Comparing Hydrologic Responses to Tractor-Yarded Selection and Cable-Yarded Clearcut Logging in a Coast Redwood Forest[1]

Leslie M. Reid[2]

Abstract

Initial increases in dry-season flow after selective logging of second-growth coast redwoods (*Sequoia sempervirens*) in the 424 ha South Fork Caspar Creek watershed disappeared by 7 years after logging ended, and low flows then dropped to below expected values for the next 20 years. During the 16 years after clearcut logging in the 473 ha North Fork watershed, late-summer flows increased to nearly twice those expected and then declined to pre-treatment levels on a trajectory that suggests further decline is likely. This contrast in dry-season flow responses is consistent with expected differences in post-logging recovery rates for transpiration after selective and clearcut logging. The South Fork showed a delayed peakflow response relative to that in the North Fork, and a maximum 3 year increase (per unit area of clearcut equivalent) about 40 percent lower. South Fork peaks remained slightly elevated for more than 20 years after logging ended, and North Fork peaks remained elevated for at least 12 years after logging.

Keywords: cumulative watershed effects, logging, low flow, peakflow, recovery

Introduction and study site

Studies at different sites often provide conflicting information about the hydrologic effects of logging (e.g., Moore and Wondzell 2005), indicating that different settings, forest types, or silvicultural strategies may produce different outcomes. Silvicultural preferences shift through time, and the extent to which past experimental results apply to new management strategies is often unknown. Uneven-age management is again being used in some coast redwood (*Sequoia sempervirens*) forests instead of clearcutting, so it would be useful to know how hydrologic responses to selective logging and clearcutting compare. This study evaluates low flow and peakflow responses to these silvicultural strategies during two watershed experiments.

The Caspar Creek Experimental Watersheds (N39°21′ W123°44′; *fig. 1*) are underlain by sandstone and shale of the Coastal Belt of the Franciscan Complex. Rainfall averages 1170 mm/yr and about half reappears as streamflow. Snow is uncommon. October through May account for 95 percent of the rainfall, and annual minimum flows generally occur in early October. By 1962, the old-growth forests logged in 1865 to 1905 had regrown into mature stands dominated by coast redwood

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[2] Research geologist, U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, 1700 Bayview Dr., Arcata, CA 95521. (lreid@fs.fed.us).

and Douglas-fir (*Pseudotsuga menziesii*). The 424 ha South Fork Caspar Creek watershed was selectively logged during the first of the two experiments, and the 473 ha North Fork watershed was partially clearcut during the second. Similar forest types at similar sites were thus subject to different silvicultural strategies, allowing comparison of their hydrologic responses.

However, the two studies used different experimental designs, produced different kinds of data, and weathered different storms. Because the control watershed for the first experiment became the treatment watershed for the next, post-logging results for the first study spanned only 12 years. Previous reports (described by Ziemer 1998) presented short-term North and South Fork results. To compare responses over a longer period, the current analysis required development of methods to permit tracking of South Fork responses after logging began in the North Fork.

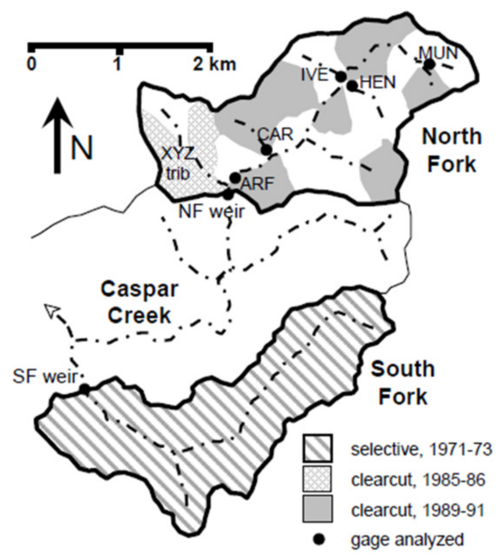

Figure 1—North and South Fork Caspar Creek watersheds.

Methods

The South Fork experiment began in 1962 with 4 years of monitoring to calibrate relations between measurements at the North and South Fork gaging weirs. More than 4 km of mainline road were constructed along the South Fork riparian zone in 1967, and the watershed was then selectively logged from 1971 to 1973 using tractors, with about 2/3 of the timber volume removed. Treatment effects were evaluated until 1985, when logging began in the control watershed.

