Flooding and Stormflows[1]

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Abstract: *The effects of road building and timber harvest on storm flow were evaluated at the North and South Forks of Caspar Creek in north coastal California. From 1963 through 1975, a total of 174 storms that produced peak discharges larger than 0.016 L $s^{-1}ha^{-1}$ in the untreated North Fork were studied. Storms producing flows this size and larger occur about 14 times each year and about 10 percent of the time. They are responsible for 83 percent of the annual water discharge and transport 99 percent of the suspended sediment. Selection cutting and tractor yarding second-growth redwood and Douglas-fir in the 424-ha South Fork did not significantly change peak streamflows that occur about eight times a year — those larger than about 1 L $s^{-1}ha^{-1}$. For flows smaller than 1 L $s^{-1}ha^{-1}$, the first peaks in the fall increased by 300 percent after logging. The effect of logging on peak flow was best predicted by the percent of area logged divided by the sequential storm number, beginning with the first storm in the fall. For example, the second storm of the fall produced half the response to logging than the first storm. In 1985, the second stage of the Caspar Creek study began with the installation of an additional 13 gaging stations in the North Fork. From 1985 through 1996, 59 storms and 526 peak flow events were measured. There was a mean peak flow increase of 35 percent in entirely clearcut and 16 percent in partially clearcut tributary watersheds for the class of flows greater than 4 L $s^{-1}ha^{-1}$ — those that occur less frequently than twice a year. When the unlogged South Fork was used as the control, peak streamflows in the North Fork after clearcut logging were not significantly larger for flows greater than about 1 L $s^{-1}ha^{-1}$, as was also observed after selection cutting the South Fork. However, when the more sensitive uncut North Fork tributaries were used as controls, an increase in peaks was detected at the North Fork weir after logging.*

Debate over the beneficial influence of forests in protecting against floods has continued in the United States for at least a century. Some believe that flooding problems can be solved by proper forest conservation, whereas others maintain that forests do not reduce flooding. The arguments being made today are not unlike those made in the past. For example, Chittenden (1909) stated that forest cutting alone does not result in increased runoff. But, concern about overexploitation of forests and the argument that conservation could reduce floods resulted in passage of Weeks' Law in 1911. Weeks' Law authorized the purchase of private land to establish National Forests in the eastern United States "... for the protection of the watersheds of navigable streams...."

During the early part of the 20th century there were many opinions but little data to test the relationship between forests and floods. To address these varied opinions, watershed research was initiated in the 1930's at experimental watersheds in southern California (San Dimas), Arizona (Sierra Ancha), and North Carolina (Coweeta). The studies at Coweeta produced the first scientific evidence that converting a forest into a mountain farm greatly increased peak flows, but clear-cutting the forest without disturbing the forest floor did not have a major effect on peak flows (Hoover 1945). By the 1960's, there were 150 forested experimental watersheds throughout the United States. When Lull and Reinhart (1972) released their definitive paper summarizing what was known about the influence of forests and floods, about 2,000 papers had been published reporting research results about the hydrology of forested watersheds. Lull and Reinhart (1972) focused on the eastern United States. A decade later, Hewlett (1982) studied the major forest regions of the world to answer the question "Do forests and forest operations have sufficient influence on the flood-producing capacity of source areas to justify restrictions on forest management?" Hewlett concluded, as did Chittenden (1909) and Lull and Reinhart (1972), that the effect of forest operations on the magnitude of major floods "is apt to be quite minor in comparison with the influences of rainfall and basin storage." Subsequent studies have resulted in similar conclusions.

Caspar Creek Watershed Study

In 1955, the largest regional storm of the previous 50 years produced great damage in recently logged watersheds in northern California. Extensive damage to watersheds such as Bull Creek near Rockefeller Grove State Park in northwestern California resulted in public debate over the need for increased regulation of forest practices in California. A principal objective of initiating the Caspar Creek study in 1962 on the Jackson Demonstration State Forest, near Fort Bragg, California (Preface, fig. 1, these proceedings), was to examine the effect of improved logging practices being recommended at the time upon streamflow and sediment production (Henry, these proceedings).

The Caspar Creek study is unique in the western United States. While other experimental watershed studies in the West were evaluating the effects of logging old-growth virgin forests, none were studying second-growth forests. The old-growth redwood forest had been removed from Caspar Creek between 1860 and 1904 and, by the 1960's, the second-growth forest was commercially feasible to harvest. Soon, most of the previously logged forests in northwestern California, and eventually much of the West, would be in a condition suitable for reharvesting. By the early 1960's, it was becoming increasingly important to understand the hydrologic dynamics of managing second-growth forests.

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Selective Logging

Stream gaging structures consisting of 120° V-notch weirs with concrete upper rectangular sections were constructed at the North and South Fork of Caspar Creek in 1962. Streamflow was measured at these weirs from 1963 to 1967, when both the North Fork and South Fork watersheds were in an "undisturbed" second-growth condition. That is, neither watershed had been logged since the old-growth forest was removed. A main-haul logging road and main spurs were constructed in the South Fork watershed in summer 1967 (Henry, these proceedings). In summer 1971, 59 percent of the stand volume was selectively cut and tractor yarded from the lower 101 ha of the South Fork. In summer 1972, 69 percent of the volume was removed from 128 ha in the middle, and, in summer 1973, 65 percent of the volume was removed from the remaining 176 ha in the upper South Fork (Preface, fig. 1, these proceedings).

To evaluate the effects of road building and timber harvest on storm flow, Ziemer (1981) tabulated data from 174 storms from 1963 through 1975 that produced peak discharges in the untreated North Fork larger than 0.016 L $s^{-1}ha^{-1}$. Storms producing flows this size and larger occur about 14 times each year and about 10 percent of the time. They are responsible for 83 percent of the annual water discharge, and transport 99 percent of the suspended sediment (Ziemer 1981). Wright and others (1990) increased the size of the smallest peak to 0.056 L $s^{-1}ha^{-1}$ and used several different hydrograph components to study 129 storms for these same years. Storm peaks within this range would occur on average about 10 times each year.

