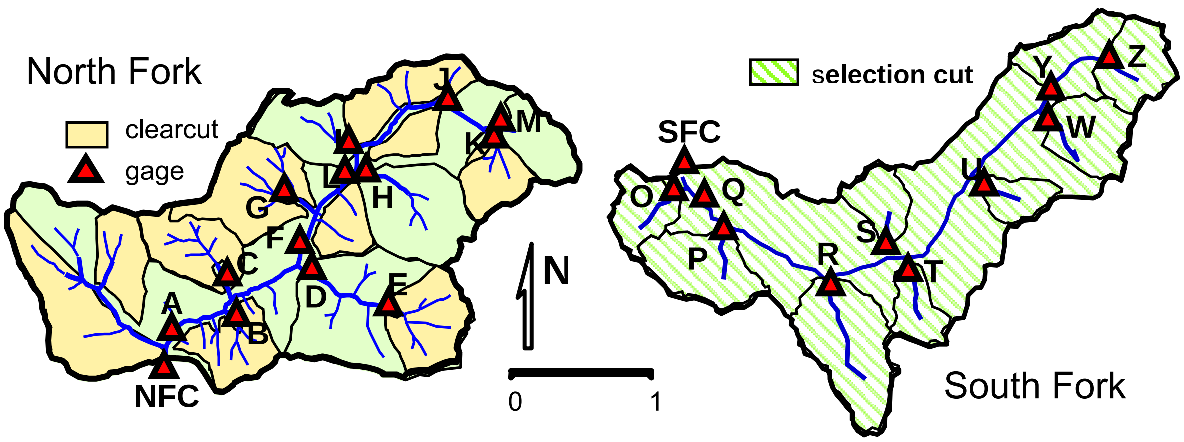

Figure E.2. Gaging stations in the North and South Fork Caspar Creek watersheds.

Table E.1. Comparison of predicted and observed annual peak discharges with 10-year recurrence intervals at nine gaging stations in the North Fork Caspar Creek watershed.

	BAN	CAR	DOL	EAG	GIB	IVE	JOH	KJE	MUN
Watershed area (acres)	26	66	190	66	49	51	135	38	40
Watershed length (ft)	1430	2140	3780	1930	1610	2080	3260	1560	1690
Watershed slope	0.307	0.244	0.169	0.27	0.297	0.25	0.16	0.23	0.189
t_c (minutes)	21.4	28.2	42.2	25.9	22.9	27.6	40.0	24.5	27.3
I_{10} (inches/hr)	1.75	1.52	1.24	1.59	1.68	1.54	1.28	1.63	1.54
Years of record	10	18	18	18	10	18	10	10	12
Predicted Q_{10} (cfs)	5.8	12.8	30.5	13.5	10.6	10.1	22.2	7.9	8.0
Observed Q_{10} (cfs)	4.7	12.9	37.4	13.4	9.5	7.6	25.8	8.8	9.4
Predicted/Observed	1.23	0.99	0.82	1.00	1.11	1.34	0.86	0.90	0.86

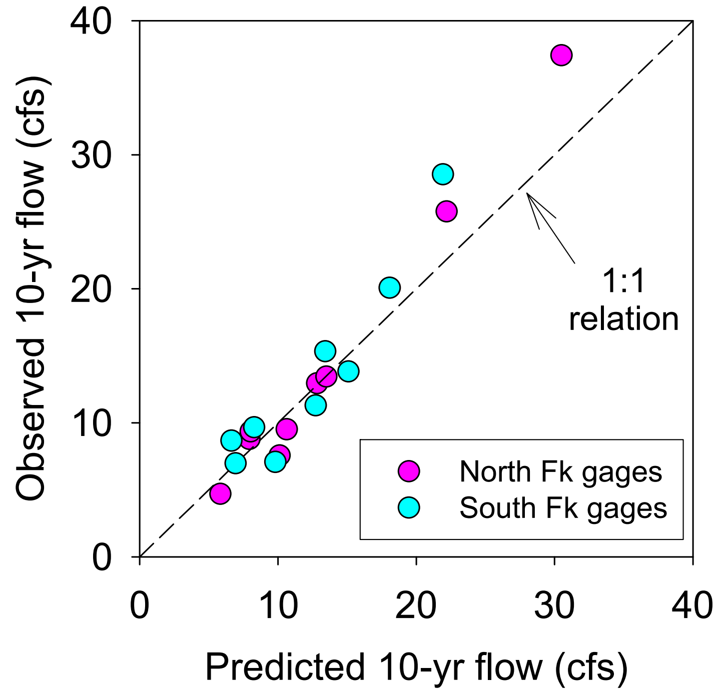

Figure E.3. Predicted and observed annual peak discharges with 10-year return intervals at gaging stations in the North and South Fork Caspar Creek watersheds.