Thirteen new stream gages were installed in the North Fork watershed in 1984 and 1985, with three gaged subwatersheds selected to be left unlogged as controls. XYZ tributary enters the head of the North Fork weir pond and was not a part of the second study; 60 ha of XYZ were clearcut in 1985 and 1986. Hydrologic recovery could not be assured by then at the South Fork, so neither weir record could be compared to that from a calibrated control after 1985. The second experiment instead compared records from 10 of the new stations to those of the control tributaries (HEN, IVE, and MUN). Calibrations were established from 1985 to 1989, then 37 percent of the watershed was clearcut in 1989 to 1992, with selectively logged buffer strips left along channels draining more than about 10 ha. Cut logs generally were cable-yarded to ridge-top roads. About 20 percent of the watershed was burned after logging, and most units were pre-commercially thinned a decade later.

Rainfall has been monitored near the South Fork weir since 1963 using a series of weighing and tipping-bucket gages, but dry-season data were not collected consistently until 1972. The National Weather Service recorded rainfall for most of this period 12 km north in Fort Bragg. Summer storm totals of >0.6 mm at the Fort Bragg and South Fork (S620) gages are strongly correlated for 1989 to 1999 ($Rain_{S620} = 1.03\ Rain_{FtBragg} + 0.73$ mm, $r^2 = 0.89$), but smaller events often reflect coastal fog and are less common at S620. This study combines the daily rainfall measured at S620 for October through May (accounting for 98 percent of the annual rainfall) with Fort Bragg data for daily rainfalls >0.6 mm in June through September to construct a continuous rainfall record from September 1962 through August 2008.

The North and South Fork gaging structures are concrete sharp-crested compound weirs. Weir pond stages have been measured since 1962 in stilling wells, first using strip-chart recorders and then data-logged pressure transducers, and flow is calculated from pond stage using standard equations. Flows are monitored in Parshall flumes or rated sections at each upstream or tributary station by using data loggers to record stage at 10-minute intervals. Most tributaries run dry by late June, so dry-season flow analyses are based on data from the North and South Fork weirs.

Keppeler (1998) evaluated changes in low flow after North and South Fork logging, and her data suggest that South Fork flows may have dropped below pre-treatment levels by the late 1980s. However, results were complicated by the lack of a control record after the onset of North Fork logging. Because summer rainfall is minimal, late-summer flows are sustained primarily by moisture stored from winter storms. The current study thus uses relations between runoff and antecedent precipitation indices (APIs) to calculate expected flows directly from rainfall, allowing flow deviations to be estimated after the control record ends.

Periods in August and September were identified that had no rain in the preceding 3 days and <9 mm in the preceding 30 days. Mean daily flow was tabulated for 3 to 5 such days each year, with dates selected to be at least 6 days apart and to have records for both the North and South Forks, if possible. Records were not used during periods when weir ponds were drained to remove sediment. APIs were calculated for each selected date using a range of coefficients (0.99 to 0.60). The selected North Fork flows between 1963 and 1984 were regressed against each of the API sets, and a recession coefficient of 0.977 was found to best predict flows:

$$L_N = 0.0272\ API_{977} + 0.0366 \qquad r^2 = 0.87 \qquad n = 46 \qquad (1)$$

where API_{977} (mm) is calculated as 0.977 times its value on the previous day plus the current day's rainfall, and L_N (L km^{-2}s^{-1}) is the mean discharge for the day at the North Fork weir (*fig. 2A*). The same approach was used to develop a predictor for expected South Fork flows (L_{S1}, L km^{-2}s^{-1}) based on data from 1963 to 1970 (*fig. 2B*), with API_{985} calculated using a coefficient of 0.985:

$$L_{S1} = 0.0143\ API_{985} - 0.0320 \qquad r^2 = 0.94 \qquad n = 22 \qquad (2)$$

An equation was also developed to predict South Fork flows from those observed at the North Fork (L_{NO}, *fig. 2C*):

$$L_{S2} = 1.52\ L_{NO} + 0.0706 \qquad r^2 = 0.91 \qquad n = 22 \qquad (3)$$

An analogous regression using expected North Fork flows produced a relation not significantly different from equation 3, allowing expected South Fork flows to be calculated from either observed or expected North Fork flows.