From these studies, only those peaks within the smallest flow class [<0.67 L $s^{-1}ha^{-1}$ (Ziemer 1981); <1.12 L $s^{-1}ha^{-1}$ (Wright and others 1990)] increased after logging. In addition, the largest changes in the South Fork's peak streamflow after logging were found to be for the first storms after lengthy dry periods. The first streamflow peaks in the fall increased by 300 percent after logging, but these early fall storms produced only small peak flows. Ziemer (1981) found that effect of logging on peak flow was best predicted by the percent of area logged divided by the sequential storm number, beginning with the first storm in the fall. For example, the second storm of the fall produced half the response to logging than the first storm. Selection cutting and tractor yarding the second-growth redwood and Douglas-fir forest in the 424-ha South Fork did not significantly affect peak streamflows larger than those that occur on average about 8 times a year. Further, there was no significant change in the largest peak flows (>10-year return interval) after selectively logging the South Fork (Wright and others 1990).

The peak flow data analyzed by Ziemer (1981) and Wright and others (1990) ended in 1975, only a few years after logging concluded in the South Fork. A fresh look at streamflow peaks in the South Fork was conducted by adding an additional 10 years of streamflow peaks to the analysis. For this analysis, pairs of North Fork and South Fork peaks larger than about 1 L $s^{-1}ha^{-1}$ were used. There were 58 pairs for the pre-logging period (fall 1962 through spring 1971) and 101 pairs for the post-logging period (fall 1971 through spring 1985). Based on this expanded data set, as with the earlier analyses, there was no significant difference between the regression lines of peak flows before and after logging the South Fork (*fig. 1*).

Clearcut Logging

Storm Peaks

The second stage of the Caspar Creek study began in 1985 with the installation of an additional 13 gaging stations in the North Fork (Preface, fig. 2, these proceedings). Four of these new stations were on the main stem, and nine were located on tributaries of the North Fork. The lowest three mainstem stations (ARF, FLY, and LAN) are rectangular plywood sections, rated by streamflow measurements. Streamflow at the fourth and uppermost mainstem station (JOH) and at the nine tributaries is measured using calibrated Parshall flumes.

From 1985 through 1996, 526 peak flow observations, representing 59 storms, were made at the 10 stations gaging treated watersheds. A comprehensive discussion of the analytical model and detailed statistical analysis of these data is nearing completion (Lewis and others 1998). The complete data set is available on compact disk (Ziemer 1998). Storm events were generally included in the study when the peak discharge at the South Fork weir exceeded 1.6 L $s^{-1}ha^{-1}$. Storms producing a discharge larger than 1.6 L $s^{-1}ha^{-1}$ occur about 7 times per year. A few smaller peaks were included in dry years. Multiple peak hydrographs were treated as multiple storms when more than 24 h separated the peaks and the discharge dropped by at least 50 percent in the intervening period. When multiple peak hydrographs were treated as a single storm, the peak corresponding to the highest peak at the North Fork weir was selected for the analysis. Thus, the same feature was used at all stations, even if that feature was not the highest peak on the hydrograph at all stations. However, differences in peak discharge caused by this procedure were very small.

To compare peak flow response from clearcutting in the North Fork with the earlier selective cutting in the South Fork, the same 58 pairs from the earlier study were used for the pre-logging period (fall 1962 through spring 1971). These peaks were compared to 40 pairs of peaks measured at the North Fork and South Fork weirs during the North Fork post-logging period (fall 1990 through spring 1996). Peak streamflows following clearcut logging behaved similarly to those observed after selection cutting in the South Fork; that is, no change was detected in peak streamflows larger than about 1 L $s^{-1}ha^{-1}$ at the weirs (*fig. 2*). However, using a different uncut control period (1985 to 1989) and the more sensitive uncut tributaries as the controls instead of the South Fork, an increase in peaks was detected ($p < 0.0025$) at the North Fork weir after logging.

Of the 526 storm peaks observed from 1985 through 1996, 226 represented peaks during the pre-treatment period from 1985 to 1989. The control watersheds HEN, IVE, and MUN correlated best with the watersheds to be treated. Higher correlation was obtained by using the mean of the combined peak flows from the control watersheds, rather than peak flows from any of the individual control watersheds. Because MUN was not monitored during the last year of the study, the mean of each peak from uncut watersheds HEN and IVE (designated HI) was chosen as the control for the peaks analysis.

When all 14 subwatersheds in the North Fork are analyzed together, there was a mean peak flow increase of 35 percent in those tributaries that were entirely clearcut and a 16 percent increase in those watersheds that were partially clearcut, for the class of flows

