# Changes in Storm Hydrographs due to Clearcut Logging of Coastal Watersheds

By

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A THESIS

submitted to

Oregon State University

in partial fulfillment of

the requirements for the

degree of

Master of Science

June 1969

APPROVED:

Professor of Forest Management in charge of major

Head of Department of Forest Management

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Date thesis is presented: May 9, 1969

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# AN ABSTRACT OF THE THESIS OF

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(Name of student) (Degree)

In FOREST MANAGEMENT presented on May 9, 1969
(Major) (Date)

TITLE: CHANGES IN STORM HYDROGRAPHS DUE TO CLEARCUT LOGGING OF COASTAL WATERSHEDS

Abstract approved: ______________________
James T. Krygier

The purpose of this study was to determime the effect of clearcut logging on stormflow by analysis of characteristic parameters of individual storm hydrographs. Parameters considered included height-of-rise, peak discharge, volume and time-to-peak. The hydrologic data were derived from experimental watersheds of the Alsea Study located in the Oregon Coast Range.

Three clearcut watersheds were selected for study; Deer Creek IV (39 acres) was clearcut, and Needle Branch (175 acres) was clearcut and burned. Both watersheds were compared to Flynn Creek (502 acres), an untreated control, before and after treatment.

Change in hydrologic parameters was determined from differences between pre- and post-logging linear regressions. Statistical techniques were utilized to test for difference in slope or vertical position.

Significant increases were found in peak discharge from both Needle Branch and Deer Creek IV following clearcut logging. Larger increases were noted during the fall period than during the winter period. Volume parameters of quick flow, delayed flow, and total flow were increased for Needle Branch. Volume of flow was not shown to increase from Deer Creek IV. This may have been due to a lack of usable storm events for analysis from this watershed. Time-to-peak was not altered in Needle Branch but was decreased for low flows and increased for high flows on Deer Creek IV. The height-of-rise parameter did not prove to be of value for detecting change in this study. Comparison of the burned watershed (Needle Branch) to the unburned watershed (Deer Creek IV) did not produce a noticable difference in any of the parameters.

The observed changes in stormflow were related to clearcut logging and the effect of vegetative removal on watershed response.

# ACKNOWLEDGMENTS

Gratitude is expressed to the Water Resources Research Institute at Oregon State University for providing the financial aid necessary for this study.

My appreciation is extended to Professors James T. Krygier, George W. Brown III, and Peter C. Klingeman for their advice, guidance and assistance both during the research and during the preparation of this thesis.

Appreciation is extended to my fellow graduate students for their help and assistance, especially to Kenneth R. Holtje, Jr. for his assistance in design of the computer programs used in this study.

Deep appreciation is extended to my wife who not only provided assistance in the preparation of this thesis but more importantly provided the support and encouragement necessary for its completion.

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# CHANGES IN STORM HYDROGRAPHS DUE TO CLEARCUT LOGGING OF COASTAL WATERSHEDS

## INTRODUCTION

An understanding of the impact of existing logging practices on floods and water supply is vital to the development and management of both timber and water. This impact is especially important in the Northwest where large amounts of timber are removed from forested watersheds each year. Logging, a principal industry in Oregon, removes timber from approximately 600,000 acres of land annually. Forested lands are typically in areas of higher rainfall and the watersheds logged may constitute flood source areas. Therefore, effect of logging practices on floods may be of considerable importance -- a point not clarified in the literature.

Clearcut logging is a common practice in the region, being both silviculturally and economically desirable; hence evaluation of this type of operation should be emphasized. The potential for altering the pattern and volume of runoff from a watershed by clearcutting is quite high. Evapotranspiration from trees is temporarily eliminated and surface soil conditions may be changed by the logging operation. Thus, the effect of clearcutting has implications for both water supply augmentation and structural design criteria. These same flow parameters may alter fish habitat and the magnitude of sediment transport. The effect of clearcutting on storm hydrograph characteristics has not been satisfactorily determined. For these reasons a study of the impact of clearcut logging on individual hydrograph parameters should lend insight into changes of hydrologic significance.

The experimental watersheds of the Alsea Study in the coast range provided a basis for determining possible changes on individual hydrograph factors.

## Objectives

The primary objective of this research is to determine the effect of clearcut logging on individual runoff events from two watersheds in Oregon's Coast Range. Detection of change is sought by examining several parameters defining principal components of storm hydrographs. Parameters considered are peak discharge, height-of-rise, storm volume, and time-to-peak.

Secondary objectives are to:

1. Explain any hydrologic changes in terms of possible physical processes involved.

2. Evaluate the method used to determine its

ability to detect hydrologic changes.

## Scope

Concern about the possible influence of logging on aquatic resources in the state of Oregon led to the initiation of the Alsea Watershed Study in 1958. The present study was formulated to evaluate hydrologic data being collected on a number of experimental watersheds. As illustrated in Figure 1, the experimental watersheds are within the Alsea Basin of the Oregon Coast Range, about 12 miles south of Toledo, Oregon, and approximately 10 miles from the Pacific Ocean.

The Alsea Watershed Study includes a number of gaged watersheds. The stream gages at the outlet of the three major watersheds were installed in 1958 by Oregon State University in cooperation with the U. S. Geological Survey and have been in continuous operation. Deer Creek, one of the major watersheds, was subidivided in 1964 by Oregon State University to gain a more precise evaluation of the effect of logging on stream hydrology.

Two of these watersheds were selected for a complete clearcut treatment: Deer Creek IV (39 acres), a subdrainage of the Deer Creek basin delineated in Figure 1, is the smaller of the two treated watersheds and Needle Branch (175 acres) is the larger. The watershed

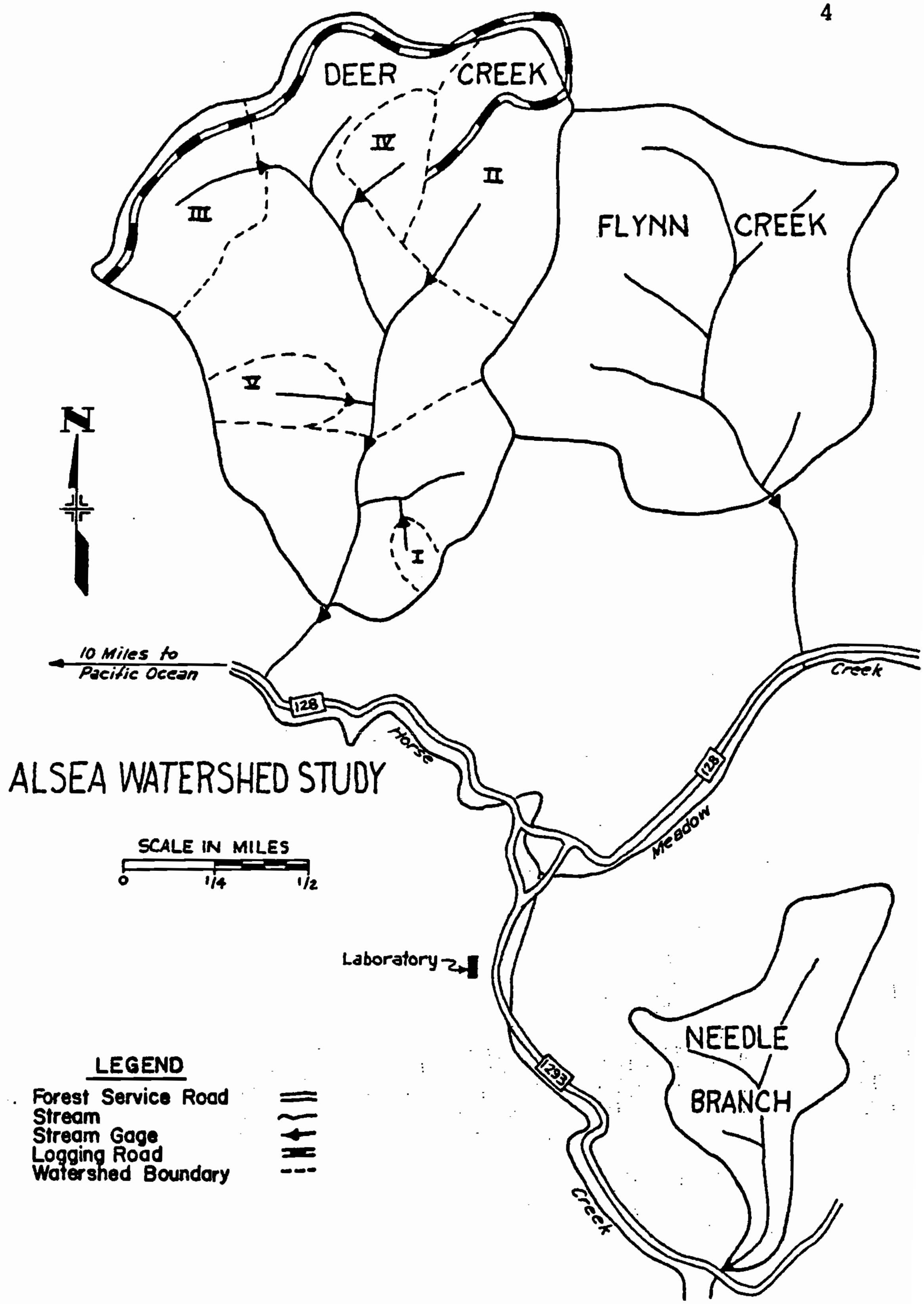

Figure 1. Planimetric map of watersheds in the Alsea Watershed study.

used as a 'control' is Flynn Creek (502 acres).

The effect of logging practices on streamflow is evaluated by considering individual hydrograph parameters as obtained from individual storm events. This study has been restricted to the effect of logging on streamflow parameters which should yield insight into the hydrologic changes that occurred on the streams under study.

# DESCRIPTION OF FLYNN CREEK, DEER CREEK IV, AND NEEDLE BRANCH

The experimental watersheds are within the Alsea Basin of the Oregon Coast Range. Needle Branch, Deer Creek, and Flynn Creek, the three streams included in this study are tributary to Drift Creek, a stream which enters Alsea Bay near Waldport.

## Climate

These watersheds are subjected to a marine climate, typical of the Oregon coastal regions. This type of climate produces cool wet winters and warm dry summers. Rainfall is the principal precipitation type with at least 90 per cent occurring during the winter months of October through May. Snow is uncommon. Average annual precipitation from 1959 to 1968 for the area is 95 inches. Storm intensities are low and aerial extent is generally quite wide, especially during the winter period. This type of climate is the result of a large number of frontal systems moving in from the Pacific Ocean, especially during the winter period.

Temperatures are generally mild with approximate monthly averages of 35° F during the colder winter months and 50° F during the summer months. During the winter period average daily maximum is 45° F and average daily minimum is 30° F. For the summer period average maximum and minimum is 75° F and 45° F respectively.

## Soils and Geology

Soils were developed from the Tyee formation, a formation consisting of arkosic sandstone and siltstone. Both of these rock types are sedimentary rocks having an estuarine and marine origin. The two dominant soil types resulting from these rock types and making up the soil complex for the study watersheds are: Bohannon and Slickrock. These two types are generally found in association, with Bohannon on the steeper slopes and Slickrock on the more moderate slopes (U. S. Soil Conservation Service, 1964).

Slickrock makes up 75 to 80 per cent of the soils on Flynn Creek. Needle Branch is primarily Bohannon with 65 to 75 per cent of the area occupied by this soil type. Ninety per cent of Deer Creek IV is made up of the Bohannon soil type. Bohannon soils are well-drained, medium-textured, shallow, gravelly and stony, and are found on moderate to steep slopes. The A and B horizons are typically 11 and 13 inches thick respectively, and total soil depth to bedrock is about 24 inches. Percolation rate is moderately rapid and storage capacity is low.

Slickrock soils occupy gentle undulating slopes, and are moderately well-drained, deep, moderately gravelly and cobbly, and are moderately fine textured. The A and B horizons are often seven inches and 40 inches respectively with a total soil depth near 55 inches. Percolation rate is moderately rapid and water storage capacity is high.

## Topography

Relative shape of each of the three watersheds may be noted by reference to Figure 1. Deer Creek IV and Flynn Creek are essentially circular while Needle Branch is elongate in shape. Average slope on Needle Branch, Flynn Creek, and Deer Creek IV is 37 per cent, 34 per cent and 30 per cent respectively. Valleys on Needle Branch are narrow and steep sided with some slopes approaching 70 per cent. Hillsides are less steep on Flynn Creek and Deer Creek with a large portion of the area between 35 and 40 per cent.

Stream pattern is dendritic for each watershed, with the major streams of Needle Branch and Flynn Creek flowing in a southerly direction. Deer Creek IV, however, flows in a westerly direction.

Drainage density for Needle Branch is 5.26 miles of stream channel per square mile of area, Flynn Creek, 3.03 miles per square mile, and Deer Creek IV, 3.07 miles per square mile. Channel length was obtained from maps prepared from aerial photographs by P. E. Black for the Forest Management Department. These maps included ephemeral portions of many stream channels and therefore the drainage figures given do not necessarily reflect the length of perennial channel. If only perennial stream length is used, the drainage density for Needle Branch, where the upper portion of both channels become dry during the summer period, would be much lower than shown above. Drainage density for Deer Creek IV, where the channel becomes completely dry for its entire length, would be zero. The length of channel used on Flynn Creek is probably near the length of perennial channel.

## Vegetation

In the pre-logging condition, overstory vegetation approached 90 per cent for the whole study area. The overstory consisted principally of varying combinations of two species; Douglas-fir and red alder. Douglas-fir stands were approximately 120 year old second growth timber and the stands of alder were uneven aged. Thirty per cent of Deer Creek IV was covered by pure stands of alder and the remainder of the watershed was covered by mixed stands of Douglas-fir and alder. Flynn Creek is covered by similar vegetation to that found on Deer Creek IV prior to logging. Thirty-nine per cent of the area is covered by pure stands of alder and the remainder is covered by mixed stands of alder and Douglas-fir. Needle Branch had two per cent of the area in pure stands of alder, and 76 per cent in pure stands of Douglas-fir. The remainder was covered by mixed stands of both species.

The understory, prior to treatment on all watersheds, consisted of communities dominated by species of vinemaple, sword fern, and salmonberry. These three species, in varying proportions, make up the understory over the whole area.

Following treatment in 1966, the deep rooted vegetation on Needle Branch and Deer Creek IV was removed and the area was almost devoid of vegetation. In time the cleared watershed was revegetated by shallow rooted species including Senecio and other forbs, grasses, and shrubs. Rooting depth of these species will increase and they will again be replaced by trees.

# LITERATURE REVIEW

Water yield studies under almost all environmental conditions have indicated that vegetative manipulation will result in alteration of streamflow response. Hibbert (1967) reported results of 39 studies dealing with effect of forest cover alteration on annual water yield. He concluded that these studies, when taken collectively, indicate that forest reduction increases water yield and reforestation decreases water yield. He found results of individual treatments to vary widely and for the most part they were not simply predictable from the treatments applied to watersheds.

The effect on individual hydrograph parameters in most water yield studies has not been considered. It is these parameters, such as peak discharge, time-to-peak, and volume which allow determination of actual change in the hydrology of a stream. However, water yield studies do give an indication as to effect of vegetative removal on yearly quantity of flow, which in turn yields information as to direction of response which might be expected of individual storm parameters.

## Clearcut Logging and Water Yield

The largest increases of water yield resulting from forest removal have been found in humid climates. This includes studies located at Coweeta, North Carolina, Fernow, West Virginia, H. J. Andrews Experimental Forest in Oregon, and Kenya, East Africa (Krygier, 1969). On Watershed 13 at Coweeta, Kovner (1956) found an increase of 46.7 per cent in yearly flow the first year following treatment. The mixed hardwood on this watershed was clearcut in 1940 and the vegetation was allowed to return. The increase in flow declined in succeeding years to 25.7 per cent in 1944, the fifth year following treatment. In 1962 the treatment was repeated producing a 46.8 per cent increase, a result very similar to the response in 1940 (Hibbert, 1967).

Watershed 17 at Coweeta was clearcut in 1941 and the regrowth cut back annually. Hoover (1944) found an increase in annual water yield of 52 per cent the first year following treatment. He was able to show that the largest increases occurred in the late summer and fall, during periods of low flow. He concluded that this response could be the result of reduced drain on soil moisture, produced by reduced transpiration on the clearcut watershed. Hoover indicates that because of this lower drain on soil moisture, the precipitation occurring during the summer and fall periods result in runoff rather than going to satisfy depleted storage. This effect was found to decrease with time as the vegetation grew back.

A similar study was conducted at the Fernow Experimental Forest in West Virginia. One watershed was clearcut and four others were subjected to various percentages of total watershed area treated. Forest cutting was found to produce an increase in streamflow, the increase generally in proportion to the severity of cutting (Reinhart, Eschner and Trimble, 1963). Most of the increase came during the May to October period. Reinhart states that the July to September increases could be explained by a decrease in transpiration during these months. The October increase can also be explained by a decrease in transpiration during the July to September months. Transpiration was reduced during the growing season thus resulting in the requirement of less water to replace depleted storage. Increases in streamflow due to decreased summer transpiration often occurred in November and sometimes in December. The study indicates a large positive effect on low flows with the more heavily cut watersheds producing the greater effect. Presumably this was the result of reduced transpiration and the resulting reduction of soil moisture depletion, thus contributing more water to low flow.

At the H. J. Andrews Experimental Forest in Oregon, Rothacher (1965) reported an increase of 12 to 28 per cent in low flows from a clearcut watershed. Low flows in this area occur during the summer growing season. With respect to the low flow increases, Rothacher states that the removal of vegetation and the subsequent decrease in transpiration should produce higher soil moisture levels. More water would be available during these months, thus increasing summer low flows.

Following clearing of bamboo over 34 per cent of a watershed in Kenya, East Africa, Pereira (1962) found an increase in streamflow of 80 per cent. The area was cleared for a tea plantation and therefore only one year of record following treatment was available.

Several studies have been conducted in the dryer climates and the snow influenced climates of the western United States. They are not as directly related to the present study as are the studies given previously for moist areas. However, they are of importance in showing trends that might be expected when timber is removed from a watershed.

Forest cover was removed and replaced by grass on the Workman Creek Watershed near Globe, Arizona, producing an increase in annual yield (Rich, 1960; Rich and

Reynolds, 1961). Approximately 46 per cent of the merchantable timber was removed on the treated watershed. The first year indicated a small positive change. However, the change was not as large as would be expected considering the results of previous studies. The second year following treatment an increase of almost 50 per cent was indicated. The results of this study are inconclusive and as was noted by Rich, the two years of available record is not really sufficient to determine if a change did or did not occur. However, the largest change should be noted in the first year following treatment, due primarily to vegetative regrowth that tends to reduce increases in water yield with succeeding years.

Following removal of chaparral from the 3-Bar watersheds in Arizona by wild fire, an increase in total runoff was experienced (Glendening, 1959). These watersheds were established for the purpose of applying and evaluating various management techniques. After only three years of calibration, however, a wild fire burned over the area and the experiment had to be redesigned. During the year following the fire, an increase in total yield from nine per cent to 38 per cent was observed. These data represent only three years of calibration, as mentioned above, and includes only one year of post-treatment data. Even under these conditions it appears that an increase was experienced.

Numerous experiments in forest hydrology have been conducted in the snow influenced climates of the western states. The earliest study was conducted at Wagon Wheel Gap in Colorado (Bates and Henry, 1928). Bates found an increase in water yield of almost 22 per cent the first year following treatment. The greater part of the increase occurred during the spring freshet following snow melt. Bates suggested that the increased flow was a result of the effect of forest removal on the winter snow accumulation. He states that "there is no evidence in this study that the summer demand for moisture was appreciably affected by the removal of the forest cover" and that drying of the soil was the same for both forest and herbaceous cover. However it seems probable that reduced transpiration should result in less drain on storage during summer months, thus making more water available both to the spring peak and to low flow later in the growing season.

At Fraser, Colorado, a study area affected by similar climatic conditions, Goodell (1958) and Martinelli (1964) found an increase of 30 per cent following application of a treatment which clearcut in strips 40 per cent of the watershed area. Love and

Goodell (1960) and Wilm and Dunford (1948) attempted to determine effects of timber harvest on snow accumulation and yield. Love states that although the accumulation of snow was greater on the clearcut plots, the snow disappeared just as rapidly from the uncut plot. This would indicate increased snow melt rate and increased volume for streamflow.

Following an attack of Englemann spruce beetle, an increase of 15 per cent was indicated when flows from the White River watershed above Meeker, Colorado, were averaged over a five year period. The attack of Englemann Spruce Beetle reduced the forest stand by 80 per cent, on 30 per cent of the area (Love, 1955). The White River watershed is similar to the Fraser Experimental Forest in soil type, precipitation amount and distribution, elevation, and in vegetative type. No analysis was given for the seasonal distribution of runoff. Due to precipitation occurring primarily as snow, it would be logical to assume that the increase was during the spring snow melt period. Reduced interception and transpiration are given as the reasons for observed streamflow increase.

Many studies have been conducted to determine the effect of reforestation, afforestation, or stand improvement on water yield. Notable examples include Pine Tree

Branch in western Tennessee (Tennessee Valley Authority, 1955), White Hollow in eastern Tennessee (Tennessee Valley Authority, 1961), Central New York study (Schneider and Ayer, 1961), and Coshocton in Ohio (Harrold et al, 1962). As might be expected, the change following treatment was in the opposite direction as that experienced on areas that were logged; i.e., annual water yield was reduced. An exception is White Hollow where no effect on total water yield was noted (Rothacher, 1953).

All the preceding studies indicate that an increase in quantity might be expected following logging. However in many of the studies no indication was given as to how the increase was distributed in time, or how individual hydrographs were effected. Hypotheses with respect to change in hydrograph parameters, such as peak discharge, time-to-peak, volume, and height-of-rise, must largely be formulated from theoretical considerations. An exception is peak discharge. Some indication of change is found in the literature.

## Clearcut Logging and Hydrograph Parameters

Vegetation plays an important role in the hydrologic cycle by preventing water from reaching the soil, by removing water stored in the soil profile, and by affecting the rate of travel over and through the soil. Therefore, physical and vegetative factors which might cause changes in individual hydrograph parameters include interception, evapotranspiration, and infiltration.

## Evapotranspiration

Interception loss is a part of evapotranspiration and is made up of storage capacity and water evaporated from storage during the storm (Leonard, 1967). Thus it is an abstraction from storm yield. After storage capacity is satisfied, interception is dependent only on evaporation rate, and for increasing storm duration interception becomes a decreasing percentage of total rainfall. Interception may account for a large percentage of the total precipitation during low-intensity, short-duration events, but may be a small percentage during long-duration storms. Interception storage for rainfall has been found to range in magnitude from 0.01 to 0.36 inches, with an average of 0.05 inches for most grasses, shrubs and trees (Zinke, 1967).

Rainfall interception for Douglas-fir has been found to range from 19 to 100 per cent depending on storm size. Rothacher (1963) found a storm of 0 to 0.5 inches to intercept 100 per cent while a storm 1.5

to 2.0 inches intercepted 19 per cent of incoming rainfall.

Transpiration is probably the more significant aspect of well-stocked vegetative communities with respect to influence on individual hydrograph parameters. This mechanism of a plant system extracts water from soil at depths below that affected by surface evaporation, and releases it to the atmosphere through the stomates. In a study to determine effect of trees on soil moisture removal, Ziemer (1964) found that forested areas lost water more rapidly than adjacent areas cleared of trees. The rate of moisture loss was greater in early summer and then decreased as water became limiting. Maximum depletion occurred in early September with nearly all available moisture removed from the forest. The openings, however, still maintained soil moisture levels considerably above those found in the forest.

It has been shown that evaporation from bare soil extracts water from relatively shallow depths, four inches for clays and about eight inches for sands (Veihmeyer, 1964). Therefore, water loss from a vegetated site will generally be much greater than from a bare soil. Even if potential evapotranspiration is the same for all vegetative types, as has been suggested (Penman, 1963), the actual water use for a site will be dependent on rooting depth and available moisture when water becomes limiting. Potential evapotranspiration is defined as that amount of water lost by a plant when water is continuously supplied to the root system (Penman, 1963). In nature the soil surrounding the root system is seldom held at saturation. Following a rainfall event the ground is saturated only until drainage through the profile is completed. Potential evapotranspiration is a process that occurs for a period following recharge until water becomes limiting in the root zone. Because a deep rooted species extracts water from a greater depth, it will remove more water under limiting conditions than a shallow rooted species. This would lend support to the hypothesis that removal of a forest and replacement with a shallower rooted species will result in an increased quantity of water available for streamflow.

## Infiltration and Soil Water Movement

Logging may cause soil compaction which can lead to reduced infiltration and percolation. Overland flow will result when precipitation intensity is greater than the infiltration rate of the soil (Chow, 1964). When this situation occurs on a mountain watershed as a result of road building or logging, increased peak flows and storm volumes may be expected.

On forested watersheds however, there is evidence that when the forest floor is in its natural state, or when logged with little or no disturbance to the forest floor, infiltration is not reduced (Dils, 1957; Rothacher, 1965). The lack of overland flow suggests that quick flow is a result of subsurface flow (Whipkey, 1965; Hewlett and Hibbert, 1967). The rapid response of a watershed to precipitation, when assuming no overland flow, may be explained by the variable source concept presented by Hewlett and Hibbert (1967). As rainfall continues, the "saturated" area is extended further up the watershed. Due to these saturated zones, or zones that are above field capacity, water is contributed to the stream channel by a pulse action. The outflow to the stream is from pressure displacement, rather than from percolation.

A temporary water table may also develop at a less permeable layer, or along the wetting front in a dry soil, permitting water to flow from a watershed prior to saturation (Whipkey, 1965).

## Evidence of Change from Watershed Studies

Changes in individual hydrograph parameters may be a result of reduced infiltration and interception.

However, a major factor appears to be the reduction in transpiration with the resulting reduction in soil moisture depletion.

The increase in amount of water in storage due to reduced evapotranspiration following forest removal will alter timing and magnitude of peak flow as well as quantity of flow. This is substantiated by Reinhart (1963) at Fernow, West Virginia. He found peak discharge increased 21 per cent during the growing season following a clearcutting operation. It was felt that increases were a direct result of reduced evapotranspiration. Less water was required to replenish that removed by vegetation following logging, making more available for streamflow.

Two studies in Japan indicated increases in peak discharge following logging. Maruyama (1952) found average instantaneous peaks increased more than 20 per cent following clearcutting. Nakano (1967) found an increase in peak flow of 69 to 114 per cent following logging. He states that the cause might be that vegetation removal reduced transpiration on the watersheds.

When snow melt was a significant factor, peaks were increased following logging; however, this increase occurred primarily during the spring freshet. Snow is the predominant form of precipitation in many western watersheds. Any increase in peak flow or yield must be attributed to reduced interception, decreased transpiration especially during the growing season, and also changes in deposition of snow and shading affects.

The experiments at Wagon Wheel Gap (Bates and Henry, 1928) and Fraser, Colorado (Goodell, 1958) both indicate increased peak flow in the spring following logging. At Fraser, Goodell found the rise during the spring freshet more rapid than formally and the spring peak higher. Peak flows were similarly increased on the White River experiment where the timber was killed by the Englemann Spruce Beetle.

After considering both reforestation and forest removal it must be concluded, as did Hewlett and Hibbert (1961), that in most well-watered lands, conversion of mature forest to low-growing vegetation will increase streamflow. Reinhart et al (1963) further stated that the results are more pronounced in areas of abundant moisture such as Coweeta, Fernow, and Kamabuti, while areas of low precipitaiton will show less response, such as Wagon Wheel Gap and Workman Creek.

The timing of increases depends on form and amount of precipitation. When the precipitation comes mostly in the form of winter snow the increases will most likely occur during the spring freshet or snow melt period. This could be a response to changing snow accumulation and melt conditions or could be attributed to lower water use during the growing season. This would result in a lower recharge requirement before runoff could result. Observed increases, in most cases, are probably due to a combination of both conditions. Summer, or growing season, increases would not be expected except where rainfall is sufficient to replace the small amount of soil moisture depleted by evapotranspiration due to the shallow rooted vegetation. Sustained flow, or low flow has been shown to increase on the H. J. Andrews Experimental Forest following logging as a result of less water use (Rothacher, 1965).

