Long-term Patterns of Hydrologic Response after Logging in a Coastal Redwood Forest

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Abstract

Experimental watersheds generally provide the only setting in which the more subtle patterns of long-term response to land use activities can be defined. Hydrologic and sediment responses have been monitored for 35 yrs after selective logging and for 16 yrs after clearcut logging of a coastal redwood forest at the Caspar Creek Experimental Watersheds in northwest California. Results show that recovery periods differ for different hydrologic attributes and between the two silvicultural treatments. Total water yield, peakflows, and low flows responded similarly in both settings during the initial post-logging period, but low flows reattained pre-treatment levels more quickly after selective logging. Sediment loads initially recovered relatively quickly after both treatments, but in both cases loads rose once again 10–20 yrs after logging, either because road networks began to fail (South Fork) or because pre-commercial thinning again modified hydrologic conditions (North Fork).

Process-based studies provide the information needed to understand the differing watershed responses. Altered interception after logging provides the primary influence on water yield and peakflow responses, while altered transpiration is largely responsible for the low-flow response. Differences in recovery times between hydrologic attributes and between silvicultural practices may be explained by changes in the relative importance of interception and transpiration and by the long-lasting repercussions of ground disturbance.

Keywords: streamflow, sediment, hydrologic recovery, timber harvest, cumulative watershed effects

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Introduction

Since the installation of stream gaging weirs on the North and South Forks of Caspar Creek in 1962, researchers have been investigating the effects of forest management on streamflow, sedimentation, and erosion under a partnership between State and Federal forestry agencies. As the hydrologic record lengthens following experimental treatments, differing patterns of recovery have become evident. A suite of ongoing process-based studies provides the information needed to understand the contrast in watershed responses. Previous publications detail the range of hydrologic response to the logging treatments. Here, we discuss results from further analyses and provide an updated look at recovery in the Caspar Creek Experimental Watersheds.

Methods

Site

The Caspar Creek Experimental Watersheds are located on the Jackson Demonstration State Forest about 7 km from the Pacific Ocean and about 10 km south of Fort Bragg in northwestern California at 39°21'N 123°44'W (Figure 1). The watersheds are incised into uplifted marine terraces underlain by greywacke sandstone and weathered, coarse-grained shale of late Cretaceous to early Cenozoic age.

Elevations in the watersheds range from 37 to 320 m. Hillslopes are steepest near stream channels and become gentler near the broad, rounded ridgetops. About 35 percent of the slopes are less than 17 degrees and 7 percent are steeper than 35 degrees. Soils are 1- to 2-m-deep, well-drained clay-loams. Hydraulic conductivities are high and subsurface stormflow is rapid, producing saturated areas of only limited extent and duration.
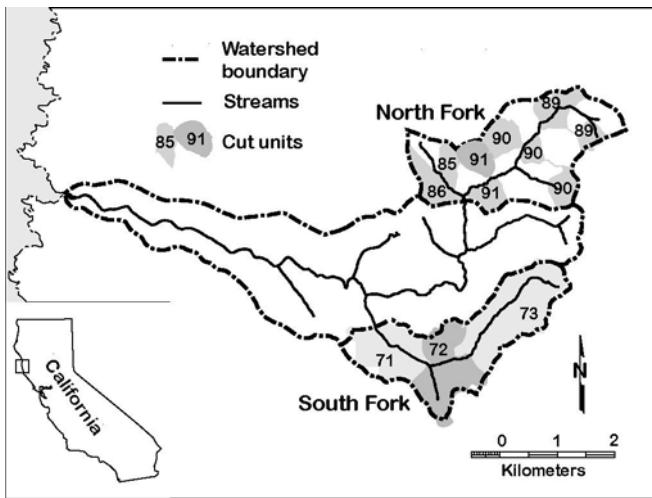
Figure 1. Caspar Creek Experimental Watersheds and 20th century harvest dates.

The climate is typical of low-elevation coastal watersheds of the Pacific Northwest. Winters are mild and wet, characterized by frequent, low-intensity rainstorms interspersed with occasional high-intensity events. About 95 percent of the average annual precipitation of 1,170 mm falls October through April, and snow is rare. Summers are moderately warm and dry, with maximum temperatures moderated by frequent coastal fog. Mean annual runoff is 650 mm.