Results show agreement to within 20% for seven of the nine sites tested. Peak flows were over-estimated in a watershed (IVE) that has been recognized to have atypically low peaks with longer-than-usual lags to peak, and flows were under-predicted for two watersheds that had earlier been noted to have quicker response times and more peaked hydrographs than usual (KJE and MUN). These variations in accuracy of the predictions correspond to observed variations in the hydrologic behavior of the gaged watersheds, indicating the types of errors likely when hydrologic conditions vary across even a relatively uniform landscape. Flows were also under-predicted for the two largest watersheds evaluated, JOH (135 ac) and DOL (190 ac). Dunne and Leopold (1978) note that the rational runoff method should not be used in watersheds larger than about 200 ac, and Chow (1964) recommended that the rational method generally should be limited to use in watersheds of less than 100 acres.

In only two cases (IVE and MUN) were the test watersheds unlogged throughout the period of record. The remaining watersheds were 30% to 100% clearcut four to six years after the onset of gaging. Peak flows were found to increase after logging (Reid and Lewis 2007), but the effects generally began to decline within a few years (Figure 14). The extra variance introduced by such changes within the periods of record are likely to reduce the accuracy of the 10-year-return-interval flows estimated from gaging records. In addition, the period of record was 12 years or less in five of the watersheds, also reducing the accuracy of 10-year flow estimates.

Results shown in Table E.1 and Figure E.3 support the use of a *C*-value of about 0.13 for application of the rational runoff method and airport drainage equation to calculate 10-yr flows at sites with conditions similar to those at Caspar Creek.[27] The utility of the equations and the empirically determined *C*-value can be further tested by applying them to gaged catchments in the nearby South Fork Caspar Creek watershed (Figure E.2), where stand history is quite different than in the North Fork. South Fork hillslopes remain partially compacted from tractor logging of the 1970s, so a *C*-value characteristic of 100-yr-old second-growth forests at HEN might be expected to underestimate peak flows in the South Fork.[28]

Calculated results (Table E.2, Figure E.3), however, show no significant difference in the mean ratio between predicted and observed values for North Fork and South Fork gaging stations. Six of the nine South Fork watersheds show values within 20% of those predicted, and the 36% overestimate of the OGI peak may reflect the presence of a small impoundment in the OGI watershed.

Caspar Creek data can also be used to test the applicability of the method to watersheds larger than the recommended upper limit of 200 ac. In this case (Table E.3), results for larger North Fork watersheds indicate that the method indeed provides poor estimates relative to those in smaller watersheds (Table E.1), supporting the recommended limit for application of the rational runoff method.

Table E.2. Comparison of predicted and observed annual peak discharges with 10-year recurrence intervals at nine gages in the South Fork Caspar Creek watershed.

	OGI	POR	RIC	SEQ	TRE	UQL	WIL	YOC	ZIE
Watershed area (acres)	47	77	116	42	35	32	64	131	64
Watershed length (ft)	1640	1896	3718	2005	1932	1896	2187	3281	1640
Watershed slope	0.24	0.21	0.14	0.23	0.24	0.28	0.27	0.18	0.24
t_c (minutes)	25	27	37	28	27	27	29	35	25
I_{10} (inches/hr)	1.63	1.57	1.33	1.55	1.56	1.57	1.52	1.37	1.63
Years of record	10	10	10	10	10	10	10	10	10
Predicted Q_{10} (cfs)	9.6	15	19	8.2	6.8	6.4	12	23	13
Observed Q_{10} (cfs)	7.1	14	20	9.7	7.0	8.7	11	29	15
Predicted/Observed	1.36	1.10	0.97	0.85	0.98	0.73	1.09	0.79	0.86

[27] Storms with long return intervals (e.g., 100-yr events) generally produce a higher proportion of runoff than shorter-return-interval storms and so may require use of larger *C*-values in calculations (Dunne and Leopold 1978, Caltrans 2001). However, preliminary calculations for the estimated 100-yr storm in this case suggest that *C*-values for 100-yr storms are similar to those for 10-yr storms at Caspar Creek.

[28] Immediately following logging, approximately 15% of the South Fork watershed was estimated to be compacted by roads, skid trails, and landings, while roughly 3% of the North Fork was estimated to be newly compacted (Henry 1998).

Table E.3. Comparison of predicted and observed annual peak discharges with 10-year recurrence intervals in larger Caspar Creek watersheds.

	ARF	FLY	LAN	NFC	SFC
Watershed area (acres)	949	536	385	1170	1048
Watershed length (ft)	11800	8100	5970	12110	14480
Watershed slope	0.061	0.074	0.100	0.059	0.068
t_c (minutes)	62	51	44	107	112
I_{10} (inches/hr)	1.03	1.14	1.23	0.78	0.76
Years of record	10	10	10	18	18
Predicted Q_{10} (cfs)	124	77	60	118	103
Observed Q_{10} (cfs)	181	137	82	226	239
Predicted/Observed	0.69	0.56	0.74	0.52	0.43

Testing a Hypothesis about the Rational Runoff Coefficient

The pattern of deviations in Tables E.1 and E.3 suggests that the effective value for *C* may increase with watershed area. To explore this possibility, the method used to estimate *C* for the HEN watershed was applied to all the other watersheds (Table E.4), and the resulting *C*-values were plotted against watershed area. Separate regressions for North Fork (ARF through NFC in Table E.4) and South Fork (OGI through SFC) watersheds are not significantly different from one another at the 0.05 level, so data were pooled. Results show a statistically significant relation between the calculated *C*-value and the drainage area (*A*, acres) for the Caspar Creek watersheds (Figure E.4):

$$C = -0.0190 + 0.0864 \log_{10} A \qquad r^2 = 0.75 \quad n = 24 \qquad \text{(E4)}$$

Table E.4. *C*-values calculated from 10-year-return-interval flows at Caspar Creek gaging stations.