There has been a fairly large accumulation of information regarding the response of a watershed to treatment but it remains doubtful that this information can be transposed to other watersheds. As Hewlett and Hibbert (1961) states, it will not be possible to predict the response of a watershed to a particular treatment until we can identify and isolate the parameters which contribute to that change.

## Hydrograph Separation

In a study such as this one, where the expressed purpose is not only to determine change but to explain why this change occurred, it is essential to estimate the source of flow. The sources of flow consist of precipitation directly on the surface of the contributing waters, surface runoff, subsurface flow, and ground water flow (Wisler and Brater, 1959). Thus with a knowledge of the change and a knowledge of the source of that change it is possible to describe cause and effect relations. Unfortunately it is difficult in a real situation to divide a hydrograph into its component parts of surface, subsurface and ground water flow or into direct runoff and base flow. Therefore, any method of separation must be based on arbitrary decisions as to rates or amounts of flow to be included in each catagory.

Three methods (Chow, 1964) are traditionally used to separate direct runoff (surface and subsurface) from base (ground water) flow. In each method, flood flow is terminated at that point where the base flow line intersects the recession of the hydrograph (Figure 2). The area above the separation lines is considered direct runoff or flood flow and that area below the line is considered base flow. The time when direct recession ceases may be estimated by relationships such as:

$$N = A^{0.2}$$

where A is drainage area in square miles, and N is the number of days after the peak when direct runoff ceases. The value of N should remain relatively constant from storm to storm, as would be the case when using the above formula, but N determined in this manner may yield unrealistic results. It may be better to determine N by visual inspection of a number of storms, keeping in mind that the total time base should not be excessively long or the rise of ground water too great, as suggested by Linsley, Kohler and Paulhus (1958).

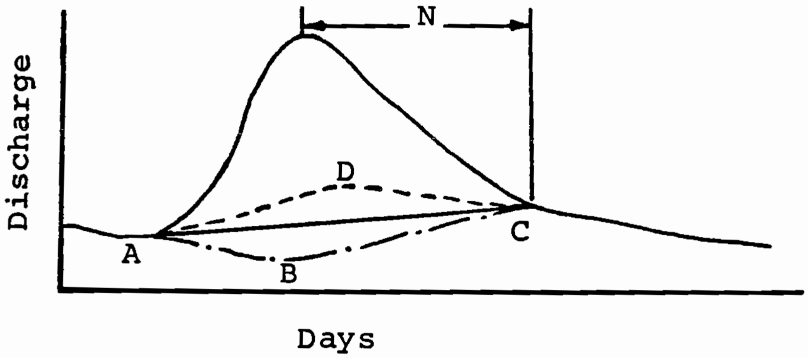

Figure 2. Method of hydrograph separation

The first method consists of extending the recession existing before the storm under the hydrograph to a point directly under the peak. From this point a straight line is drawn to a point on the recession curve such as N days after the peak. This is represented by the line ABC in Figure 2.

Support is given this method by considering that flow should be into the bank as long as the stream is rising and base flow should therefore decrease until the peak passes. There is no real reason, however, that the decrease in base flow should conform to the original recession (Linsley et al, 1958).

A second method uses a straight line from the point of initial rise to a point N days after the peak. This is illustrated by the line AC in Figure 2.

The above methods do not differ appreciably in volume of direct runoff. The difference is probably unimportant as long as one method is used consistently.

The third method involves projection of the ground water recession back under the hydrograph to a point below the "point of inflection" of the recession. The "point of inflection" is defined as that point on the recession where the change in slope is zero, i.e. where

$$\frac{d^2q}{dt^2} = 0$$

An arbitrary curve is then drawn to the point of rise. This method, as illustrated by line ADC in Figure 2, would probably be used in an area where ground water reached the stream rather quickly.

Another method has been proposed by Hewlett and

Hibbert (1967) and by Hibbert and Cunningham (1967). This method is an application of the straight line method given earlier, but has some distinct advantages. Hydrograph separation as described above has been developed with the idea that direct flow exists for a period of time during the storm event, and that this flow can be separated on the hydrograph.

In reality it is almost impossible to separate direct flow from base flow on a physical basis. It is necessary, however, for purposes of hydrograph analysis to separate flow that runs quickly from a watershed from that which is delayed, or is well controlled. As pointed out by Hewlett and Hibbert (1967), the problem with elaborate separation methods is that an arbitrary classification for rate of flow is added to an arbitrary classification for source of flow. A decision is made as to what rates are considered storm flows and these rates are arbitrarily divided into direct runoff and base flow. Because the decision is arbitrary in any case, it would seem logical to base the separation on one arbitrary decision rather than two and base the classification on a fixed, universal method applicable to all hydrographs on small watersheds.

Based on the above ideas, Hewlett suggests a line of constant slope that could be readily adapted to a computer system. After analysis of about 200 water-years of record, collected on 15 small forested watersheds in the Applachian-Piedmont region, he decided on a line projected from the initial rise, at a slope of 0.05 cubic feet per second per square mile (csm) per hour, until it intersected the falling limb of the hydrograph. Hewlett refers to the flow thus divided as "quick flow" and "delayed flow" (Figure 3). The controversial idea of source referred to in methods presented earlier is thus avoided.

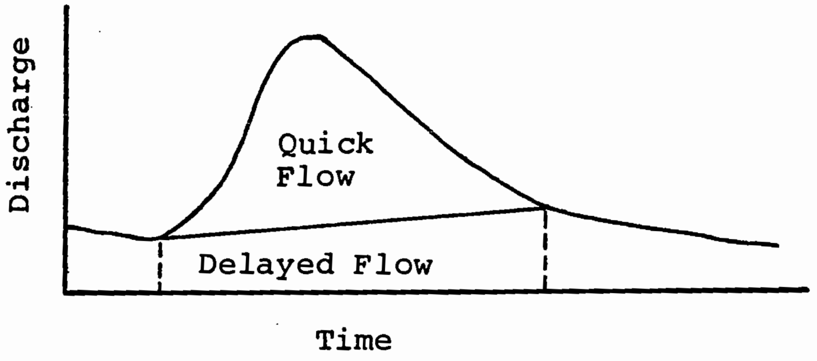

Figure 3. Quick flow-delayed flow hydrograph separation

This method would also have the advantage of removing personal bias from the separation procedure. Rather than being subject to personal judgment on every storm, each hydrograph separation would be conducted in exactly the same way, thus making the statistical comparisons before and after treatment much more uniform.

## Methods to Detect Change

A common denominator running through past studies is the use of average annual flow for comparisons to detect change (Kovner, 1956; Hoover, 1944; Reinhart, et al, 1963). A comparison utilizing regression analysis for annual flow does not give the actual flow to be expected at some point in time but rather an expected yearly total as related to the control watershed.

Comparisons using individual storm events could be used instead, producing several distinct advantages. By study of individual hydrograph parameters it is possible to gain insight as to actual change of the streamflow hydrology, and it is possible to hypothesize where and why this change occurred. Important parameters such as time-to-peak, peak discharge, and storm volume cannot be determined in an annual yield study. However these are major parameters which show actual change in the flow regime.

A further advantage is a decrease in the time required for detection of a change. In statistics, the greater the number of points, the greater the reliability of the relationship established. With this in mind, it is readily apparent that if a comparison of individual storm events, rather than annual values is used, enough points may be obtained in only a few years to make statistically significant comparisons between two watersheds. Wilm (1949) developed a method for determining the length of watershed calibration. Kovner and Evans (1954) developed a relation for determining duration for watershed experiments using this method. These methods indicate that a sufficient number of observations can be obtained in one or two years by utilizing individual storm events.

Bethlahmy (1963) developed a method of rapid calibration of watersheds utilizing this idea. An important advantage to the shorter time interval is the increased probability that an experiment will proceed to completion without disruption from unforseen catastrophies. Bethlahmy compared the change in stage in the rising limb and the elapsed time for the period of rise. An important reason for using the rising limb is because discrete values are involved. This eliminates the need for additional computations that might lead to additional error. The method consists of four steps:

1. Tabulation of the rise-in-stage and time-to-peak of both control and treated watersheds.
2. Computation of a regression line for the pre-treatment years.
3. Computation of a regression line for the post-

treatment years.

4. Comparison of the two regression lines in magnitude and slope.

Gilleran (1968) applied this method to determine the effects of road building on small coastal streams. He was able to show statistically significant change with only 2.5 years of calibration and only one year of data following treatment.

## Low Flow Analysis

Three methods of recession analysis are presented by Linsley et al (1958). The first method uses a semi-logarithmic plot of the recession or depletion curve to determine values of Kr where Kr is a characteristic slope constant. Using graphical methods, the ground water recession is projected back under the hydrograph. Again using graphical techniques the interflow and surface runoff recessions are determined, and from these the values of Kr are determined. This method represents a degree of refinement rarely necessary for engineering problems but which may be needed to detect the effect of minor treatments.

Two other methods given by Linsley et al involve the development of base-flow recession curves. One method pieces together sections of recession from various storms until a composite curve is obtained. The second method for developing the curve is to plot values of $q_o$ against $q_t$ some fixed time t later. The plotted data should form a straight line on logarithmic paper if the relation $q_t = q_o Kr^t$ is strictly correct, but generally a gradual change in Kr results. Lines could be developed in this manner for both the pre- and post-treatment periods and comparisons made to determine effect of treatment. The technique does not compare treated and control watersheds but rather the pre-treatment and post-treatment periods are compared on the same watershed.

A method valuable in demonstrating the change in peak discharge and recession flow is the use of flow duration curves. Again a comparison is established between the treated watershed and the control. These curves could produce a meaningful estimate of the amount of flow that could be expected a given percentage of time. If extended to a long term flow duration curve a good estimate of yearly mean, both before and after treatment could be obtained. Also use of double mass analysis has been found useful in describing percentage change in flow (Chow, 1964). A prerequisite to these two methods is a continuous record over all ranges of flow.

A method showing change in individual hydrograph parameters would be of as much value as a comparison of yearly flows in showing effects of watershed treatments. Regression analysis of yearly flows indicate relative change of average flows, but analysis of individual storm events has the added advantage of demonstrating actual changes in hydrograph shape. Either method will give the same trends but study of individual parameters yields the added advantage of producing insight to causes by defining changes in hydrograph shape.

# DESIGN OF EXPERIMENT

## Treatments

Following a calibration period of approximately two years (January 1964 through March 1966) on Deer Creek IV and a calibration period of eight years (October 1958 through March 1966) on Needle Branch, both watersheds were subjected to a clearcut logging operation. Needle Branch,but not Deer Creek IV, was burned following timber removal in 1966. The calibration period provided a period of time when both watersheds to be treated were compared to Flynn Creek, the control watershed. This provided the pre-logging relation necessary in a paired watershed analysis to determine effect of treatment. During the spring of 1965, one year prior to logging, roads were constructed along watershed boundaries on both Needle Branch and Deer Creek IV.

Needle Branch, with a longer period of record and a watershed area more nearly equal in size to the control was selected as the principal study watershed. The effects of clearcutting the smaller Deer Creek IV watershed were used for supplementing the results obtained on Needle Branch.

## Instrumentation

The gaging station on Deer Creek IV has a Belfort FW-1 (Belfort Instrument Co., n.d.) water level recorder and an H-type flume (U. S. Dept. of Agriculture, 1962) is used for the control section. The 2.0 foot deep H-type flume is designed to measure runoff from small watersheds where flow does not exceed 11 cubic feet per second. This is equivalent on this watershed to 180 csm. Measured values of discharge through the flume were found to differ slightly from theoretical values given by the U. S. Dept. of Agriculture (1962). Therefore a rating curve based on these measured values was constructed.

Instrumentation on Needle Branch includes both a Leupold and Stevens A-35 (Leupold and Stevens Instrument Company, n.d.) and a series 1540 Fisher and Porter (Fisher and Porter Company, n.d.) water level recorder. The control section consists of a v-notch weir with a rounded concrete surface and a stilling pond upstream of the weir. The control section was not constructed to any theoretical model and it was therefore necessary to develop the rating curve by measurement over the full range of stage. In order to adequately define the rating, measurements have been obtained monthly and during storm periods through the period of record by the U. S. Geological Survey. The rating has been adjusted when needed.

The gaging station on Flynn Creek is very similar to that given above for Needle Branch. The primary difference lies in the size and shape of the control section weir. The weir for Flynn Creek is larger and continues in a v-shape for the entire range in stage, while the higher stages on Needle Branch are controlled by a rectangular-shaped section.

# DATA ANALYSIS

## Definition of Parameters

In this study, each streamflow rise was considered an independent event. In order to determine hydrologic changes it was necessary to select parameters that would define the hydrograph shape as completely as possible. Recession, time-to-peak and height-of-rise were selected for this purpose. These three parameters were discrete values easily obtained directly from the time-stage record. Volume and peak discharge were two additional parameters selected to define shape. These parameters were not obtained directly but were computed using time-stage records and rating curves.

### Peak Discharge

Peak discharge defines the maximum flow attained during a given storm event. It may be converted from the time-stage trace using the appropriate rating curve. Peak discharge was selected both to help define hydrograph shape and because it has practical significance. Significance is related to its importance in design considerations for structures influenced by flood events.

## Height-Of-Rise

Height-of-rise indicates the fluctuation in elevation of the water surface from the beginning of the storm event until it reaches a peak. It does not include stage of base flow at initiation of the event nor is it dependent upon rating curves. Therefore this parameter eliminates antecedent flow conditions from the analysis of stream response to a particular storm event. In addition, it does not contain errors due to incorrect construction of the rating curve.

## Volume

Volume was selected to help define hydrograph shape and also to quantitatively define the effect of logging. For instance, an increase in peak discharge does not necessarily indicate an increase in quantity of flow for a given storm event. An increase in peak discharge could reflect faster runoff of the same quantity. By utilizing the volume parameter it is possible to quantify changes in watershed yield for a particular storm event, by comparison to a control watershed for a particular treatment.

### Time-To-Peak

The time-to-peak parameter is defined as the time required to reach a peak, starting with an initial time when the stream first responds to a storm event. This parameter gives an indication of possible changes in travel time due to watershed treatment. A shorter time interval from initial rise to the peak would indicate a reduction in detention storage and less resistance to flow. The increase in velocities that may result could produce channel changes by increased scour and filling.

### Recession

Three points were selected on the recession to define changes in storage flow following removal of vegetation. These points were located on the hydrograph 24, 48 and 72 hours after occurrance of the peak. This parameter gives an indication of change in the storage relation on the watershed and also helps define hydrograph shape.

## Selection of Events

The primary consideration for including the peak discharge of a particular storm event in the sample, was that the same streamflow rise could be detected on both control and treated watersheds. Hydrographs did not have to possess a sharp initial rise or peak to be considered for the peak discharge parameter.

These same considerations were used in selecting samples for the height-of-rise parameter. An additional requirement for the latter, however, was that the initial rise had to be distinct on the streamflow trace.

Any well-defined hydrograph that could be detected on both watersheds could be considered for the volume parameter. Due to the labor and time involved it was not possible to analyze all storms. Instead storms were selected which would cover the full range in storm flows. Multiple peaks were not considered a problem since storm flow ceased when the delayed flow line intersected the recession of the hydrograph. It was assumed (and justified by experimental data) that what happened in terms of number of peaks on one watershed was repeated on the other. When two peaks occurred on the treated watershed before the base flow line intersected the recession, two peaks also occurred on the control. This would be expected if the control and treated watersheds were in fact correlated.

Before a storm was considered for the time-to-peak parameter, it had to have both a well-defined initial rise and a well-defined peak. This precluded use of any storm flow which did not possess a sharp peak. Therefore, many of the storm flows with broad peaks used for peak discharge, height-of-rise and volume parameters could not be used for time-to-peak considerations.

When selecting storms for recession considerations it was necessary that the hydrograph possess a definite peak and well-defined recession, a recession that continued to base flow uninterrupted (for at least 72 hours) by any succeeding storm flows. In practice, storms already selected for the other parameters were utilized for this parameter, provided they fit the selection criteria given above.

In preliminary data analysis, a problem was detected with regard to multiple peaks. As noted above, multiple peaks were not a problem with regard to the volume parameter. However, they were an important consideration for all other parameters. When several peaks were encountered in a time interval of two or three days, and when each was treated as an independent event, very poor correlations were obtained between treated and control watersheds. This correlation was improved considerably by treating each multiple-peaked storm as one complex hydrograph. It was therefore necessary to develop criteria to determine when a peak was an independent event and when it could be considered a part of a complex storm hydrograph. When multiple peaks were encountered, criteria developed by the U. S. Geological Survey were used to determine whether these peaks were independent (U. S. Geological Survey, 1951). Only the highest peak was used when two or more occurred within 48 hours, unless it was probable that the peaks were independent. It was considered probable for these peaks to be independent if the hydrograph receded to base flow during the time interval between peaks.

An additional problem was encountered with data from Deer Creek IV. Leakage flow occurs through the very deep alluvial deposits under the flume. When flow did not exist prior to initial rise it was impossible to determine the time or volume of runoff necessary to produce surface flow in the channel. Therefore, events were not considered unless flow existed prior to the initial streamflow rise, i.e., events starting at zero flow were not considered.

A double-mass analysis was performed on the precipitation data with the purpose of detecting any change in precipitation pattern during the experimental period. Monthly precipitation totals were accumulated for the rain gage on Needle Branch and plotted against values for the rain gage on Flynn Creek. Precipitation data from Deer Creek was also plotted against Flynn Creek. Any break in slope of these lines would indicate a change in the precipitation pattern over the watersheds. If such a change is indicated, this change must be considered when analyzing results of the streamflow parameters.

## Data Reduction

The height-of-rise, time-to-peak, and recession parameters were obtained directly from the gage height traces for the respective gaging station. For these parameters height was recorded to the nearest 0.01 foot and time in hours was recorded to the nearest 0.5 hour. Peak discharge and volume were converted from a simple time-stage function to discharge and volume in terms of csm and csm-hour respectively.

Gage height data on Deer Creek IV was reduced using the rating formula developed by the Forest Management Department. This formula was developed from field measurements and is similar to the one provided by the Agricultural Research Service (U. S. Department of Agriculture, 1962). The formula as developed is:

$$Q = 1.459H^2 + 0.854H^3$$

where Q is discharge in cfs and H is the gage height in feet. Discharge is reduced to csm when Q is divided by area of the watershed in square miles. This value is more desirable than cfs, because it eliminates the effect of watershed size.

The gage height traces on Needle Branch and Flynn Creek were reduced to discharge in cfs using rating tables and "shifts" supplied by the U. S. Geological Survey office in Portland, Oregon. These rating curves were the result of field determination, as conducted by the Survey. Again cfs values were divided by area in square miles to obtain csm.

To determine volume for a particular storm runoff it was necessary to develop a method to integrate the area under each hydrograph. First the gage height trace for a given hydrograph was reduced to time-csm coordinates. Enough points were selected so as to completely define hydrograph shape. However further restriction was necessary in the selection of these points. Due to the non-linear stage-discharge relation, points were selected such that when discharges for two successive gage heights were averaged, this value was within ten per cent of the discharge computed for the average gage height.

These time-discharge points were placed on IBM cards and a computer program (Appendix II) developed to obtain hydrograph separation and volume. This program was designed to make a straight line separation using a constant slope of 0.05 csm per hour. This slope was selected for consideration in this study from the work of Hewlett and Hibbert (1967). Several flood events were plotted and the separation lines constructed to determine its applicability to this locality. Figures 4, 5, and 6 present separation lines for low, medium, and high flow respectively. The separation line intersects the recession at a point which approximates the location that might be selected for a straight line separation, using methods described in Linsley et al (1958). The separation line for high flow (Figure 6) intersects the recession at 144 hours after initiation of the hydrograph. This time interval is longer than would be expected using the straight line separation as presented by Linsley. However, reference in this study is to quick and delayed flow and not surface and base flow. Also it should be remembered that the treated watershed is compared to the control watershed in all the statistical analyses. Therefore it should make no difference where the point lies on the recession because it is the change of the treated watershed with respect to the control that is important.

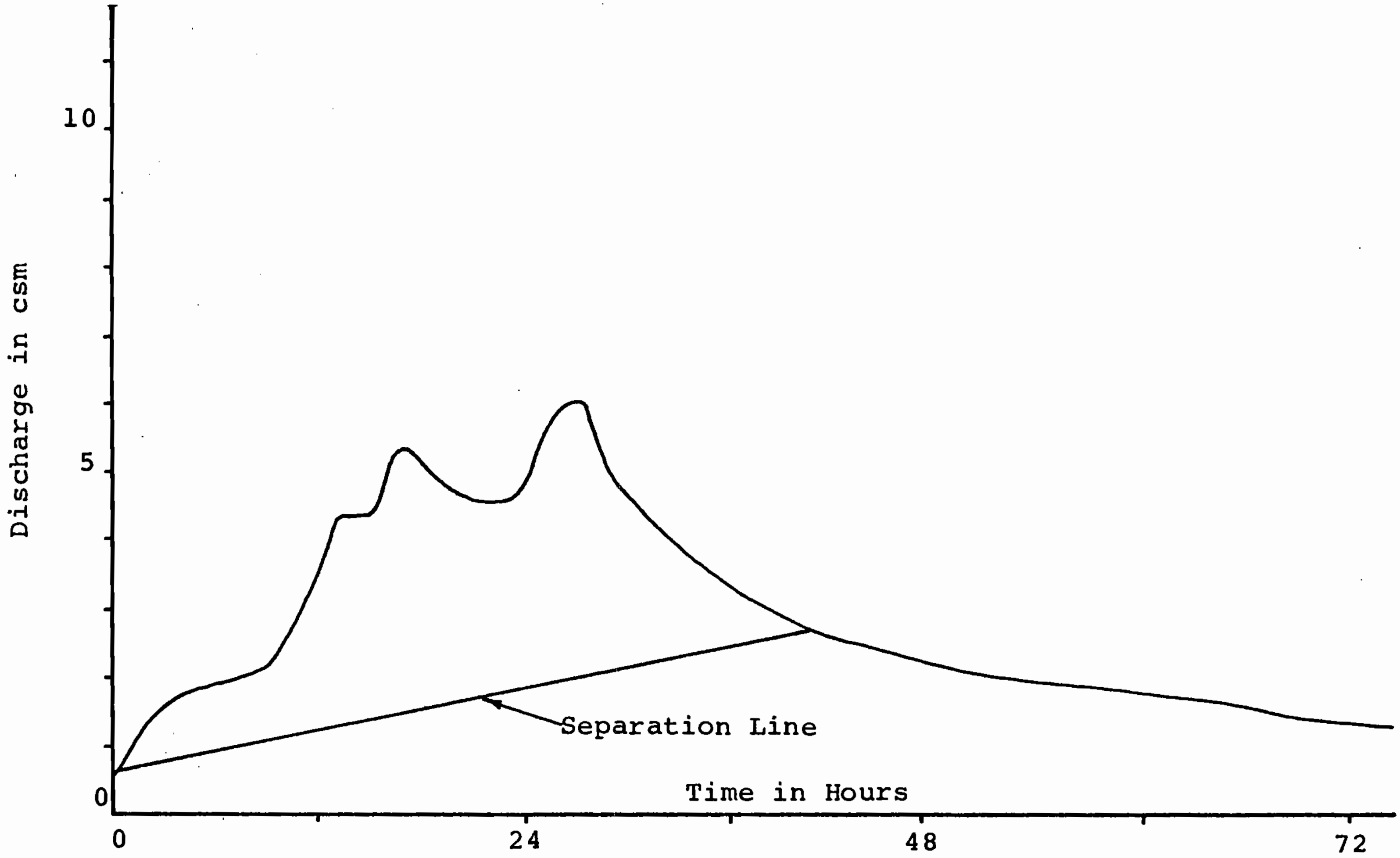

Figure 4. Hydrograph illustrating quick flow separation of a small event for storm of October 28, 1960, on Needle Branch.

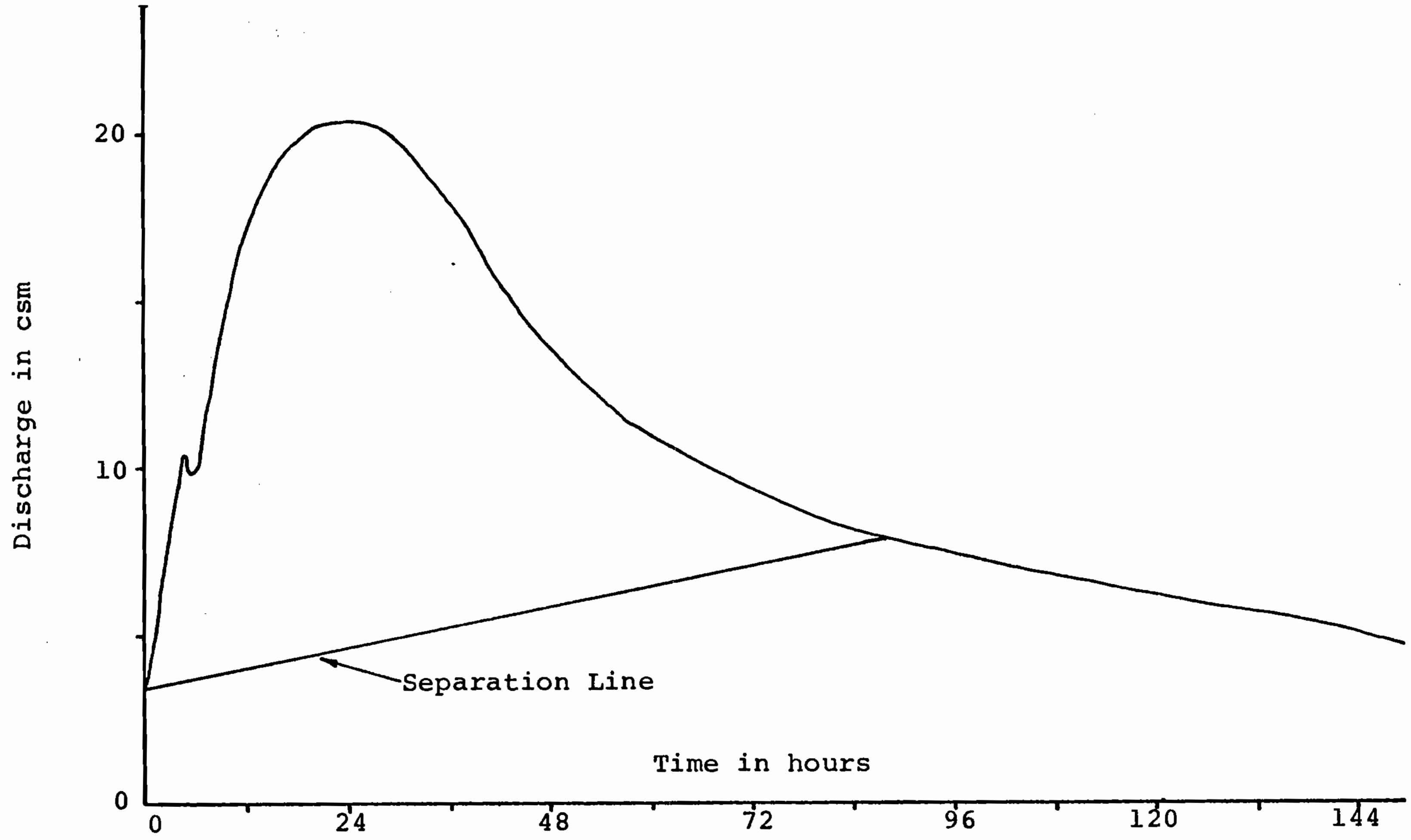

Figure 5. Hydrograph illustrating quick flow separation of a median event for storm of November 23, 1959, on Needle Branch.

