EFFECTS OF TIMBER HARVESTING
ON THE LAG TIME OF
CASPAR CREEK WATERSHED

by

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ABSTRACT

Hydrograph lag time was analyzed to determine changes after road construction and after selective, tractor-yarded logging in a Caspar Creek watershed, Mendocino County, California. The paired watershed technique was used. Hydrograph lag time for each storm was the time separation between the midpoint of precipitation and the time coordinate of the runoff centroid. No significant change in lag time was detected after road construction. After logging, the lag time generally increased for small, early fall storms and decreased for larger storms.

To determine whether the change after logging was influenced primarily by the rising or falling limb of the hydrograph, each hydrograph record was split at the peak and the lag time was measured to the centroid time coordinate of each segment. A statistically significant reduction in both the rising and falling limb lag times was observed.

Six hydrologic variables were examined as predictors of the effect of logging on lag time. Proportion of area logged and the ratio of proportion of area logged divided by the storm sequence number were the best predictors. Other variables examined were North Fork peak flow, storm sequence number, storm size, and antecedent precipitation.

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INTRODUCTION

The effects of timber harvesting activities on streamflow has been the subject of many studies, often with conflicting results. This area of research is becoming increasingly important, as forested watersheds are being intensively managed to meet short and long term goals with a minimum of adverse impacts. The analysis of lag time, a stream flow variable, may contribute to a better understanding of streamflow processes and how these processes can be affected by timber management practices.

Hydrograph lag time was defined as the difference between the time when half the rainfall of each storm had fallen and the time coordinate of the centroid of resulting runoff. Lag time represents the time required for fifty percent of the input into the watershed to produce fifty percent of the output. Lag time reflects the, efficiency of the basin channels and subsurface flaw network to deliver runoff to a downstream point in the stream channel (Dunne and Leopold 1978). Hence, a significant change in lag time would indicate sane degree of alteration in the physical characteristics of a watershed (Leopold 1981). Such a change in the hydrologic regime may or may not cause degradation of the drainage, depending on the nature and severity of the alteration (Rice 1981).

Streamflow Processes

The processes involved in the delivery of precipitation to the stream channel in forested watersheds are not fully understood.

The applicability of the classic Horton overland flow concept (Horton 1933) has been extensively questioned and tested during the past two decades. Hydrologic studies on forested watersheds have shown that, because high infiltration capacities usually exceed precipitation rates, overland flaw rarely occurs in these areas (Hewlett and Hibbert 1963, Harr 1976, Dunne 1978).

Freeze (1972), in a theoretical study of subsurface flow as a part of stormflow, concluded that there are stringent limitations on the occurrence of subsurface stormflow. He suggested subsurface stormflow is significant only in areas with steep slopes and shallow soils, with a saturated hydraulic conductivity above a threshold level. Many studies have shown that forest soils commonly fall within those limitations and that subsurface flow is likely to dominate the runoff hydrograph (Beasley 1976, Mosley 1979). Hence, more appropriate streamflow models emphasizing subsurface drainage have been developed. One such model is the variable source area concept, which focuses on channel expansion as streamflow is generated in saturated areas adjacent to the channel (Hewlett and Hibbert 1963). Troendle (1979) developed a computer model of this concept, based on subsurface flow as the most significant component of storm runoff and the source of all non-storm flow.

Refinement of the variable source area concept to a concept of an expanding and contracting wedge has been the basis of several recent reports. Weyman (1973) suggested the existence of a zone of permanent soil saturation at the base of a slope. In response to precipitation, water movement into the saturated zone from adjacent unsaturated areas across the pressure gradient results in the wedge extending farther upslope and becoming thicker. In New Zealand forest soils, Mosley (1979, 1982) observed saturation of the entire soil depth at the lower slopes, with a saturated wedge thinning upslope.

Subsurface flow in itself is a complex process, and the mechanisms controlling it vary depending on site conditions. In New Zealand, Mosley (1979) found that subsurface flow made a significant contribution to stormflow due to rapid flow through large macropores, particularly root channels and holes and cracks in the soil, and through seepage zones. Aubertin (1971) reported that root channels and macropores produced by soil fauna such as earthworms and rodents often are stable conduits for rapid subsurface water movement. This phenomena may be less pronounced in areas of a different soil character, soil depth, and root network density. For example, a study on a small forested watershed in Vermont showed that subsurface flow was too slow to contribute to stormflow; the main source instead was small saturated areas that produced overland flow (Dunne and Black 1970). Unlike typical Pacific Northwest forest soils, soils on this Vermont study site were moderately to poorly drained, and precipitation was added to storage causing overland flow rather than percolating toward the stream channel.

Studies have shown the construction of a road network in forested watersheds can alter subsurface flow and influence the storm hydrograph (Reinhart 1964, Megahan 1972). Infiltration rates are low on heavily compacted road surfaces, and road cuts can intercept subsurface drainage patterns. As a result, flow is concentrated into ditches and more efficiently routed to the stream channel or directed to undisturbed areas where it is re-infiltrated. Many researchers have reasoned that impacts on the storm hydrograph would include a shortened lag time, due to a faster streamflow response to precipitation (Harr et al. 1975, 1979; Leopold 1981).

Similarly, heavy equipment used in logging operations can compact the soil surface on skid trails and landings, significantly reducing the infiltration capacity (Munns 1947, Reinhart 1964, Johnson and Beschta 1980). Similar analyses have shown decreases in bulk density, and a conversion from macropore space to micropore space (Campbell et al. 1973, Dickerson 1976, Froelich 1978, Cafferata 1983). The impact of tractor-logging on soil surfaces is well documented; however, the effects these alterations have on the processes of streamflow are not well understood. It can be reasoned that increased overland flow could take place if infiltration rates dropped below precipitation rates. This occurrence, coupled with the possible channeling of flow on skid trails, could increase site erosion and alter the storm hydrograph. Again, many researchers suggest this more efficient delivery system after treatment would result in a shorter lag time (Harr et al. 1975, 1979; Leopold 1981).

Rothacher (1971) suggested normal logging activity may not sufficiently compact the soil to reduce the infiltration capacity below the rate of precipitation. Due to high infiltration rates and relatively low precipitation rates in the Pacific Northwest, there may be no large scale change from subsurface to surface flow.

Other researchers report that lag time may be increased after timber harvesting activities (Chamberlin 1972, Cheng et al. 1975, DeVries and Chow 1978). They suggest that during a storm event on an undisturbed site a significant proportion of infiltrated water tends to bypass the soil matrix as a result of conduction through decayed root channels. Disturbance of the forest floor to mineral soil by logging activities could close off a significant number of root channels, causing a greater precentage of the infiltrating water to move through the soil matrix. Increased subsurface flows through the soil matrix would result in slower water movement and a longer lag time.

The process of streamflow as it relates to lag time is complex and includes such factors as soil infiltration, permeability, and storage. Freeze (1972) studied the influence of rainfall intensity and duration, soil thickness, and slope on runoff rates and found that variations in these variables had no major effects. He reported saturated hydraulic conductivity of the soil to be the most important control of direct runoff volume and lag time.

Previous Studies

Many studies have analyzed peak flows, discharge volumes, and less commonly, lag times as streamflow characteristics which indicate hydrologic changes caused by road building and logging. Although results have varied, general trends have become apparent and have provided insight into a watershed's response to logging.

After clearcutting a 96-hectare watershed in the H.J. Andrews Experimental Forest in Oregon, the first fall storms produced streamflow peaks that increased by 40 to 200 percent over the expected values (Rothacher 1971 and 1973). Larger winter runoff events were found to be unaffected by the treatment. In the same experimental area, patchcutting 25 percent of a 101-hectare watershed caused a significant increase in the mean peak flaw. After roadbuilding alone, peaks were lower than predicted for no known reason (Rothacher 1973). After clearcutting and cable-yarding a third small nearby watershed, no significant changes in size or timing of peak flows from all rainfall storms were found (Harr and McCorison 1979).

Harr et al. (1975) reported finding an increase in peak flows during the fall recharging period in three partially clearcut watersheds in the Alsea Watershed Study in the Oregon Coast Range. Large winter peaks were not affected. They reported that the most significant changes in peak f laws attributed to roading were found in the areas with the heaviest road density (12 percent). The most significant post-logging increases in peak flows were in the areas that were most heavily harvested. No increase in discharge volume was noted after road construction, but this parameter did generally increase after logging. They reasoned that the volume increase in the logged watersheds was because less water was lost to evapotranspiration and interception, and instead it was available for streamflow. No consistent change in time to peak was found in this study.