	Area (acres)	*C*-value		Area (acres)	*C*-value		Area (acres)	*C*-value
ARF	948	0.229	IVE	51	0.098	RIC	116	0.142
BAN	26	0.105	JOH	135	0.148	SEQ	42	0.149
CAR	66	0.130	KJE	38	0.142	TRE	35	0.130
DOL	190	0.156	LAN	384	0.203	UQL	32	0.165
EAG	66	0.128	MUN	40	0.149	WIL	64	0.115
FLY	536	0.269	NFC	1169	0.234	YOK	131	0.165
GIB	49	0.116	OGI	47	0.095	ZIE	64	0.146
HEN	96	0.129	POR	77	0.119	SFC	1048	0.276

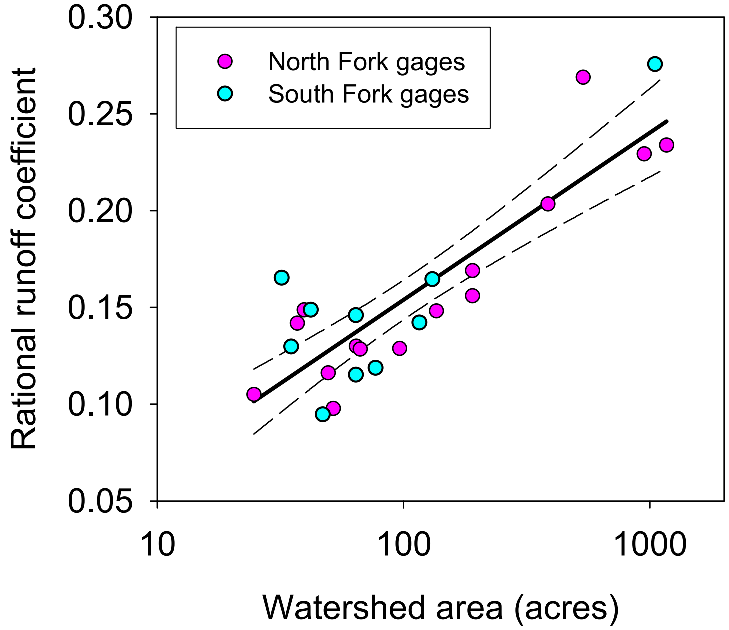

Figure E.4. Values of *C* calculated from observed 10-year-return-interval flows at gages in the North and South Fork Caspar Creek watersheds.

Once again, we need to stress that this relation simply expresses an empirical association between two attributes. In particular, the values calculated for times of concentration (used to define I_{10}) do not represent measureable times of concentration for these watersheds. Nonetheless, those values appear to represent useful empirical indices of watershed characteristics for the purpose of estimating peak flows. Similarly, the empirically determined *C*-values simply calibrate the rational runoff equation for use in the area—the empirical calibration of *C* compensates also for inaccuracies in estimating t_c. Because of this, no physical interpretation of the variation in *C* with watershed size (equation E4) is possible: here, too, apparent variations in *C* may simply reflect a systematically increasing error in estimation of t_c as watershed size increases.

The scatter of points in Figure E.4 suggests that there is no significant dependence of the calculated *C*-value on watershed size for watersheds smaller than 100 ac at Caspar Creek, and a separate regression for this portion of the data shows that this is indeed the case. Within this size range, the mean of calculated *C*-values is 0.128 with a 95% prediction interval of ±0.045 for individual values.

<u>Conclusions</u>

We have used data from Caspar Creek in this appendix in three ways: first to calibrate an existing model for predicting flows, then to determine whether the calibration is valid for other similar watersheds and for watersheds with a different management history, and finally to test for an association between the effective *C*-value and watershed size. Results show generally good agreement when hydrologic conditions in the watershed of interest are similar to those in the watershed for which calibrations were carried out, and also demonstrate that the results are reasonably consistent over the range of watershed areas for which use of the method has been advised. However, calculated values significantly underestimate flows in the larger watersheds tested.

Empirically-based coefficients and relations are useful if they work, but the lack of a physical basis for a result means that considerable care must be taken if the coefficient or relation is to be applied at other sites. The pattern of variation among results for the Caspar Creek watersheds suggests that hydrologic characteristics within individual watersheds can significantly influence the accuracy of the predictions, reinforcing an important conclusion: flow prediction models can provide useful information, but results of even a well-calibrated and validated model should be accepted only as well-founded estimates rather than as truth.

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