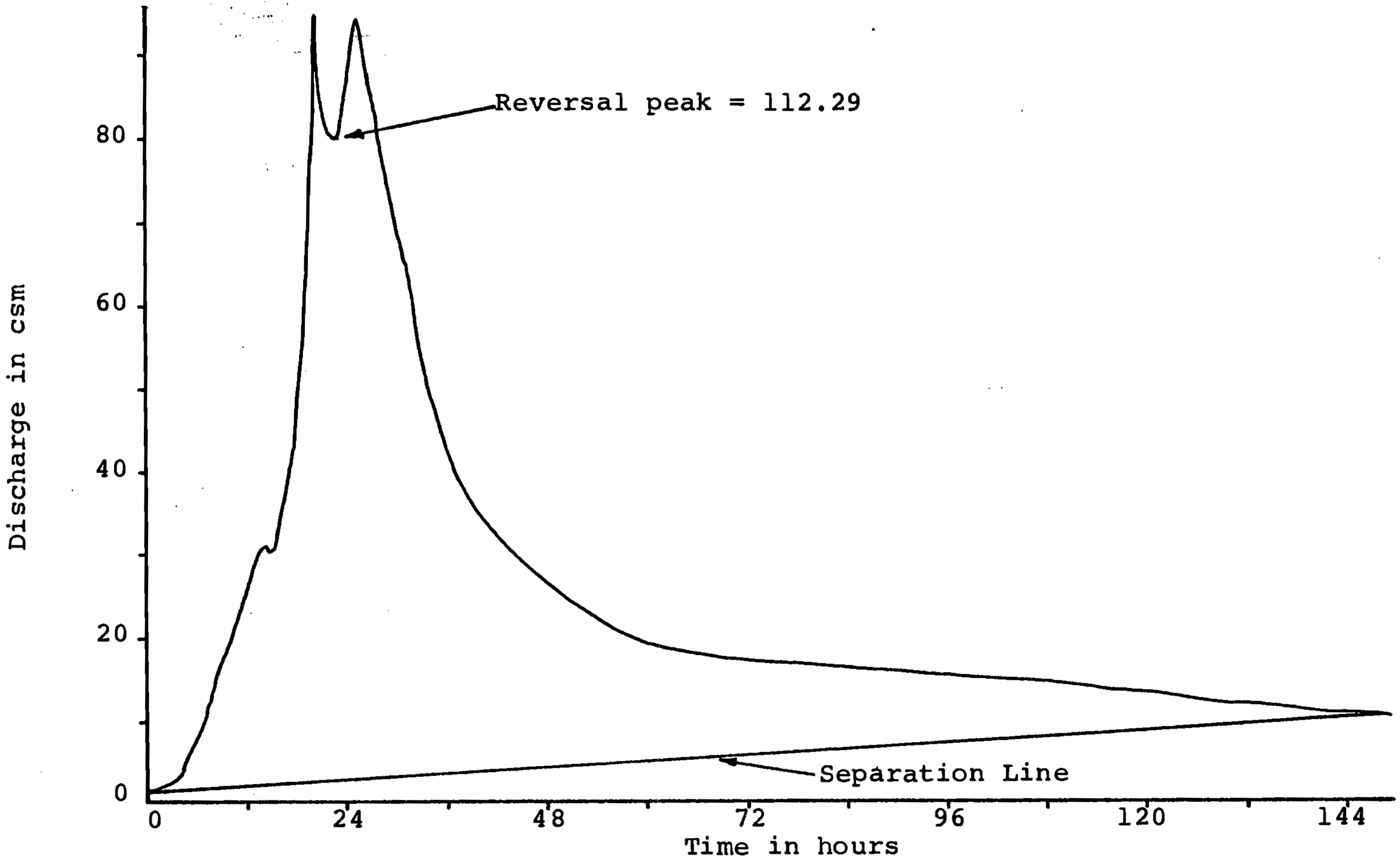

Figure 6. Hydrograph illustrating quick flow separation of a large event for storm of November 22, 1961, on Needle Branch.

Following separation, three values were computed -- quick flow, delayed flow, and total flow. All three values included a time base equal to the interval between initial stream rise and the time at which the separation line intersected the recession. Quick flow consisted of that area above the line and enclosed by the hydrograph, while delayed flow consisted of that area below the separation line. Total flow is the sum of these two. No attempt was made to distinguish origin of the water with regard to direct flow or base flow.

A change in any one of these values would yield information regarding change in stream hydrology, both as to timing and quantity of flow. An increase in quick flow and a decrease in delayed flow would indicate less water held in storage while an increase in total flow would indicate less consumptive use of water on the watershed.

## Statistical Techniques

### Determination of Regression Relations

All the parameters values for peak discharge, height-of-rise, volume, time-to-peak, and the three points on the recession were placed on IBM cards so statistical analysis could be accomplished with the aid of a CDC 3300 computer.

A computer program was developed to make the necessary computations for a linear regression analysis. This program was designed to give a prediction equation for each parameter on the treated watersheds, as compared to the control watershed. A line of prediction was computed for both the pre- and post-logging periods.

Values of the coefficient of determination, $r^2$, defined as:

$$r^2 = \frac{\text{(Sum of Squares due to Regression)}}{\text{(Total Sum of Squares, corrected for the mean)}}$$

after Draper and Smith (1968), were then examined to determine the value of the regression lines as predictors. It was necessary to examine $r^2$ because a paired watershed study requires a high degree of correlation between the test watershed and the control during the calibration period. The value of a regression equation as a predictor increases as $r^2$ approaches unity or 100 per cent. An $r^2$ value of 100 per cent indicates that all points lie on the regression line and the line is a perfect predictor. The basic assumption in the use of $r^2$ is that two variables are related, with one variable independent and one dependent. This assumption makes it possible to use the line of regression as a predictor, using the independent variable X to determine the dependent variable Y. This is the essence of the data analysis for this study. A prediction line is developed for the pre-logging (calibration) period between the control watershed and the treated watershed for each of the parameters -- peak discharge, height-of-rise, volume, time-to-peak, and recession. This is followed by development of a prediction line between the same two watersheds for the post-logging period. An analysis of the difference between these two prediction lines gives an indication of the change that has occurred and the significance of that change.

## Tests for Change

Further statistical tests were used to determine the statistical equality of the pre- and post-logging relationships, i.e., tests were used to determine whether these two lines were actually different, or whether the difference that occurred could have happened by chance. In any statistical test of this type the level of significance must be chosen. In this study two levels were considered. The first was the 95 per cent level and the second was the 99 per cent level. These two are designated as "significant" and "highly significant", respectively. The level of significance gives the probability of obtaining the same results in repeated sampling. For example, the 99 per cent level indicates a hypothesis of equality between two equal regression parameters will be rejected only one per cent of the time.

Any indicated change in the regression for a particular parameter as a result of treatment was subjected to two tests; a test for change in slope and a test for change in vertical position. A distinction should be made between change in slope and change in vertical position of the prediction lines. Both indicate a change as a result of the treatment, but each has a different physical meaning. A change in slope would imply that the effect of the treatment varied with increasing values of the parameter while a change in vertical position implies that the effect is the same over the full range of values.

### Change in Slope

This test compared differences in slope between pre- and post-logging regressions for each parameter. The coefficient under consideration is $b_1$ as in the expression:

$$y = b_o + b_1x.$$

This test, as given by Lee (1957), may be noted by reference to Appendix III. The hypothesis tested is that $b_{11} = b_{12}$, i.e., the slope prior to logging is equal to the slope following logging. The second subscript (1 or 2) designates pre-logging (1) or post-logging (2) period.

The test for change in slope yields a computed value of "t" which must be compared with the critical value of t. The critical value of t is dependent on the level of significance selected and the degrees of freedom involved. If the computed value of t is greater than the critical value of t, the hypothesis is rejected in favor of the alternate hypothesis that the slopes are in fact different. If the slopes were found to be different, no further testing was required.

### Change in Vertical Position

If slopes were not found to be statistically different, a test for change in vertical position was required. For this analysis it was necessary to make the assumption that slopes not statistically different are equal.

The test for change in vertical position, which is given the name "mean of means", is a modification of the test for change in intercept given by Draper and Smith

(1968), i.e., the change in $b_o$, as in the expression:

$$y = b_o + b_1x.$$

The development of this test and its final form may be found by reference to Appendix III.

In many studies, covariance techniques have been used to test for change in vertical position. In the test of homogenity of adjusted means, as well as other covariance tests, an assumption that variances before and after treatment are equal must be accepted. This does not seem probable for this study. The whole regime of water production has been changed as a result of the drastic treatment applied. It seems unlikely that variance has remained unchanged following clearcut logging.

If a change was indicated using the statistical techniques, this change was further defined in terms of percentage in order to define the change in quantitative terms. Such information is valuable for comparative purposes.

## Seasonal Variation

Following analysis using all available data, the data were then divided to determine change as related to a particular season. A seasonal segregation of the data was made because it has been indicated that the largest effect of vegetation removal on streamflow often occurs during the fall recharge period (Reinhart, 1963). The fall months of September, October and November were analyzed using the same analytical techniques described above. December, January, February and March were analyzed separately as the winter period. Thus, the pre-logging regression of a given parameter for a given season was compared with the post-logging regression of the same parameter for the same season.

Statistical justification for this separation based on physical theory was obtained by comparing fall and winter regressions in the pre-logging period. A regression was developed between the fall period of record on each treated watershed and the fall period of record on the control for the pre-logging period. A second series of regressions was developed using only the winter pre-logging period of record. These two regressions were then compared statistically to determine whether a seasonal difference actually existed. The same technique was applied to the post-logging data to test for seasonal variations in the data. This analysis was used for statistical justification of the seasonal separation already assumed, using previous studies for justification. It was applied to all parameters which indicated a statistically significant change as a result of treatment when analyzed on a seasonal basis, both on Deer Creek IV and Needle Branch.

# RESULTS

Roads were constructed along the ridges on both Deer Creek IV and Needle Branch watersheds in 1965. A statistical comparison of the data for this year with the previous non-treatment years indicated road building had no effect on streamflow. These data were then included in the pre-logging period in all subsequent tests to detect change in peak discharge, height-of-rise, volume, and time-to-peak.

Comparative watershed studies have an underlying assumption of homogeneous precipitation patterns over both watersheds. For this reason a double-mass analysis of precipitation data for years 1960 to 1967 was conducted (Appendix I, Figures I and II). The cumulative relation was established between rain gages at Deer Creek and Flynn Creek and between Needle Branch and Flynn Creek. A change in slope occurred during 1965 and 1966 for Needle Branch but the relation came back to the original slope by 1967. A check of the records indicated the data were of good quality through this period. The change resulted in less precipitation over the Needle Branch watershed and hence will qualify conclusions. An increase in any given parameter may be conservative, while a change found non-significant might be significant if the precipitation change was included as a parameter in the prediction equation.

The variables are presented in sequence of peak discharge, height-of-rise, quick flow, delayed flow, total flow, and time-to-peak. A summary of the statistical analysis for each parameter is given in Appendix I, Table I, II, and III.

In order to assess the practical significance of changes shown statistically, percentage differences between regression lines at the pre-logging mean, maximum and minimum levels of the control are presented in Table 1 for each parameter changed by clearcut logging.

## Peak Discharge

### Needle Branch

Variation between fall and winter peak discharge data occurred following logging. This was reflected in a statistical difference between the two periods significant at the 95 per cent level (Appendix I, Table III). Seasonal difference was also indicated by the increase in $r^2$ from 0.80 for the full year data to 0.98 for the fall period and 0.83 for the winter (Appendix I, Table I). Flows during the fall period were consistently greater than during the winter period.

Table 1. Summary of absolute and percentage change in significant variables for minimum, average and maximum values for Needle Branch and Deer Creek IV.

| Parameters2/ | Predicted Values of Parameters 1/ | | | | | | Percentage Change | | |
|---|---|---|---|---|---|---|---|---|---|
| | Minimum | | Average | | Maximum | | | | |
| | Pre | Post | Pre | Post | Pre | Post | Min | Ave | Max |
| Needle Branch | | | | | | | | | |
| Peak Discharge (csm) | | | | | | | | | |
| Full year | 3.2 | 7.2 | 30.3 | 41.0 | 205.0 | 257.9 | 127.7 | 35.0 | 25.6 |
| Fall | 1.9 | 4.2 | 19.3 | 36.6 | 120.7 | 226.2 | 116.2 | 89.9 | 87.4 |
| Winter | 7.2 | 6.9 | 44.0 | 56.3 | 198.3 | 262.9 | - 3.2 | 28.5 | 33.4 |
| Quick Flow (csm-hr.) | | | | | | | | | |
| Full year | 263.0 | 578.8 | 2063.8 | 2397.3 | 8966.9 | 9368.9 | 120.1 | 16.0 | 4.3 |
| Fall | 189.9 | 449.2 | 1133.0 | 2486.9 | 5495.8 | 11912.2 | 136.6 | 119.3 | 116.5 |
| Delayed Flow (csm-hr.) | | | | | | | | | |
| Full year | 183.2 | 191.2 | 1020.3 | 1299.8 | 2622.9 | 3422.2 | 4.2 | 26.4 | 29.3 |
| Fall | 64.6 | 255.8 | 561.0 | 1605.0 | 2087.9 | 5756.0 | 295.1 | 185.3 | 174.8 |
| Winter | 550.5 | 92.5 | 1382.9 | 1782.6 | 2478.9 | 4007.8 | -83.0 | 29.1 | 61.9 |
| Total Flow (csm-hr.) | | | | | | | | | |
| Full year | 350.9 | 816.7 | 3081.2 | 3663.1 | 11550.4 | 12492.8 | 132.7 | 18.8 | 8.1 |
| Fall | 253.3 | 701.6 | 1693.4 | 4034.3 | 7571.6 | 17638.2 | 176.8 | 137.7 | 132.3 |
| Winter | 865.1 | 1038.4 | 4163.4 | 4802.7 | 11355.4 | 13011.1 | 20.1 | 15.5 | 14.7 |
| Deer Creek IV | | | | | | | | | |
| Peak Discharge (csm) | | | | | | | | | |
| Full year | 3.6 | 15.4 | 49.2 | 62.9 | 241.9 | 263.6 | 328.7 | 27.9 | 9.0 |
| Fall | 4.5 | 18.6 | 19.4 | 44.5 | 40.9 | 81.7 | 311.0 | 127.9 | 100.0 |
| Winter | 3.3 | 10.6 | 54.5 | 66.1 | 243.3 | 270.5 | 225.8 | 21.6 | 11.4 |
| Time-to-peak (hr.) | | | | | | | | | |
| Full year | 7.2 | -7.3 | 39.8 | 41.5 | 85.9 | 110.7 | -200.3 | 4.2 | 28.6 |

1/ The minimum, maximum and average values used for computation were taken from the pre-logging period.

2/ Full year is defined as September to April; fall is September to December; winter is December to April.

Since a seasonal analysis was indicated, fall and winter peaks were compared separately before and after logging. The effect of logging using the full year (September to March) is given for comparative purposes (Figure 7). Fall peak discharges were found significantly greater at the 95 per cent level following treatment. Scatter diagrams and regressions before and after clearcutting for the fall period are presented in Figure 8.

Increases in winter peak discharge was also found significant at the 95 per cent level (Figure 9). However, the percentage increase was not as great as for the fall period (Table 1).

### Deer Creek IV

Seasonal variation was found in the peak discharge data on Deer Creek IV following logging. Difference between fall and winter data for the post-logging period was found statistically significant at the 95 per cent level (Appendix I, Table III). Seasonal differences in the data were also suggested by the change in $r^2$ values following seasonal separation. The $r^2$ value was increased from 0.80 for the full year data to 0.97 for the fall data (Appendix I, Table I). As was found on Needle Branch,

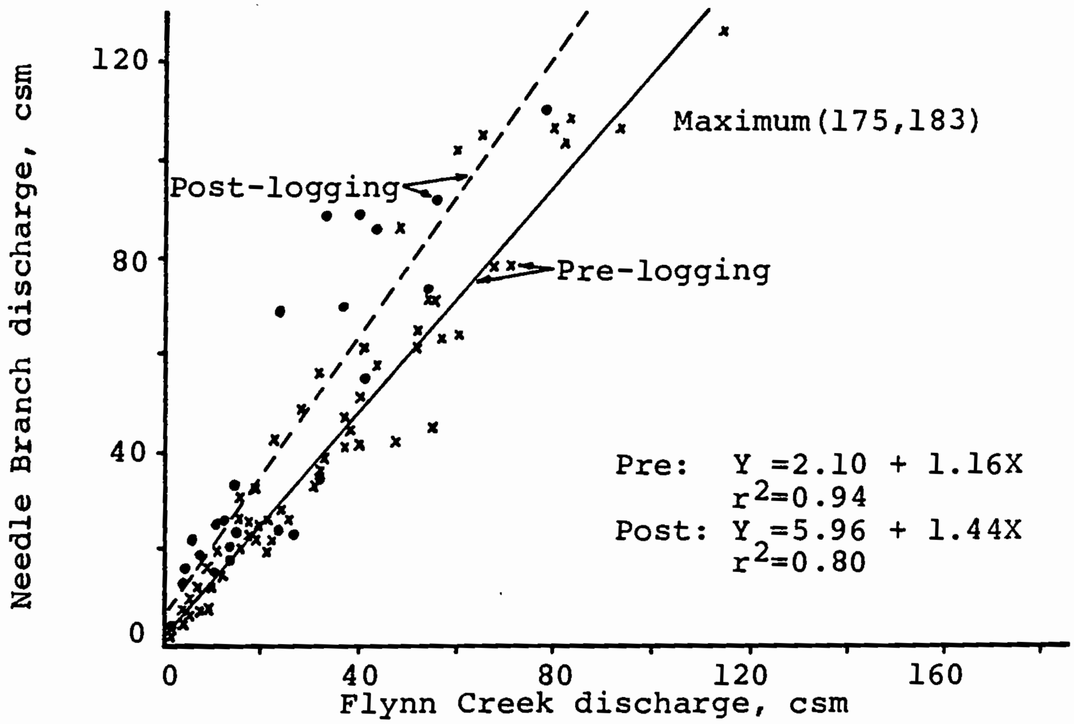

Figure 7. Peak discharge on Needle Branch regressed on Flynn Creek for full period, pre- and post-logging.

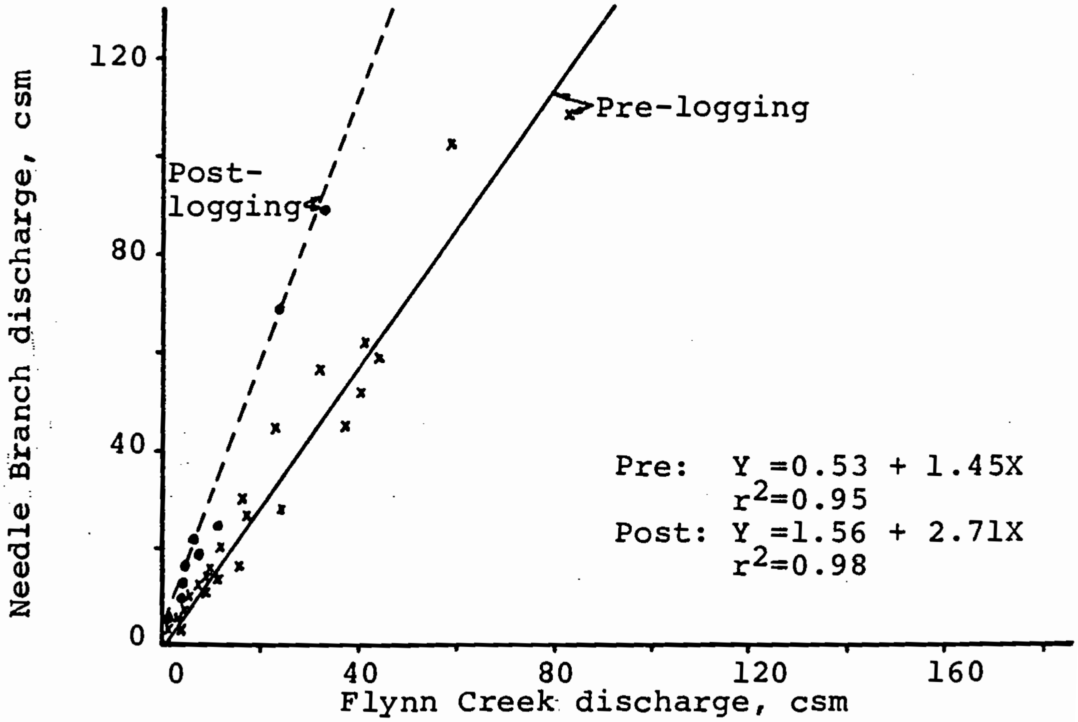

Figure 8. Peak discharge on Needle Branch regressed on Flynn Creek for fall period, pre- and post-logging.

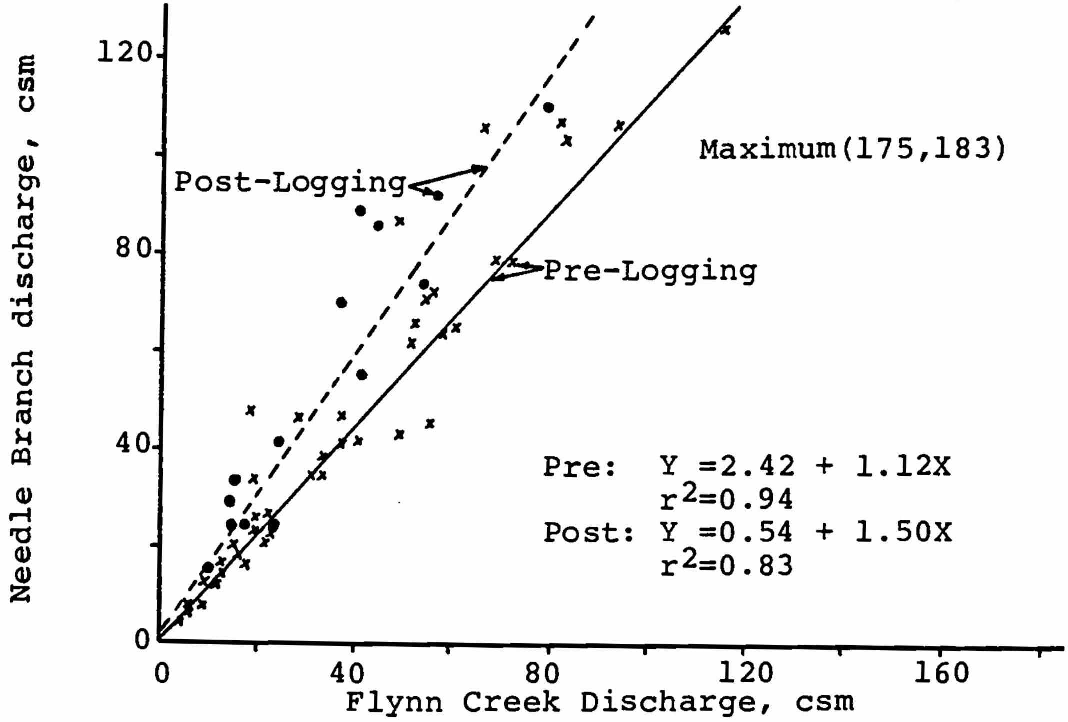

Figure 9. Peak discharge from Needle Branch regressed on Flynn Creek for winter periods, pre- and post-logging.

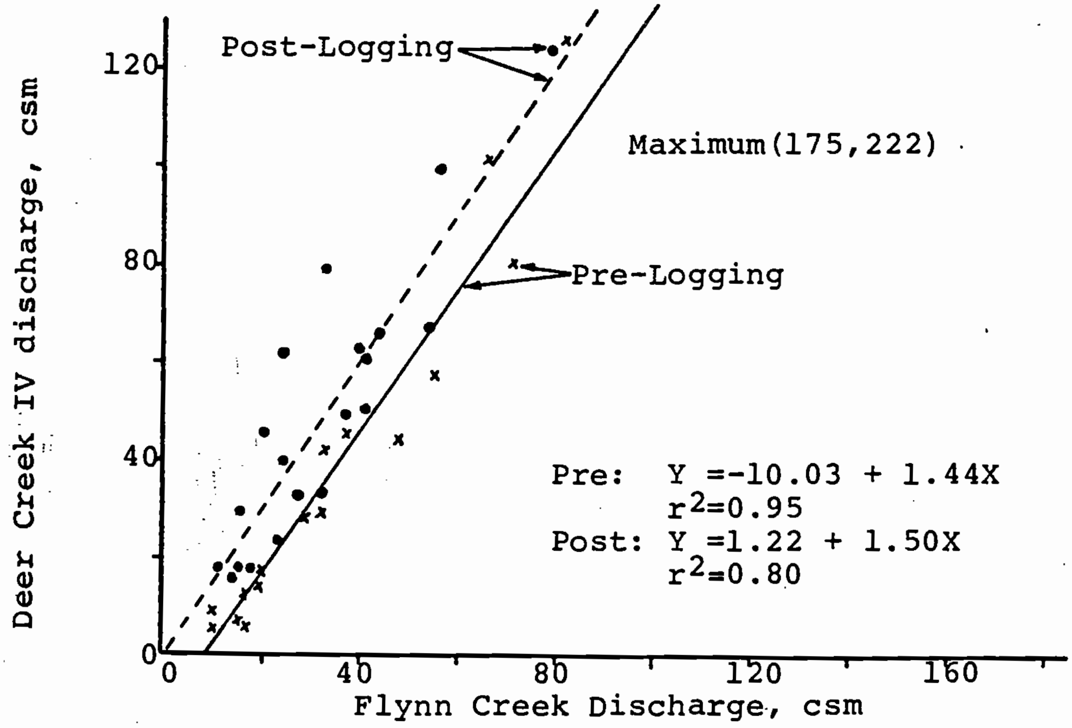

Figure 10. Peak discharge from Deer Creek IV regressed on Flynn Creek for full period, pre- and post-logging.

the $r^2$ value was not increased as much for the winter period. The $r^2$ value for the winter data was 0.90 as compared to the full year value of 0.80. The scatter diagrams for the full year data may be noted by reference to Figure 10.

Fall period analysis indicated a significant increase after clearcutting at the 99 per cent level (Appendix I, Table II). Scatter diagrams and regression before and after are presented in Figure 11.

Winter period analysis indicated a statistically significant increase at the 99 per cent level (Figure 12). The percentage increases for the winter period were not as great as for the fall period (Table 1).

## Height-Of-Rise

### Needle Branch

Analysis of the height-of-rise parameter on Needle Branch did not indicate a change as a result of the treatment. A change was not found when the data was analyzed using the full year (Figure 13) nor was a change indicated when analyzed by season, i.e., fall (Figure 14) and winter (Figure 15).

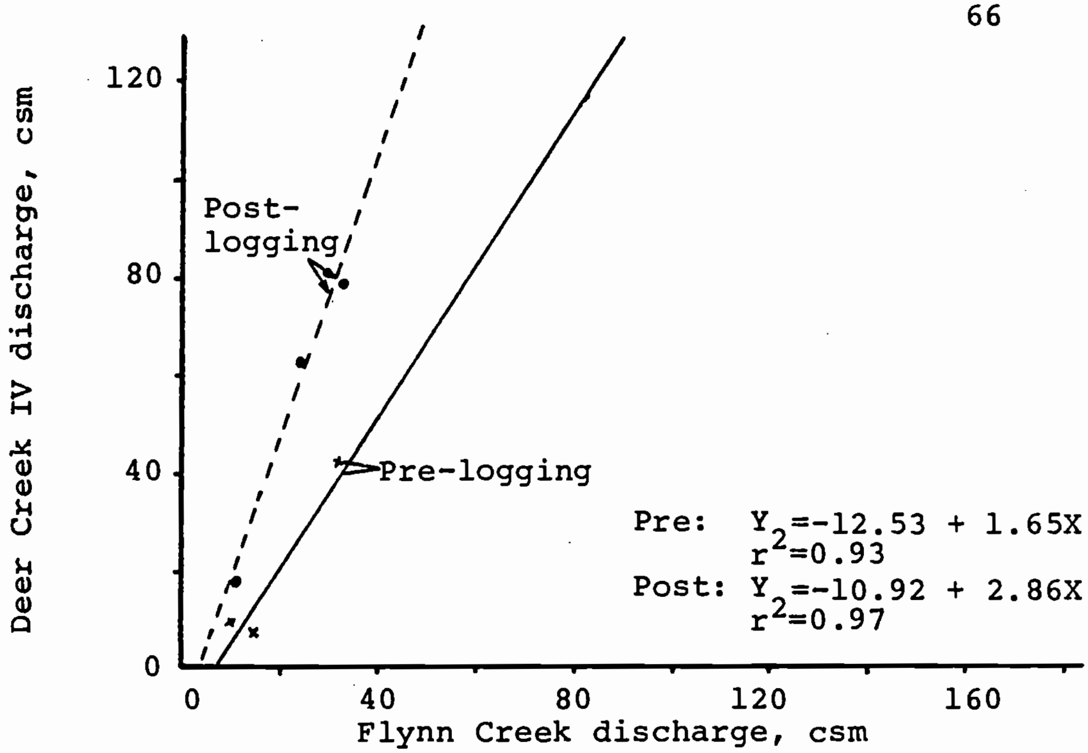

Figure 11. Peak discharge from Deer Creek IV regressed on Flynn Creek for fall periods, pre- and post-logging.