Harr et al. (1979) found increases in fall peak flows after constructing roads in three watersheds on Coyote Creek in Oregon.

They felt the changes resulted from reduced soil permeability on the road surfaces and the interception of subsurface water by roadcuts and ditches. In the same study, peak flows were shown to increase significantly after clearcutting a 50-hectare watershed and after shelterwood harvesting a 69-hectare watershed. No significant change in peak flows was found after patchcutting a 68-hectare watershed. However, data from all three drainages indicated proportionally larger seasonal increases in peak flows during the fall storms. In a more recent report, Johnson and Beschta (1980) suggested that skid trails influenced subsurface flows, increasing water delivery to the stream channel, and that reduced infiltration capacity was significant only on the highly disturbed clearcut drainage. They reported that if logging had influenced infiltration capacities and erodibility, effects had almost disappeared six years after treatment on the two partially cut watersheds. Some recovery was apparent on the highly disturbed clearcut drainage.

A study at Coweeta Hydrologic Laboratory in North Carolina showed early fall streamflow increased after clearcutting (Douglas and Swank 1975). Response differences between the treated and control watersheds decreased after both watersheds were recharged. Similar results were reported by Kochenderfer and Aubertin (1975) after logging at Fernow Experimental Forest in West Virgina.

In a study on the effects of partial forest cover removal on storm runoff, Lynch et al. (1972) found increases in discharge volumes and peak flows on a Pennsylvania watershed. The most significant increases were during the growing season and at low antecedent moisture conditions, when the soil moisture difference between the logged and unlogged state were the greatest. Time to peak was shortened by three percent during both seasons, which was not statistically significant.

Springer and Coltharp (1980) reported a significant decrease in dormant season peakflow rates after construction of a mid-slope logging road on a Kentucky watershed. They concluded that increased detention storage in the loosely packed fill material and interception of subsurface stormflow resulted in storm hydrograph changes. No significant change was found in time to peak after road construction.

Fujieda and Abe (1982) reported the results of a study on a 17-hectare clearcut watershed in Japan. The drainage was monitored for six years after treatment until pine regeneration occurred, then again at stand age 25 to 30 years. Storm runoff volume, especially surface runoff components, decreased after the development of forest cover. The average lag time of 60 minutes was prolonged by 10 to 20 minutes after the regrowth of forest cover.

In a study in British Columbia, Cheng et al. (1975) reported an increase in time to peak and a decrease in peakflow magnitude after timber havesting. They concluded these changes were due to the disturbance and closure of large soil channels and macropores, forcing a greater proportion of subsurface flow to enter the soil matrix. The subsequent slower movement of stormflow resulted in a significantly longer lag time after treatment.

Caspar Creek

Four years after roads were constructed in the South Fork Caspar Creek watershed in northern California, Krammes and Burns (1973) investigated the impacts of roadbuilding on streamflow, sedimentation, aquatic habitat, and fish populations. They found an increase in suspended sediment, particularly during the first winter, to be the only significant alteration caused by road and bridge construction. After logging, Tilley and Rice (1977) and Rice et al. (1979) analyzed sedimentation and erosion data. They concluded that disturbances from roadbuilding and logging changed the sediment/discharge relationship of the South Fork from a supply dependent relationship to a relationship which was more stream power dependent, resulting in substantial increases in suspended sediment discharges. The overall effect of sedimentation and erosion was not reported to be a cause for concern.

Stormflow response of the South Fork after treatment was analyzed by Ziemer (1981). He found no change in the magnitude of peak flows after roadbuilding. After logging, a 300 percent increase in peak flow during small, early fall storms was reported. No change was detected in the large, winter storm peaks. These results, consistent with other paired watershed studies in rain-dominated areas, indicated increased runoff after logging during the first few storms because of soil moisture differences between the logged and unlogged watersheds. Once the North and South Fork watersheds were similarly recharged, response differences were no longer significant.

Ziemer (1981) also examined discharge volume, using an indirect variable, and reported no change after roadbuilding. In the post-logging period, he found an indication of increases in the volumes of small storms and decreases in the volumes of large storms.

STUDY AREA

Caspar Creek is located 11 kilometers southeast of Fort Bragg, California, in Jackson Demonstration State Forest (Figure 1). Stream gaging stations were established on the North and South Fork watersheds in 1962. A compound weir, composed of a sharp-crested rectangular weir superimposed over a 1200 V-notch, was constructed at each station, creating a debris basin/settling pond on the upstream side.

The North and South Fork watersheds have areas of 497 and 424 hectares, respectively. Altitude of the watersheds ranges from 37 to 320 meters.

Topography of the North and South Fork watersheds runs from broad, rounded ridgetops to steep inner gorges. Side slopes are moderately steep. About 35 percent of the total study area has slopes less than 30 percent. About 7 percent of the North Fork slopes, and less than 1 percent of the South Fork slopes, are greater than 70 percent (Rice and Sherbin 1977).

Recent preliminary soil classifications by the Soil Conservation Service indicate that the majority of the North and South Fork watersheds lie within the mapping unit designated as IrmulcoTramway loam with 30 to 50 percent slopes (Rittiman, C., Soil Conservation Service, Fort Bragg, CA 95437). Part of the North Fork lies in the mapping unit described as Vandamne clay loam with 19 to 30 percent slopes. Soils in these units formed in residuum derived predominately from sandstone and weathered, coarse-grained shale of Cretaceous Age. These soils are moderately to very deep and are

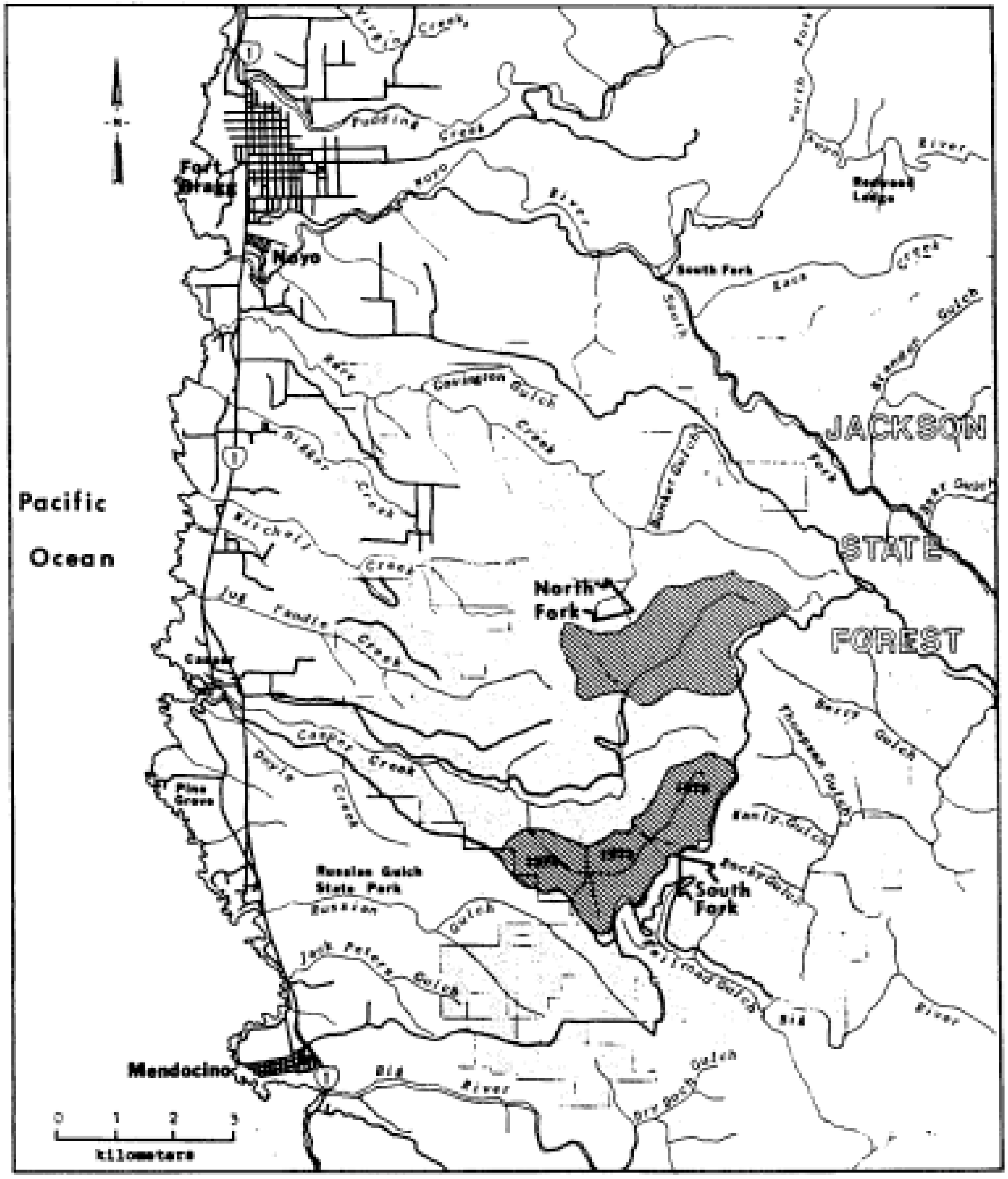

Figure 1. Location of the North and South Fork Caspar Creek Watersheds, Mendocino County, California