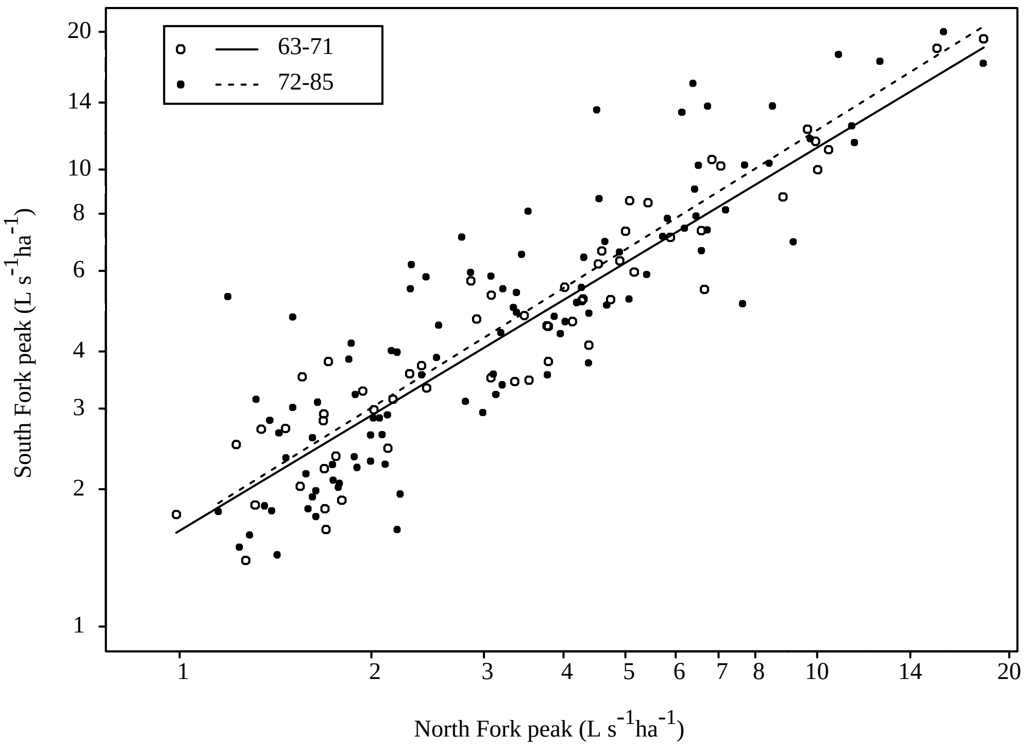

Figure 1 — Relation between peak streamflow in the South Fork of Caspar Creek, using the North Fork as a control. Pre-logging years were 1963-1971, post-logging years were 1972-1985. The two regression lines are not significantly different.

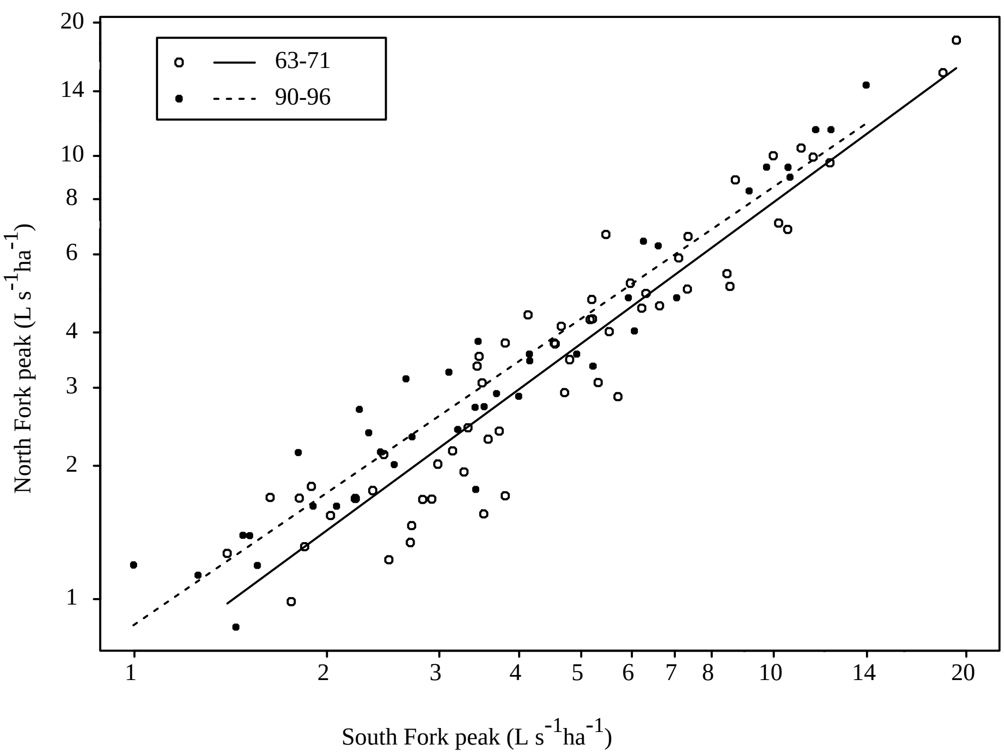

Figure 2 — Relation between peak streamflow in the North Fork of Caspar Creek, using the South Fork as a control. Pre-logging years were 1963-1971, post-logging years were 1990-1996. The two regression lines are not significantly different.

greater than 4 L s^{-1}ha^{-1}. Storms that produce peaks larger than 4 L s^{-1}ha^{-1} occur about twice a year.

The Chow (1960) tests, based on this combined HI control, revealed strong evidence that post-treatment data differed from pre-treatment regressions. Regressions for 8 of the 10 treated watersheds, including the North Fork, departed ($p < 0.005$) from the pre-treatment regressions after logging commenced. The other two, FLY and LAN, located on the mainstem, had *p*-values less than 0.05. When the post-treatment data are fit by locally weighted regression (Cleveland 1993), it is clear that the greatest departures from the pre-treatment data are found for the small peaks in the 100 percent clearcut tributaries (*fig. 3*). However, even for the largest peaks, the post-logging departures are still positive. For the size of storm peak expected once every 2 years (8 L s^{-1}ha^{-1}), there was an average increase of 27 percent for the 100 percent clearcut tributaries BAN, KJE, GIB, CAR, and EAG (21, 28, 39, 19, and 27 percent, respectively). As the size of the watershed increases and the proportion of the watershed logged decreases, the post-logging and pre-logging observations become more similar. However, for the same 2-year storm, the peak in the 50 percent cut NFC watershed increased by 9 percent after logging (*fig. 3*).

Seasonal patterns in the departures from the predicted peak were evident in most of the treated watersheds. For example, when the departures for watershed EAG are plotted against storm number, the largest departures occurred early in the season (*fig. 4*). The pattern is less pronounced in the absolute departures (*fig. 4a*) than in the departures expressed as a percentage of the predicted peak (*fig. 4b*). Storms 28 and 29 occurred shortly after 50 percent of watershed EAG had been winter-logged, but did not show treatment effects, which indicates that the time since harvesting had been inadequate for soil moisture differences to develop between the control watersheds and EAG.