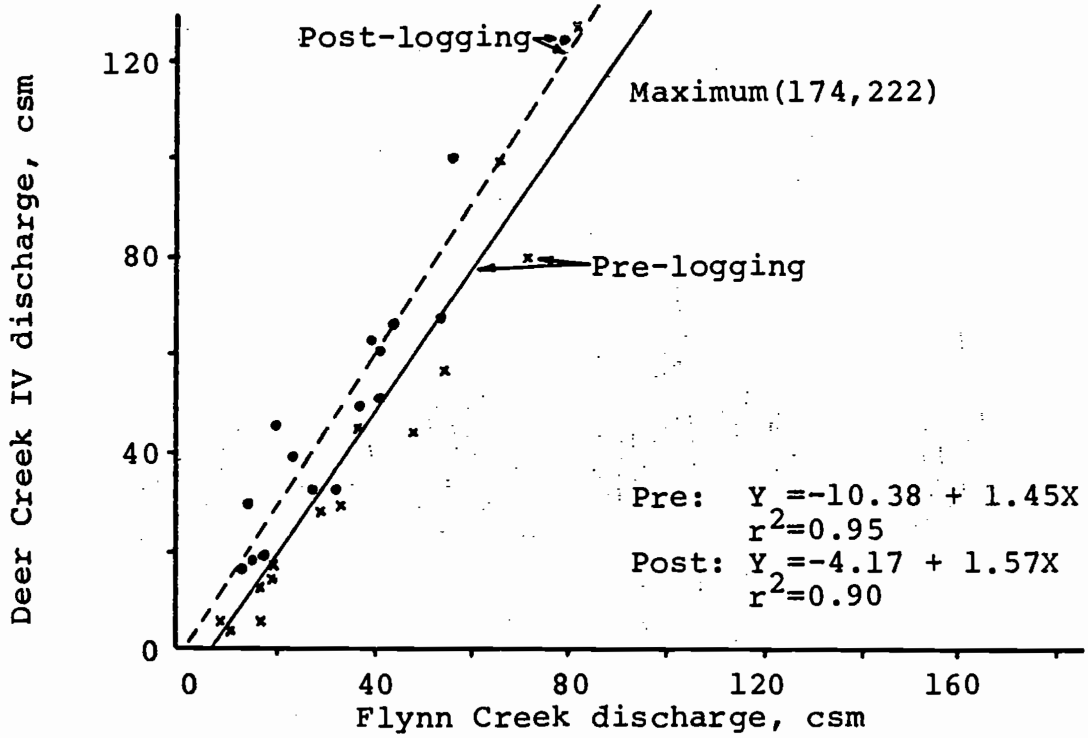

Figure 12. Peak discharge from Deer Creek IV regressed on Flynn Creek for winter period, pre- and post-logging.

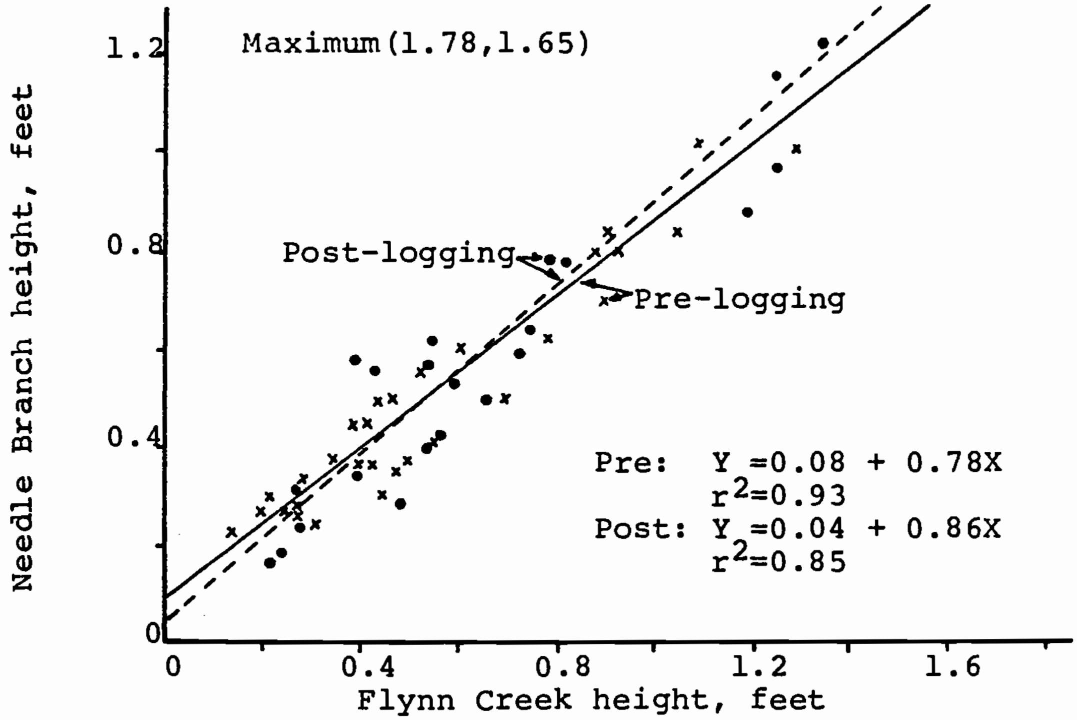

Figure 13. Height-of-rise for Needle Branch regressed on Flynn Creek for full period, pre- and post-logging.

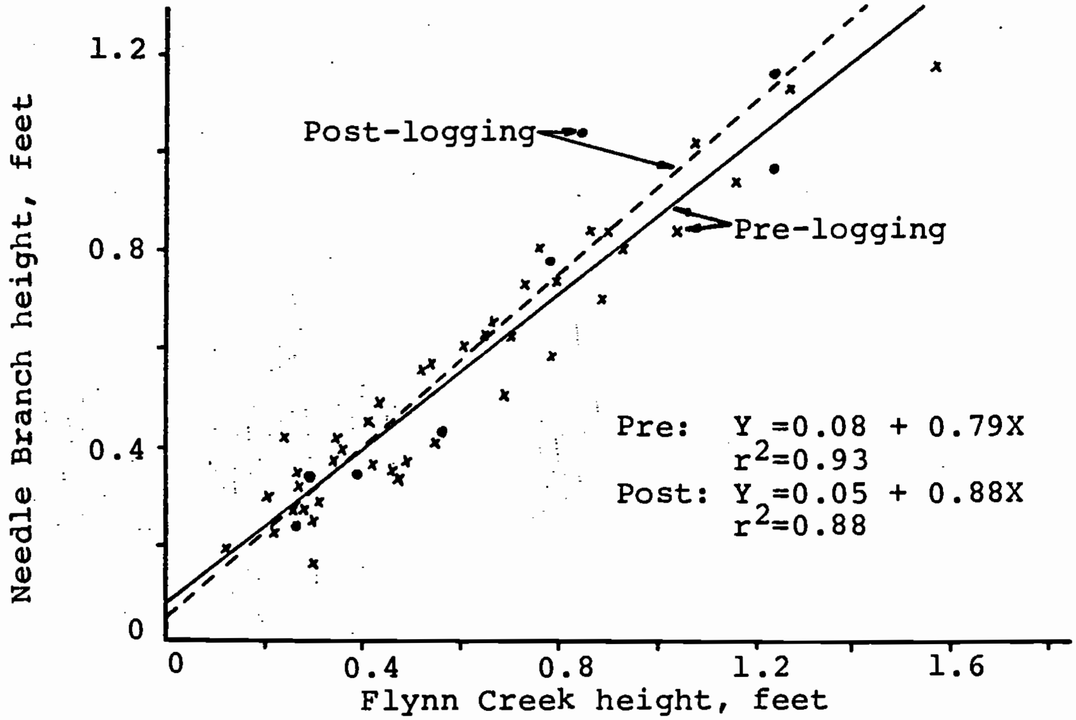

Figure 14. Height-of-rise for Needle Branch regressed on Flynn Creek for fall period, pre- and post-logging.

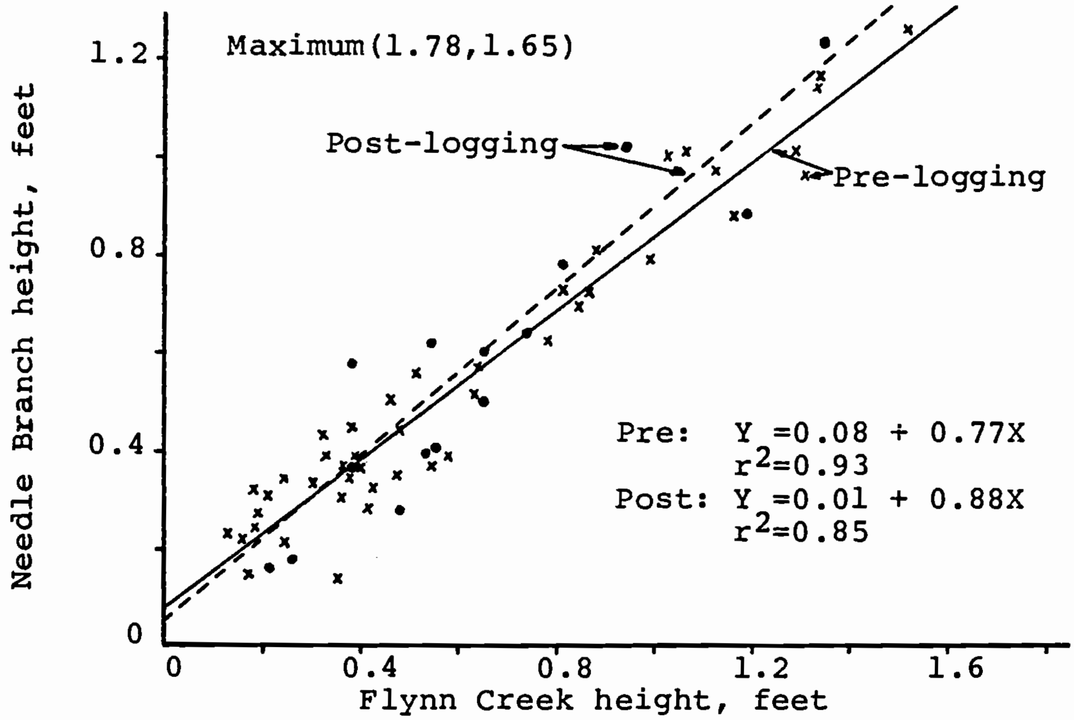

Figure 15. Height-of-rise for Needle Branch regressed on Flynn Creek for winter period, pre- and post-logging.

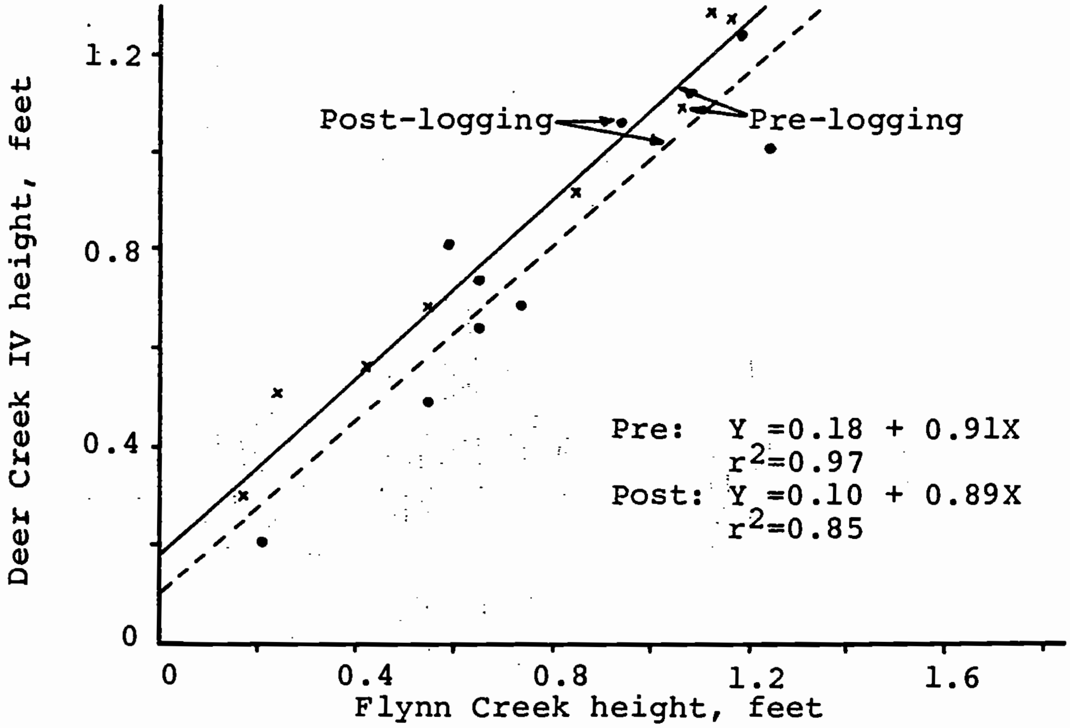

Figure 16. Height-of-rise for Deer Creek IV regressed on Flynn Creek for full period, pre- and post-logging.

### Deer Creek IV

Analysis of data for Deer Creek IV failed to indicate any effect of clearcutting on height-of-rise. The small change in regression lines between pre-logging and post-logging periods was not found to be significant for the full year analysis (Figure 16). There was not sufficient data for this parameter to permit seasonal separation.

## Quick Flow

### Needle Branch

Quick flow analysis for Needle Branch did not indicate a statistically significant difference between fall and winter periods (Appendix I, Table III). However, the scatter of data at the low end of the regression indicated the possibility of some difference in seasonal response. The data were therefore divided and analyzed by season. The full year analysis is presented in Figure 17. Increases for the full year were found significant at the 95 per cent level.

Seasonal variation in the data was also suggested by the increase in $r^2$ from 0.87 to 0.91 following data separation for the fall period as compared to the full

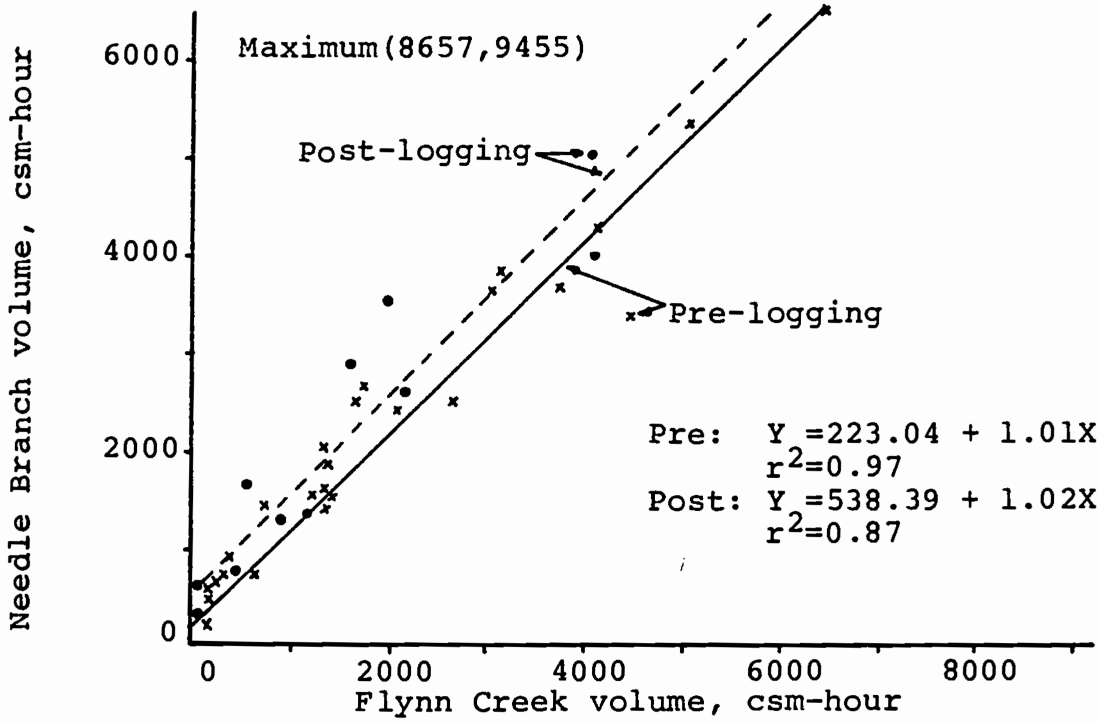

Figure 17. Quick flow volume from Needle Branch regressed on Flynn Creek for full period, pre- and post-logging.

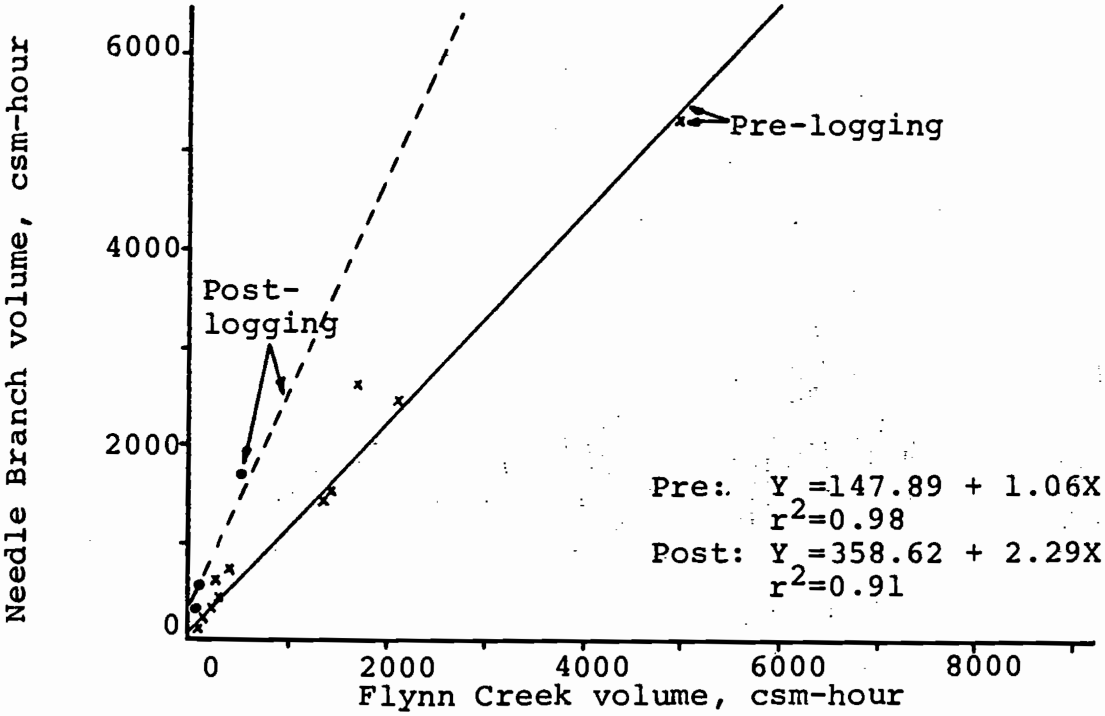

Figure 18. Quick flow volume from Needle Branch regressed on Flynn Creek for fall period, pre- and post-logging.

year (Appendix I, Table I).

Following separation of the data by season, an increase in quick flow volume was indicated for the fall period (Figure 18). This increase was found significant at the 99 per cent level. No changes were discernable for the winter period (Figure 19). Percentage increases were much larger for the fall period than for the winter period (Table 1).

### Deer Creek IV

A change in quick flow was not found for Deer Creek IV when the full period of record was analyzed. This relation is presented in Figure 20. Due to a lack of usable storm events during the fall period, it was not possible to consider the effect of seasonal separation.

## Delayed Flow

### Needle Branch

A difference in delayed flow between the fall and winter seasons was observed during the pre-logging period. This was reflected in a statistical difference between the two periods significant at the 95 per cent level. Seasonal differences were also indicated by the

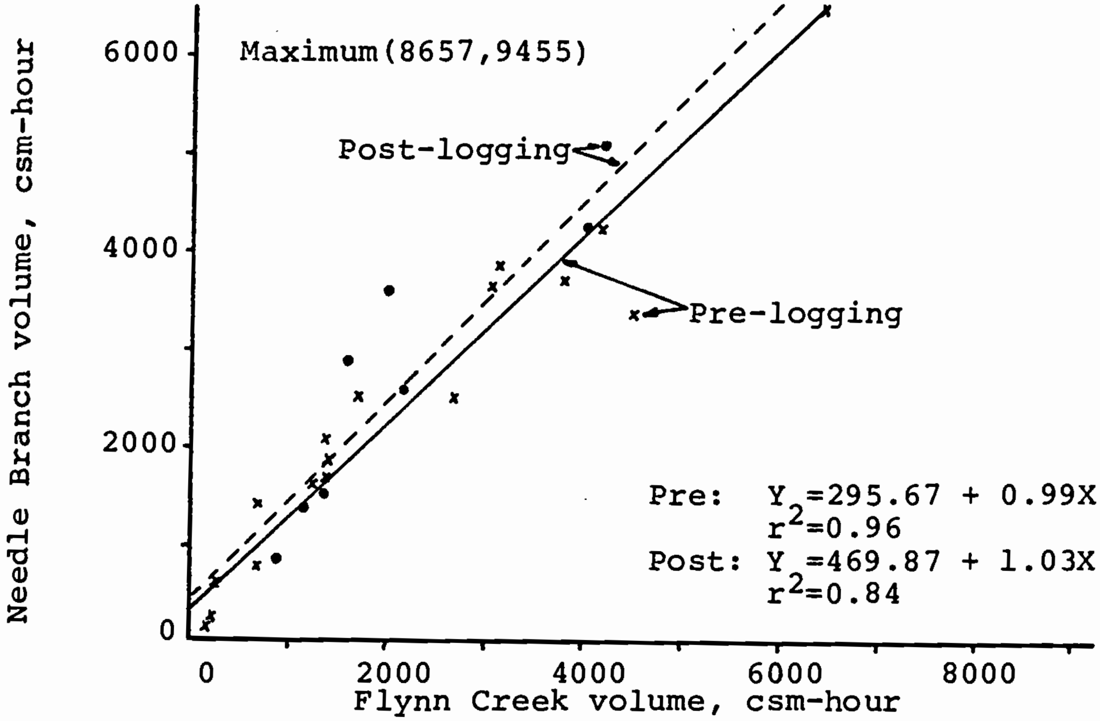

Figure 19. Quick flow volume from Needle Branch regressed on Flynn Creek for full period, pre- and post-logging.

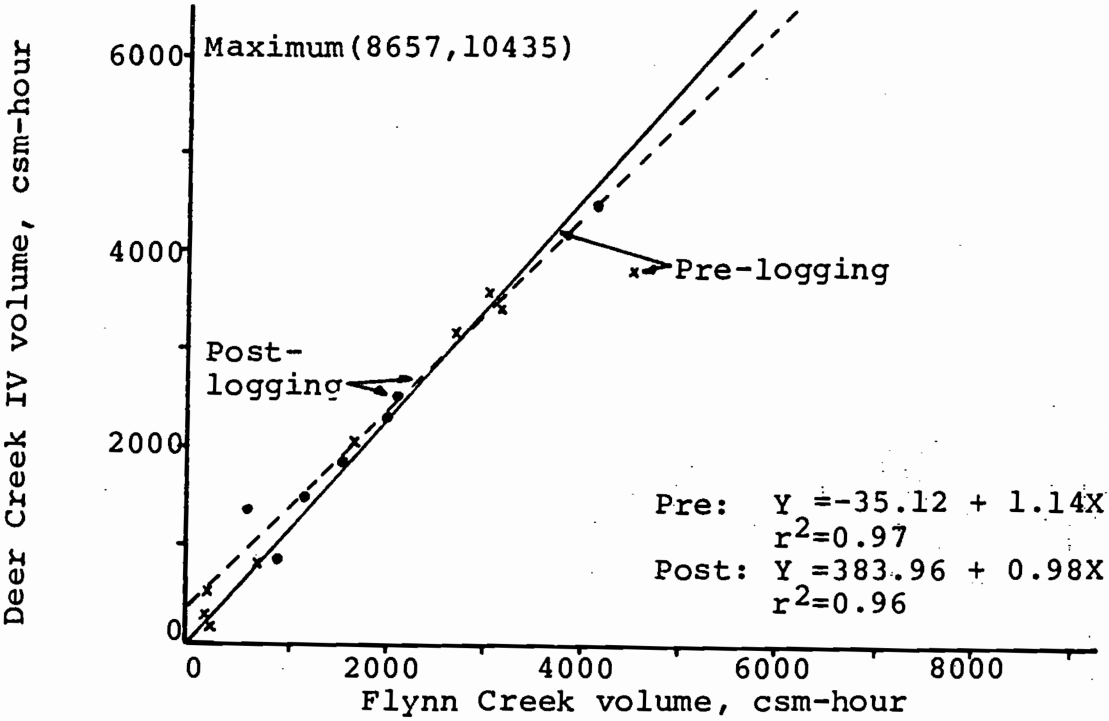

Figure 20. Quick flow volume from Deer Creek IV regressed on Flynn Creek for full period, pre- and post-logging.

increase in $r^2$ from 0.85 for the full year to 0.90 for the fall period. The winter period however remained at 0.85.

Effect of logging over the full year is given for comparative purposes (Figure 21). The fall period analysis indicated an increase significant at the 99 per cent level (Appendix I, Table I, Figure 22). Increases in winter delayed flow volume was found significant at the 95 per cent level (Figure 23) Percentage increases were smaller during the winter period than during the fall period (Table 1).

### Deer Creek IV

A change in delayed flow was not indicated on Deer Creek IV when the full year data were analyzed. Regressions for these data are presented in Figure 24. Due to a lack of usable storm events during the fall period, it was not possible to consider the effect of seasonal separation.