well-drained. About ten percent of the South Fork watershed lies in an as yet unidentified mapping unit in which soils formed from marine terrace deposits of sand and gravel of Pleistocene Age.

The climate of the study area is typical of the Northern California coast, with mild, wet winters and warm, dry summers. Annual precipitation of the Caspar Creek drainage is about 1140 millimeters (Rice and Sherbin 1977). The rainy season usually runs from October through April; about 90 percent of the annual precipitation falls during these months. Fogdrip makes a small contribution to the total precipitation, primarily in the summer months. Snowfall in this area is extremely rare.

Both the North and South Fork watersheds were clearcut and burned in the late 1800s. Fairly dense stands of second-growth redwood (*Sequoia sempervirens* ((D. Don) Endl.) and Douglas-fir (*Pseudotsuga menziesii* ((Mirb.) Franco) developed, with some associated western hemlock (*Tsuga heterophylla* ((Raf.) Sarg.) and grand fir (*Abies grandis* ((Dougl.) Lindl.). Scattered old-growth redwoods remained in both watersheds. Some Bishop pine (*Pinus muricata* (D. Don) and hardwood species including tanoak (*Lithocarpus densiflorus* ((Hook. & Arn.) Rohn.) and red alder (*Alnus rubra* (Bong.) also developed. Undergrowth consisted of brush species including evergreen huckleberry (*Vaccinium ovatum* (Pursh), Pacific rhododendron (*Rhododendron macrophyllum* (D. Don) and swordfern (*Polystichum munitum* (Kaulf. Presl.).

Treatment of Caspar Creek

At the beginning of this study (1962), about 85 years had passed since the South Fork was logged and about 65 years since the North Fork was logged. Forest cover on both watersheds was estimated at 700 cubic meters per hectare (Krammes and Burns 1973). Because of the stand age difference, the South Fork drainage was harvested while the North Fork remained uncut as a control.

Right-of-way clearing for the road system in the South Fork began in May 1967. About 18,900 cubic meters of timber was removed from 19 hectares to facilitate construction of the main haul logging road and spurs, totaling 6.8 kilometers, 3.9 km of the main road, and 2.1 km of the spur roads, were within 61 meters of the stream channel. All road and bridge construction, as well as the removal of most of the coarse debris that entered the channel during construction, was completed by mid-September. Fill slopes, landings, and other major areas of soil exposed by construction were fertilized and seeded with ryegrass (*Lolium multiflorum* (Lam.)).

The South Fork watershed was divided into three consecutive annual timber sales. Starting at the lower end in the summer of 1971, 59 percent of the stand volume was selectively harvested from 101 hectares. In 1972, 69 percent of the stand volume was selectively cut from 128 hectares. The remaining upper 176 hectares was selectively harvested in 1973, removing 65 percent of the stand volume. Each harvest was directed at the removal of single trees and small groups of trees in order to reserve healthy, fast-growing stands of the more desirable species, redwood and Douglas-fir. The objectives were to promote growth of these trees as well as provide openings to encourage regeneration of these species. Each annual sale removed 49 to 68 thousand cubic meters. Including the timber removed for the 1967 road construction, an average of 65 percent of the total timber stand volume was removed.

About 15 percent of the land surface had been converted to relatively impervious areas by fall 1973. About 22 hectares (5 percent) was occupied by roads. Skid trail and landing area totaled 10 percent (35 hectares was covered by skid trails and 8 hectares by landings).

METHODS

Concomitant hydrologic data have been collected from the North and South Fork watersheds from 1962 to the present. A water-stage recorder at each weir provided a continuous streamflow record, which was converted to discharge volume using the discharge rating curve for Caspar Creek (King and Brater 1963). A continuous precipitation record was obtained from a weighing, recording raingage installed in the study area. Due to data collection problems during hydrologic year 1977, no data were available from that year for this study.

The onset and cessation of each rainfall event was determined from the precipitation charts. Each corresponding hydrograph was separated into an individual runoff event. Only those storms with complete records for both watersheds were used in this analysis.

A simple and commonly used method of hydrograph separation was utilized to delineate quick and delayed flow. A computer program was written to project a line from the beginning of each storm hydrograph rise at a slope of 0.55 liters per second per square kilometer per hour until it intersected with the recession limb of the hydrograph. Hewlett and Hibbert (1967) developed this technique in order to apply the same mathematical rule in all hydrograph analyses, and found it provided reasonable separations for watersheds under fifty square kilometers in area. Their studies showed that quick flow was appropriately shut off after the passage of high, damage producing flows but before the return to the pre-storm flow level.

In most cases, separate storm events were easily discernible, as the junction of the falling limb and separation line usually occurred prior to the onset of a successional storm. In those situations where the recession limb did not quite reach the separation line, the lower end of the recession limb was graphically extrapolated to the point of intersection. This adjustment was based on the determination that each watershed had little variation in the configuration of the tail end of the recession limb. Extrapolation was performed in about 15 percent of the hydrographs and only in cases where a minor adjustment was needed and where less than 15 percent of the volume fell under the extrapolation. If continuing rainfall events produced long, flat hydrographs, or hydrographs with two or more inseparable peaks, they were considered unsuitable for lag time analysis and were not included in this study.

After hydrograph separation was performed on each runoff event, the time coordinate of the quickflow centroid was determined. The centroid is the point in a geometrical figure whose coordinates are the average values of the coordinates of the points contained in the figure. A centroid is actually defined in terms of infinitesimals, but can be approximated using small increments of area. Because only the time coordinate of the quickflow hydrograph centroid is needed to calculate lag time, the "partial areas" were approximated by narrow vertical trapezoids having widths equal to a small constant increment of time and sides with lengths equal to the quickflow discharges at the boundaries of the intervals. Denoting these partial areas by m_j, and the time coordinates of their midpoints by r_j, the time coordinate of a storm centroid, r, is approximated by:

$$r = \frac{\sum\left(r_j m_j\right)}{\sum\left(m_j\right)} \qquad (1)$$

Applied to a hydrograph, this equation was expressed in a computer program algorithm:

$$r = \frac{\sum\left(\frac{T_n+T_{n+1}}{2}\right)\left(\frac{D_n+D_{n+l}}{2}\right)(T_n-T_{n+l})}{\sum\left(\frac{D_n+D_{n+1}}{2}\right)(T_n-T_{n+1})} \qquad (2)$$

where T_n and T_n+1 were the time in minutes at the start and the end, respectively, of each interval. D_n and D_n+l were the corresponding quickflow discharges in liters per second. The centroid time coordinate is given in units of time (minutes) from the origin (Figure 2).

The onset and cessation of individual rainfall events corresponding to the storm hydrographs were determined from the raingage charts, and the rainfall volume (P) of each storm was calculated. The time when one-half of the rainfall for that storm had fallen was recorded, and is referred to as the precipitation midpoint (Figure 2).

The lag time for each event was measured as the time separation between the occurrences of the precipitation midpoint and the time coordinate of the quick flow runoff centroid (Figure 2).