To evaluate the relationships between peak discharge and possible explanatory variables, an aggregated regression model was fit simultaneously to all of the subwatershed peaks (Lewis and others 1998). The overall model was grown in a stepwise fashion. An initial model with only an intercept and slope for each watershed was fit using least squares. The residuals from this model show a strong interaction between the proportion of the area logged and antecedent wetness. Area logged includes clearcut areas and a portion of each streamside buffer zone corresponding to the proportion of the timber removed (Henry, table 2, these proceedings). Antecedent wetness was derived by accumulating and then decaying, using a 30-day half-life, the mean daily discharges measured at the South Fork weir. The relation of the residual from the peaks model with area logged is linear, with the positive slope decreasing with increasing antecedent wetness (*fig. 5a*). The relation with the logarithm of wetness is linear, with the negative slope increasing in magnitude with increasing logged area (*fig. 5b*). These relations imply that a product term is an appropriate expression of the interaction, and the coefficient is expected to be negative. The fact that the average residual increases with different categories of area logged, but not with wetness, suggests that a solo logged area term is needed in the model as well as the interaction product, but a solo antecedent wetness term is not. No variables related to roads, skid trails, landings, firelines, burning, or herbicide application

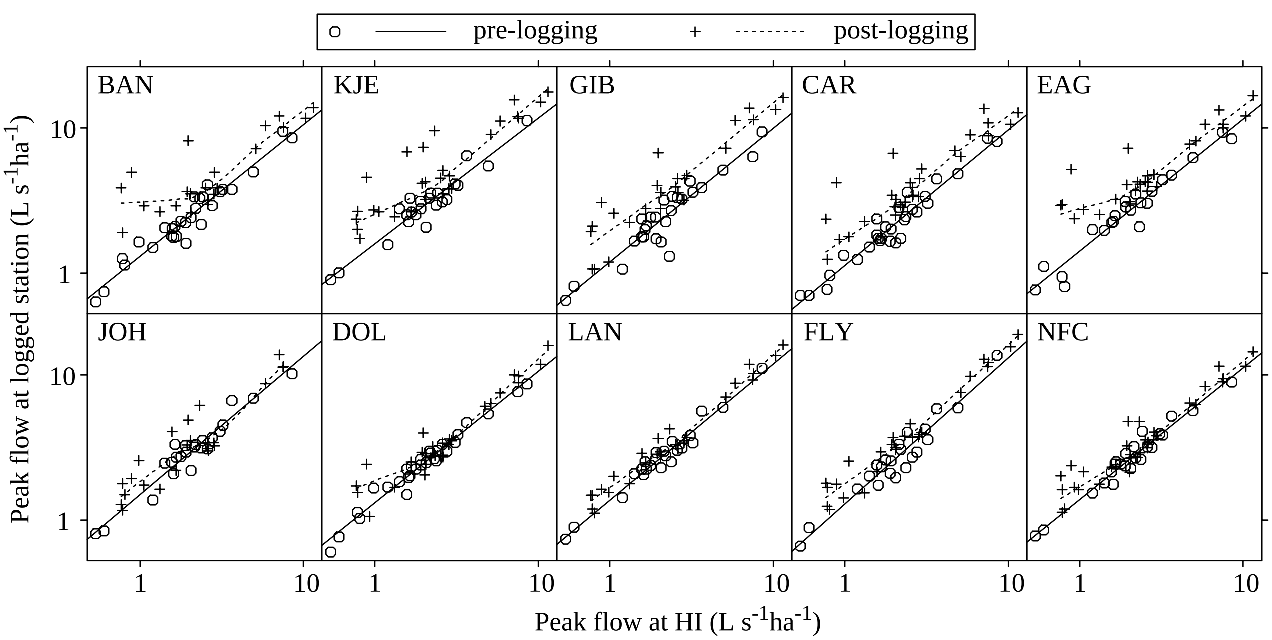

Figure 3 — Relation between peak streamflow in the 10 treated tributaries in the North Fork of Caspar Creek, using the mean of untreated tributaries HEN and IVE (HI) as a control. Pre-logging years began in WY1986. Post-logging years began in 1990, 1991, or 1992 depending on watershed (see Henry, table 1, these proceedings).

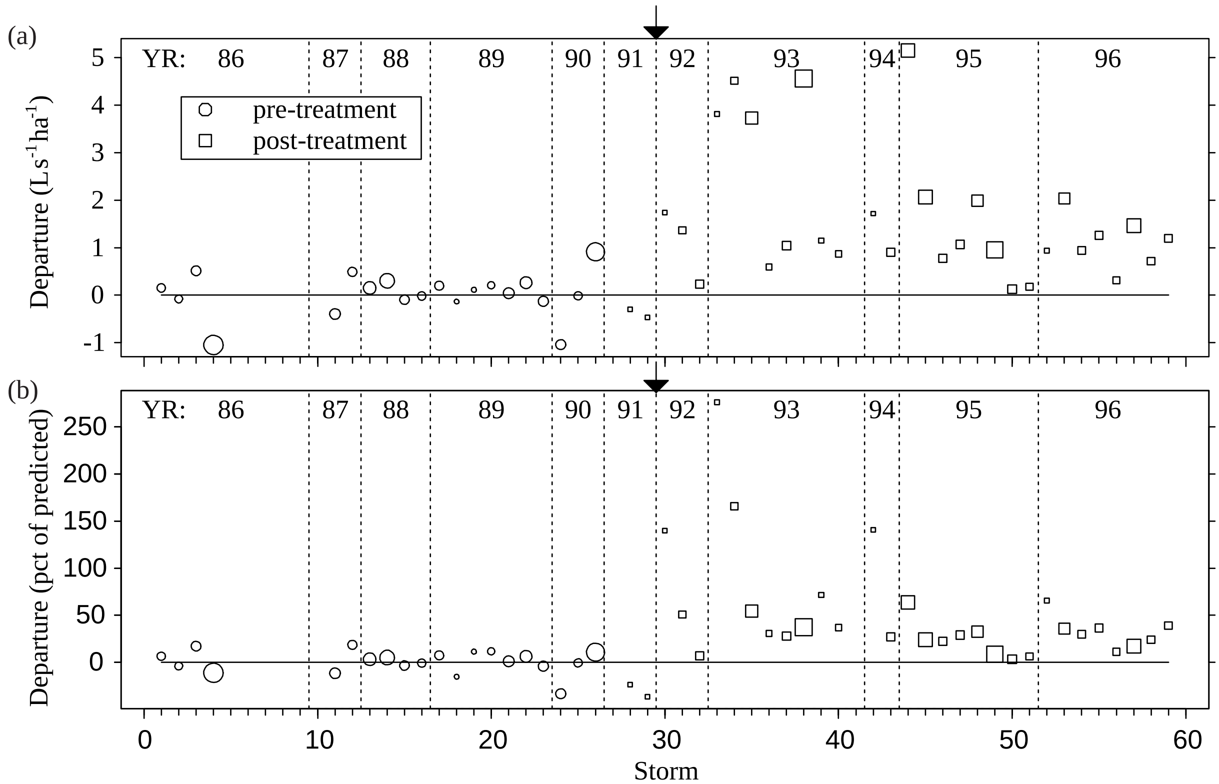

Figure 4 — Absolute (a) and percent (b) departures from the predicted peak for watershed EAG plotted against storm number. The largest departures occurred early in the season. Arrows indicate end of first summer after logging began. Areas of symbols are proportional to the size of the peak at HI.