August and September South Fork flows expected in the absence of logging can now be estimated using either equation 2 or equation 3, and results can be compared to observed values to evaluate long-term patterns of deviation after selective logging. Similarly, North Fork deviations can be calculated by comparing measured values with those predicted from rainfall records using equation 1.

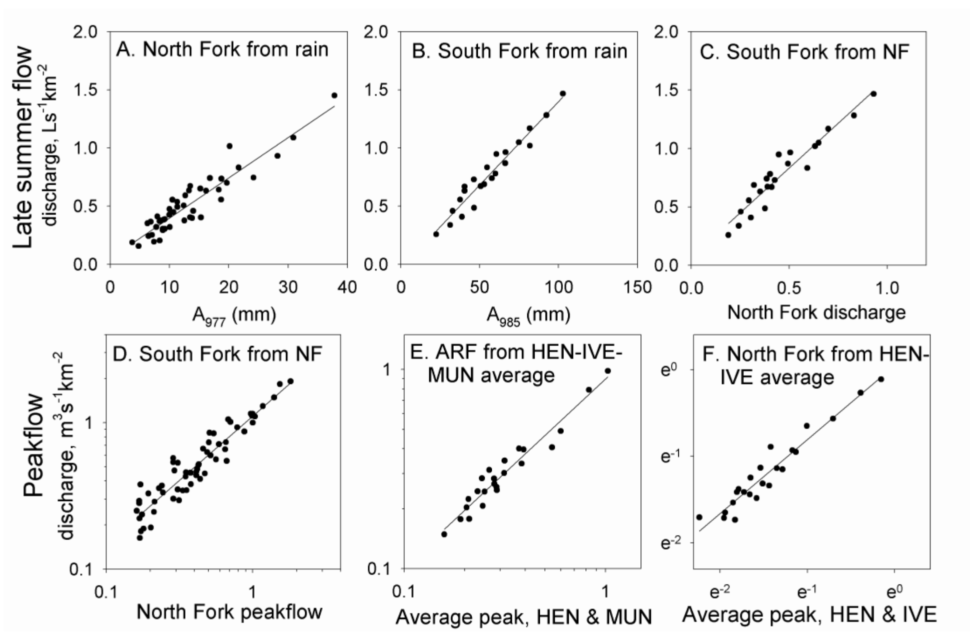

Figure 2—Calibrations between A. North Fork late-summer flows and API_{977}; B. South Fork late-summer flows and API_{985}; C. South Fork late-summer flows and those observed at the North Fork; D. South Fork and North Fork peakflows; E. ARF peakflows and the average of those at HEN, IVE, and MUN; and F. North Fork peakflows and the average of those at HEN and IVE.

Past analyses of South Fork peakflows compared pre-logging correlations to North Fork peaks with those from between the onset of logging and either 1 (Ziemer 1981) or 2 years (Wright et al. 1990) after logging ended, thus including 3 years of logging. No significant increase was found for moderate to large peaks. However, results of the North Fork study later showed that effects of logging may not appear until the following wet season (Lewis et al. 2001), so inclusion of data collected during logging may increase variance enough to hinder detection of responses.

The present peakflow analysis incorporates all peaks higher than 0.16 $m^3s^{-1}km^{-2}$ in the North or South Fork. Pre-logging South Fork peaks were first regressed against observed North Fork peaks (P_{NO}, $m^3s^{-1}km^{-2}$) from 1963 through 1971 (*fig. 2D*):

$$P_S = 1.130\ P_{NO}^{\ 0.876} \qquad r^2 = 0.88 \qquad n = 61 \qquad (4)$$

allowing expected peakflows in the South Fork (P_S) to be estimated from observed or expected North Fork peakflows.