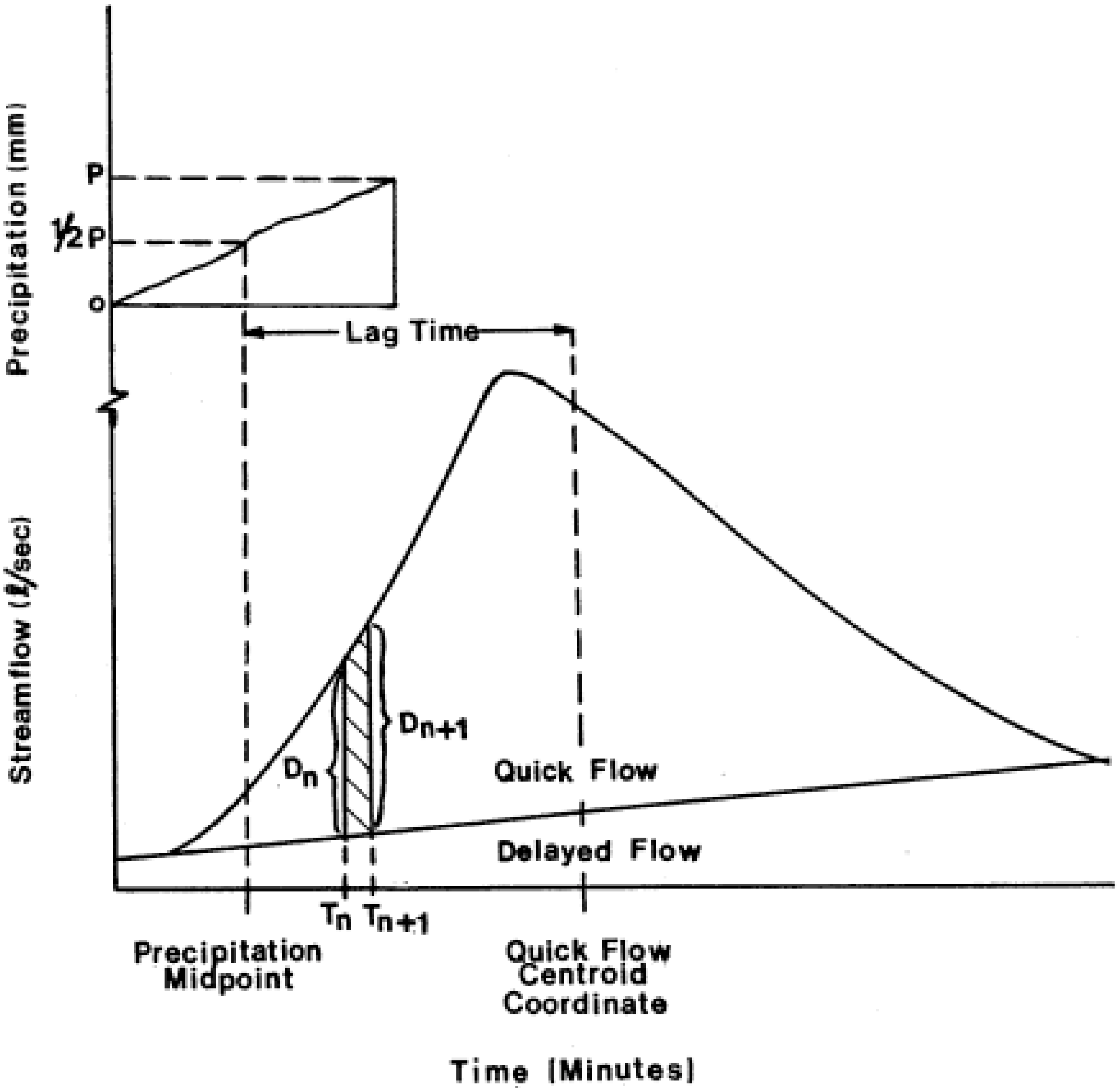

Figure 2. Schematic for Determination of Hydrograph Lag Time.

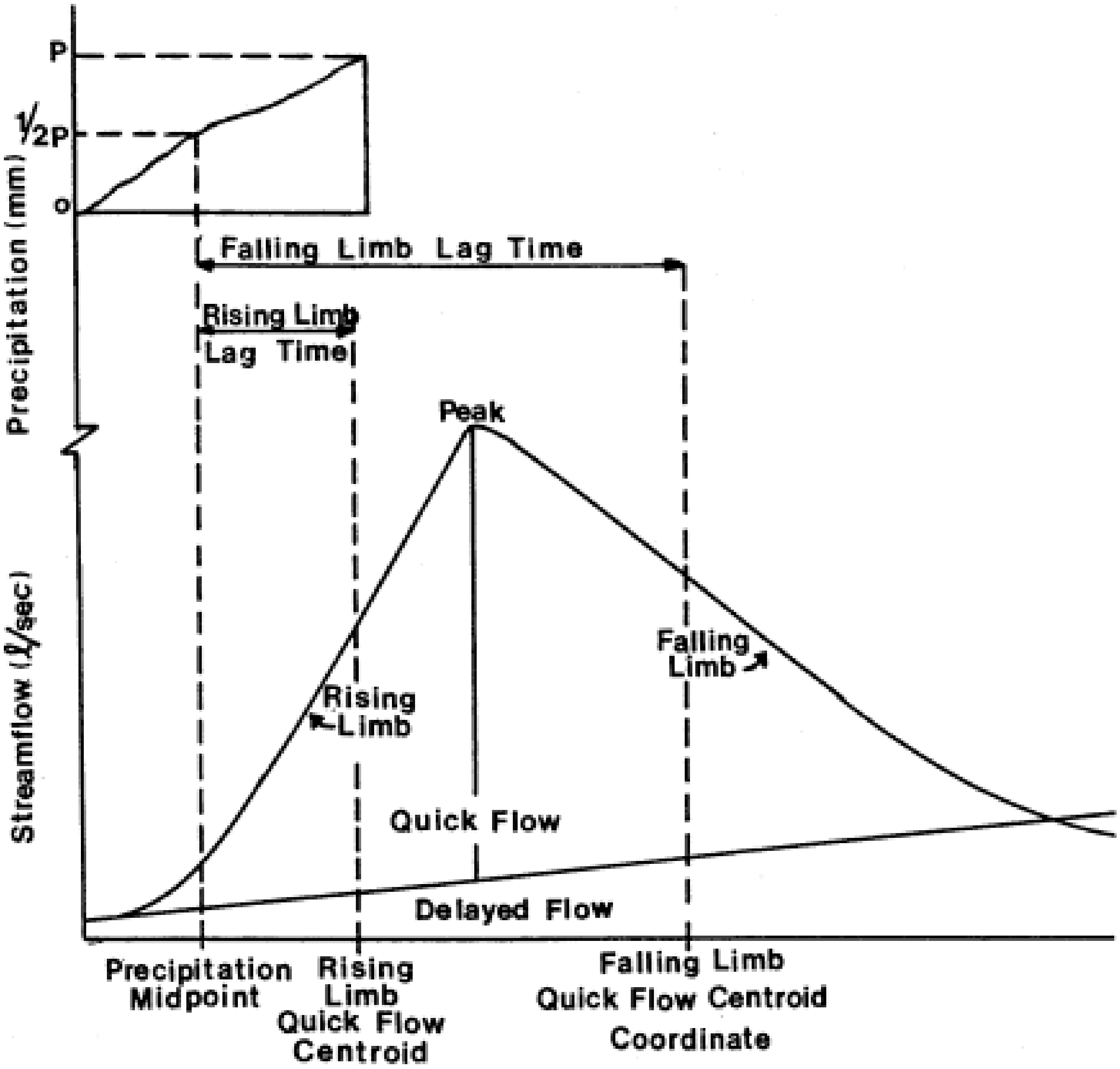

Figure 3. Schematic for Determination of Rising and Falling Limb Lag Times.

To investigate whether a change in lag time after logging was specific to either the rising or falling segment of the hydrograph, each hydrograph was separated at the peak. Using equation (2), the quick flow centroid time coordinates of the rising and falling segments were determined. Lag times were computed from the rainfall midpoint to each of the rising limb and falling limb centroid time coordinates (Figure 3).

The data were analyzed in three segments: calibration (hydrologic years 1963-1967), post-roading (1968-1971), and post-logging (1972-1981). The South Fork lag time was regressed on the North Fork lag time for each of the three periods. The data were checked for inconsistencies, and Chow's Test (Chow 1960) was used (alpha = 0.05) to test for significant differences in lag time after treatment.