## Total Flow

### Needle Branch

A seasonal difference in the total flow data is indicated by the increase in $r^2$ from 0.87 for the

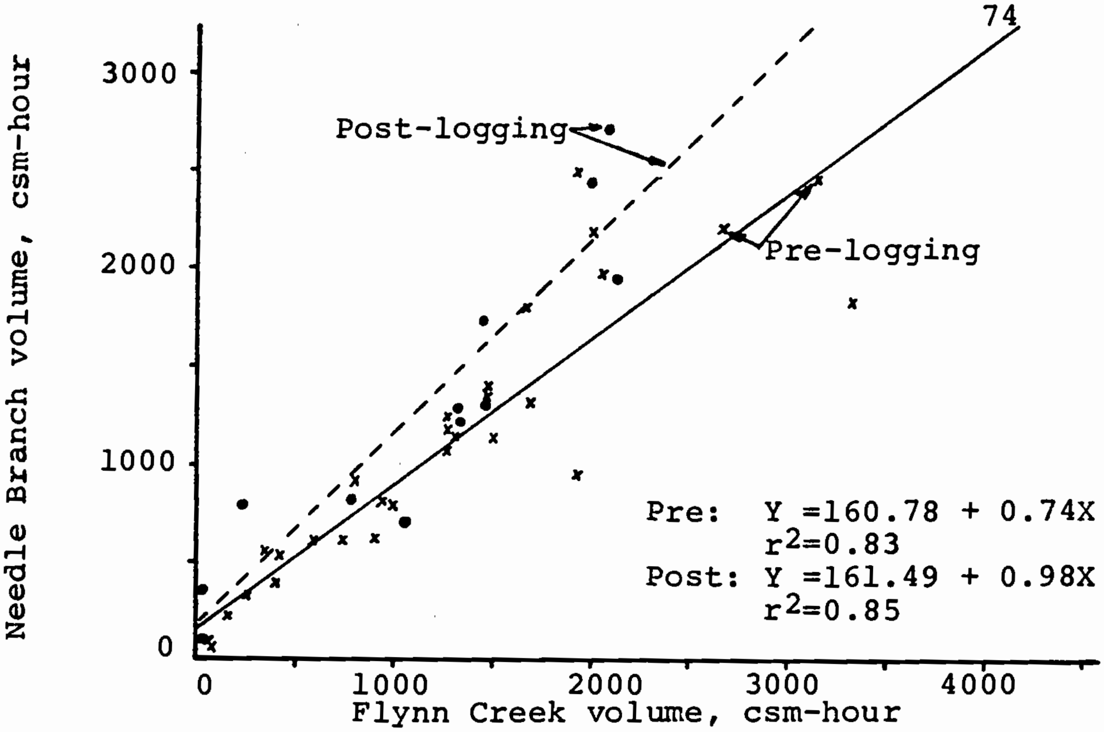

Figure 21. Delayed flow volume from Needle Branch regressed on Flynn Creek for full period, pre- and post-logging.

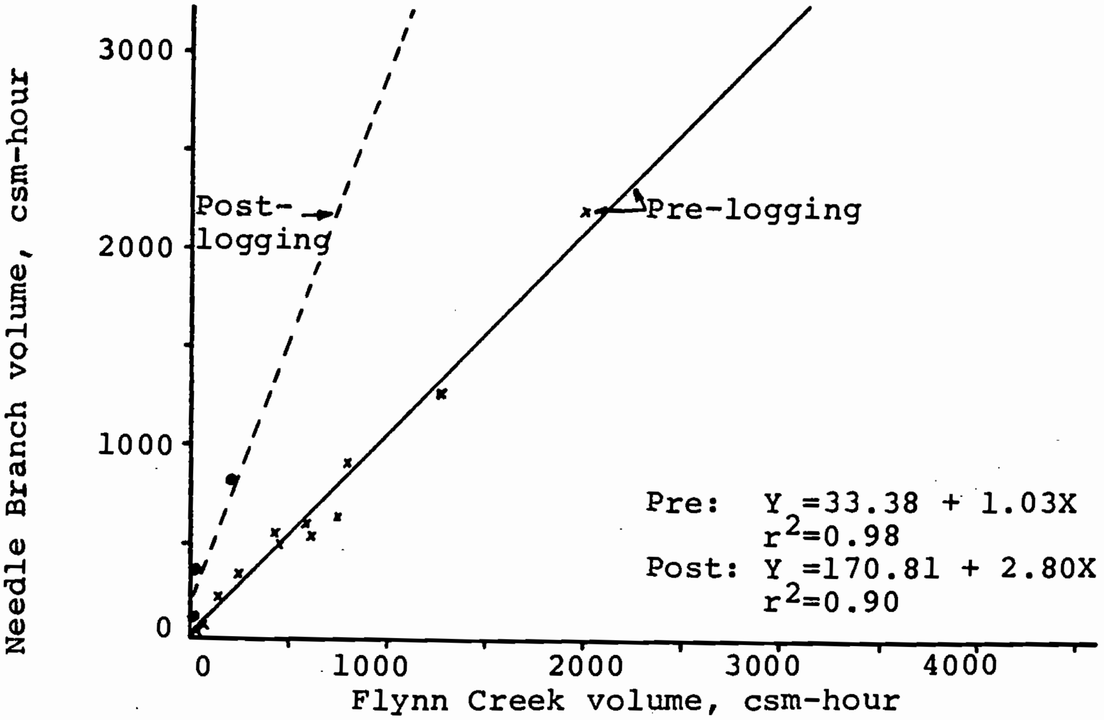

Figure 22. Delayed flow volume from Needle Branch regressed on Flynn Creek for fall period, pre- and post-logging.

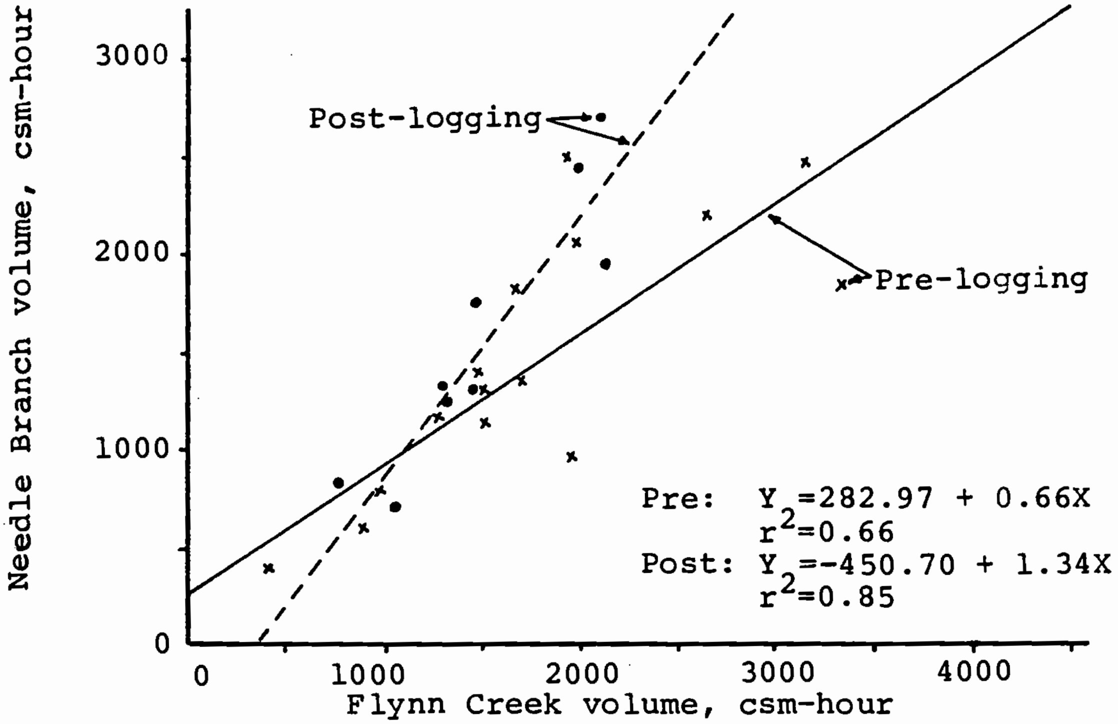

Figure 23. Delayed flow volume from Needle Branch regressed on Flynn Creek for winter period, pre- and post-logging.

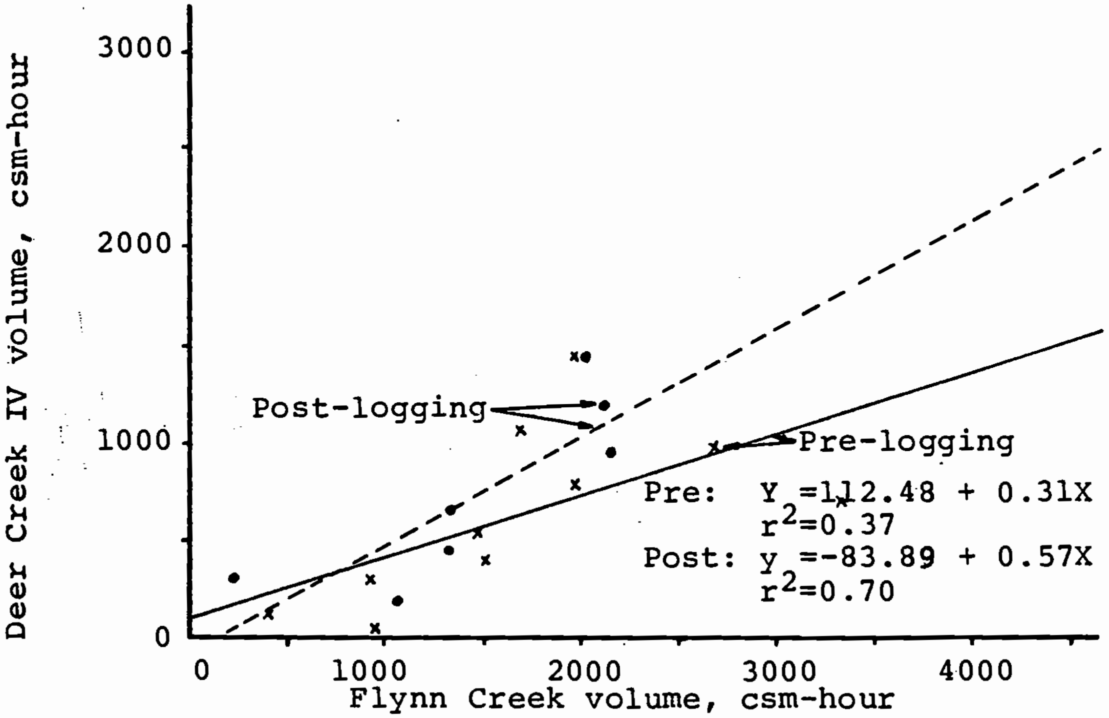

Figure 24. Delayed flow volume from Deer Creek IV regressed on Flynn Creek for full period, pre- and post-logging.

full year analysis to 0.90 for the fall period. The $r^2$ value dropped to 0.83 for the winter period (Figures 25, 26, and 27). The full year analysis (Figure 25) is presented for comparative purposes.

When the data were separated and analyzed according to fall and winter periods, a change in total flow had occurred as a result of logging. The fall period increase was signficant at the 99 per cent level and the winter period at the 95 per cent level (Appendix I, Table I). Percentage increases however were found greater for the fall period (Table 1).

### Deer Creek IV

A change in total flow was not found for Deer Creek IV when the full-year record was analyzed (Figure 28). Due to a lack of usable storm events during the fall period, it was not possible to consider the effect of seasonal separation.

## Time-To-Peak

### Needle Branch

There was no notable change as a result of treatment in the time-to-peak relation on Needle Branch. A change was not found when the data was analyzed by

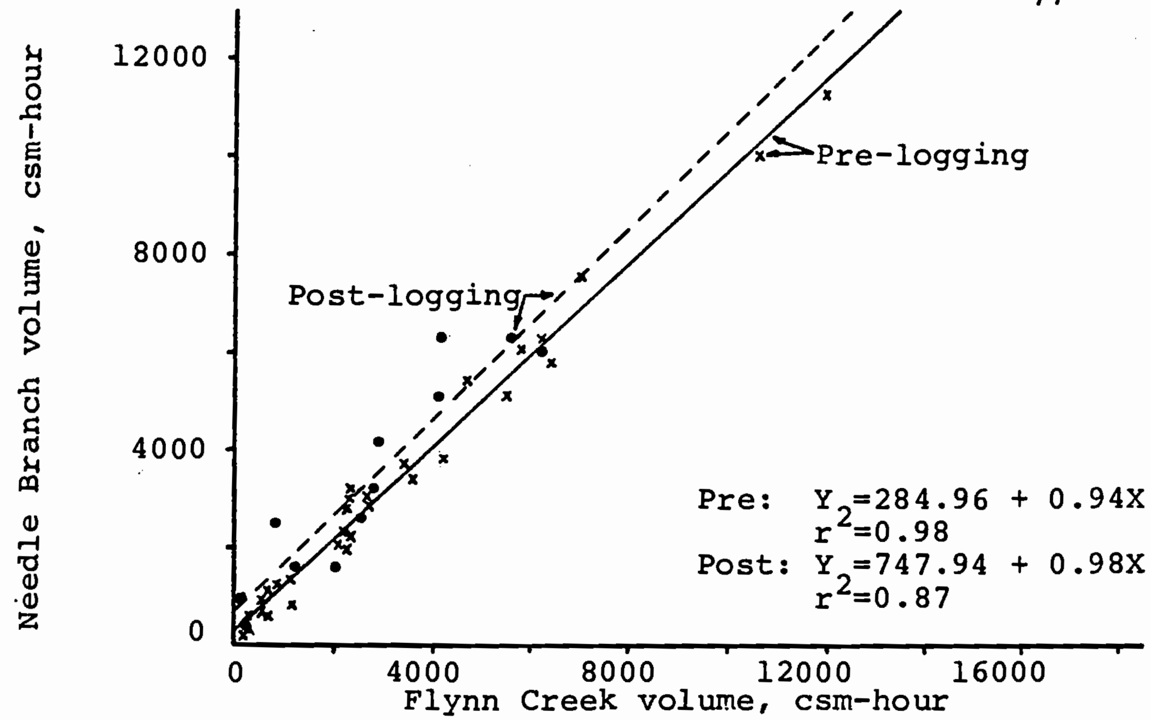

Figure 25. Total flow volume from Needle Branch regressed on Flynn Creek for full period, pre- and post-logging.

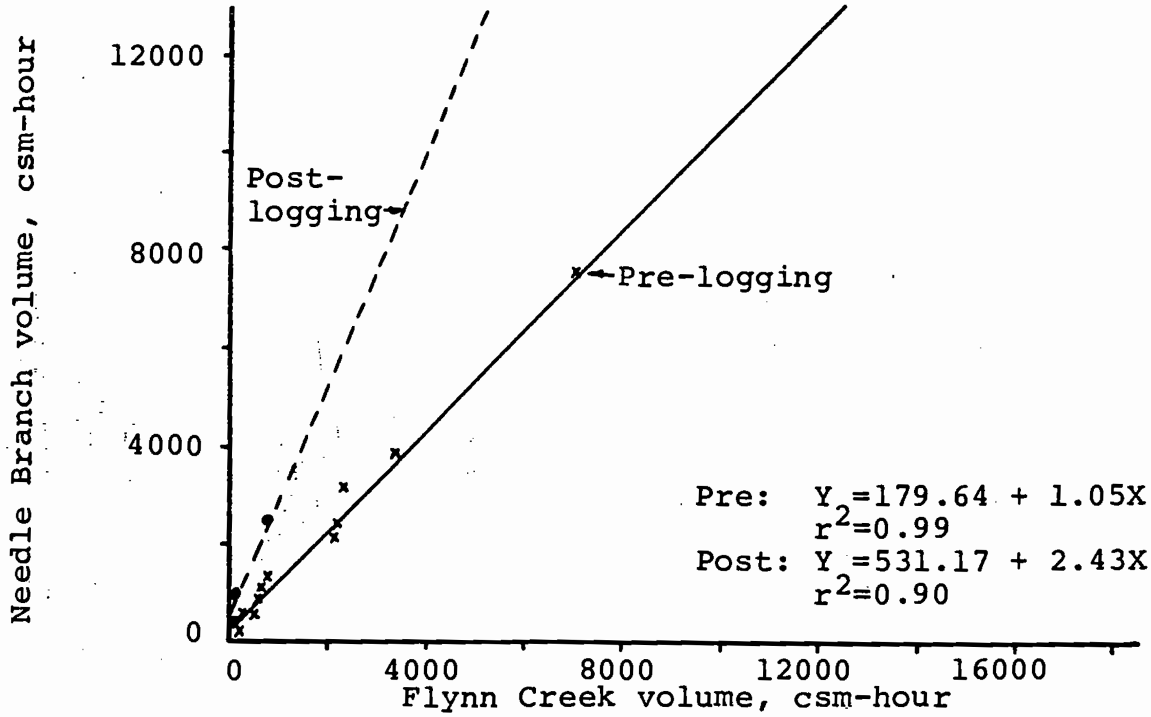

Figure 26. Total flow volume from Needle Branch regressed on Flynn Creek for fall period, pre- and post-logging.

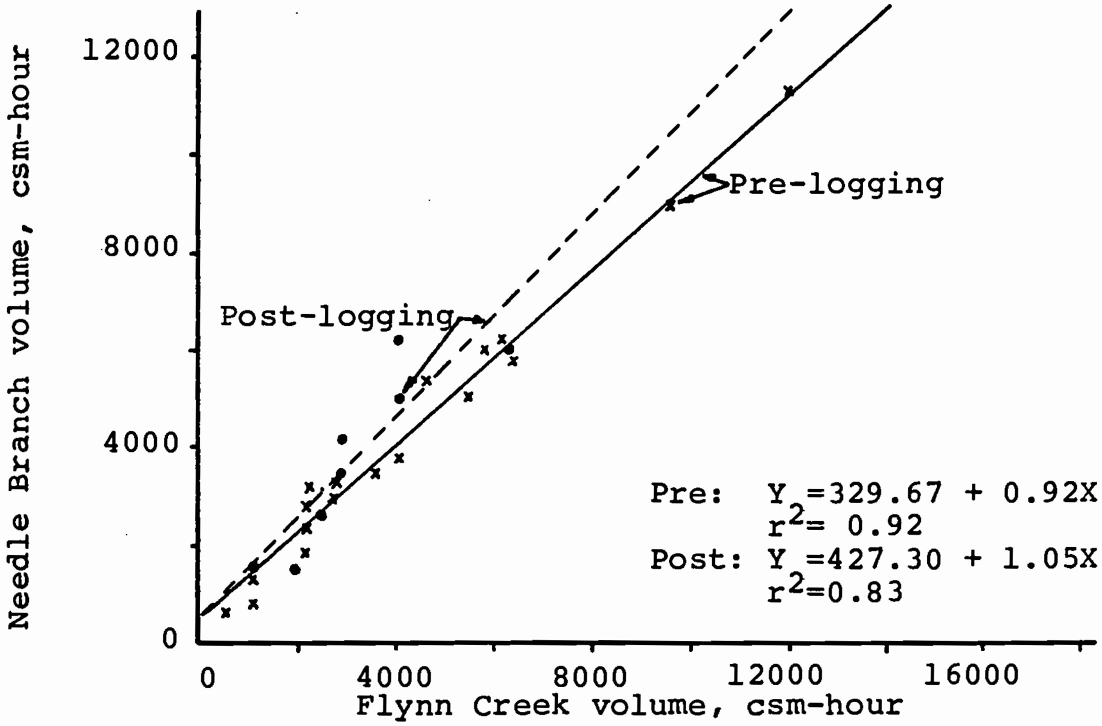

Figure 27. Total flow volume from Needle Branch regressed on Flynn Creek for winter period, pre- and post-logging.

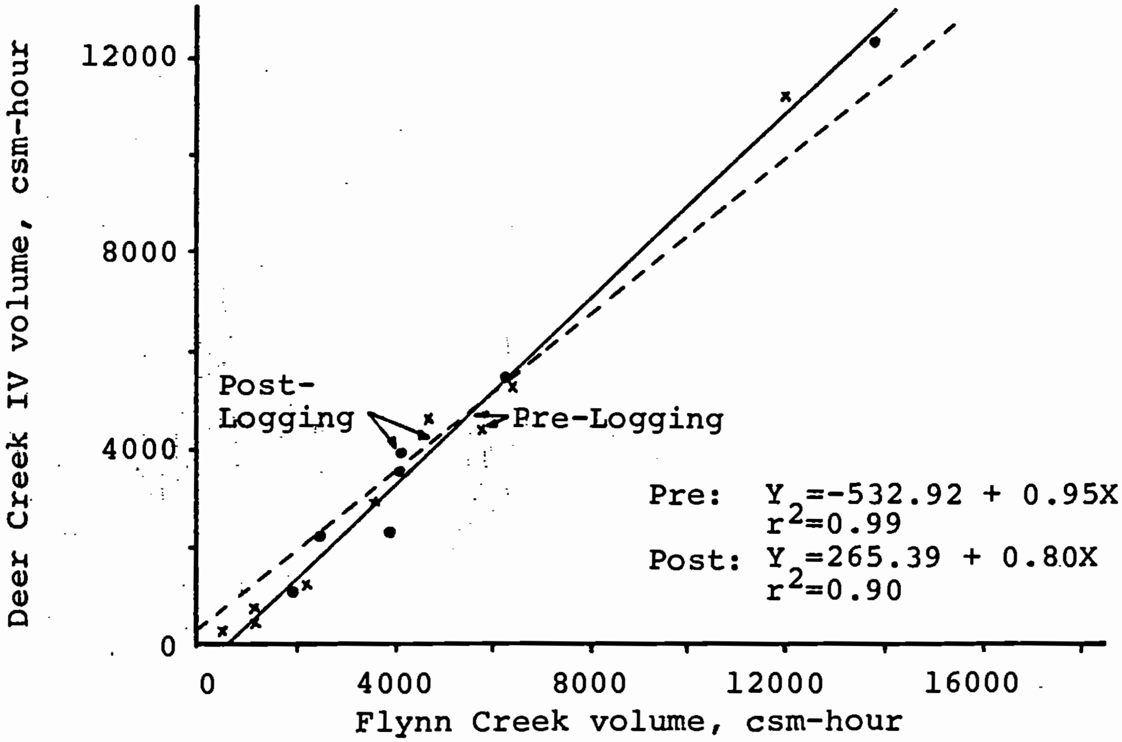

Figure 28. Total flow volume from Deer Creek IV regressed on Flynn Creek for full period, pre- and post-logging.

season nor was a change indicated when analyzed for the full year (Figures 29, 30, 31).

### Deer Creek IV

A change in time-to-peak was indicated on Deer Creek IV when the data was analyzed for the full year record (Figure 32). This change was found significant at the 95 per cent level (Appendix I, Table II). Average time-to-peak increased, minimum time-to-peak decreased, and maximum time-to-peak increased following treatment (Table I).

Due to an insufficient number of storms during the fall period, it was not possible to divide the data into fall and winter periods.

## Recession

Analysis of recession flow using 24, 48 and 72 hours following the peak of each event showed very low correlations between the treated watersheds and the control. The $r^2$ values ranged from 0.2 to 0.8. Because of this wide range in correlation coefficients, the recession parameter has not been included in the graphical or tabular presentations.

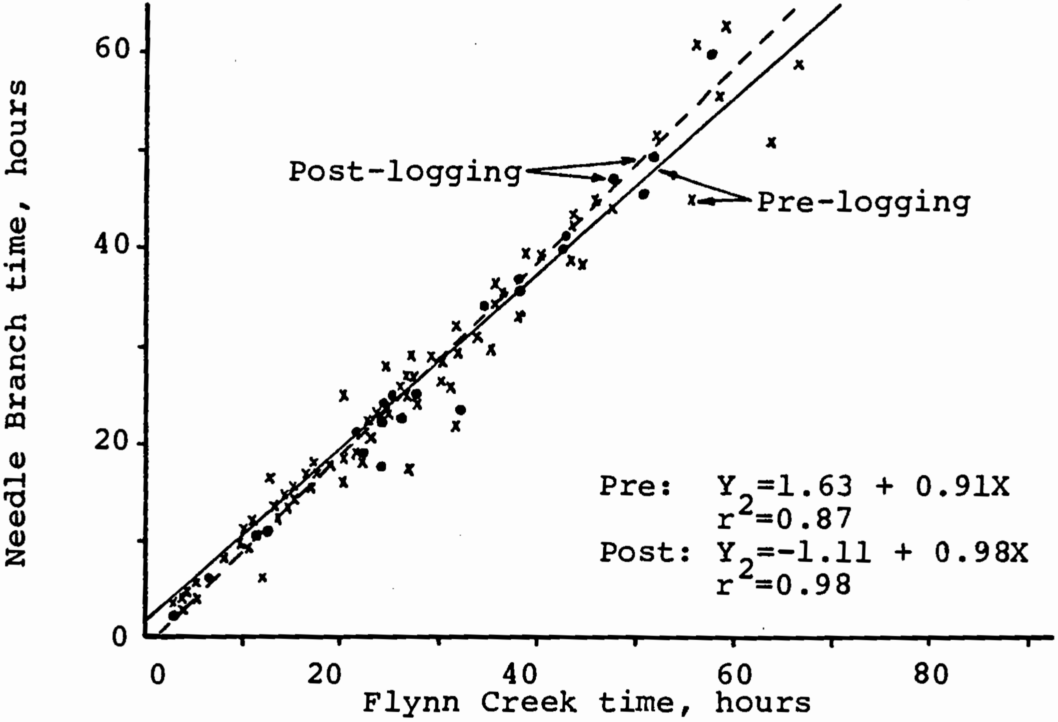

Figure 29. Time-to-peak on Needle Branch regressed on Flynn Creek for full period, pre- and post-logging.

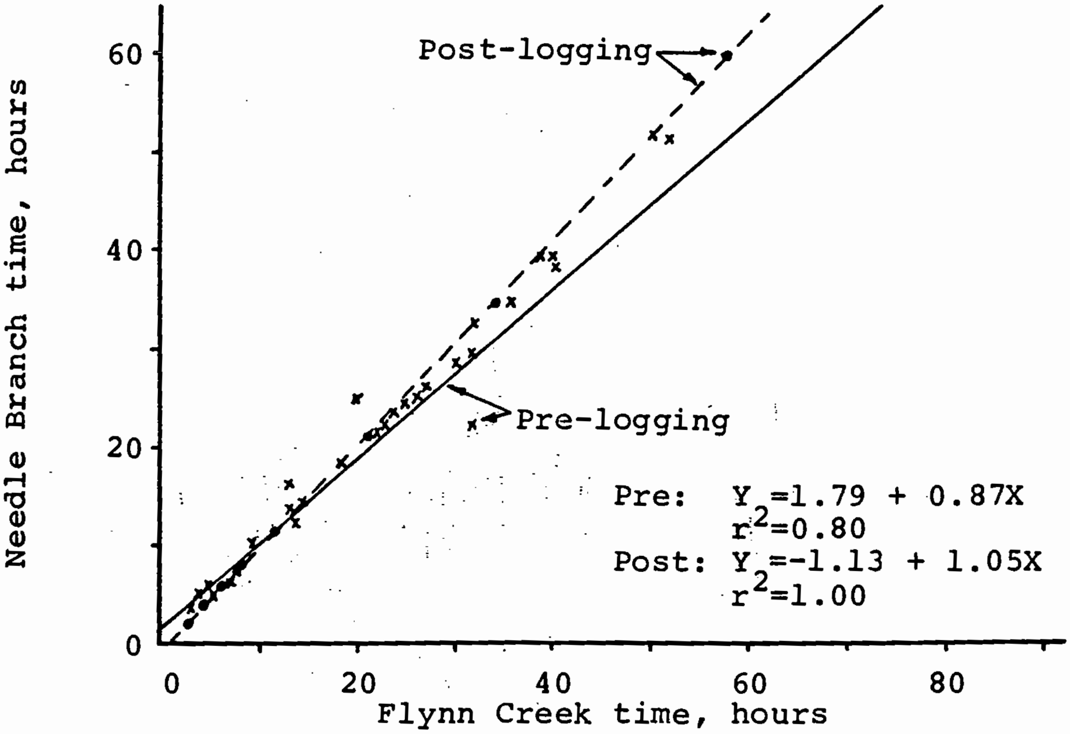

Figure 30. Time-to-peak on Needle Branch regressed on Flynn Creek for fall period, pre- and post-logging.