were found to improve the fit of the linear least squares model that includes logged area and its interaction with antecedent wetness. After adding logged area and the wetness interaction to the model, a plot of post-treatment residuals against time after logging indicates an approximately linear recovery rate of about 8 percent per year in the first 7 years after logging (*fig. 6*).

There was no trend of the relationship between unit area storm peak and watershed area. When the peaks model was fit to the data, the coefficient of a variable designed to express cumulative effects did not differ significantly from zero ($p = 0.21$). There was a weak suggestion ($p = 0.047$) that the effect of logged area on peak flows tended to diminish in larger storms.

The residuals conformed remarkably well to the normal distribution, as did plots for individual stations. The model fitted the data very well (observed versus fitted). For the regression between observed and fitted values, $r^2 = 0.9460$. This compares with $r^2 = 0.8481$ for a model with no disturbance variables and $r^2 = 0.9367$ for the model fit to only the pre-treatment data, so the complete model fits better than expected.

Pipeflow peaks. In addition to the 15 stream gaging stations, two zero-order swales, each having a drainage area of about 1 ha (Preface, fig. 2, these proceedings) were instrumented to measure subsurface pipeflow (Ziemer and Albright 1987, Ziemer 1992). Pipeflow accounted for nearly all of the storm flow from these swales. There was no surface channel flow and no near-surface flow through the colluvial wedge.

Elevated pore water pressures (Keppeler and Brown, these proceedings, Keppeler and others 1994) produced by inefficient subsurface water drainage are a primary cause of large mass erosion events (Cafferata and Spittler, these proceedings). Where subsurface piping networks exist, as in Caspar Creek, matrix interflow can be captured and efficiently routed to surface downslope channels. However, large hydrostatic forces can develop rapidly and cause slope failure if the pipe network is discontinuous or a constriction or collapse retards water flow within the pipe (Tsukamoto and others 1982).

After two winters of data collection in the two swales, all of the trees in one swale (K2) were felled and removed by cable yarding in August 1989. The other swale (M1) was kept as an uncut control. After logging, peak pipeflow increased in swale K2 to about 3.7 times greater than that expected in an unlogged condition, based on the peak pipeflow observed in the uncut control swale (Ziemer 1992). However, all but two of the pipeflow discharge measurements after logging were from moderate storms (less than 300 L min^{-1}).

If pipeflow during large storms also increases after logging, there may be important consequences for slope stability and gully

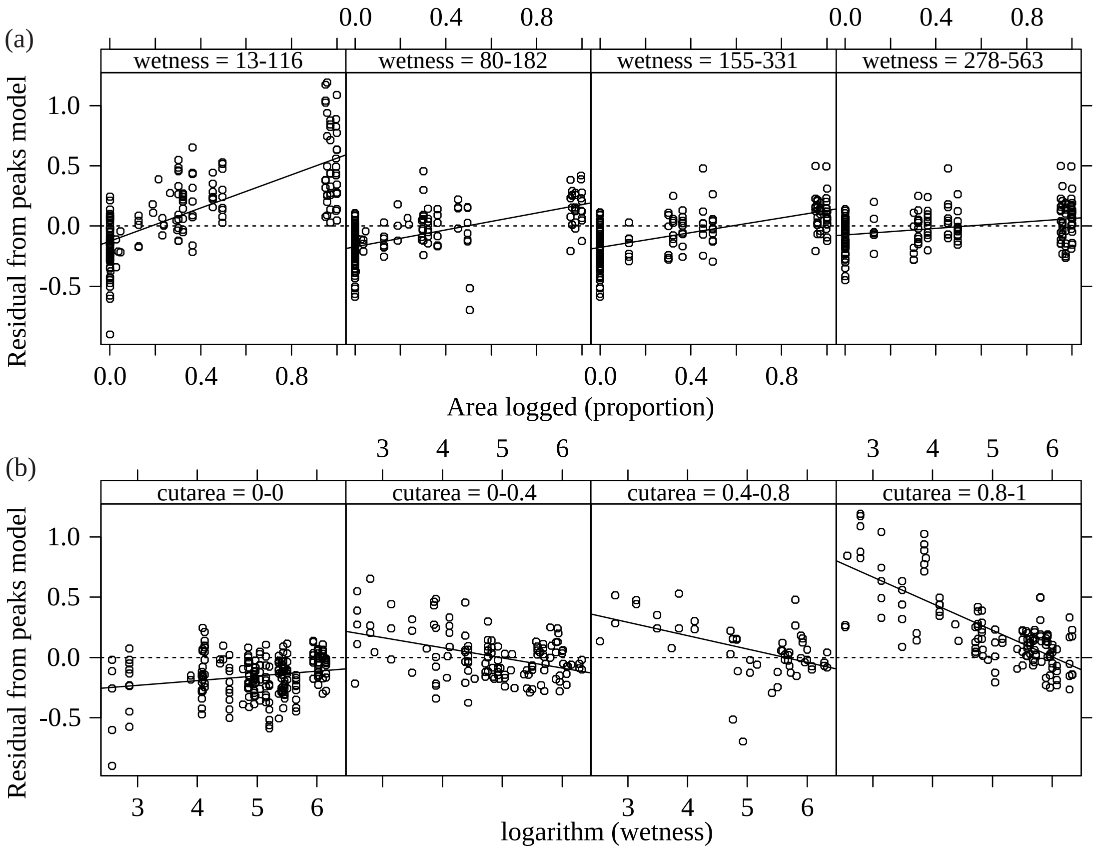

Figure 5 — (a) Relation of residuals from the peaks model (with no disturbance variables) with area logged, for different levels of watershed wetness, and (b) relation of residuals from the peaks model with watershed wetness, for different levels of area logged.