To examine changes that occurred seasonally and with time after treatment, a ratio (LAGSHIFT) was plotted in time sequence for all three periods, in which:

$$\text{LAGSHIFT} = \frac{\text{North Fork lag time - South Fork lag time}}{\text{North Fork lag time}} \qquad (3)$$

Plotting LAGSHIFT for, each storm in chronological order demonstrated, on a per storm basis, the changes in lag time after each treatment as compared to the calibration period.

To demonstrate which variables were most useful in predicting the ratio LAGSHIFT, six variables were screened to determine the best possible subset. The Biomedical Computer Program (BMDP) P9R: All Possible Subsets Regression (Frame 1981) was used. The variables included North Fork peak flow, storm sequence number within hydrologic year, storm size, proportion of area logged, antecedent precipitation, and the ratio of the proportion of area logged to the storm sequence number.

RESULTS

The hydrograph lag times of the North and South Fork watersheds for each runoff event were computed (Appendix A). A least squares regression of the lag times of the North Fork control watershed against those of the South Fork watershed was used to analyze differences in lag time during each of the three periods, using Chow's Test (Chow 1960) (Table 1; Figure 4). In comparing post-roading to calibration the two equations were not significantly different ($P=0.27$); a significant change in lag time after road construction was not detected.

In comparing the lag times of the post-logging and calibration periods a significant difference ($P<0.01$) in lag times was detected. After logging, the lag times of the South Fork watershed generally increased during storms with lag times less than 8 hours, and decreased during storms of longer duration.

An all possible subsets regression was performed, using Mallow's Cp (Daniel and Wood 1971) as a criterion (Table 2). The dependent variable was the ratio LAGSI3IFT (Equation 3). The variables that were examined were North Fork peak flow, storm sequence number within each hydrologic year, storm size, antecedent precipitation, proportion of area logged (PROPLOG), and the ratio of proportion of area logged to the storm sequence number (LOGSEQ). This analysis indicated that most of the variance of the difference between the logged and unlogged conditions was explained by PROPLOG and LOGSEQ.

Table 1. Results of Least-squares Regressions of South Fork Lag Time on North Fork Lag Time.

Lag Time	Regression	Intercept	Coefficient	R^2	n	F[a]	P[a]
Hydrograph	Calibration	0.936	0.791	0.94	29	-	-
	Post-roading	1.402	0.697	0.86	27	1.28	0.27
	Post-logging	2.736	0.589	0.77	44	2.46	<0.01
Rising Limb	Calilbration	0.002	0.758	0.90	29	-	-
	Post-logging	0.029	0.523	0.59	44	2.31	<0.01
Falling Limb	Calibration	0.580	0.828	0.96	29	-	-
	Post-logging	3.327	0.611	0.71	44	4.42	<0.01

[a] Critical 'F' and significance probability 'P' values refer to Chow's Test regression comparisons.

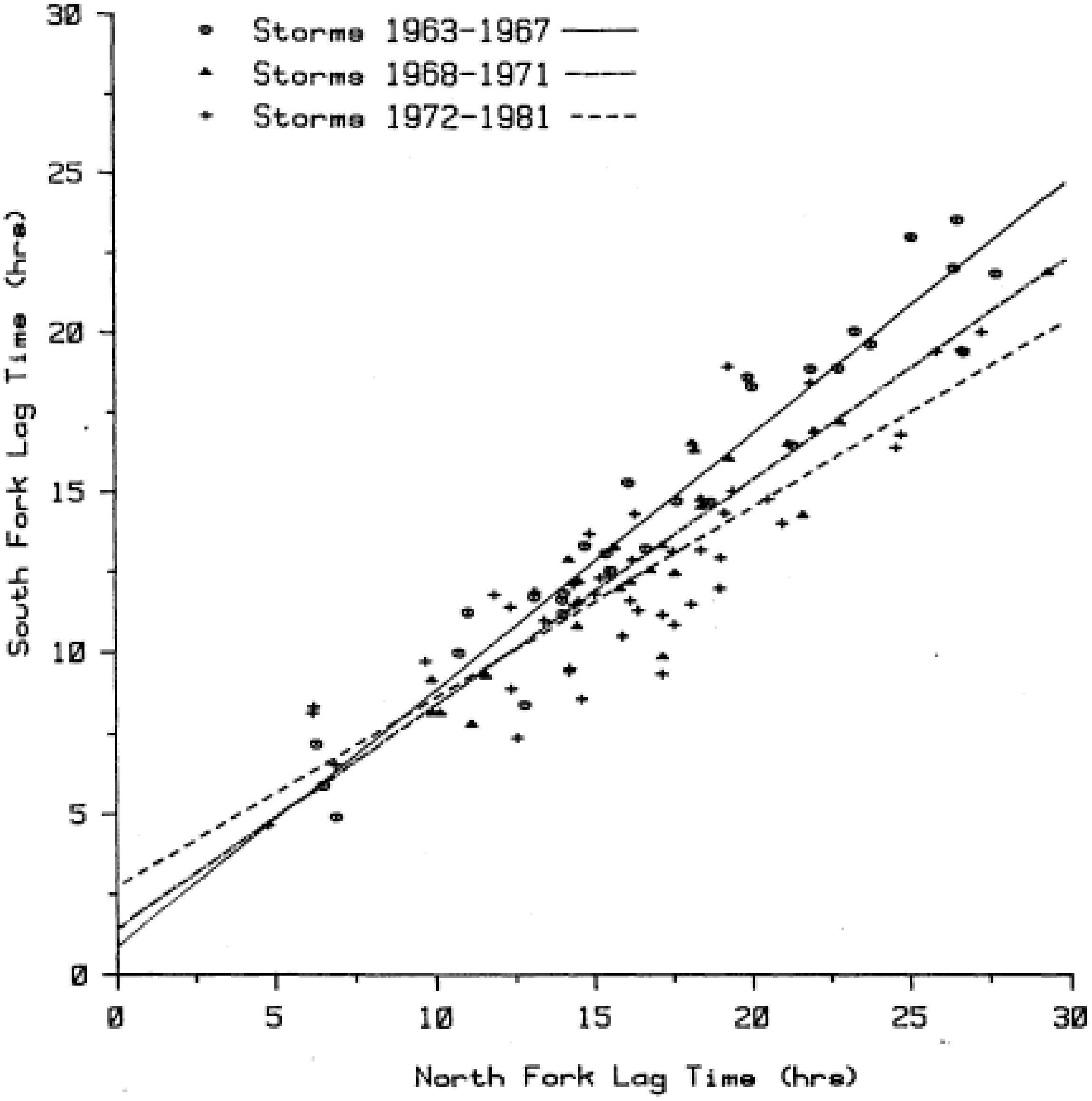

Figure 4. Regression of South Fork on North Fork Hydrograph Lag Times for Calibration (1963-1967), Post-roading (1968-1971), and Post-logging (1972-1981) Periods.

Table 2. Results of Best Possible Subset from All Possible Subsets Regression Analysis in which the Dependent Variable Was LAGSHIFT.[a]

Variable	Regression Coefficient	Standard Error	Standard Coefficient
Intercept	0.16198	0.06827	0.962
Proportion of Area Logged	0.00246	0.00080	0.347
$\frac{\text{Proportion of Area Logged}}{\text{Storm Sequence Number}}$	-0.00428	0.00062	-0.773

[a] For best subset, which contains the above variables, $R^2=0.54$; standard error estimate = 0.117; F = 23.89.

These two variables formed the best subset with an R^2 of 0.54 for the regression equation.

As a means of graphical comparison of hydrograph lag times seasonally and with time, the ratio LAGSHIFT for each storm was plotted in time sequence (Figure 5). From the plot it appears that the effects of logging were most pronounced in the years immediately following treatment and that the ratio was affected by seasonal influences.

Rising and falling segment lag times were computed for each event in the calibration and post-logging periods (Appendix A). Least squares regressions of the rising and falling limb lag times of the North Fork Watershed against those of the South Fork were used to compare differences (Table 1; Figures 6 and 7). Chow's Test was again used to compare regression lines. A significant ($P<0.01$) decrease in the rising limb lag time was detected after logging. A significant ($P<0.01$) difference after logging in the falling limb lag time was also found, which decreased during large storms. The regression lines intersected at a lag time of about 12 hours, indicating an increase in lag time for small storms after logging.