Like most of California's north coast, the watersheds were clearcut and broadcast burned largely prior to 1900. By 1960, the watersheds supported an 80-year-old second-growth forest with a stand volume of about 700 m^3 ha^{-1}, composed of coast redwood (*Sequoia sempervirens*), Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and grand fir (*Abies grandis*).

Study design

The Caspar Creek study is a classic paired watershed design where one or more gaged catchments are designated as controls and others are treated with road building, logging, and other timber management practices. Statistical relationships are first defined between control watersheds and those to be treated, then post-treatment responses are evaluated as the deviation between observed conditions and those expected based on the pre-treatment calibrations.

The 473-ha North Fork and the 424-ha South Fork of Caspar Creek have been gaged continuously since 1962 using 120° V-notch weirs widening to concrete

rectangular sections for high discharges. During the early 1980s, three rated sections were constructed upstream of the North Fork weir and 10 Parshall flumes were installed on tributary reaches with drainage areas of 10 to 77 ha.

Stream discharge was initially recorded using mechanical chart recorders. These were replaced in the mid-1980s with electronic data loggers equipped with pressure transducers. Subsequent upgrades have been implemented as technology has progressed. Early suspended sediment estimates were derived from sediment rating curves, manual depth-integrated sampling, and fixed stage samplers (Rice et al. 1979). Statistically based sampling algorithms that trigger automated samplers were utilized beginning in the 1980s (Lewis et al. 2001). Sediment accumulations in the weir ponds have been surveyed annually since 1963.

South Fork treatment: Selection harvest with tractor yarding

Calibration relationships between the North and South Forks were established for flow and sediment by 1967. That year, right-of-way logging and road construction along the riparian corridor proceeded in the South Fork. The watershed response to roading was monitored for 4 yrs before the remainder of South Fork watershed was logged and tractor yarded between 1971 and 1973. Single-tree and small group selection was used to harvest about two-thirds of the stand volume. Roads, landings, and skid trails covered approximately 15 percent of the watershed area (Ziemer 1981).

North Fork treatment: Clearcutting with skyline-cable yarding

A study of cumulative effects began in 1985 in the North Fork watershed. Three gaged tributary watersheds within the North Fork were selected as controls, while five were designated for harvest in compliance with the California Forest Practice rules. Two additional downstream units (13 percent of the North Fork watershed) were clearcut in 1985–86 and excluded from the cumulative effects study. After the 1985–89 calibration period, clearcut logging began elsewhere in the study area in May 1989 and was completed in January 1992. Clearcuts totaling 162 ha occupied 30–99 percent of treated watersheds. Between 1985 and 1992, 46 percent of the North Fork watershed was clearcut, 1.5 percent was thinned, and 2 percent was cleared for road rights-of-way (Henry 1998).

In contrast to the harvest treatment of the South Fork in the 1970s, watercourse protection rules mandated equipment exclusion and 50 percent canopy retention within 15–46 m of streams containing aquatic organisms. Skyline-cable systems yarded 81 percent of the clearcut area from log landings constructed far from streams. New road construction and tractor skidding was restricted to ridgetop locations with slopes of generally less than 20 percent. Four harvest blocks, 92 ha total, were broadcast burned and later treated with herbicide to control competition (Lewis et al. 2001). Pre-commercial thinning in 1995, 1998, and 2001 eliminated much of the dense regrowth, reducing basal area in treated units by about 75 percent.

Results

Water yield and low flows

Both treatments resulted in increased water yields for a period of 10 yrs or more (Keppeler and Ziemer 1990, Keppeler 1998). When calculated per unit of equivalent clearcut area, the magnitudes of the initial changes were found to be quite similar (Figure 2), but South Fork began to show a trend toward recovery after 7 yrs while North Fork did not. Changes in low flow exhibited a contrasting pattern. Initial changes were similar in the North and South Forks, but South Fork low flows recovered to pre-treatment conditions within 8 yrs of logging, while North Fork low flows had not recovered by year 14.