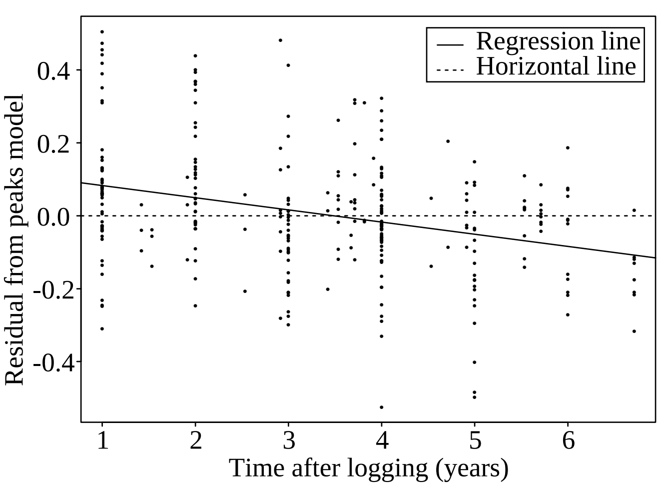

Figure 6 — Relation of post-treatment residuals with time after logging, after logged area and watershed wetness have been included in the peaks model.

initiation. In contrast to open channel conditions, soil pipe discharges are limited by the physical capacity of the pipe. The diameter of pipe K201 is about 50 cm at its outlet while that of M106 is about 70 cm (Albright 1991). Consequently, the capacity of the K201 soil pipe appears to limit discharge above about 500 L min^{-1}, while M106 can freely pass discharges of at least 1700 L min^{-1} (Keppeler and Brown, these proceedings). If pipeflow during the largest storms has increased after logging, but this additional flow cannot freely pass through the pipe because of limited capacity, then large hydrostatic forces can develop rapidly and increase the potential for slope failure and gully initiation.

Storm Runoff Volume

In addition to evaluating storm peak discharge following logging, the total volume of streamflow for the duration of each storm was analyzed. The storm volume analysis included 527 observations representing 59 storms. As in the peaks analysis, an aggregated regression model was fit simultaneously to the storm runoff volumes from all of the subwatersheds (Lewis and others 1998). HI (the mean of HEN and IVE) was chosen as the control. The results were very similar to those from the peaks analysis discussed earlier.

The maximum increase in storm runoff volume based on aggregated regression model was 400 percent, but the runoff volume of most storms increased by less than 100 percent. The mean percentage increase in storm volume declined with wetness but was still positive even under the wettest conditions of the study, when it was 27 percent for clearcuts and 16 percent in partially cut watersheds. Increases more than 100 percent generally occurred only in clearcuts under relatively dry conditions and when runoff volume in the control watersheds was less than 250 m^3ha^{-1}. Large increases in storm volume occurred less frequently as the winters progressed, but increases more than 100 percent did occur in January and February. The mean percentage increase in storm runoff volume declined with storm size and then leveled off at an average increase of 30 percent in clearcuts and 13 percent in partially cut watersheds for storm runoff greater than 250 m^3ha^{-1}.

Annual storm runoff volume (sum of storms) increased an average of 60 percent (1133 m^3ha^{-1}) in clearcut watersheds and 23 percent (435 m^3ha^{-1}) in partly clearcut watersheds. Based on the complete discharge record at the North Fork weir, the runoff volume for the storms included in this analysis represents about 45 percent of the total annual runoff volume in individual tributaries.

Discussion

When discussing land-use effects on floods, it is important to be conscious about the difference between an analysis of hydrograph peaks and an analysis of floods. When the public thinks of a "flood," the image is likely a rare and unusual event that inundates and causes damage to roads, homes, businesses, or agriculture. Floods generally refer to major discrete events that overflow the banks of rivers and streams. These floods are events that occur perhaps once a decade. However, a stream discharge that is expected each year or once every couple of years is usually considered by most observers to be representative of a "normal" high flow event, not a "flood." The human infrastructure is usually constructed to cope with such "normal" events. Further, a rise in stream discharge during the five to 10 rainstorms that occur commonly each winter results in hydrograph peaks, but these would not be considered to be floods.

To evaluate changes in hydrologic response associated with land use, a sufficient number of streamflow events must be observed to obtain the statistical power needed to determine significance. Within a 50-year record, it would be extremely fortunate to measure a 25-year streamflow event before land treatment to compare with a 25-year event after treatment. Even with this great fortune, there would be little that an analyst could say statistically about the events. Only about five 10-year events would be expected during that 50-year record, and those events probably would be scattered throughout the record, before, during, and after treatment. Consequently, to increase statistical power, the analyst is forced to increase the number of observations by including progressively smaller events into the category of large flow. Often, this results in the category of "large peaks" no longer meeting the common definition of a "flood."

Results from watershed studies in the Pacific Northwest are variable. Rothacher (1971, 1973) found no appreciable increase in peak flows for the largest floods attributable to clearcutting. Paired-watershed studies in the Cascades (Harr and others 1979), Oregon Coast Range (Harr and others 1975), and at Caspar Creek (Wright and others 1990, Ziemer 1981) similarly suggested that logging did not significantly increase the size of large peak flows that occurred when the ground was saturated.

Using longer streamflow records of 34 to 55 years, Jones and Grant (1996) evaluated changes in peak flow from timber harvest and road building from a set of three small basins (0.6 to 1 km^2) and three pairs of large basins (60 to 600 km^2) in the Oregon Cascades. In the small basins, they reported that changes in small peak flows were greater than changes in large flows. In their category of "large" peaks (recurrence interval greater than 0.4 years), flows were significantly increased in one of the two treated small basins, but the 10 *largest* flows were apparently unaffected by treatment. Jones and Grant (1996) reported that forest harvesting increased peak discharges by as much as 100 percent in the large basins over the past 50 years, but they did not discuss whether the 10 largest peak flows in the large basins were significantly affected by land management activities. A subsequent analysis of the same data used by Jones and Grant concluded that a relationship could not be found between forest harvesting and peak discharge in the large basins (Beschta and others 1997).