Between 1985 and 1989, only the new North Fork control tributaries are assured to provide stable records. Two methods provide estimates of expected North Fork peaks. First, the ARF gage (384 ha) is upstream of the XYZ confluence, so ARF peaks were unaffected by XYZ logging and can be calibrated against the average of peaks at control catchments HEN, IVE, and MUN (P_{HIM}, $m^3km^{-2}s^{-1}$) for 1986 to 1989 (*fig. 2E*), providing a predictor for expected ARF flows (P_A) from 1985 to 1995:

$$P_A = 0.775\ P_{HIM}^{\ 0.943} \qquad r^2 = 0.91 \qquad n = 21 \qquad (5)$$

Second, because only 13 percent of the North Fork watershed was logged in 1985 and 1986, North Fork peakflows are likely to have changed little over this period. If the North Fork record is assumed to be stable for the period, calibration of weir peaks to the mean of peakflows at controls HEN and IVE (P_{HI}, $m^3km^{-2}s^{-1}$; *fig. 2F*) provides a predictor for expected North Fork weir peakflows (P_N) for 1985 to 2004:

$$P_N = 1.06\ P_{HI}^{\ 0.854} \qquad r^2 = 0.93 \qquad n = 23 \qquad (6)$$

If North Fork peakflows had increased during the calibration period due to XYZ logging, use of equation 6 would provide lower estimates of change per percent forest removed than would an analysis based on equation 5. The validity of the assumption of stability can thus be tested.

Results and discussion

Application of equation 2 to the rainfall record provides estimates of expected late-summer North Fork flows for the selected dates in August and September from 1963 to 2007. Observed and expected flows agree relatively closely until 1985 (*fig. 3A*), when variance increases and several flows exceed expected values by >50 percent. Flows again increased after completion of most logging in 1991, and between 1996 and 2000 the mean of sampled flows is 1.7 times that expected. An unusual 50 mm/day storm in June 2001 produced a higher summer API than baseflows reflect, so expected flows are anomalously high in 2001. Flows begin to decrease after 2003, and by 2007 the mean again equals the expected value, but the slope of the recovery curve suggests that flows will continue to decrease. Values since 2001 reflect effects of both clearcutting and pre-commercial thinning. Overall, dry-season flow remained higher than expected for at least 15 years after North Fork clearcutting ended.

Low-flow deviations show a different pattern in the South Fork. Analyses based on equations 2 and 3 show similar results (*fig. 3B, C*): dry-season flow was enhanced for at least 4 years after South Fork logging began and reattained pre-logging values by 10 years. By 15 years after the onset of logging, flow had consistently dropped below expected levels, reaching a minimum at 21 years. Flows neared pre-treatment levels once again about 30 years after selective logging began. More data are needed to determine whether the apparent renewed downturn at 36 years represents the start of a new trend or simply reflects a short-term aberration.

Late summer flows began to show an effect during the first year of logging in the South Fork (*fig. 3D*), while North Fork responses to the major period of logging were not evident until the third year. The downstream portion of the South Fork was logged the first year, so hydrologic changes would have occurred first near the gage. North Fork logging progressed in the opposite direction, so riparian vegetation along the entire channel length could utilize increased flow before it reached the gage. At each site, the response became evident soon after areas near the gage were logged.