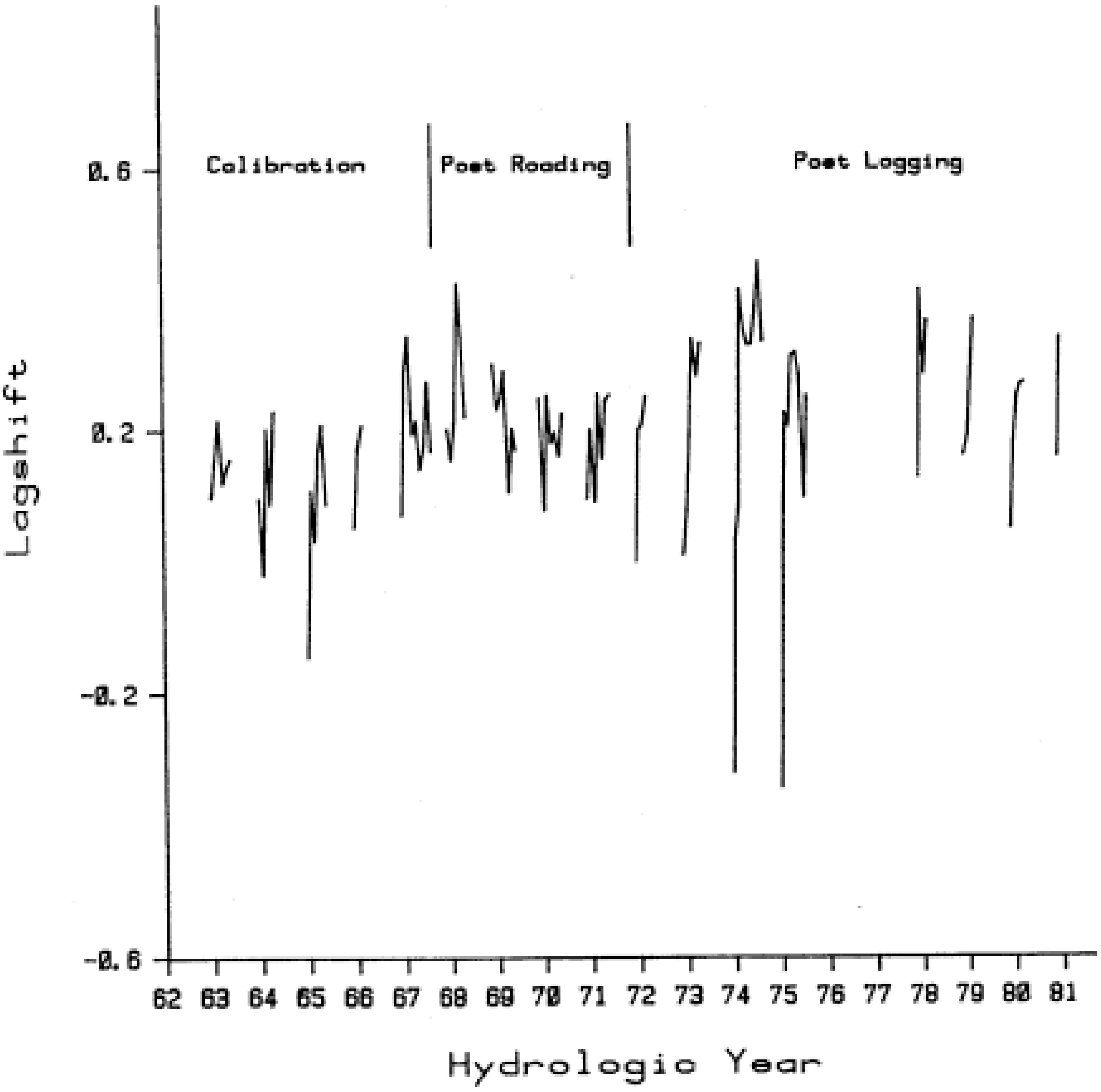

Figure 5. LAGSHIFT as Occurred with Time During the Study Period within each Hydrologic Year.

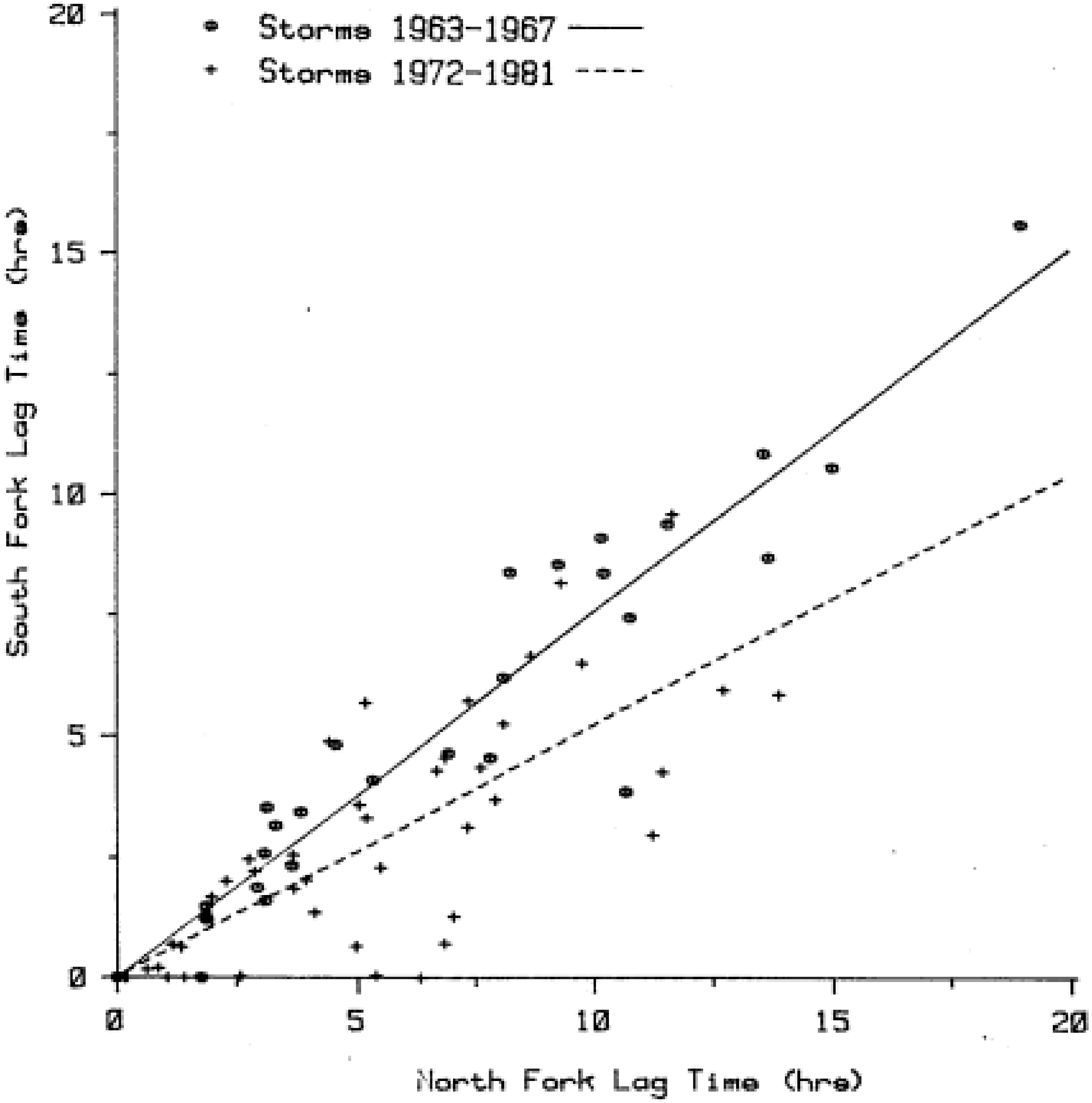

Figure 6. Rising Lamb Lag Time Regression for Calibration (1963-1967) and Post-logging (1972-1981) Periods.