Throughout much of the Pacific Northwest, a large soil moisture deficit develops during the dry summer. With the onset of the rainy season in the fall, the dry soil profile begins to be recharged with moisture. In the H.J. Andrews Experimental Forest in the Oregon Cascades, the first storms of the fall produced streamflow peaks from a 96-ha clearcut watershed that ranged from 40 percent to 200 percent larger than those predicted from the pre-logging relationship (Rothacher 1971, 1973). In the Alsea watershed near the Oregon coast, Harris (1977) found no significant change in the mean peak flow after clear-cutting a 71-ha watershed or patch cutting 25 percent of an adjacent 303-ha watershed. However, when Harr (1976) added an additional 30 smaller early winter runoff events to the data, average fall peak flow was increased 122 percent. In Caspar Creek, Ziemer (1981) reported that selection cutting and tractor yarding of an 85-year-old second-growth redwood and Douglas-fir forest increased the first streamflow peaks in the fall about 300 percent after logging. The effect of logging on peak flow was best predicted by the percent of area logged divided by the sequential storm number, beginning with the first storm in the fall. These first rains and consequent streamflow in the fall are usually small and geomorphically inconsequential in the Pacific Northwest. The large peak flows, which tend to modify stream channels and transport most of the sediment, usually occur during mid-winter after the soil moisture deficits have been satisfied in both the logged and unlogged watersheds. These larger events were not significantly affected by logging in the H.J. Andrews (Rothacher 1973), Alsea (Harris 1977, Harr 1976), or Caspar Creek studies.

There are several explanations why relationships between land

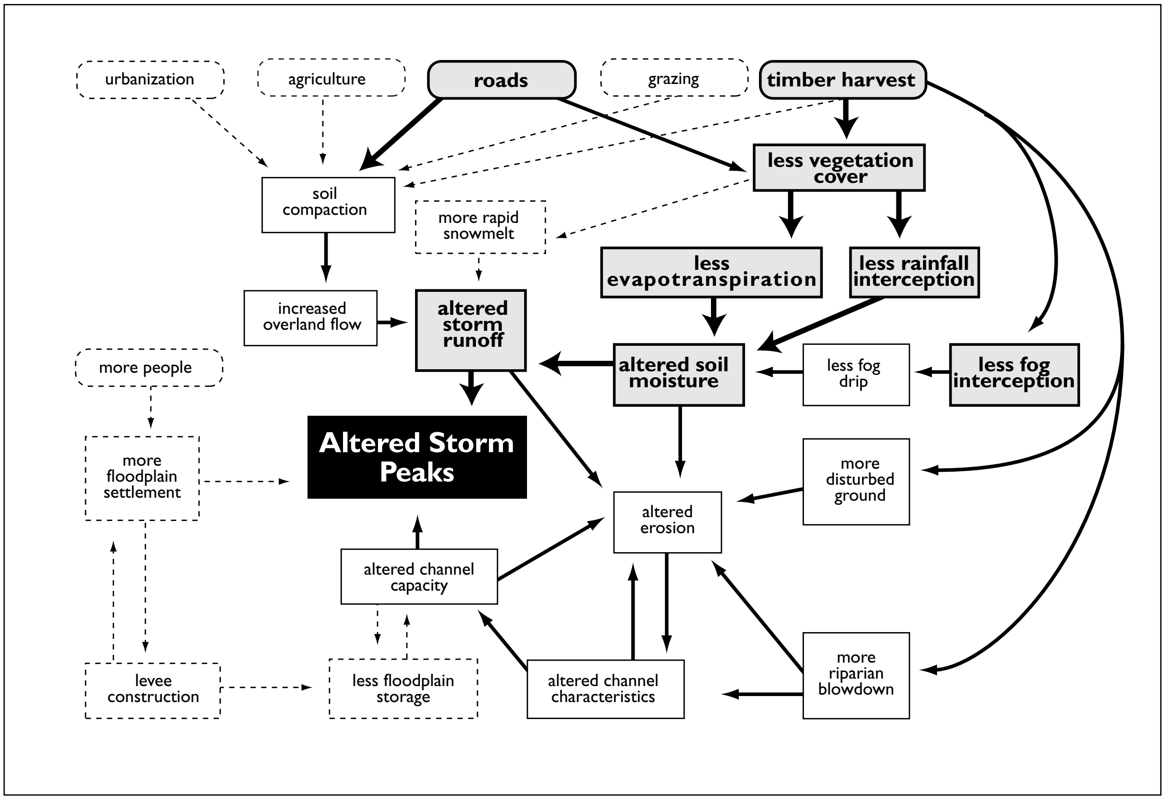

Figure 7 — A process model of the relation between land use and altered storm peaks. The components and linkages thought to be most important at Caspar Creek are bold, those not applicable to Caspar Creek are dotted.

management activities and a change in storm peaks have been difficult to document. First, the land management activity may actually have no effect on the size of storm peaks. Second, if there is an effect, it may be difficult to detect without a large number of observations because the variability of the observations is large relative to the change. Hirsch and others (1990), for example, reported that annual floods often have a coefficient of variation (ratio of standard deviation to mean) of one or more. This means that if the frequency distribution changed abruptly halfway through a 40-year annual flood record, the change in the mean would have to be at least 45 percent to be discernible with 95 percent power. However, land-use changes in the watershed are often gradual rather than abrupt, making detection of a change even more difficult. Third, the range of observations may not adequately cover the range of interest. As discussed earlier, there is a low chance of observing many major storms in any record.

No change in peak streamflow was detected at the North Fork weir after logging when the South Fork was used as the control (*fig. 2*), but an increase in peaks was detected when the uncut tributaries were used as the controls (*fig. 3*). This apparent discrepancy has several possible explanations:

1) The pre-treatment relationship between the North Fork and the South Fork is more variable (RMSE = 0.232) than that between the North Fork and the control tributaries (RMSE = 0.118). Using the tributary controls allows detection of a smaller magnitude of change.