The contrast in low flow responses between the two experiments probably reflects the difference in silvicultural treatments used. In the South Fork, about a third of the tree canopy remained distributed across the landscape after logging, and the surviving trees no longer had competition for dry-season soil moisture. Under these conditions, actual dry-season transpiration could more closely approach potential transpiration, and the post-logging "excess" of water would contribute to transpiration once root networks expanded. In North Fork clearcuts, no nearby trees could take advantage of the excess water, and this water instead will continue to contribute to dry-season flows until new vegetation is well established on the cut units. In addition, most North Fork clearcut units were later treated with herbicides and pre-commercially thinned, again reducing leaf area and suppressing transpiration.

Water yields, in contrast, are dominated by wet-season flows. After logging at Caspar Creek, the change in foliar interception of rainfall was found to be a stronger influence on the wet-season water balance than was transpiration (Reid and Lewis 2007), as about 22 percent of rainfall is intercepted by foliage in uncut stands (Reid and Lewis 2007). In the case of interception, rates depend more strongly on the amount of canopy removed than on the distribution of remaining trees. The wet-season response—reflected by the water yield—is thus more similar for the two silvicultural strategies than is the transpiration-dependent dry-season response.
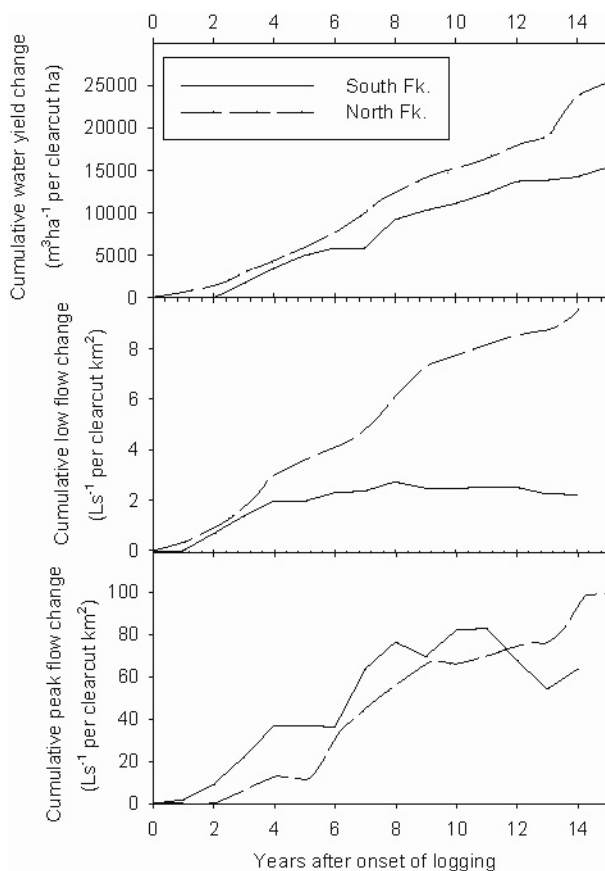

Figure 2. Cumulative change per unit area of clearcut equivalent by time after major logging for water yield, low flow, and peak flow. Minor logging occurred 4 yrs before the major onset in both watersheds and thinning occurred in the North Fork in years 6, 9, and 12.

Peakflows

Changes in major winter peakflows were not initially detected in the dataset from the South Fork, but reanalysis using temporal categories suggested by

North Fork results showed a statistically significant increase between 3 months and 8 years after logging ended. The discharge-weighted average peakflow was 13 percent higher than predicted and the 2-yr storm peak increased 14 percent.

The North Fork study design, wherein five clearcut tributaries and three control tributaries were gaged, yielded a larger dataset. Storm peaks with 2-yr return periods increased an average of 27 percent in the fully clearcut watersheds (Ziemer 1998), and in partially clearcut watersheds the magnitude of the change was proportional to the percentage of the watershed logged (Lewis et al. 2001). Peakflows in clearcut watersheds had nearly reattained pre-treatment levels within about 10 yrs after logging, but pre-commercial thinning then triggered new increases. As of 2007, ongoing measurements in two fully clearcut watersheds indicate that peakflows remain an average of 40 percent above pre-treatment predictions 6 yrs after pre-commercial thinning and 16 yrs after logging (Figure 3).
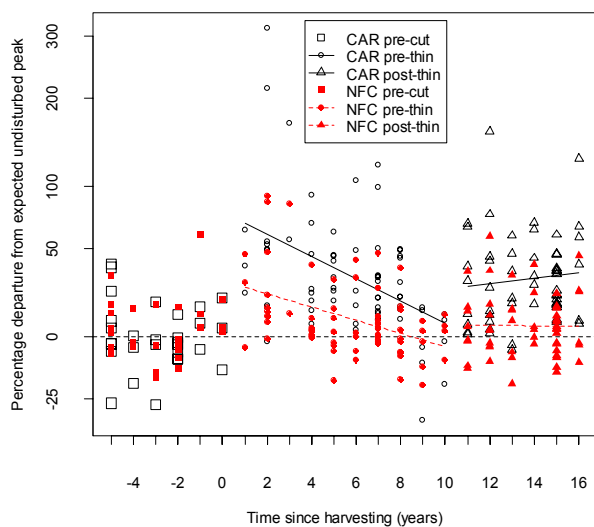