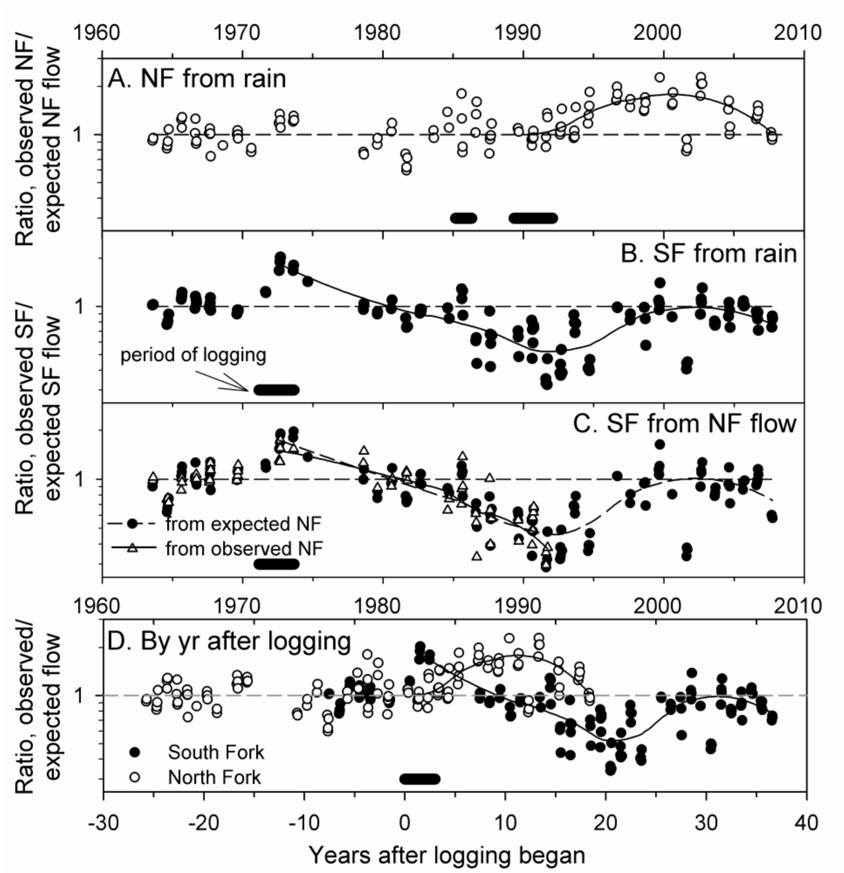

Figure 3—Ratio of observed to expected late summer flows at A. the North Fork weir; B. at the South Fork weir calculated from rainfall; C. at the South Fork weir calculated from North Fork flows; and D. at both weirs (calculated from rainfall) as a function of years after logging began. Post-logging curves are fitted using loess regression and exclude data from 2001.

Once the response is under way, the contrast in response trajectories is consistent with the differing silvicultural strategies used. South Fork selective logging left a third of the stand well distributed across the watershed. Because summers are dry, potential transpiration exceeds actual transpiration after May, and trees must compete for a limited water supply. When competition is reduced by selective logging, the remaining trees can quickly begin to use moisture that in the past would have sustained neighboring trees, and soil moisture reserves are again depleted by the end of the dry season. Such a response would be particularly rapid in stands containing coast redwoods because most second-growth redwoods originate as stump-sprouts, so neighboring trees often share root networks. In contrast, trees left uncut after clearcutting are not within reach of most the surplus moisture, and hydrologic recovery must rely on establishment of new vegetation on the clearcut surface. In addition, North Fork burned units were treated with herbicides in the mid-1990s, and most units were pre-commercially thinned in 2001, further prolonging the effects.

Reduced interception and transpiration appear to largely explain hydrologic changes after North Fork logging (Reid and Lewis 2007), with altered interception dominating wet-season changes. If summer rain is minimal, dry-season transpiration and residual moisture storage from the wet season are major influences on late-summer flow, so both transpiration and interception may be influential. Comparison of sampled late summer flows with those from 60 days earlier (with <20 mm of rain between the dates) shows that a given early summer flow leads to higher than expected late summer flow in the immediate post-logging period at both sites (*fig. 4*) and to lower than expected flow during the later period of flow depression after South Fork logging. A major causal mechanism thus is active during the summer, suggesting that altered summer transpiration is an important influence. The North Fork record is not yet long enough to test for depressed flows.

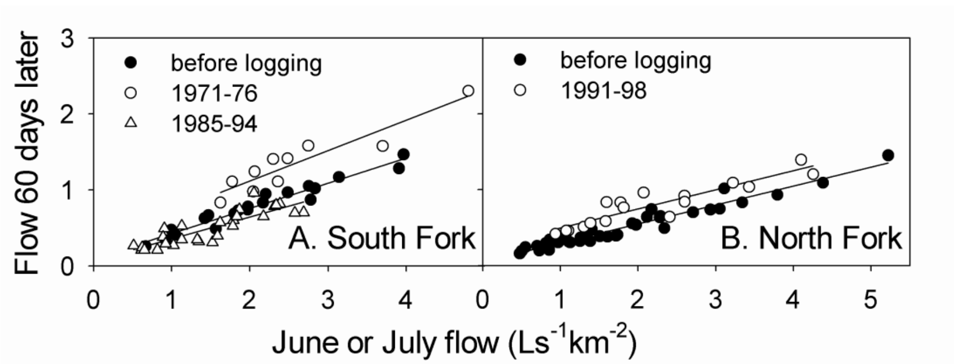

Figure 4—Comparison of early and late dry-season flows before and after logging at the A. South Fork and B. North Fork Caspar Creek weirs.