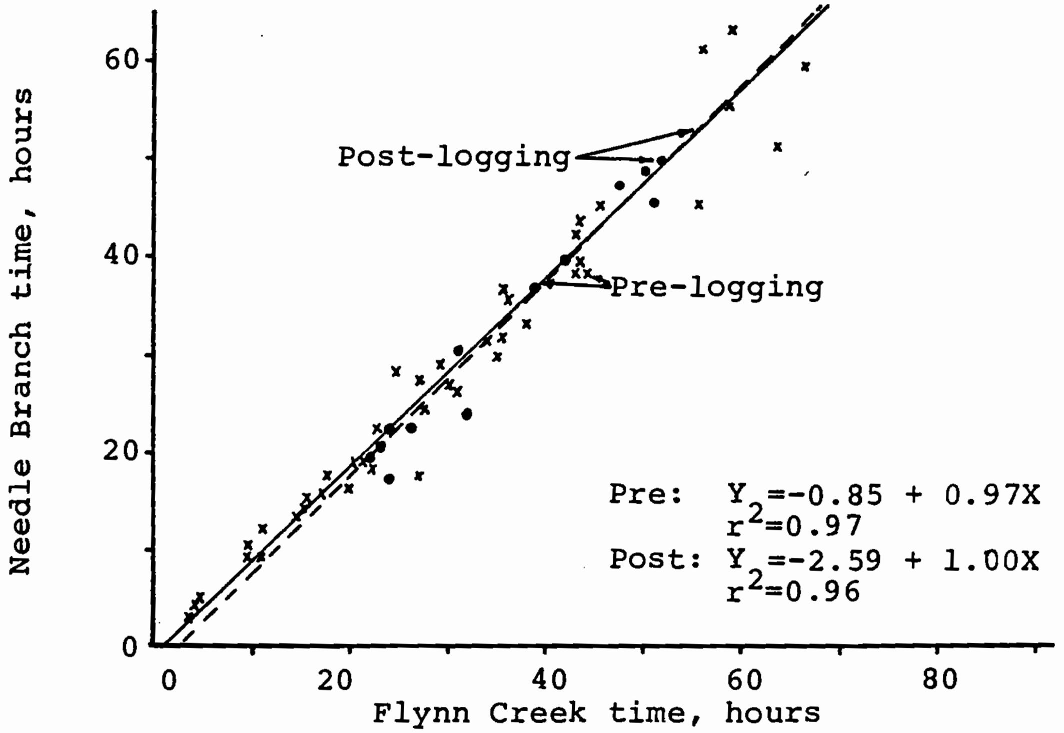

Figure 31. Time-to-peak on Needle Branch regressed on Flynn Creek for winter period, pre- and post-logging.

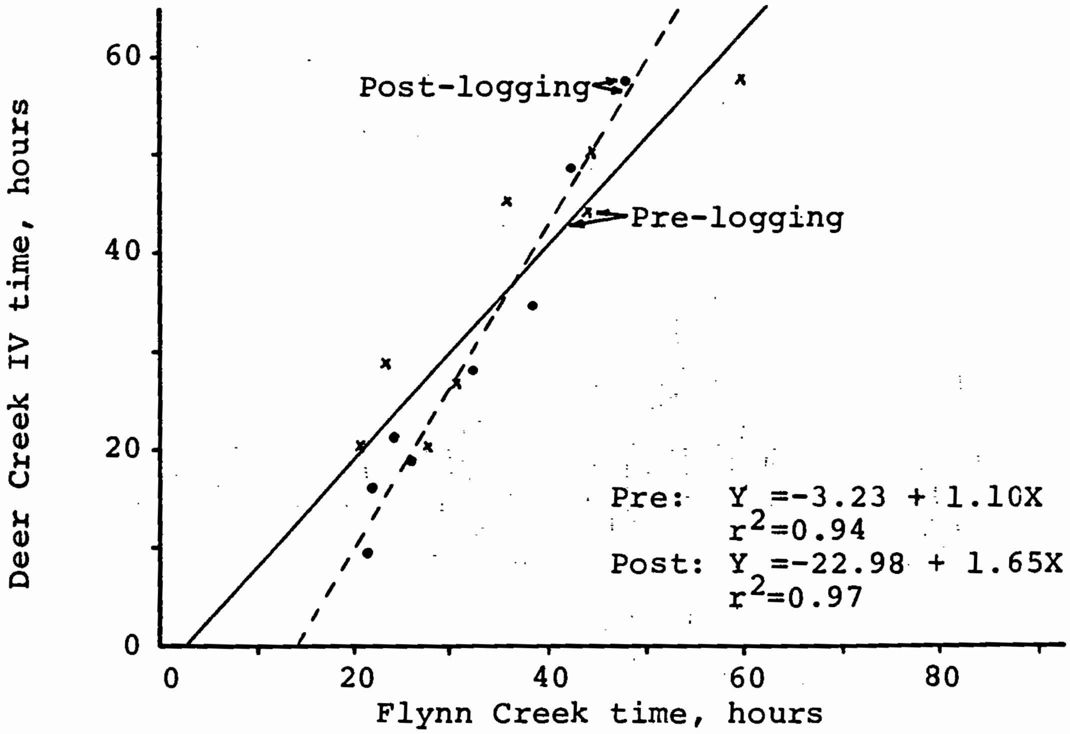

Figure 32. Time-to-peak on Deer Creek IV regressed on Flynn Creek for full period, pre- and post-logging.

# DISCUSSION

Past studies concerned with forest removal have indicated that changes in runoff relations should be manifested by changes of hydrograph shape. In this study increases of peak discharge were found on both Needle Branch and Deer Creek IV following clearcut logging. Volume parameters of quick flow, delayed flow, and total flow were increased for Needle Branch but not for Deer Creek IV. Time-to-peak relations were decreased for low flows and increased for high flows on Deer Creek IV only. These changes in stream hydrology, as reflected by hydrograph changes, demonstrate a change in runoff relations has occurred as a result of forest removal and burning.

## Peak Discharge

Seasonal variation in peak discharge can be accounted for by the role of evapotranspiration on soil moisture storage, as reported by Reinhart (1963), Ziemer (1964) and others. They indicated that the larger increases in flow from a clearcut watershed should occur during the fall recharge period because reduced evapotranspiration should cause the moisture level in the soil to remain at a higher level than on a similar forested area. This would result in a reduction of water required to satisfy depleted storage on the clearcut area. The findings of this study substantiate the results and conclusions of the previous studies. Peak discharges were increased in both fall and winter; however, much larger increases were indicated during the fall period (Table 1).

Increases in winter peaks can be explained by the evapotranspiration process presented above. Evapotranspiration does occur from a forested watershed during the winter period, however the rate is less as compared to the summer growing season. Because of evapotranspiration and subsurface drainage the watershed does not remain at the same level of wetness for the full winter period. The "winter period" in this study included the months of December through March. During this period, cutover watersheds may cycle less water than unforested watersheds to evapotranspiration between storms. Therefore, peak flows should be larger from the clearcut watershed. The effect would not be as great for the winter period as during the fall because the intervals between storms are insufficient to produce a major effect on storage.

Interception has a role as part of total evapotranspiration both for the fall and winter periods. Storage on leaf surfaces must be satisfied before appreciable amounts of water will reach the ground. This effect however diminishes with increasing storm duration. Increase from reduced interception can be expected but the effect on the total increase is probably minor even for short duration storms.

Another contributing factor, other than vegetative changes, that might result in increased flow following forest removal is a change in infiltration and percolation characteristics of the soil. Soil compaction may result from road construction, tree felling and tree removal. As compaction occurs infiltration tends to decrease and surface runoff tends to increase. Decreased infiltration may also be due to rain drop impact on exposed soils which can cause clogging of pores of surface soil. Infiltration has also been shown to decrease following burning due to the formation of a hydrophobic surface layer on some soils in southern California (DeBano, Osborn, Krammes and Letey, 1967).

Differences between Needle Branch and Deer Creek IV with respect to peak discharge were not discernable. Increases of peak discharge in terms of csm, were of the same magnitude for both streams. The fact that burning was a part of the treatment on Needle Branch did not seem to make an appreciable difference.

The large increase in average flows is significant because these flows recur with the greatest frequency. This would be of greater importance to total quantity of flow over a given time interval than it would be to structural design. With respect to design, the maximum peak flows expected would be of greater importance. As noted in the scatter diagrams (Figures 7 through 12), however, this is where observations tend to be more widely scattered and interpretation should be made with caution.

## Height-Of-Rise

Height-of-rise of the flood hydrograph did not increase as a result of clearcut logging as would be expected considering the results of the peak discharge analysis. This variable should offer a means of comparison free from error due to rating table construction. However, there are too many factors involved in this study to make it of value for detection of change. Differences in control sections between watersheds, as well as changes over time of one or both sections, rendered this variable valueless.

## Volume

There is evidence to suggest that fall quick flow volumes were increased more than winter volumes, even though a statistically significant difference between fall and winter data was not indicated. The points in the regression analysis for three fall storms following logging (Figure 18) indicate a much greater response than either the winter relation or the fall relation before treatment. Unfortunately these points all lie at the low end of the relation and therefore do not carry enough weight to show a significant difference from the full range of winter data. There is a strong possibility that if the data had included points at the upper end of the regression relation a difference would have been noted.

The Deer Creek IV analysis did not indicate a change in any of the volume parameters. It cannot be stated with certainty that this is a true response of the watershed because there may have been insufficient data to detect a change.

The fall period for Needle Branch indicated much larger increases than the winter period for all three volume parameters; quick flow, delayed flow, and total flow. A possible explanation for increases in these volume parameters is related to reduced evapotranspiration and the resulting reduction in soil moisture depletion following logging. The effect would not be as great during the winter as during the fall however, due to less soil moisture depletion between storms during the winter period.

Factors other than vegetative considerations which may have caused a part of the increases in volume are the alterations in the infiltration and percolation relations. As discussed under peak discharge, both infiltration and percolation rates may have been decreased as a result of soil compaction during the logging operation. This is not thought to be a large factor, however, due to the high infiltration rates characteristic of the area, even following logging.

The higher variation of data during the winter period reflects the effect of antecedent conditions on watershed response. Variation in antecedent conditions is at a maximum during the winter period when the watershed may reach varying degrees of dryness between subsequent storms. This variation in response due to antecedent conditions indicates that for future studies a data separation procedure based on antecedent conditions would be better than one based only on a seasonal separation as used in this study. A more satisfactory separation might be based on antecedent moisture conditions, such as time since last rainfall, soil moisture stress or base flow.

## Time-To-Peak

Following logging on Deer Creek IV, the time required to reach a flood peak following the initial rise was decreased for low flows and increased for high flows. Any change in time-to-peak must reflect changes in travel time of the runoff from the watershed in question. This would indicate changes in detention storage. The observed phenomenon may be explained by changes in infiltration and hydraulic conductivity of the soil. Initially, infiltration and hydraulic conductivity on the clearcut area are both lower than those on similar forested areas due to compaction resulting from the logging operation. As rainfall continues, storage in the soil is filled more readily on the uncut area and a point in time is reached when infiltration on the logged area is greater. This is because reduced infiltration and conductivity increases the time required to fill soil moisture storage. This process could result in the availability of more water for runoff in a shorter time, and therefore a shorter time of concentration for small events. For large events, however, the time of concentration is increased. The result from this study with respect to this parameter agree with the results found by Gilleran (1968) in a study of the effect of road building on these same experimental watersheds.

Time-to-peak was not altered on Needle Branch. The reason is not readily apparent but it may be related to watershed size and soil characteristics that differ from Deer Creek IV.

## Hydrograph Shape

It has been demonstrated by the analysis of individual variables that peak discharge, quick flow, delayed flow, and total flow have all increased following clearcut logging on Needle Branch. These changes can be illustrated by comparison of hydrographs prior to logging with hydrographs following logging. For example, a fall storm and a winter storm in the pre-logging period were compared with a fall and winter storm during the post-logging period for each basin (Figures 33 through 35). Storms were selected that produced equal peaks on Flynn Creek, the control. The hydrographs of Flynn Creek and Needle Branch produced by these storms are compared in Figure 33 (fall storms) and Figure 34(winter storms). The greater response of the fall period storms may be noted by comparing Figures 33 and 34. The difference in response of Needle Branch in both figures is indicative of clearcut logging effect.

The change in response for actual storms occurring

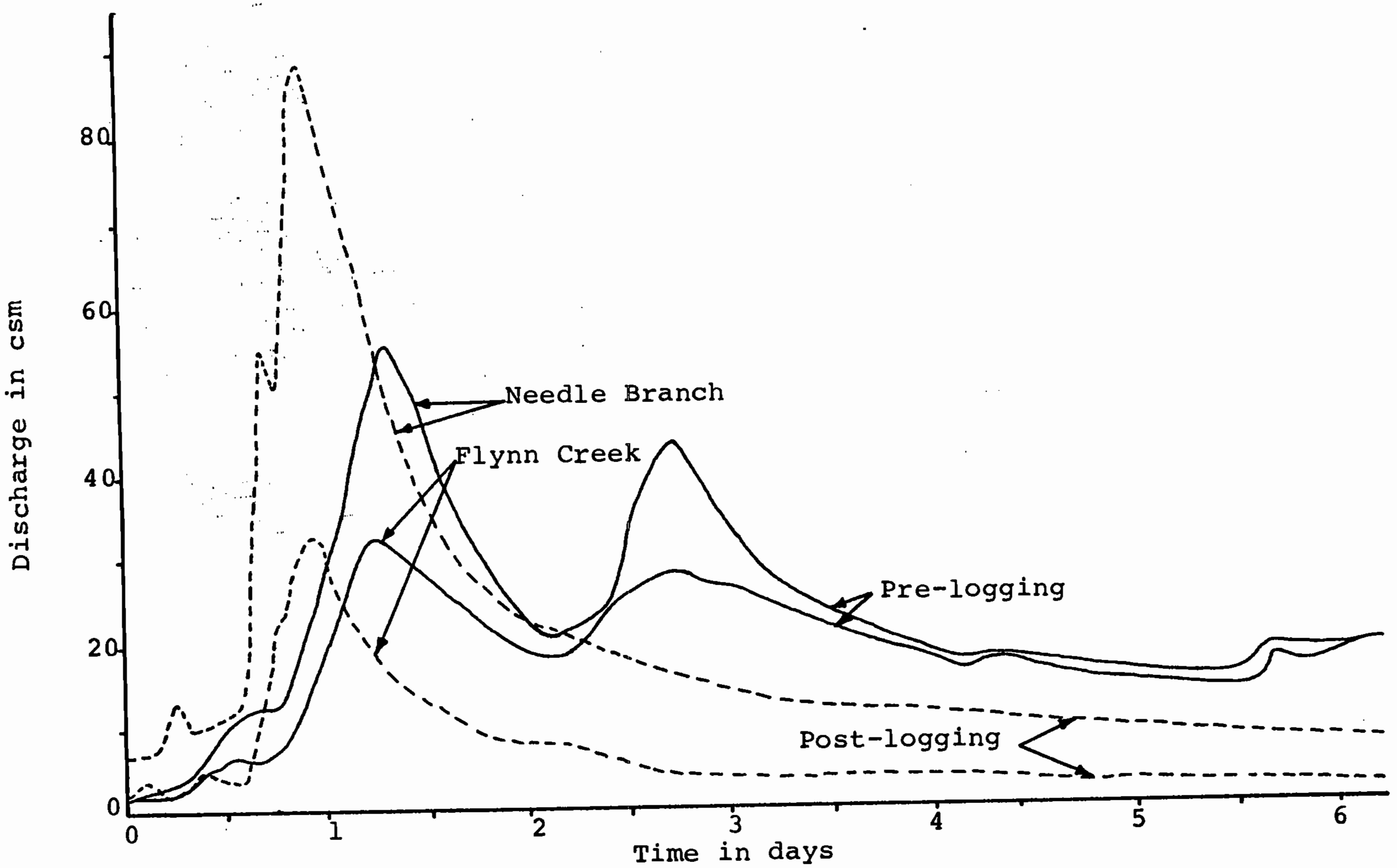

Figure 33. Hydrographs of Nov. 24, 1964 and Oct. 27, 1967 for Needle Branch and Flynn Creek illustrating pre-logging and post-logging relationships for the fall period.

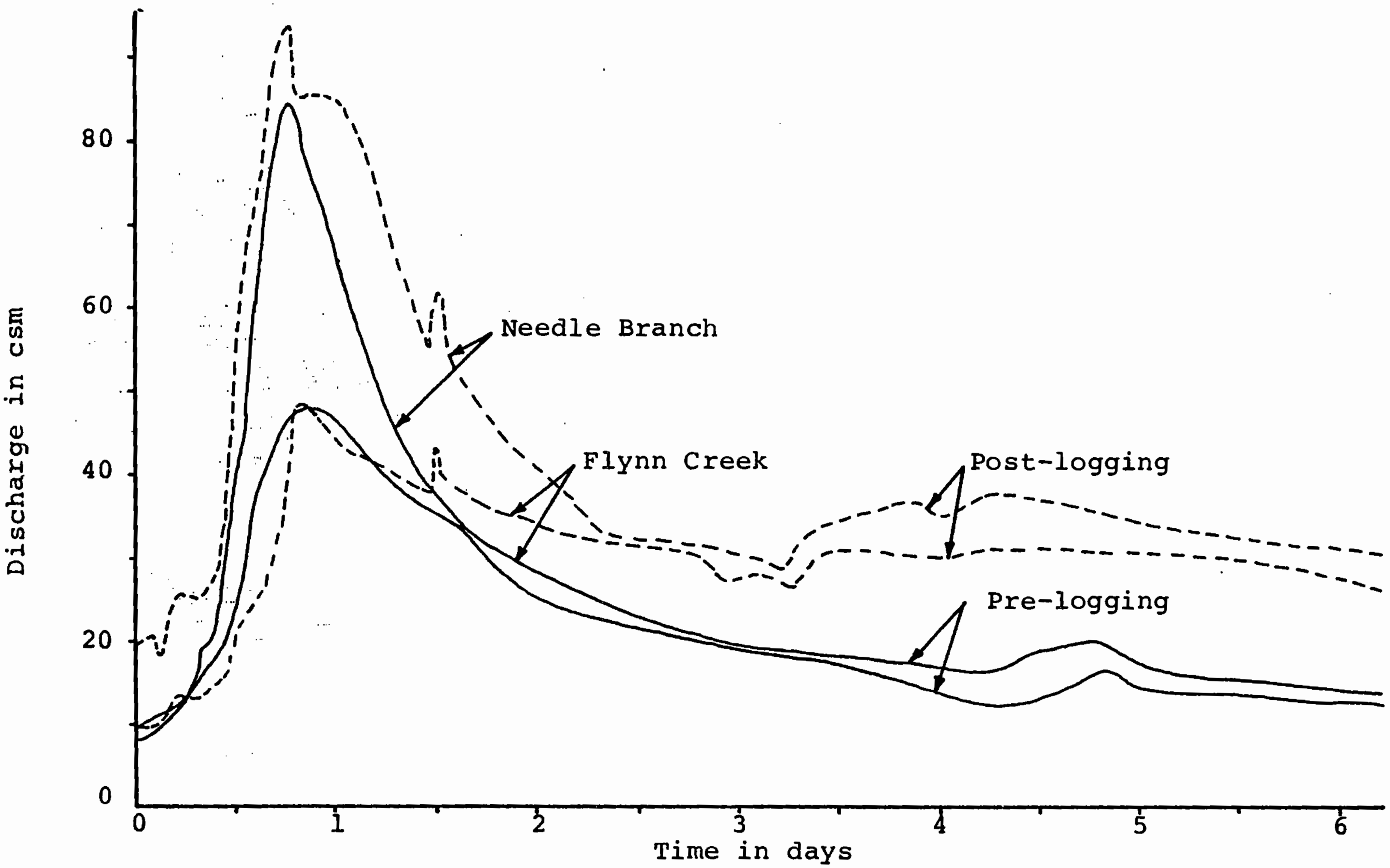

Figure 34. Hydrographs of Jan. 6, 1964 and Dec. 4, 1966 for Needle Branch and Flynn Creek illustrating pre-logging and post-logging relationships for the winter period.

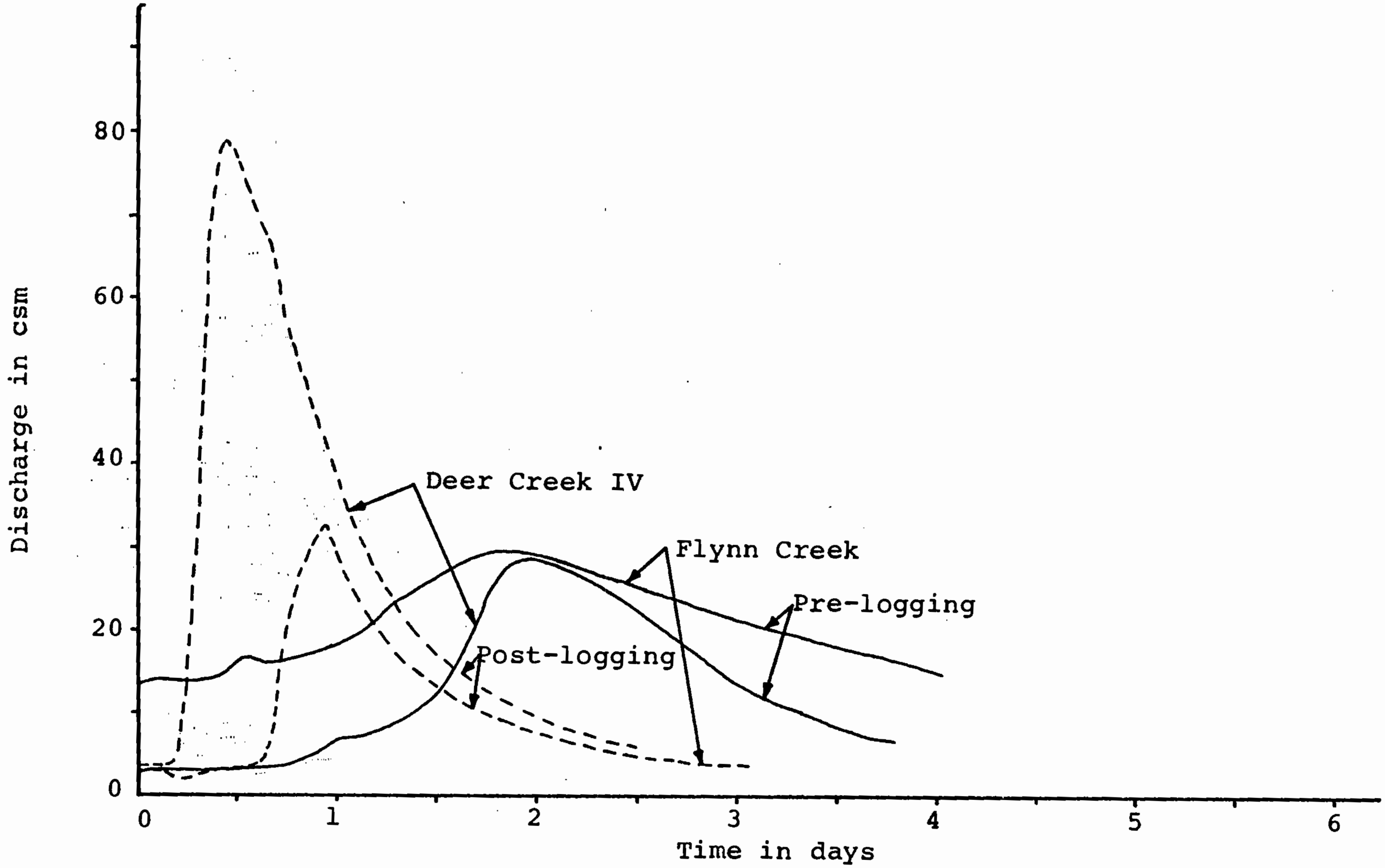

Figure 35. Hydrographs of Jan. 15, 1966 and Oct. 27, 1967 for Deer Creek IV and Flynn Creek illustrating pre-logging and post-logging relationships for the fall period.

on Deer Creek IV during the fall period is presented in Figure 35. Peak discharge and volume are both shown to increase significantly. The change in the time-to-peak parameter may also be noted in this figure. For the storm representing the pre-logging period, the storm peak occurs at very nearly the same point in time. Following logging, illustrated by the two dashed lines, the time-to-peak is much shorter on Deer Creek IV. This is the same result as found in the preceding parameter analysis where time-to-peak decreased by 200 per cent for the shorter duration storms.

Base flow recession also appears to have increased as a result of logging. This statement is based on Figures 33 and 34. In both figures the base flow recession for Needle Branch prior to logging is below or almost coincident with that on Flynn Creek. Following logging however, the base flow recession remains above that of Flynn Creek for almost the whole period of six days shown in the figures.

# CONCLUSIONS

This study has indicated a change in the hydrology of small coastal streams in Oregon as a result of clearcut logging. These changes are reflected in alteration of hydrograph shape as defined by peak discharge, volume, and time-to-peak. Conclusions drawn from these changes are:

1. Peak discharge was increased from both Needle Branch and Deer Creek IV, the largest increases occurring during the fall period. Increases were of similar magnitude for both watersheds.

2. Burning on Needle Branch did not produce a noticable difference when compared to Deer Creek IV, the unburned watershed.

3. Volume of flow was increased from Needle Branch. This was reflected in changes in quick flow, delayed flow, and total flow, with the largest increases occurring during the fall period.

4. Volume of flow was not shown to increase from Deer Creek IV. This may have been due to a lack of usable storm events for analysis from this watershed.

5. Time-to-peak was altered on Deer Creek IV but not on Needle Branch. Time-to-peak was decreased for minimum flows and increased for high flows.

6. The use of the height-of-rise parameter for detecting change may be questionable if channel controls lacking a constant stage discharge relation with time are involved.

7. In future studies of this type there is need for a data separation procedure based on antecedent conditions rather than on time of year.

8. The method of analysis used in this study has demonstrated its ability to detect hydrologically significant change.

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# APPENDIX I

Table I. Summary of statistics for Needle Branch including number of observations(n), $r^2$, t for slope($t_s$), t for vertical position($t_m$), and variance, for years 1957-68.

| Parameter | Pre-log |  | Post-log |  | $t_s$1/ | $t_m$2/ | Variance |  |
|---|---|---|---|---|---|---|---|---|
|  | n | $r^2$ | n | $r^2$ |  |  | Pre-logging | Post-logging |
| Peak discharge(csm) |  |  |  |  |  |  |  |  |
| Full year | 101 | 0.94 | 29 | 0.80 | 2.58**4/ |  | 67.84 | 188.77 |
| Fall | 44 | .95 | 9 | .98 | 6.58** |  | 34.04 | 14.59 |
| Winter | 49 | .94 | 17 | .83 | 2.68** |  | 81.68 | 165.09 |
| Height-of-rise(ft.) |  |  |  |  |  |  |  |  |
| Full year | 100 | .93 | 26 | .85 | 1.31 | 0.80 | .01 | .01 |
| Fall | 44 | .93 | 8 | .88 | .90 | .77 | .01 | .02 |
| Winter | 48 | .93 | 15 | .85 | 1.26 | .05 | .01 | .01 |
| Quick flow(csm-hr.) |  |  |  |  |  |  |  |  |
| Full year | 32 | .97 | 12 | .87 | .08 | 2.17*3/ | 154601.96 | 339439.81 |
| Fall | 14 | .98 | 3 | .91 | 2.29* | 3.77** | 51023.91 | 96718.09 |
| Winter | 18 | .96 | 9 | .84 | .31 | 1.25 | 243787.94 | 408288.95 |
| Delayed flow(csm-hr.) |  |  |  |  |  |  |  |  |
| Full year | 32 | .83 | 12 | .85 | 1.71 | 2.60** | 90450.10 | 105526.96 |
| Fall | 14 | .98 | 3 | .90 | 3.22** |  | 7201.80 | 26247.63 |
| Winter | 18 | .66 | 9 | .85 | 2.41* | 2.45* | 137965.04 | 83189.56 |
| Total flow(csm-hr.) |  |  |  |  |  |  |  |  |
| Full year | 32 | .98 | 12 | .87 | .48 | 3.31** | 136602.07 | 639901.05 |
| Fall | 14 | .99 | 3 | .90 | 3.14** |  | 156814.57 | 228660.69 |
| Winter | 18 | .98 | 9 | .83 | 1.00 | 2.49* | 167701.38 | 728108.73 |
| Time-to-peak(hr.) |  |  |  |  |  |  |  |  |
| Full year | 99 | .87 | 26 | .98 | .89 | -.57 | 43.25 | 5.42 |
| Fall | 44 | .80 | 8 | 1.00 | 1.50 | .28 | 29.84 | .64 |
| Winter | 47 | .97 | 15 | .96 | .41 | -.78 | 11.36 | 6.15 |

1/ $t_s$ is the computed t value for change in slope.