2) The range of the South Fork pre-treatment data included larger storms (20 L $s^{-1}ha^{-1}$), whereas the largest storm observed in the control tributaries did not exceed 11 L $s^{-1}ha^{-1}$. Using the South Fork as the control, thereby including larger storms, increases the variability, but it also improves the relevance of the analysis concerning larger storms.

Process Model of Storm Peaks

Based on the small-watershed studies at Caspar Creek and elsewhere, a schematic hypothesis of the relationship between land use and storm peaks can be constructed (*fig. 7*). Typical land uses in small watersheds in the Pacific Northwest are urbanization, agriculture, roads, grazing, and timber harvest. Each land use influences storm peaks somewhat differently. Urbanization, grazing, and agriculture are not present in the North Fork of Caspar Creek. Roads, landings, and skid-trails in the North Fork are all located near the ridges and well away from any streams. Further, soil compaction from roads and timber harvest represent only 3.2 percent of the North Fork watershed and range from 1.9 percent to

8.5 percent for the tributary watersheds. Consequently, roads, soil compaction, and overland flow did not produce important changes in peak flow response of the North Fork watersheds. Snow is extremely rare and is not an important component of the hydrology of Caspar Creek.

The data from the streamflow, pipeflow, and soil moisture studies at Caspar Creek all suggest that the peak flow response to logging is related to a reduction in vegetative cover. Reducing vegetative cover, in turn, reduces evapotranspiration, rainfall interception, and fog interception. Since little soil moisture recharge occurs during the spring and summer growing season, large differences in soil moisture can develop between logged and unlogged watersheds by late summer because of differences in evapotranspiration. For example, by late summer, a single mature pine tree in the northern Sierra Nevada depleted soil moisture to a depth of about 6 m and to a distance of 12 m from the trunk (Ziemer 1968). This single tree transpired about 88 m^3 more water than the surrounding logged area. This summer evapotranspiration use by one tree is equivalent to about 180 mm of rainfall over the affected area. At Caspar Creek, the largest changes in peak streamflow after logging were found to be for the first storms after lengthy dry periods (Ziemer 1981). Similarly, after logging the North Fork, there was a strong interaction between the proportion of the area logged and watershed wetness that explained differences in streamflow peaks.

Reduced vegetative cover also results in less rainfall interception. Rainfall interception can result in a substantial reduction in the amount of rainfall that reaches the ground. Although we have not measured rainfall interception at Caspar Creek, studies elsewhere have documented that a large portion of annual rainfall is intercepted and evaporated from the forest canopy. For example, Rothacher (1963) reported that under dense Douglas-fir stands in the Oregon Cascades, canopy interception loss averaged 24 percent of gross summer precipitation and 14 percent gross winter precipitation. Interception losses are greatest during low-intensity rainfall interspersed with periods of no rain. As with evapotranspiration, rainfall interception can contribute to important differences in antecedent conditions between logged and unlogged watersheds. During the large high-intensity storms that result in large streamflow peaks, rainfall interception is probably less important. However, differences in interception between logged and unlogged areas probably explain most of the observed increases in the larger peaks.

Similarly, reduced vegetative cover can result in less interception of fog. Much of north coastal California has persistent summer fog, and Caspar Creek is no exception. Fog interception affects watershed hydrology in several ways. First, fog reduces evapotranspiration by raising humidity and by wetting transpiring leaf surfaces. Second, in some areas, fog drip from the tree canopy can add water to the soil, resulting in more streamflow than might occur from rain alone. When the forest is removed, the fog-drip contribution is lost. For example, Harr (1980) reported that after 25 percent of two small watersheds were patch clearcut in the Bull Run Municipal Watershed near Portland, Oregon, annual water yields and the size of peak flows were not changed, but summer low flows *decreased* significantly. In a followup study, Harr (1982) reported that fog drip accounted for 200 mm, or about a third of all precipitation received from May through September. At Caspar Creek, the presence of fog certainly reduces the rate of evapotranspiration. However, although the amount has not been measured directly, there is abundant circumstantial information to suggest that fog *drip* at Caspar Creek is not an important contributor to either soil moisture (Keppeler and others 1994, Keppeler, these proceedings) or to streamflow (Keppeler, these proceedings, Ziemer 1992, Ziemer and others 1996) — and certainly not to peak stormflows (Ziemer 1981).

The Bottom Line

The effect of logging second-growth forests on streamflow peaks in Caspar Creek is consistent with the results from studies conducted over the past several decades throughout the Pacific Northwest. That is, the greatest effect of logging on streamflow peaks is to increase the size of the smallest peaks occurring during the driest antecedent conditions, with that effect declining as storm size and watershed wetness increases. Further, peaks in the smallest drainages tend to have greater response to logging than in larger watersheds. The reason for this is both physical and social. Stormflow response of small basins is governed primarily by hillslope processes, which are sensitive to forest practices, whereas stormflow response of large basins is governed primarily by the geomorphology of the channel network (Robinson and others 1995), which is less likely to be affected by forest practices. From the social standpoint, Forest Practice Rules and economics tend to limit the amount of intense activity occurring within any given watershed in any year. Therefore, it is possible for entire small first-order watersheds to be logged within a single year. However, as the size of the watershed increases, a smaller proportion of the watershed is likely to have been logged in any given year. In the largest watersheds, harvesting may be spread over decades, within which time the earliest harvested areas will have revegetated.

The effect of logging on stormflow response in Caspar Creek seems to be relatively benign. The resulting changes in streamflow do not appear to have substantially modified the morphology of the channel (Lisle and Napolitano, these proceedings) or the frequency of landsliding (Cafferata and Spittler, these proceedings). However, increased stormflow volume after logging was the most significant variable explaining differences in suspended sediment load (Lewis, these proceedings). Further, logging has increased soil moisture and summer lowflow (Keppeler, these proceedings), subsurface and soil pipe flow (Keppeler and Brown, these proceedings), woody debris (Reid and Hilton, these proceedings), and modified other riparian conditions. The ecological significance of these changes remains to be determined.

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