South Fork logging may have contributed to low-flow depression in several ways. First, selective logging promotes growth of young trees among the residuals. Water competition may thus be more intense than in the original stand, in which mortality during drought years likely achieved a long-term balance between stand density and water availability. Second, the lack of buffer strips increased light in riparian zones, increasing growth at sites where plants may disproportionately affect summer flow by removing water directly from the hyporheic zone. Third, regrowth along the South Fork included many red alders (*Alnus rubra*), which tend to use more water than conifers (Hicks et al. 1991). Fourth, a young, dense, rapidly growing age cohort may simply use more water than a mature stand (Moore et al. 2004). Low-flow depression has also been observed in other young stands in the Pacific Northwest (Perry 2007).

Peakflow deviations at the ARF gage after North Fork logging show increased peaks after 1990 (*fig. 5A*), a pattern also shown by deviations calculated using the assumption that weir peakflows did not change after XYZ logging (*fig. 5b*). For 1992 to 1994, the North Fork at ARF and at the weir both show a mean discharge-weighted peakflow increase of 0.62 percent per percent of forest logged in the catchment upstream, where percent logged at the weir includes only the portion logged between 1989 and 1992. This agreement suggests that North Fork peakflows were not strongly affected by XYZ logging. The weir record indicates that pre-commercial thinning in 2001 may have renewed the effect, and pre-treatment levels had not been reattained by 12 years after logging ended. The temporal pattern shown by *figure 5B* is similar to that identified for the 27-ha CAR sub-watershed (*fig. 5C*), which was 96 percent clearcut in 1991 (*fig. 1*).

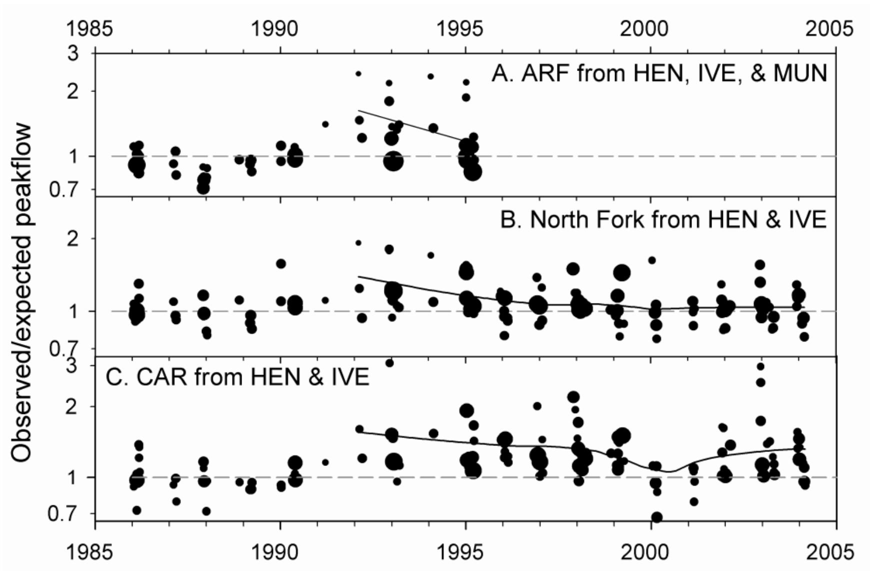

Figure 5—Ratios between observed and expected peakflows at A. ARF from average of peaks at HEN, IVE, and MUN; B. the North Fork weir from average at HEN and IVE; and C. clearcut sub-watershed CAR from average at HEN and IVE. Symbol areas are proportional to unit area discharges, and post-logging curves are fitted using loess regression for B and C, and linear regression for A.

Comparison of observed South Fork peakflows with those expected on the basis of correlations to observed or expected North Fork peaks shows that most South Fork peakflows were higher than expected 3 to 11 years after logging began (*fig. 6A*), and that they appear to remain slightly elevated until about 1995. If expected North Fork peaks are overestimated due to increased flow from XYZ logging during the calibration period, South Fork deviations after 1986 would be larger than shown. Overall, South Fork peaks showed a maximum 3-yr discharge-weighted mean increase of 0.36 percent per percent of forest logged in the catchment, about 60% of that seen in the North Fork. The South Fork response also appears to be delayed relative to that in the North Fork (*fig. 6B, C*).