2/ $t_m$ is the computed t value for change in vertical position.

3/ * significance at the 95 per cent level.

4/ ** significance at the 99 per cent level

Table II. Summary of statistics for Deer Creek IV including number of observations (n), $r^2$, t for slope($t_s$), t for vertical position($t_m$), and variance, for years 1965-68.

| Parameter | Pre-log |  | Post-log |  |  |  | Variance |  |
|---|---|---|---|---|---|---|---|---|
|  | n | $r^2$ | n | $r^2$ | $t_s$1/ | $t_m$2/ | Pre-logging | Post-Logging |
| Peak discharge(csm) |  |  |  |  |  |  |  |  |
| Full year | 21 | 0.95 | 20 | 0.80 | 0.32 | 3.27**3/ | 165.46 | 170.89 |
| Fall | 3 | .93 | 3 | .97 | 1.85 | 4.43** | 55.04 | 51.55 |
| Winter | 18 | .95 | 17 | .90 | .67 | 2.65** | 191.78 | 92.59 |
| Height-of-rise(ft.) |  |  |  |  |  |  |  |  |
| Full year | 10 | .97 | 9 | .85 | - .14 | -2.03 | 289518.50 | 67750.74 |
| Quick flow(csm-hr.) |  |  |  |  |  |  |  |  |
| Full year | 10 | .97 | 7 | .96 | - .96 | .33 | 136708.99 | 81836.73 |
| Delayed flow(csm-hr.) |  |  |  |  |  |  |  |  |
| Full year | 10 | .37 | 7 | .70 | 1.07 | 1.21 | 175881.88 | 282816.72 |
| Total year(csm-hr.) |  |  |  |  |  |  |  |  |
| Full year | 10 | .99 | 7 | .90 | -1.27 | 1.07 | .01 | .02 |
| Time-to-peak(hr.) |  |  |  |  |  |  |  |  |
| Full year | 10 | .94 | 9 | .97 | 2.93*4/ |  | 32.25 | 10.76 |

1/ $t_s$ is the computed t value for change in slope
2/ $t_m$ is the computed t value for change in vertical position
3/ ** significance at the 99 per cent level
4/ * significance at the 95 per cent level

Table III. Summary of statistical results for test to determine difference between fall and winter data, including number of observations(n), $r^2$, t for slope($t_s$), and t for vertical position($t_m$), as tested against the control.

| Watershed | Variable | Period | n | $r^2$ | $t_s$ 1/ | $t_m$ 2/ |
|---|---|---|---|---|---|---|
| | | | Winter/Fall | Winter/Fall | | |
| Needle Branch | Peak Discharge | Pre | 49/44 | 0.87/0.95 | 4.88** 3/ | |
| | | Post | 17/9 | 0.83/0.98 | 3.10** | |
| Needle Branch | Quick Flow | Pre | 18/14 | 0.96/0.98 | 0.81 | -0.13 |
| | | Post | 9/3 | 0.84/0.91 | 0.89 | 0.97 |
| Needle Branch | Delayed Flow | Pre | 18/14 | 0.66/0.98 | 2.21* 4/ | |
| | | Post | 9/3 | 0.85/0.90 | 0.89 | 1.51 |
| Needle Branch | Total Flow | Pre | 18/14 | 0.98/0.99 | 2.30* | |
| | | Post | 9/3 | 0.83/0.90 | 1.01 | 1.21 |
| Deer Creek IV | Peak Discharge | Pre | 17/3 | 0.95/0.93 | 0.24 | 0.33 |
| | | Post | 16/3 | 0.93/0.97 | 2.22* | |

1/ $t_s$ is the computed t value for change in slope
2/ $t_m$ is the computed t value for change in vertical position
3/ ** significance at the 99 per cent level
4/ * significance at the 95 per cent level

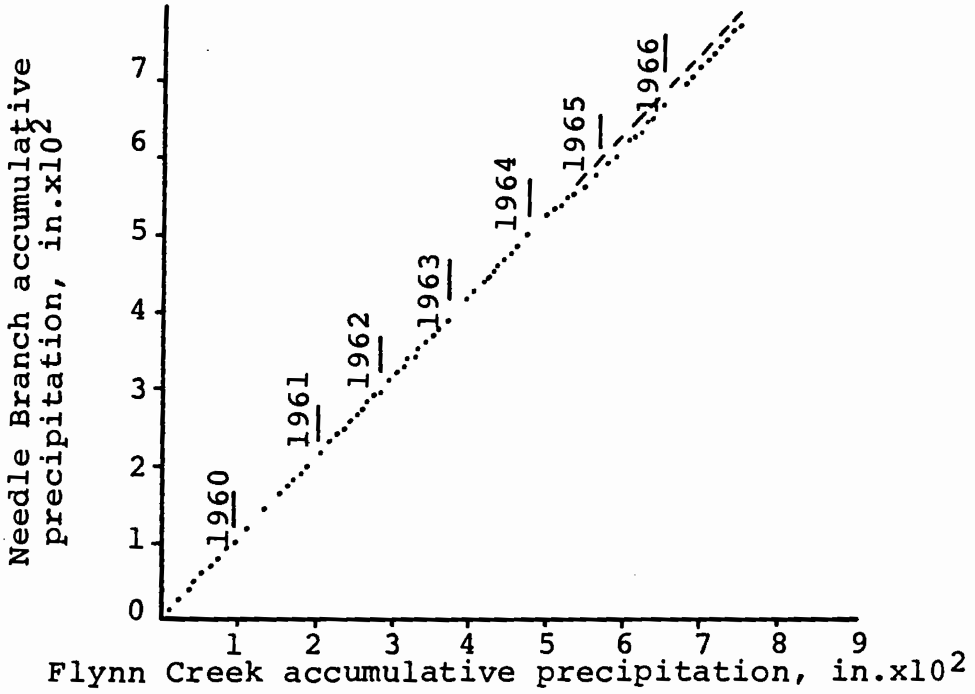

Figure I. Double-mass-analysis of precipitation for Needle Branch and Flynn Creek, years 1960 through 1967.

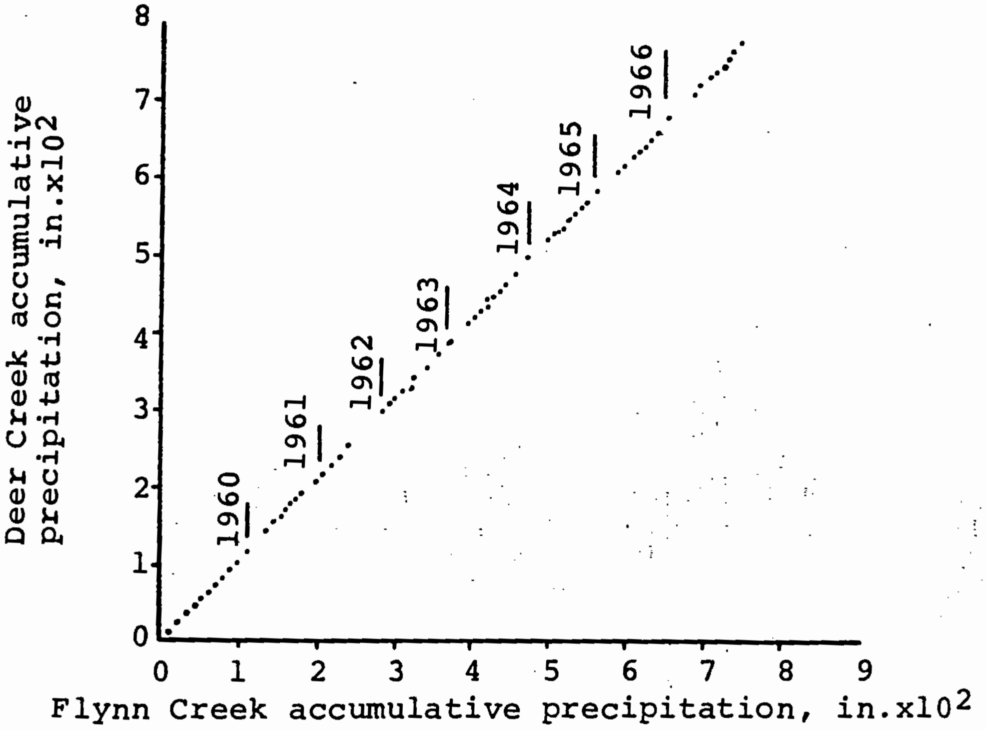

Figure II. Double-mass-analysis of precipitation for Deer Creek and Flynn Creek, years 1960 through 1967.

# APPENDIX II

Data for hydrographs and parameters were placed on IBM cards using the format presented below. This format must be used in conjunction with the following computer programs.

Hydrograph Cards

| Description | Column |
|---|---|
| Watershed Number | 1- 2 |
| 1 = Flynn Creek | |
| 4 = Deer Creek IV | |
| 5 = Needle Branch | |
| Year | 3- 4 |
| Month | 5- 6 |
| Day | 7- 8 |
| Time (0 to 2400 hours) | 9-12 |
| Discharge (in csm) | 13-17 |
| Time | 18-21 |
| Discharge | 22-26 |
| Time | 27-30 |
| Discharge | 31-35 |
| Time | 36-39 |
| Discharge | 40-44 |
| Time | 45-48 |
| Discharge | 49-53 |
| Time | 53-57 |
| Discharge | 58-62 |
| Time | 63-66 |
| Discharge | 67-71 |
| Time | 72-75 |
| Discharge | 76-80 |

Parameter Cards

| Description | Column |
|---|---|
| Storm Number | 1- 3 |
| Watershed Number | 4- 6 |
| Month | 7- 9 |
| Day | 10-12 |
| Year | 13-15 |
| Time-to-peak | 16-21 |
| Height-of-rise | 22-26 |
| Peak Discharge | 27-33 |
| Peak + 24 hours | 34-38 |
| Peak + 48 hours | 39-43 |
| Peak + 72 hours | 44-48 |
| Quick flow | 49-56 |
| Delayed flow | 51-64 |
| Total flow | 65-72 |

# PROGRAM FOR HYDROGRAPH SEPARATION

```
      PROGRAM FOR HYDROGRAPH SEPARATION
      DIMENSION A (400,5)
      DIMENSION B (8,4,50)
      DIMENSION M (400,4)
      DIMENSION N (4,50)
    1 FORMAT(1H1)
    3 FORMAT(4I2,8(2F2.0,F5.2))
   10 FORMAT(20X,*WATERSHED*,I4/24X,*19*,I2///)
   11 FORMAT(16X,*INITIAL HYDROGRAPH RISE AT*/)
   12 FORMAT(22X,*MONTH*,I5/22X,*DAY*,I7/22X,*TIME*,F9.2,2X,*HOURS*/22X,
     1*FLOW*,F9.2,2X,*CSM*///)
   13 FORMAT(20X,*HYDROGRAPH*//10X,*MONTH  DAY   TIME   TIME/START   FLO
     1W*/22X,*(HOUR)    (HOURS)     (CSM)*/)
   14 FORMAT(10X,I3,I7,F8.2,F9.2,F10.2)
   15 FORMAT(20X,F8.2,F9.2,F10.2)
   16 FORMAT(///10X,*HYDROGRAPH SEPARATION COMPLETED AT*/)
   22 FORMAT(///10X,*HYDROGRAPH CHARACTERISTICS FOR STORM*//)
   23 FORMAT(10X,*SEPARATION BEGAN - MONTH*,I3,* - DAY*,I3,* - TIME*,F6.
     12,* - CSM*,F7.2)
   24 FORMAT(10X,*SEPARATION ENDED - MONTH*,I3,* - DAY*,I3,* - TIME*,F6.
     12,* - CSM*,F7.2)
   25 FORMAT(/10X,*SLOPE OF SEPARATION LINE = 0.05 CSM/HR*/)
   26 FORMAT(10X,*TOTAL QUICK FLOW*,F17.2,2X,*CSM/STORM*)
   27 FORMAT(10X,*TOTAL DELAYED FLOW*,F15.2,2X,*CSM/STORM*)
   28 FORMAT(10X,*TOTAL FLOW / STORM*,F15.2,2X,*CSM/STORM*)
   29 FORMAT(/10X,*PEAK FLOW*11X,F13.2,2X,*CSM*)
   30 FORMAT(10X,*TIME OF PEAK (HOURS)*,F13.2,2X,*HOURS*)
   31 FORMAT(10X,*TIME TO PEAK (FROM START)*,F8.2,2X,*HOURS*)
   32 FORMAT(10X,*FLOW AT PEAK + 24 HRS*,F12.2,2X,*CSM*)
   33 FORMAT(10X,*FLOW AT PEAK + 48 HRS*,F12.2,2X,*CSM*)
   34 FORMAT(10X,*FLOW AT PEAK + 72 HRS*,F12.2,2X,*CSM*)
   35 FORMAT(10X,*FLOW AT PEAK + 96 HRS*,F12.2,2X,*CSM*)
   80 FORMAT(//1X,*TRAILER CARD READ BEFORE HYDROGRAPH SEPARATION COMPLE
     1TED - PROGRAM ABORTED*)
   81 FORMAT(//1X,*END OF FILE CARD PROCESSED - PROGRAM ENDED*)
  100 DO 101 I=1,8
      DO 101 J=1,4
      DO 101 K=1,50
      B(I,J,K)=0.
      N(J,K)=0
  101 CONTINUE
      IX=0
      L=0
      VCSM=0.
      DO 109 K=1,50
      READ(60,3)(N(L,K), L=1,4),((B(I,J,K), J=1,3), I=1,8)
      GO TO (500,106),EOFCKF (60)
  106 IF(N(1,K).EQ.99)110,109
  109 CONTINUE
  110 I=1
      DO 112 K=1,50
      DO 112 L=1,8
      DO 111 J=1,3
      A(I,J)=B(L,J,K)
  111 CONTINUE
      A(I,4)=A(I,1)+A(I,2)/60.
      I=I+1
  112 CONTINUE
      I=1
      DO 117 K=1,50
      DO 117 L=1,8
      DO 116 J=1,4
      M(I,J)=N(J,K)
  116 CONTINUE
      I=I+1
  117 CONTINUE
      I=0
  118 I=I+1
      COM1=A(I,3)+0.10
      IF(A(I,4).EQ.24.)119,123
  119 IL=0
      IL=I
      I=I+1
      IF(A(I,4).EQ.0.)120,123
  120 I=I+1
      IF(A(I,4).EQ.0.)120,121
  121 COM2=A(I,3)
      I=I-1
      IF(COM1.LT.COM2)122,118
  122 I=IL
      GO TO 124
  123 COM2=A(I+1,3)
      IF(COM1.LT.COM2)124,118
C*****HYDROGRAPH SEPARATION BEGINS
  124 WRITE(61,1)
      WRITE(61,10)M(I,1),M(I,2)
      WRITE(61,11)
      WRITE(61,12) M(I,3),M(I,4),A(I,4),A(I,3)
      WRITE(61,13)
      IC=I
      T=0.
      TS=0.
      ST=A(I,3)
      SL=A(I,3)
  125 WRITE(61,14) M(I,3),M(I,4),A(I,4),TS,A(I,3)
  126 IX=IX+1
      IF(A(I,4).EQ.24.)128,127
  127 T=A(I+1,4)-A(I,4)
      GO TO 140
  128 IL=I
  129 I=I+1
      IF(M(I,1).EQ.99)490,200
  200 IF(A(I,4).EQ.0.)129,130
  130 T=A(I,4)
      TS=TS+T
      A(I+1,5)=TS
      SL=SL+T*0.05
      VCSM=VCSM+T*((A(IL,3)+A(I,3))/2.)
      IF(IX.GT.9.)131,125
  131 IF(M(I,1).EQ.99)490,132
  132 IF(SL.GT.A(I,3))150,125
  140 TS=TS+T
      A(I,5)=TS
      SL=SL+T*0.05
      VCSM=VCSM+T*((A(I,3)+A(I+1,3))/2.)
      IF(IX.GT.9.)141,145
  141 IF(M(I,1).EQ.99)490,142
  142 IF(SL.GT.A(I,3))150,145
  145 I=I+1
      WRITE(61,15)A(I,4),TS,A(I,3)
      GO TO 126
  150 WRITE(61,16)
      WRITE(61,12)M(I,3),M(I,4),A(I,4),A(I,3)
      WRITE(61,1)
      WRITE(61,10)M(IC,1),M(IC,2)
      WRITE(61,22)
      WRITE(61,23)M(IC,3),M(IC,4),A(IC,4),A(IC,3)
      WRITE(61,24)M(I,3),M(I,4),A(I,4),A(I,3)
      WRITE(61,25)
      VDF=TS*A(IC,3)+(((A(I,3)-A(IC,3))*TS)/2.)
      VQF=VCSM-VDF
      WRITE(61,26)VQF
      WRITE(61,27)VDF
      WRITE(61,28)VCSM
      IEND=I
      AMAX=A(I,3)
      DO 159 I=2,400
      IF(A(I,3).GT.AMAX)155,159
  155 IMAX=I
      AMAX=A(I,3)
  159 CONTINUE
      I=IMAX
      WRITE(61,29)A(I,3)
      WRITE(61,30)A(I,4)
      WRITE(61,31)A(I-1,5)
      TP=A(I-1,5)
  160 I=I+1
      IF(I.GE.IEND)100,161
  161 IF(A(I,5).GE.TP+24.)162,160
  162 WRITE(61,32)A(I,3)
  170 I=I+1
      IF(I.GE.IEND)100,171
  171 IF(A(I,5).GE.TP+48.)172,170
  172 WRITE(61,33)A(I,3)
  180 I=I+1
      IF(I.GE.IEND)100,181
  181 IF(A(I,5).GE.TP+72.)182,180
  182 WRITE(61,34)A(I,3)
  190 I=I+1
      IF(I.GE.IEND)100,191
  191 IF(A(I,5).GE.TP+96.)192,190
  192 WRITE(61,35)A(I,3)
  490 WRITE(61,80)
      GO TO 100
      GO TO 100
  500 WRITE(61,81)
      STOP
      END
```

# PROGRAM FOR REGRESSION ANALYSIS

```
      PROGRAM FOR REGRESSION ANALYSIS
      DIMENSION A(200,14),B(200,14),XNAME(15),YNAME(15)
      DO 62 M=1,2
      KOUNT=IN=SUMX=SUMY=SUMXY=SUMX2=SUMY2=NN=0
      DO 4 I=1,500
      READ(60,100)(A(I,J),J=1,14)
      IF(A(I,1).EQ.999.)5,4
    4 KOUNT=KOUNT+1
    5 DO 16 I=1,500
      READ(60,100)(B(I,J),J=1,14)
      IF(B(I,1).EQ.999.)17,16
   16 CONTINUE
   17 READ(60,101)J,CON,(XNAME(I),I=1,15),(YNAME(I),I=1,15)
      GO TO (6,7,8),CON
    6 WRITE(61,125)
      GO TO 10
    7 WRITE(61,124)
      GO TO 10
    8 WRITE(61,126)
   10 DO 9 I=1,KOUNT
      IF(A(I,1)-B(I,1))60,9,60
    9 CONTINUE
      DO 14 I=1,KOUNT
      IF(A(I,J))2,14,2
    2 IF(B(I,J))3,14,3
    3 SUMX=SUMX+A(I,J)
      SUMY=SUMY+B(I,J)
      SUMXY=SUMXY+A(I,J)*B(I,J)
      SUMX2=SUMX2+A(I,J)**2
      SUMY2=SUMY2+B(I,J)**2
      IN=IN+1
   14 CONTINUE
      AVEX=SUMX/IN
      AVEY=SUMY/IN
      SSX=SUMX2-SUMX**2/IN
      B1=(SUMXY-SUMX*SUMY/IN)/(SUMX2-SUMX**2/IN)
      B0=AVEY-B1*AVEX
      REG=(SUMXY-SUMX*SUMY/IN)**2/(SUMX2-SUMX**2/IN)
      TOT=SUMY2-SUMY**2/IN
      RES=TOT-REG
      VAR=RES/(IN-2)
      F=REG/VAR
      R2=REG/TOT
      RESDF=IN-2
      TOTDF=IN-1
      GO TO (44,45),M
   44 IN1=IN
      RES1=RES
      B01=B0
      B11=B1
      SSX1=SSX
      AVEY1=AVEY
      SUMX1=SUMX
      SX21=SUMX2
      AVEX1=AVEX
      DO 71 I=1,KOUNT
      IF(A(I,J).EQ.0.)71,72
   71 CONTINUE
   72 XMIN=A(I,J)
      K=I
      DO 13 I=K,KOUNT
      IF(A(I,J).EQ.0.)13,74
   74 IF(XMIN.GT.A(I,J))15,13
   15 XMIN=A(I,J)
   13 CONTINUE
      XMAX=0
      DO 18 I=1,KOUNT
      IF(XMAX.GT.A(I,J))18,17
   11 XMAX=A(I,J)
   18 CONTINUE
      GO TO 52
   45 IN2=IN
      RES2=RES
      B02=B0
      B12=B1
      SSX2=SSX
      SX22=SUMX2
      AVEY2=AVEY
      SUMX2ND=SUMX
      AVEX2=AVEX
      AVEXB=(SUMX1+SUMX2ND)/(IN1+IN2)
      T1=(B11-B12)/SQRT((RES1+RES2)/(IN1+IN2-4.)*(1./SSX1+1./SSX2))
      W1=IN1*SSX1/(SSX1+IN1*(AVEX1-AVEXB)**2)
      W2=IN2*SSX2/(SSX2+IN2*(AVEX2-AVEXB)**2)
      T2=(AVEY1-AVEY2)/SQRT((RES1+RES2)/(IN1+IN2-4)*(1./W1+1./W2))
      T3=(B01-B02)/SQRT((RES1+RES2)/(IN1+IN2-4.)*(SX21/(IN1*SSX1)+SX22/
     1(IN2*SSX2)))
      X0=(AVEX1+AVEX2)/2.
      X2S1=SX21-2.*X0*SUMX1+IN1*X0**2
      X2S2=SX22-2.*X0*SUMX2ND+IN2*X0**2
      YX01=B01+B11*X0
      YX02=B02+B12*X0
      T4=(YX01-YX02)/SQRT((RES1+RES2)/(IN1+IN2-4.)*(X2S1/(IN1*SSX1)+X2S2
     1/(IN2*SSX2)))
      YMAX1=B01+B11*XMAX
      YMIN1=B01+B11*XMIN
      YAVE1=B01+B11*AVEX1
      YMAX2=B02+B12*XMAX
      YMIN2=B02+B12*XMIN
      YAVE2=B02+B12*AVEX1
      YMAXP=(YMAX2-YMAX1)/YMAX1*100.
      YMINP=(YMIN2-YMIN1)/YMIN1*100.
      YAVEP=(YAVE2-YAVE1)/YAVE1*100.
   52 GO TO (33,11,33,11,33,34,35,36,37,38,39,41,80,81),J
   33 WRITE(61,117)
      GO TO 40
   34 WRITE(61,118)
      GO TO 40
   35 WRITE(61,119)
      GO TO 40
   36 WRITE(61,120)
      GO TO 40
   37 WRITE(61,121)
      GO TO 40
   38 WRITE(61,122)
      GO TO 40
   39 WRITE(61,123)
      GO TO 40
   61 WRITE(61,141)
      GO TO 40
   80 WRITE(61,148)
      GO TO 40
   81 WRITE(61,149)
   40 WRITE(61,127)(XNAME(I),I=1,15),(YNAME(I),I=1,15)
      DO 41 I=1,KOUNT
      IF(A(I,J))42,41,42
   42 IF(B(I,J))43,41,43
   43 WRITE(61,103)A(I,1),A(I,3),A(I,4),A(I,5),A(I,J),B(I,J)
      N=N+1
      IF(N.NE.43)48,41
   48 IF((N+NN).EQ.KOUNT)70,50
   70 WRITE(61,142)(XNAME(K),K=1,15),(YNAME(K),K=1,15)
      GO TO 41
   50 IF(N.EQ.50)51,41
   51 WRITE(61,142)(XNAME(K),K=1,15),(YNAME(K),K=1,15)
      NN=NN+N
      N=0
   41 CONTINUE
      WRITE(61,104)SUMX,SUMY
      WRITE(61,105)SUMX2,SUMY2
      WRITE(61,106)AVEX,AVEY
      WRITE(61,107)SUMXY
      WRITE(61,108)B0
      WRITE(61,109)B1
      WRITE(61,110)IN
      WRITE(61,111)B0,B1
      WRITE(61,112)
      WRITE(61,113)REG,REG,F
      WRITE(61,114)RESDF,RES,VAR
      WRITE(61,115)TOTDF,TOT
      WRITE(61,116)R2
      GO TO (62,46),M
   46 WRITE(61,140)T1
      WRITE(61,143)T2
      WRITE(61,147)T3
      WRITE(61,150)T4
      WRITE(61,145)XMAX,YMAXP,XMIN,YMINP,AVEX1,YAVEP
   62 CONTINUE
      GO TO 61
   60 WRITE(61,139)
  100 FORMAT(5F3.0,F6.1,F5.2,F7.2,3F5.2,3F8.2)
  101 FORMAT(I2,F2.0,15A1,15A1)
  103 FORMAT(14X,*EVENT*,1X,F3.0,2X,F2.0,1X,F2.0,1X,F2.0,3X,F10.2,12X,F1
     10.2)
  104 FORMAT(14X,*SUM*,19X,F12.4,10X,F12.4)
  105 FORMAT(14X,*SUM OF SQUARES*,4X,F14.4,6X,F16.4)
  106 FORMAT(14X,*AVERAGE*,13X,F14.4,10X,F12.4)
  107 FORMAT(14X,*SUM OF PRODUCTS*,5X,F14.4,10X,F12.4)
  108 FORMAT(14X,*COEFFICIENT B0*,9X,F12.4)
  109 FORMAT(14X,*COEFFICIENT B1*,8X,F12.4)
  110 FORMAT(14X,*NUMBER OF OBSERVATIONS*,F7.0//)
  111 FORMAT(*1*,///////,14X,*CONTINUED*//32X,*Y =*,F7.2,3X,*+*,1X,
     1 F6.2,*X*,//)
  112 FORMAT(14X,*SOURCE*,5X,*DF*,13X,*SS*,9X,*MS*,8X,*F*/)
  113 FORMAT(14X,*REGRESSION*,2X,*1*,3X,F14.2,F14.3,F8.2)
  114 FORMAT(14X,*RESIDUAL*,3X,F2.0,3X,F14.2,F14.3)
  115 FORMAT(14X,*TOTAL*,6X,F2.0,3X,F14.2//)
  116 FORMAT(20X,*REGRESSION COEFFICIENT = *,F6.2)
  117 FORMAT(1X,*ERROR*)
  118 FORMAT(14X,*TIME TO PEAK*/)
  119 FORMAT(33X,*HEIGHT OF RISE*/)
  120 FORMAT(33X,*PEAK DISCHARGE*/)
  121 FORMAT(32X,*PEAK + 24 HOURS*/)
  122 FORMAT(32X,*PEAK + 48 HOURS*/)
  123 FORMAT(32X,*PEAK + 12 HOURS*/)
  124 FORMAT(///35X,*PRELOGGING*)
  125 FORMAT(*1*,///34X,*POSTLOGGING*)
  126 FORMAT(30X,*CHANGE IN SLOPE*)
  127 FORMAT(18X,15A1,8X,15A1)
  139 FORMAT(1X,*STORMS DO NOT MATCH*)
  140 FORMAT(//20X,*COMPUTED T FOR CHANGE IN SLOPE*,F7.2)
  143 FORMAT(/20X,*COMPUTED T FOR ADJUSTED MEANS*,F7.2)
  141 FORMAT(31X,*VOLUME(QUICK FLOW)*/)
  142 FORMAT(*1*,///14X,*CONTINUED*,///39X,15A1,8X,15A1)
  145 FORMAT(/20X,*MAXIMUM X*,F10.2,5X,*PERCENT CHANGE*,F8.2//20X,*MINIM
     1UM X*,F10.2,5X,*PERCENT CHANGE*,F8.2//20X,*AVERAGE X*,F10.2,5X,*PE
     2RCENT CHANGE*,F8.2/)
  147 FORMAT(/20X,*COMPUTED T FOR CHANGE IN INTERCEPT*,F7.2)
  148 FORMAT(30X,*VOLUME(INFLATED FLOW)*/)
  149 FORMAT(31X,*VOLUME(TOTAL FLOW)*/)
  150 FORMAT(/20X,*COMPUTED T FOR CHANGE AT MEAN OF MEANS*,F7.2/)
   61 STOP
      END
```

# STATISTICAL TESTS

## Test for Change in Slope

This test as given by Lee (1957) may be stated as:

$$t = \frac{b_{11} - b_{12}}{\sqrt{\left(\frac{\text{Res SS}_1 + \text{Res SS}_2}{n_1 + n_2 - 4}\right)\left(\frac{1}{\text{SSX}_1} + \frac{1}{\text{SSX}_2}\right)}} \qquad \text{(A-1)}$$

where $b_1$ is the regression coefficient defining slope, Res SS the residual sum of squares, n the number of observations, SSX the sum of squares of x, or $\sum(x_i - \bar{x})^2$. The second subscript (1 or 2) designates pre-logging or post-logging period.