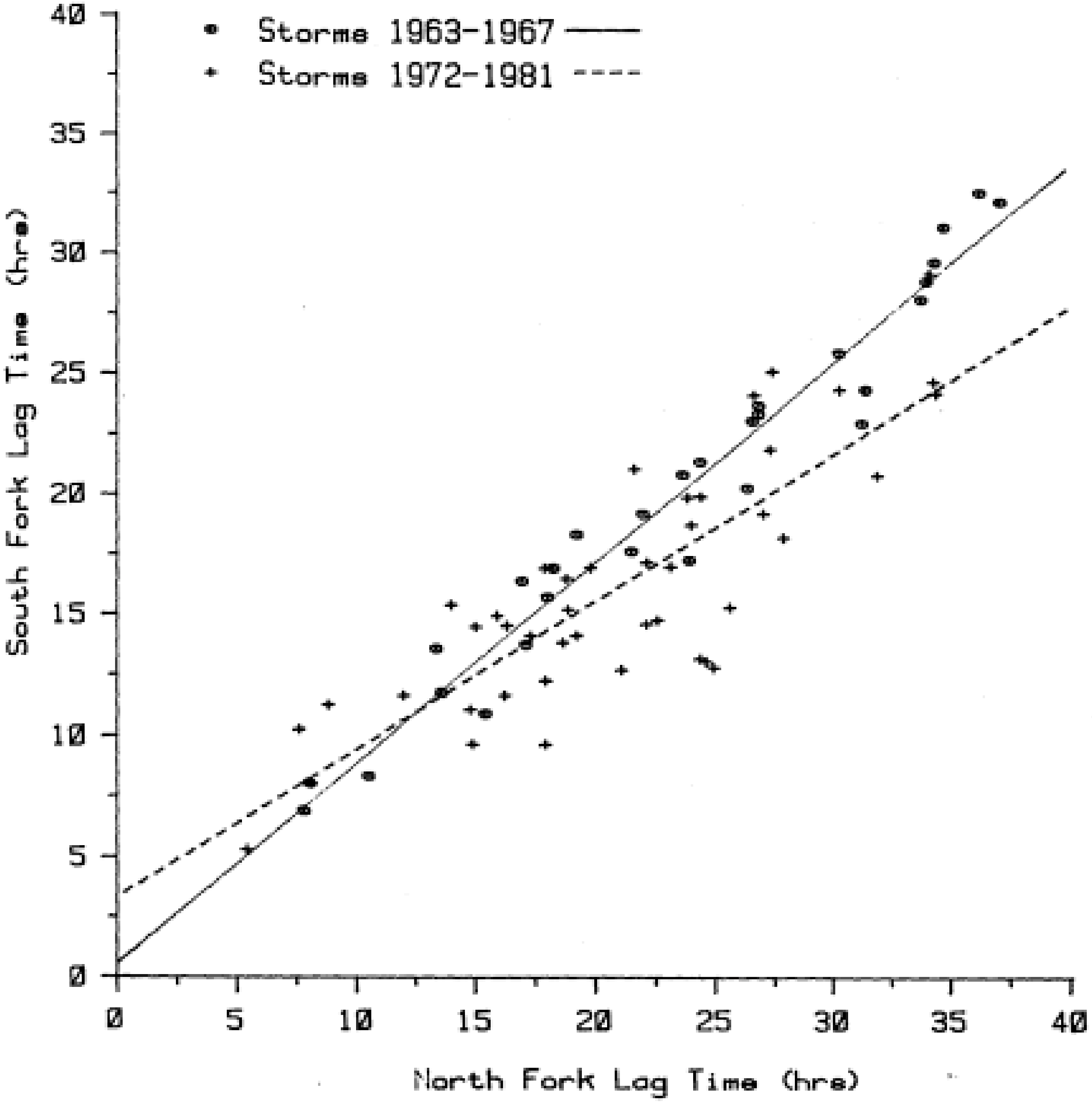

Figure 7. Falling Limb Lag Time Regression for Calibration (1963-1967) and Post-logging (1972-1981) Periods.

DISCUSSION

Effects of Road Construction

Regression analysis of hydrograph lag times before and after treatment indicated that the lag time of the South Fork watershed was not significantly altered by road construction. The lag time was slightly shortened after road-building, but not significantly. These results are consistent with those of other similar studies. Roads occupied 5 percent of the land surface in the South Fork drainage. This figure is notably lower than the threshold density of 12 percent, at or above which significant impacts have been observed in other studies (Harr et al. 1975).

Road systems can alter streamflow by reducing infiltration on road surfaces, intercepting subsurface flow, and quickly concentrating runoff into ditches. Although these effects most likely occurred in the study area to some degree, the impacts were not severe enough to expedite flow to the stream channel to significantly decrease the lag time. Thus, these results suggest that no deleterious effects on the streamflow regime of the South Fork watershed took place after road construction. Similarly, Ziemer (1981) used peak flow analyses of Caspar Creek to conclude that road construction had no major impact on the runoff processes.

Effects of Logging

Statistical comparison of the lag time regressions, which showed that lag time was significantly changed after logging the South Fork, suggests that lag time increased for smaller storms and decreased for larger storms after logging. However, the intersecting paint may vary widely because of to sample variation in estimating the position of the regression lines.

The small storms, which underwent increases in lag time, were generally the early fall storms. The most marked increases occurred in the years during and immediately following treatment. Previous analysis of Caspar Creek showed that these small, early fall storms had increased peak flows after logging (Ziemer 1981). He attributed this increase to soil moisture differences between the logged and unlogged sites. He suggested that evapotranspiration losses were reduced after logging, thereby increasing soil moisture storage. Interception losses were also reduced after logging, allowing more precipitation to became available earlier for soil moisture recharge. Thus, the South Fork watershed responded to the first fall precipitation with higher peaks and with runoff volume increases that were large enough to increase the lag time. It can be reasoned that the hydrograph started to rise earlier on the wetter, more charged site. However, the lag time as measured to the runoff centroid was lengthened because the runoff volume was increased.

After soil moisture recharge had occurred and soil moisture differences between the watersheds were small, the lag time generally decreased on the South Fork drainage. These results imply that the hydrologic regime was disturbed in such a way that runoff to the point of measurement in the stream channel accumulated more quickly after treatment than in a non-disturbed state. The entire hydrograph was moved on the time axis to a faster response time. Because Ziemer's (1981) analysis showed no increase in peak flows in large winter storms, it appears that, although the hydrograph response time was shortened, hydrograph configuration did not significantly change.

Further support of this concept was found in the analyses of the rising and falling limb lag times, in which significant differences after logging were detected in these two additional measures of lag time. These results demonstrate that the change in lag time after treatment was not exclusive to either the rising limb or the recession limb of the hydrograph, but rather that both were altered by logging. For large storms, the lag times for both the rising and falling limbs were shortened by logging.

Multiple regression analysis indicated that the two most important variables among those screened were the proportion of area logged (PROPLOG) and the ratio LOGSEQ, which was PROPLOG over the storm sequence number within a hydrologic year. Ziemer (1981) found that LOGSEQ was the most important variable in his peak flow analysis on Caspar Creek.

Previous studies of the flow processes on undisturbed forested watersheds have shown that the concept of an expanding and contracting wedge may be the basis for streamflow, in which subsurface flow is dominant (Nutter 1973, Weyman 1973). Infiltration rates are high and the majority of precipitation contributes to subsurface flow

(Hewlett and Hibbert 1963). Well-documented impacts of tractor-yarding on a watershed include soil compaction of skid trails and landings, with uncertain effects on streamflow processes (Johnson and Beschta 1980, Cafferata 1983). Although the total road, skid trail, and landing area on the South Fork watershed was 15 percent of the land surface area, Ziemer (1981) suggested that over-all watershed infiltration was not greatly reduced after logging. Because he found no increase in large, winter peaks, he inferred that precipitation continued to infiltrate and become subsurface flow.

Thus, in the undisturbed condition, water delivery to the stream channel was primarily subsurface. After logging, it appears that subsurface flow may have been interrupted by roads, skid trails, and landings and directed onto road or skid trail surfaces and channelized in roadside ditches. However, the rate of delivery to the higher velocity portions of the slope (the 15 percent in roads, landings, and skid trails) was governed by the rates of infiltration and the initial subsurface flow on the remaining 85 percent of the watershed. The effect was an earlier initiation of quickflow and faster hydrograph response time but no increase in peak flows. The implications are that the hydrographs were shifted forward in time but unchanged in shape.