Most peakflows at Caspar Creek are more strongly influenced by interception than transpiration (Reid and Lewis 2007), and recovery trajectories for interception and transpiration differ. Interception may be influenced both by a stand's canopy and by the volume of absorbent bark present. Leaf area can recover relatively quickly while bark storage cannot, so interception-controlled peaks may remain slightly elevated long after either clearcutting or selective logging ends, as appears to be the case at Caspar Creek.

Wet- and dry-season hydrologic responses appear to be decoupled in the South Fork, with peakflows remaining slightly elevated during the period of summer flow depression. Such decoupling is consistent with the presence of multiple mechanisms of hydrologic change, each with its own recovery trajectory and distinctive effects.

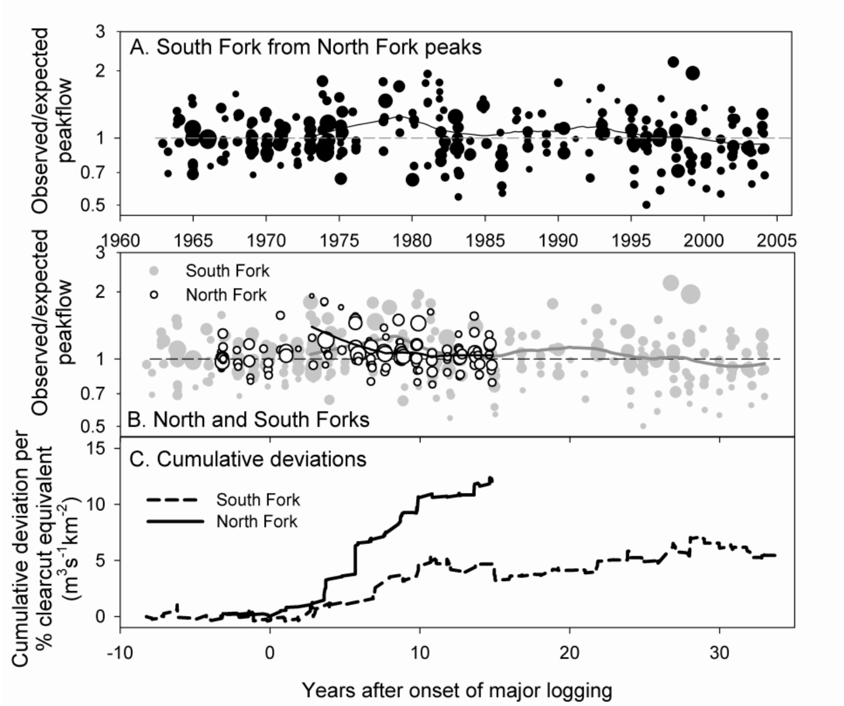

Figure 6—A. Deviations from expected peakflows at South Fork calculated from North Fork peakflows, B. comparison of recovery trajectories for North and South Fork peakflows by time after logging, and C. cumulative deviations. Symbol areas are proportional to discharges, and post-logging curves are fitted using loess regression.

Conclusions

Long-term flow records are rare for watersheds the size of the North and South Forks of Caspar Creek. For those that do exist, the questions the original monitoring studies were designed to address have often been superseded by new issues that had not yet been recognized when monitoring began. The Caspar Creek data stream, initiated a half-century ago, has provided the information needed to address two generations' controversies and concerns. Many of the watershed-related issues that have arisen since Caspar Creek monitoring began could not be resolved without long-term hydrologic data, and among these is the current need to understand mechanisms for long-term cumulative watershed effects associated with forest management.

Cumulative effects can accrue if changes resulting from a management activity are superimposed on changes induced by other contemporary or past activities. First steps in understanding the potential for cumulative hydrologic effects are to determine the length of time required for hydrologic recovery from a particular activity and to understand the factors that may affect the recovery rate. After selective logging of second-growth redwoods at Caspar Creek, it has taken at least 30 years for dry-season flows to reattain pre-treatment levels, and additional data are required before recovery can be assured to be complete. Long-term monitoring results also demonstrate that clearcut logging produced a very different recovery trajectory than selective logging, with the post-logging period of enhanced dry-season flow lasting about twice as long. Peakflow changes also show evidence of long-term persistence and differences between silvicultural treatments. Where hydrologic change is an issue of concern in a watershed, it may be useful to plan management to ensure maintenance of a diversity of stand ages and silvicultural strategies in order to desynchronize post-logging hydrologic changes.

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