Figure 3. Peakflow departures from predicted in a 26-ha clearcut catchment (CAR) tributary to the 37 percent partially clearcut North Fork (NFC).

Sediment loads

The initial sediment responses following the logging on the South Fork (1971–73) was far greater than that on the North Fork (1989–92). South Fork suspended load more than quadrupled during the 6-yr period after tractor logging, while that in the North Fork roughly doubled during the equivalent post-harvest period (Lewis 1998). In both cases, sediment yields neared or reattained pre-treatment levels by about a decade after logging. In the South Fork, much of the excess sediment production is directly attributed to road-related erosion and mass-wasting (Rice et al. 1979)—problems that were more effectively avoided on the North Fork, where road and skid trail construction was much more limited.

Recent work suggests that an important component of the excess sediment in the North Fork may originate from sources within channels, thus making sediment loads particularly sensitive to logging-related increases in flow. Data from a pair of nested stream gages illustrate the potential importance of in-stream sediment sources. The 27-ha EAG clearcut watershed lies at the headwaters of the 77-ha DOL catchment, which otherwise has not been logged since 1904. Suspended sediment loads measured during storms at the EAG gauge were subtracted from corresponding loads at the DOL flume to estimate the load derived from the unlogged portion of the DOL watershed. These loads were then compared to those expected on the basis of pre-treatment calibrations to control watersheds. The ratio of observed to expected load in the unlogged portion of DOL shows a response similar in initial timing and magnitude to that within the logged watershed upstream (Figure 4). Field observations indicate that bank and headcut erosion in the mainstem DOL channel are the principal sources of sediment in the non-logged portion of the watershed.
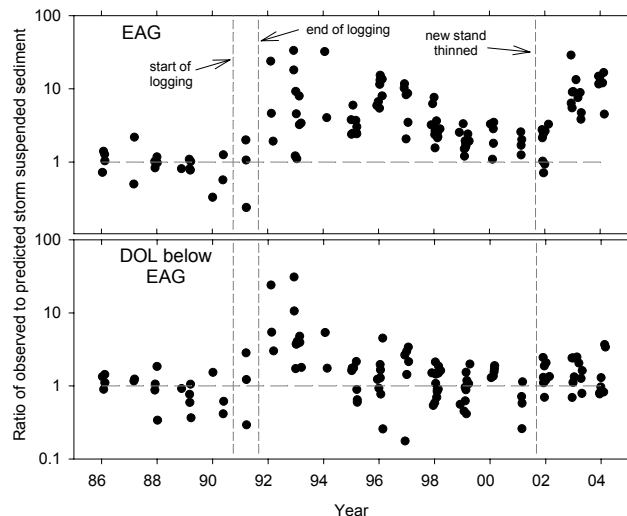

Figure 4. Suspended sediment loads observed in North Fork clearcut EAG and at downstream station DOL from hydrologic year 1986 through 2004.

Although sediment loads in both the South and North Fork watersheds had essentially recovered to

pre-treatment levels within a decade of logging (Thomas 1990, Lewis 1998), both subsequently showed renewed increases. On the South Fork, deterioration of the road system contributed to a new period of excess sediment input beginning about 20 yrs after second-cycle logging (Keppeler and Lewis 2007). On the North Fork, pre-commercial thinning 10 yrs after logging again increased runoff and peakflows (Figure 4), triggering renewed channel erosion just as excess loads had nearly recovered. Added to this excess load is the sediment input from a major landslide on a logged slope of the North Fork in 2006.