CONCLUSIONS

Regression analysis detected no change in lag time on the South Fork watershed after road construction alone. The area compacted by the road system totaled only five percent of the watershed area, and disturbance to the hydrologic regime evidently was not severe enough to alter the hydrograph lag time. No deleterious effects on the watershed as caused by road construction were indicated.

Statistical analysis showed that the lag time increased for small storms and decreased for large storms after logging, and that these changes did not occur exclusively in either the rising or falling limb of the hydrograph. Multiple regression analysis indicated that the two most important variables among those screened were PROPLOG, the proportion of area logged, and LOGSEQ, the ratio of PROPLOG over the storm sequence number within a hydrologic year.

For small storms, an increase in lag time after logging was detected. Coupled with an increase in peak flows as reported by Ziemer (1981), an increase in runoff volume was indicated. However, these storms are of minor hydrologic significance because of their relatively small size. No degradation of the watershed would be expected to be caused as a result of these changes.

For larger storms, the hydrograph appeared to have been shifted to a shorter response time but without a significant change in configuration. This change was merely one of timing of flow; no impact on sediment transport or channel stability would occur from the change in lag time. Therefore, no degradation of the hydrologic regime of the South Fork watershed was implied as the result of changes in lag time after logging.

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Appendix A. Lag Times of the North and South Fork Caspar Creek Watersheds for Selected Storms During Hydrologic Years 1963-1981.

	Lag Time (hours)					
Storm	Hydrograph		Rising Limb[b]		Falling Limb[b]	
Number[a]	NF	SF	NF	SF	NF	SF
6302	14.77	13.33	04.54	04.83	18.33	16.94
6303	14.10	11.85	03.30	03.16	18.09	15.77
6304	18.73	14.70	07.82	04.57	23.97	17.29
6305	26.68	23.53	19.02	15.70	34.48	29.71
6307	23.42	20.07	10.69	03.88	31.35	23.07
6308	15.47	13.07	03.08	01.59	34.88	31.22
6404	06.50	05.88	01.86	01.47	07.83	06.91
6405	11.05	11.27	03.81	03.45	13.43	13.61
6406	14.08	11.22	03.07	02.58	17.16	13.75
6407	20.12	18.35	10.23	08.39	26.64	23.14
6408	21.40	16.48	08.10	06.22	26.44	20.34
6502	06.28	07.18	01.84	01.25	08.06	08.07
6503	13.17	11.73	03.12	03.54	17.01	16.43
6504	19.23	18.63	10.18	09.14	26.91	23.45
6505	17.70	14.73	00.00	00.00	24.45	21.41
6506	16.73	13.23	00.00	00.00	22.06	19.24
6510	25.20	22.98	15.01	10.62	33.92	28.19
6603	16.18	15.32	05.32	04.10	19.29	18.35
6604	14.03	11.62	02.92	01.87	23.74	20.88
6608	23.88	18.92	09.27	08.57	30.39	25.96
6702	10.75	09.98	03.63	02.33	13.65	11.79
6710	06.90	04.87	01.75	00.00	10.51	08.34
6703	12.82	08.40	01.87	01.20	15.44	10.92
6711	15.60	12.57	06.92	04.66	21.57	17.65
6704	27.85	21.88	13.57	10.92	36.41	32.66
6706	22.00	18.88	08.25	08.41	26.93	23.79
6707	23.92	19.67	13.67	08.73	31.54	24.41
6708	26.82	19.43	10.77	07.47	37.26	32.29
6709	26.53	22.05	11.56	09.42	34.15	28.93
6803	10.17	08.12	-	-	-	-
6806	15.68	13.25	-	-	-	-
6807	18.48	14.55	-	-	-	-
6810	17.23	09.88	-	-	-	-
6808	21.70	14.30	-	-	-	-
6809	21.25	16.55	-	-	-	-
6904	11.15	07.78	-	-	-	-
6905	22.08	16.93	-	-	-	-
6906	22.93	17.20	-	-	-	-
6907	17.62	12.47	-	-	-	-
6911	18.28	16.33	-	-	-	-
6912	14.58	11.60	-	-	-	-

Appendix A. Lag Times of the North and South Fork Caspar Creek Watersheds for Selected Storms During Hydrologic Years 1963-1981. (continued)

Storm Number[a]	Lag Time (hours)					
	Hydrograph		Rising Limb[b]		Falling Limb[b]	
	NF	SF	NF	SF	NF	SF
6909	19.37	16.08	-	-	-	-
7002	16.23	12.18	-	-	-	-
7003	09.93	09.15	-	-	-	-
T004	16.85	12.55	-	-	-	-
T009	09.93	08.13	-	-	-	-
T005	18.45	14.80	-	-	-	-
T006	14.58	12.23	-	-	-	-
7007	17.22	13.32	-	-	-	-
7109	14.25	12.87	-	-	-	-
7112	11.63	09.28	-	-	-	-
7110	18.20	16.55	-	-	-	-
7105	29.47	21.90	-	-	-	-
7111	15.73	13.27	-	-	-	-
7106	15.90	11.98	-	-	-	-
7107	14.50	10.80	-	-	-	-
7204	09.73	09.72	02.87	02.20	12.02	11.67
7201	15.57	12.45	03.66	02.55	18.94	15.24
7202	16.28	12.88	08.10	05.28	24.49	20.00
7203	17.57	13.13	09.77	06.52	23.20	17.02
7305	11.92	11.80	05.17	05.70	14.06	15.41
7306	12.40	11.42	04.41	04.90	15.08	14.51
7307	15.28	12.33	01.86	01.33	19.88	16.99
7311	14.25	09.40	06.31	00.00	24.99	12.84
7309	12.42	08.90	01.33	00.64	14.86	11.10
7310	14.28	09.52	00.00	00.00	16.27	11.66
7401	06.17	08.15	01.97	01.67	08.85	11.28
7411	04.78	04.63	00.16	00.00	05.42	05.31
7402	14.93	13.70	07.35	05.75	17.98	16.98
7409	12.60	07.37	00.22	00.00	14.95	09.66
7403	17.23	11.20	05.47	02.29	22.19	14.64
7410	24.85	16.67	07.32	03.14	34.29	29.26
7404	21.03	14.07	09.33	08.20	27.55	25.17
7405	17.60	10.87	06.83	00.71	24.43	13.20
7407	17.27	09.35	02.57	00.03	21.16	12.72
7408	24.70	16.42	11.23	02.98	32.04	20.89
7502	06.20	08.33	02.28	02.00	07.63	10.27
7503	19.37	18.98	11.68	09.63	26.77	24.22
7504	19.48	15.05	06.85	04.57	23.95	19.93
7510	14.45	11.48	07.61	04.38	19.26	14.15

Appendix A. Lag Times of the North and South Fork Caspar Creek Watersheds for Selected Storms During Hydrologic Years 1963-1981. (continued)

Storm Number[a]	Lag Time (hours)					
	Hydrograph		Rising Limb[b]		Falling Limb[b]	
	NF	SF	NF	SF	NF	SF
7506	16.47	11.32	01.05	00.00	18.71	13.86
7511	19.05	12.97	06.68	04.32	24.10	18.80
7513	18.45	13.18	00.62	00.16	22.20	17.21
7602	13.18	11.90	03.92	02.04	15.96	14.97
7603	19.22	14.37	11.44	04.29	27.98	18.27
7802	16.40	14.32	05.19	03.33	18.88	16.55
7804	14.65	08.58	04.10	01.35	17.96	09.66
7805	16.23	11.62	05.03	03.60	21.73	21.13
7807	18.15	11.52	07.02	01.27	24.68	13.10
7901	22.00	18.47	05.37	00.05	27.13	19.27
7902	15.08	12.22	04.95	00.65	22.64	14.80
7903	20.60	14.80	08.69	06.67	27.41	21.97
7904	19.03	12.00	07.92	03.71	25.68	15.33
8002	06.87	06.53	01.15	00.68	08.13	08.03
8003	13.48	11.02	03.68	01.86	17.36	14.12
8004	25.98	19.47	13.88	05.88	34.41	24.76
8006	27.38	20.03	01.40	00.00	30.41	24.43
8007	26.72	19.48	12.72	05.98	34.55	24.30
8101	14.40	12.13	00.86	00.20	16.38	14.55
8102	15.95	10.52	02.75	02.46	17.97	12.28

[a] First two digits signify hydrologic year. Second two digits signify identification number. Presented in chronological order.

[b] Calculated only for calibration and post-logging periods.