Discussion

The relative importance of different components of the water balance varies seasonally at Caspar Creek (Figure 5), and those components respond to different silvicultural practices and to post-logging regrowth in different ways. As a result, each seasonally dependent attribute of streamflow demonstrates a unique response and recovery trajectory that is a composite response to a set of changes affecting interception, transpiration, and flow path. Transpiration dominates the water balance during the long dry season, so recovery of dry-season flows would track the recovery of transpiration potential following logging. Peakflows, in contrast, occur during months when the influence of decreased interception after logging is about twice that of transpiration reductions. Water yield, which principally reflects wet-season flows, would also be most strongly influenced by changes in rainfall interception after logging.
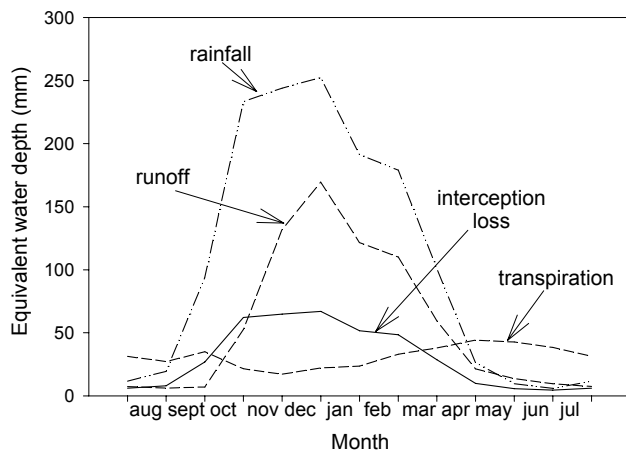

Figure 5. Monthly water balance for forested watersheds, North Fork Caspar Creek (from Reid and Lewis 2007).

Logging-related sediment inputs do not follow a smooth path to recovery. Although much of the initial increase in sediment loads in the North Fork was correlated with increased runoff (Lewis et al. 2001), hydrologic recovery has not translated into a sustained return to pre-treatment sediment loads in the South Fork. In fact, sediment loads 34 yrs after logging are once again nearly equivalent to those in the period immediately following logging. Dry years are now relatively quiescent in terms of sediment production, but years with multiple large storm events generate significant excess sediment.

In the North Fork, increased sediment loads following pre-commercial thinning are large relative to the magnitude of renewed increases in peak flow, suggesting that the new hydrologic conditions are interacting with other changes still present from second-cycle logging. This might be the case, for example, if the new reductions in transpiration and interception are synchronous with the post-logging minimum in root cohesion on hillslopes, or if channel banks already destabilized by the earlier period of increased flow are now subjected to new increases. Additional sediment might also be contributed by remobilization of logging-related sediment that remains in storage in channels downstream of logged areas or that had been trapped behind now decayed logging slash in low-order channels. In each case, new hydrologic changes interact with conditions generated earlier by logging, and the cumulative effect of the interaction is a disproportionate increase in sediment relative to that predicted on the basis of flow effects alone.

Evidence of altered hydrology, in the form of compaction, gullied stream channels, and diversions along abandoned roads and skid trails, persists in Caspar Creek's logged watersheds even as the forest regrows, maintaining an increased susceptibility of the landscape to the effects of major storms. In the North Fork, pre-commercial thinning renewed hydrologic changes, again reducing hillslope stability and contributing to channel adjustments. Through such mechanisms, the potential for enhanced sediment production may be sustained for prolonged periods after logging.

Conclusions

Timber harvest alters forest hydrology by forest canopy reduction and ground disturbances associated with road

construction, yarding, and site preparation. Recovery is governed by the rate of revegetation and the more gradual amelioration of ground disturbances and channel re-stabilization. Watershed-scale studies are useful for documenting the hydrologic response over a range of conditions while exploring the cause-and-effect linkages that explain variations in ecosystem response. Long-term studies, such as those at Caspar Creek, are particularly important for disclosing the deviations from recovery trajectories following natural or management-related shifts in vegetation conditions occurring as regrowth proceeds, or as global climatic patterns shift.

Acknowledgments

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