## Test for Change in Vertical Position

The test for change in vertical position, as given by Draper and Smith (1968), may be stated as:

$$t = \frac{b_{01} - b_{02}}{\sqrt{\text{Var } b_{01} + \text{Var } b_{02}}} \qquad \text{(A-2)}$$

where $b_0$ is the regression coefficient defining the intercept. The variance for $b_0$ may be defined as:

$$\text{Var}(b_0) = \frac{(\sum X^2)}{(n\text{SSX})} s^2 \qquad \text{(A-3)}$$

where $s^2$ is the variance about the regression and SSX, X, and the subscripts 1 and 2 are as previously defined.

This is a test for the difference between two regression lines at the intercept. Most information about the sample, however, is contained at the mean. As a result, the change in vertical displacement was tested near the mean of both populations. The variance for the mean of means then becomes:

$$\text{Var(mean of means)} = \left(\frac{((x_i - x_0)^2)}{nSSX}\right)s^2 \qquad \text{(A-4)}$$

where $x_i$ equals individual values of x and $x_0$ is any value of x at which the test is to be conducted. In this case $x_0$ was selected to be the average of both populations or

$$x_0 = \frac{\bar{x}_1 - \bar{x}_2}{2} \qquad \text{(A-5)}$$

The test for difference in vertical position then becomes:

$$t = \frac{b_{01} - b_{02}}{\sqrt{\left(\frac{ResSS_1 + ResSS_2}{n_1 + n_2 - 4}\right)\left(\frac{(x_i - x_0)^2}{n_1(SSX_2)} + \frac{(x_i - x_0)^2}{n_2(SSX_2)}\right)}} \qquad \text{(A-6)}$$

The test for change in intercept may be seen to be a modification of this equation. If $x_0$ is allowed to assume the value of 0 in equation (A-6), which would be the case at the intercept, the equation reduces to the original form of equation (A-2).

## Data Used in Study

A complete listing of all data used for all analysis is presented in Tables IV, V and VI. Table IV gives data for Flynn Creek, Table V data for Deer Creek IV, and Table VI the data for Needle Branch. In all three tables, column one is the event number. This number is the same for a given event on all three watersheds. Column two gives the date of the event, and columns three through eight give the values of the parameters used in the study. The values of volume in columns six, seven and eight are expressed in csm-hr. This corresponds to the volume of runoff for each storm event where time is defined as the interval from the initial rise to the point the separation line intersects the recession. A blank for a given parameter for any given storm event does not indicate the lack of a value. Instead, it indicates that the quality of that value for that particular event was not satisfactory for use in the analysis.

TABLE IV. DATA FOR FLYNN CREEK USED IN STATISTICAL ANALYSES

| EVENT NUMBER | DATE | TIME TO PEAK (HOURS) | HEIGHT OF RISE (FEET) | PEAK DISCHARGE (CSM) | QUICK FLOW (CSM-HR) | DELAYED FLOW (CSM-HR) | TOTAL FLOW (CSM-HR) |
|---|---|---|---|---|---|---|---|
| 1 | 10 7 58 | 10.0 | .34 | 1.44 | | | |
| 2 | 10 18 58 | 39.0 | .90 | 6.97 | 39.58 | 32.25 | 71.83 |
| 3 | 11 14 58 | 40.0 | .69 | 23.97 | | | |
| 4 | 11 20 58 | 50.0 | .89 | 40.04 | 2099.55 | 1274.58 | 3374.13 |
| 5 | 1 9 59 | 43.0 | 1.28 | 67.58 | 4130.93 | 2047.71 | 6178.64 |
| 6 | 1 27 59 | 22.5 | .88 | 53.80 | | | |
| 7 | 3 9 59 | 3.5 | .13 | 4.84 | | | |
| 8 | 6 4 59 | 10.5 | .24 | 3.81 | | | |
| 9 | 9 4 59 | 12.5 | .52 | 3.29 | | | |
| 10 | 9 19 59 | 35.5 | .53 | 3.60 | | | |
| 11 | 9 26 59 | 14.0 | 1.04 | 16.96 | | | |
| 12 | 10 8 59 | 26.5 | .43 | 5.23 | | | |
| 13 | 10 11 59 | 27.0 | .42 | 8.76 | 194.92 | 359.94 | 554.86 |
| 14 | 10 19 59 | 20.0 | .21 | 4.72 | 258.92 | 430.44 | 689.37 |
| 15 | 11 18 59 | 18.5 | .26 | 3.70 | | | |
| 16 | 11 20 59 | 3.5 | .30 | 4.46 | | | |
| 17 | 11 23 59 | 31.5 | .60 | 11.21 | 357.31 | 429.66 | 786.97 |
| 18 | 12 15 59 | 29.0 | .19 | 12.42 | | | |
| 19 | 1 8 60 | 11.0 | .26 | 6.04 | | | |
| 20 | 1 18 60 | 63.5 | .39 | 10.15 | | | |
| 21 | 2 7 60 | 15.0 | .47 | 40.04 | | | |
| 22 | 2 9 60 | 21.5 | .38 | 54.57 | 1333.03 | 1278.00 | 2611.03 |
| 23 | 3 5 60 | 56.0 | .46 | 11.98 | | | |
| 24 | 3 31 60 | 68.0 | .78 | 21.04 | | | |
| 25 | 8 23 60 | 24.5 | .44 | 2.86 | | | |
| 26 | 9 7 60 | 15.0 | .55 | 3.43 | | | |
| 27 | 10 11 60 | 5.0 | .27 | 1.36 | | | |
| 28 | 10 23 60 | 8.0 | .49 | 2.77 | | | |
| 29 | 10 28 60 | 30.0 | .41 | 4.26 | 71.95 | 77.76 | 149.71 |
| 30 | 10 28 60 | 26.0 | .27 | 2.94 | | | |
| 31 | 11 10 60 | 17.0 | 1.08 | 16.06 | | | |
| 32 | 11 15 60 | 38.5 | .92 | 22.82 | | | |
| 33 | 11 17 60 | 16.0 | .47 | 37.48 | | | |
| 34 | 1 6 61 | 43.0 | 1.02 | 27.54 | 1254.82 | 977.15 | 2231.97 |
| 35 | 1 29 61 | 10.5 | .28 | 7.11 | | | |
| 36 | 2 10 61 | 30.5 | 1.33 | 81.86 | | | |
| 37 | 2 13 61 | 20.0 | .39 | 59.92 | 6432.01 | 3159.23 | 9591.24 |
| 38 | 3 1 61 | 17.0 | .32 | 30.60 | | | |
| 39 | 3 13 61 | 22.0 | .30 | 36.98 | | | |
| 40 | 4 21 61 | 47.0 | .54 | 10.00 | | | |
| 41 | 8 31 61 | 6.0 | .41 | 2.10 | | | |
| 42 | 10 10 61 | 7.0 | .76 | 5.70 | | | |
| 43 | 10 12 61 | 22.0 | .35 | 2.94 | | | |
| 44 | 10 23 61 | 13.0 | .73 | 6.12 | | | |
| 45 | 10 27 61 | 29.5 | .67 | 7.45 | 121.96 | 145.60 | 267.56 |
| 46 | 11 3 61 | 5.0 | .12 | 2.03 | | | |
| 47 | 11 22 61 | 23.5 | 1.78 | 59.16 | 1724.12 | 585.22 | 2309.34 |
| 48 | 12 19 61 | 78.5 | 1.30 | 52.28 | 3780.12 | 1702.50 | 5482.62 |
| 49 | 2 6 62 | 9.5 | .18 | 4.26 | | | |
| 50 | 2 10 62 | 33.5 | .58 | 18.74 | | | |
| 51 | 2 17 62 | 27.0 | .39 | 20.66 | | | |
| 52 | 3 4 62 | 35.0 | .48 | 15.43 | | | |
| 53 | 4 27 62 | 27.0 | 1.03 | 26.52 | | | |
| 54 | 6 2 62 | 5.0 | .25 | 4.37 | | | |
| 55 | 10 7 62 | 9.5 | .80 | 7.78 | 56.43 | 35.19 | 91.61 |
| 56 | 11 20 62 | 26.0 | 1.16 | 43.99 | 1393.89 | 739.56 | 2133.46 |
| 57 | 11 25 62 | 31.5 | 1.57 | 82.88 | | | |
| 58 | 3 30 63 | 81.5 | .99 | 33.40 | 1329.52 | 1269.55 | 2299.07 |
| 59 | 9 15 63 | 22.5 | .24 | 1.26 | | | |
| 60 | 9 22 63 | 10.5 | .26 | 1.43 | | | |
| 61 | 10 20 63 | 4.0 | .30 | .97 | | | |
| 62 | 10 22 63 | 16.0 | .70 | 5.29 | | | |
| 63 | 11 7 63 | 13.5 | 1.11 | 40.93 | 1357.01 | 794.62 | 2151.63 |
| 64 | 12 21 63 | 43.0 | .38 | 9.56 | | | |
| 65 | 1 1 64 | 17.5 | .41 | 21.93 | | | |
| 66 | 1 6 64 | 20.0 | .86 | 47.81 | 1387.51 | 1307.00 | 2694.52 |
| 67 | 1 17 64 | | .56 | 36.98 | | | |
| 68 | 1 19 64 | 81.0 | 1.12 | 80.84 | 3140.91 | 2657.28 | 5798.19 |
| 69 | 1 24 64 | 20.5 | .55 | 54.70 | 1675.67 | 1955.22 | 3630.90 |

TABLE IV CONTINUED

| EVENT NUMBER | DATE | TIME TO PEAK (HOURS) | HEIGHT OF RISE (FEET) | PEAK DISCHARGE (CSM) | QUICK FLOW (CSM-HR) | DELAYED FLOW (CSM-HR) | TOTAL FLOW (CSM-HR) |
|---|---|---|---|---|---|---|---|
| 70 | 1 26 64 | 45.5 | .64 | 51.26 | | | |
| 71 | 2 29 64 | 14.5 | .36 | 8.92 | | | |
| 72 | 3 11 64 | 55.5 | .51 | 28.30 | 723.18 | 1482.32 | 2205.50 |
| 73 | 9 30 64 | 3.0 | .22 | 1.04 | | | |
| 74 | 11 2 64 | 24.5 | .34 | 1.78 | | | |
| 75 | 11 4 64 | 14.5 | .28 | 2.06 | | | |
| 76 | 11 24 64 | 31.5 | 1.27 | 32.38 | 5045.22 | 1994.71 | 7039.93 |
| 77 | 12 1 64 | 24.5 | .63 | 56.86 | | | |
| 78 | 12 22 64 | 66.5 | 1.51 | 114.50 | | | |
| 79 | 1 3 65 | 27.0 | .24 | 18.59 | 178.49 | 940.97 | 1119.46 |
| 80 | 1 6 65 | 38.0 | .16 | 18.96 | | | |
| 81 | 1 11 65 | 27.5 | .17 | 16.86 | 187.82 | 899.33 | 1087.15 |
| 82 | 1 25 65 | 58.5 | .81 | 32.38 | | | |
| 83 | 1 28 65 | 35.5 | 1.33 | 174.93 | 8657.32 | 3327.22 | 11984.54 |
| 84 | 3 1 65 | 36.0 | .37 | 10.56 | | | |
| 85 | 4 19 65 | 15.0 | .65 | 9.84 | | | |
| 86 | 10 5 65 | 3.5 | .65 | 3.81 | | | |
| 87 | 10 27 65 | 5.0 | .31 | 1.22 | | | |
| 88 | 11 3 65 | 13.5 | .86 | 7.79 | 39.77 | 30.35 | 70.12 |
| 89 | 11 12 65 | 26.5 | .79 | 15.43 | 250.86 | 241.40 | 492.26 |
| 90 | 11 22 65 | 52.0 | .46 | 10.31 | | | |
| 91 | 12 1 65 | 4.0 | .24 | 7.22 | | | |
| 92 | 12 4 65 | 23.0 | .33 | 9.44 | 176.64 | 405.35 | 581.99 |
| 93 | 12 24 65 | 15.5 | .86 | 18.61 | | | |
| 94 | 12 27 65 | 43.5 | 1.06 | 65.02 | 3030.22 | 1667.01 | 4697.23 |
| 95 | 1 3 66 | 59.0 | .85 | 70.89 | 4499.96 | 1928.61 | 6428.57 |
| 96 | 1 5 66 | 9.5 | .35 | 47.94 | | | |
| 97 | 1 15 66 | 44.0 | .42 | 29.32 | 693.00 | 1516.32 | 2209.32 |
| 98 | 1 19 66 | 4.5 | .11 | 8.21 | | | |
| 99 | 3 9 66 | 30.0 | 1.16 | 93.08 | 2697.33 | 1478.36 | 4175.69 |
| 100 | 3 16 66 | | | 16.42 | | | |
| 101 | 4 11 66 | 8.0 | .28 | 6.02 | | | |
| 102 | 10 21 66 | 57.5 | .85 | 5.71 | 20.36 | 19.66 | 40.02 |
| 103 | 11 11 66 | 34.5 | 1.24 | 23.51 | | | |
| 104 | 11 14 66 | | | 10.97 | | | |
| 105 | 12 4 66 | 24.0 | .74 | 44.08 | 2129.53 | 2001.84 | 4131.37 |
| 106 | 12 6 66 | | | 32.18 | | | |
| 107 | 12 13 66 | 38.0 | .65 | 40.60 | 1160.74 | 1331.78 | 2492.52 |
| 108 | 1 5 67 | 51.5 | .54 | 17.85 | | | |
| 109 | 1 13 67 | 32.0 | .59 | 23.08 | 905.80 | 1052.73 | 1958.53 |
| 110 | 1 27 67 | 42.0 | 1.18 | 79.30 | 4125.56 | 2124.39 | 6249.95 |
| 111 | 1 29 67 | | | 53.87 | | | |
| 112 | 2 13 67 | 8.0 | .38 | 9.88 | | | |
| 113 | 2 17 67 | 22.0 | .21 | 27.28 | | | |
| 114 | 3 15 67 | 26.0 | .94 | 39.91 | 1587.53 | 1322.38 | 2909.91 |
| 115 | 4 13 67 | 25.0 | .53 | 14.41 | | | |
| 116 | 10 3 67 | 12.5 | .78 | 7.22 | 55.63 | 11.89 | 67.52 |
| 117 | 10 11 67 | 8.0 | .28 | 1.25 | | | |
| 118 | 10 21 67 | 4.0 | .56 | 3.63 | | | |
| 119 | 10 22 67 | 6.5 | .39 | 4.62 | | | |
| 120 | 10 24 67 | 3.0 | .27 | 3.72 | | | |
| 121 | 10 27 67 | 21.3 | 1.24 | 32.79 | 572.06 | 224.44 | 796.49 |
| 122 | 12 3 67 | 42.5 | .65 | 37.15 | 1970.48 | 2110.50 | 4080.98 |
| 124 | 12 23 67 | 51.0 | .54 | 15.43 | 450.15 | 781.56 | 1231.71 |
| 125 | 1 9 68 | 31.0 | .81 | 23.94 | | | |
| 126 | 2 3 68 | 47.5 | .55 | 41.28 | 1384.83 | 1462.61 | 2847.45 |
| 127 | 2 19 68 | 24.0 | 1.34 | 55.97 | 4194.19 | 1477.98 | 5672.17 |
| 128 | 3 16 68 | 27.5 | .48 | 15.10 | | | |
| 129 | 3 28 68 | 38.0 | .23 | 14.43 | | | |
| 130 | 5 25 68 | 11.0 | .42 | 5.55 | | | |
| 131 | 6 2 68 | 24.0 | .72 | 20.14 | | | |

TABLE V. DATA FOR DEER CREEK IV USED IN STATISTICAL ANALYSES

| EVENT NUMBER | DATE | TIME TO PEAK (HOURS) | HEIGHT OF RISE (FEET) | PEAK DISCHARGE (CSM) | QUICK FLOW (CSM-HR) | DELAYED FLOW (CSM-HR) | TOTAL FLOW (CSM-HR) |
|---|---|---|---|---|---|---|---|
| 67 | 1 17 64 | | | 45.29 | | | |
| 68 | 1 19 64 | 87.0 | 1.30 | 126.27 | 3371.12 | 949.49 | 4320.61 |
| 69 | 1 24 64 | 20.0 | .68 | 57.26 | 1991.95 | 815.70 | 2807.65 |
| 76 | 11 24 64 | | | 42.32 | | | |
| 79 | 1 3 65 | 21.0 | .51 | 14.19 | 530.60 | 51.27 | 581.87 |
| 80 | 1 6 65 | | | 16.80 | | | |
| 81 | 1 11 65 | 20.0 | .30 | 13.21 | 260.48 | 286.80 | 547.28 |
| 82 | 1 25 65 | | | 29.30 | | | |
| 83 | 1 28 65 | 45.0 | 1.34 | 222.07 | 10434.70 | 699.44 | 11134.14 |
| 84 | 3 1 65 | | | 2.76 | | | |
| 89 | 11 12 65 | | | 7.18 | | | |
| 90 | 11 22 65 | | | 8.95 | | | |
| 92 | 12 4 65 | 28.5 | .41 | 6.53 | 168.51 | 118.79 | 287.30 |
| 93 | 12 24 65 | | | 18.50 | | | |
| 94 | 12 27 65 | 44.0 | 1.09 | 101.09 | 3570.80 | 1060.54 | 4631.34 |
| 95 | 1 3 66 | 57.5 | .91 | 80.30 | 3774.74 | 1431.55 | 5206.29 |
| 96 | 1 5 66 | | | 44.28 | | | |
| 97 | 1 15 66 | 50.0 | .56 | 28.54 | 788.15 | 411.94 | 1200.08 |
| 99 | 3 9 66 | 26.5 | 1.27 | 160.39 | 3127.34 | 529.89 | 3657.23 |
| 100 | 3 16 66 | | | 5.35 | | | |
| 103 | 11 11 66 | | | 62.05 | | | |
| 104 | 11 14 66 | | | 17.92 | | | |
| 105 | 12 4 66 | 21.0 | .69 | 65.81 | 2475.42 | 1452.25 | 3927.67 |
| 106 | 12 6 66 | | | 33.31 | | | |
| 107 | 12 13 66 | 34.5 | .74 | 60.83 | 1509.85 | 653.73 | 2163.58 |
| 108 | 1 5 67 | | | 18.50 | | | |
| 109 | 1 13 67 | 28.0 | .81 | 24.20 | 879.68 | 189.22 | 1068.90 |
| 110 | 1 27 67 | 48.5 | 1.24 | 124.35 | 4478.11 | 964.16 | 5442.27 |
| 111 | 1 29 67 | | | 67.09 | | | |
| 113 | 2 17 67 | 16.0 | .21 | 33.31 | | | |
| 114 | 3 15 67 | 18.5 | 1.06 | 63.29 | 1861.26 | 450.22 | 2311.47 |
| 121 | 10 27 67 | 9.5 | 1.01 | 79.35 | 1363.54 | 301.92 | 1665.47 |
| 122 | 12 3 67 | 47.5 | .64 | 49.44 | 2284.17 | 1186.06 | 3470.23 |
| 124 | 12 23 67 | | | 17.92 | | | |
| 125 | 1 9 68 | | | 39.48 | | | |
| 126 | 2 3 68 | 57.5 | .49 | 50.51 | | | |
| 127 | 2 19 68 | | | 99.42 | | | |
| 128 | 3 16 68 | | | 30.08 | | | |
| 129 | 3 28 68 | | | 17.36 | | | |

TABLE VI. DATA FOR NEEDLE BRANCH USED IN STATISTICAL ANALYSES

| EVENT NUMBER | DATE | TIME TO PEAK (HOURS) | HEIGHT OF RISE (FEET) | PEAK DISCHARGE (CSM) | QUICK FLOW (CSM-HR) | DELAYED FLOW (CSM-HR) | TOTAL FLOW (CSM-HR) |
|---|---|---|---|---|---|---|---|
| 1 | 10 7 58 | 11.0 | .37 | 2.60 | | | |
| 2 | 10 18 58 | 3.8 | .84 | 12.07 | 90.60 | 79.68 | 170.28 |
| 3 | 11 14 58 | 39.0 | .50 | 28.53 | | | |
| 4 | 11 20 58 | 52.0 | .70 | 51.21 | 2432.75 | 1246.76 | 3679.50 |
| 5 | 1 9 59 | 39.0 | 1.01 | 77.91 | 4261.83 | 1973.98 | 6235.81 |
| 6 | 1 27 59 | 22.0 | .80 | 70.96 | | | |
| 7 | 3 9 59 | 3.0 | .23 | 5.85 | | | |
| 8 | 6 4 59 | 9.0 | .27 | 4.64 | | | |
| 9 | 9 4 59 | 16.5 | .56 | 6.04 | | | |
| 10 | 9 19 59 | 34.5 | .56 | 6.58 | | | |
| 11 | 9 26 59 | 14.5 | .84 | 26.44 | | | |
| 12 | 10 8 59 | 25.0 | .49 | 9.88 | | | |
| 13 | 10 11 59 | 26.0 | .36 | 15.73 | 326.16 | 545.58 | 871.74 |
| 14 | 10 19 59 | 25.0 | .30 | 7.90 | 619.64 | 538.05 | 1157.69 |
| 15 | 11 18 59 | 18.0 | .27 | 5.16 | | | |
| 16 | 11 20 59 | 4.0 | .24 | 5.34 | | | |
| 17 | 11 23 59 | 22.0 | .60 | 20.30 | 721.03 | 506.46 | 1227.49 |
| 18 | 12 15 59 | 29.0 | .27 | 15.73 | | | |
| 19 | 1 8 60 | 12.0 | .28 | 6.58 | | | |
| 20 | 1 18 60 | 51.0 | .36 | 12.44 | | | |
| 21 | 2 7 60 | 14.0 | .35 | 40.96 | | | |
| 22 | 2 9 60 | 19.0 | .45 | 70.96 | 1654.13 | 1186.09 | 2840.22 |
| 23 | 3 5 60 | 61.0 | .50 | 13.82 | | | |
| 24 | 3 31 60 | 67.0 | .62 | 19.53 | | | |
| 25 | 8 23 60 | 23.0 | .30 | 2.45 | | | |
| 26 | 9 7 60 | 15.5 | .41 | 3.40 | | | |
| 27 | 10 11 60 | 5.0 | .32 | 2.05 | | | |
| 28 | 10 23 60 | 8.0 | .37 | 2.52 | | | |
| 29 | 10 28 60 | 28.5 | .45 | 5.49 | 112.15 | 67.38 | 179.53 |
| 30 | 10 28 60 | 26.0 | .33 | 4.32 | | | |
| 31 | 11 10 60 | 18.0 | 1.02 | 30.14 | | | |
| 32 | 11 15 60 | 39.5 | .80 | 43.52 | | | |
| 33 | 11 17 60 | 16.5 | .34 | 43.52 | | | |
| 34 | 1 6 61 | 42.0 | 1.00 | 45.72 | 1584.52 | 770.85 | 2355.37 |
| 35 | 1 29 61 | 9.5 | .32 | 6.80 | | | |
| 36 | 2 10 61 | 26.0 | 1.14 | 102.78 | | | |
| 37 | 2 13 61 | 16.0 | .36 | 64.01 | 6545.99 | 2459.12 | 9005.11 |
| 38 | 3 1 61 | 15.5 | .43 | 33.36 | | | |
| 39 | 3 13 61 | 18.0 | .33 | 45.72 | | | |
| 40 | 4 21 61 | 44.0 | .59 | 13.82 | | | |
| 41 | 8 31 61 | 55.0 | .45 | 3.29 | | | |
| 42 | 10 10 61 | 6.0 | .80 | 10.17 | | | |
| 43 | 10 12 61 | 21.5 | .38 | 4.54 | | | |
| 44 | 10 23 61 | 13.5 | .73 | 10.17 | | | |
| 45 | 10 27 61 | 28.5 | .65 | 12.44 | 281.05 | 209.82 | 490.87 |
| 46 | 11 3 61 | 4.0 | .18 | 3.58 | | | |
| 47 | 11 22 61 | 23.5 | 1.65 | 112.29 | 2599.29 | 594.96 | 3194.25 |
| 48 | 12 19 61 | 77.5 | .96 | 65.10 | 3693.92 | 1336.50 | 5030.42 |
| 49 | 2 6 62 | 10.5 | .24 | 4.54 | | | |
| 50 | 2 10 62 | 31.0 | .39 | 25.05 | | | |
| 51 | 2 17 62 | 17.5 | .38 | 25.53 | | | |
| 52 | 3 4 62 | 29.5 | .44 | 20.04 | | | |
| 53 | 4 27 62 | 29.0 | .82 | 25.75 | | | |
| 54 | 6 2 62 | 4.5 | .28 | 4.39 | | | |
| 55 | 10 7 62 | 9.5 | .74 | 9.88 | 72.41 | 33.35 | 105.76 |
| 56 | 11 20 62 | 25.5 | .94 | 58.16 | 1491.24 | 612.36 | 2103.60 |
| 57 | 11 25 62 | 29.5 | 1.18 | 107.90 | | | |
| 58 | 3 30 63 | 79.0 | .79 | 38.77 | 2067.43 | 1099.17 | 3166.60 |
| 59 | 9 15 63 | 22.5 | .42 | 3.47 | | | |
| 60 | 9 22 63 | 10.5 | .32 | .23 | | | |
| 61 | 10 20 63 | 5.0 | .16 | .80 | | | |
| 62 | 10 22 63 | 17.0 | .62 | 6.95 | | | |
| 63 | 11 7 63 | 12.5 | .81 | 61.45 | 1425.39 | 905.30 | 2330.69 |
| 64 | 12 21 63 | 38.5 | .35 | 12.44 | | | |
| 65 | 1 1 64 | 17.5 | .28 | 21.58 | | | |
| 66 | 1 6 64 | 18.5 | .93 | 85.95 | 1863.41 | 1148.17 | 3011.58 |
| 67 | 1 17 64 | | .54 | 40.96 | | | |
| 68 | 1 19 64 | 82.0 | .97 | 106.44 | 3835.88 | 2197.41 | 6033.30 |
| 69 | 1 24 64 | 19.0 | .37 | 44.63 | 2497.82 | 948.68 | 3446.50 |

TABLE VI CONTINUED

| EVENT NUMBER | DATE | TIME TO PEAK (HOURS) | HEIGHT OF RISE (FEET) | PEAK DISCHARGE (CSM) | QUICK FLOW (CSM-HR) | DELAYED FLOW (CSM-HR) | TOTAL FLOW (CSM-HR) |
|---|---|---|---|---|---|---|---|
| 70 | 1 26 64 | 45.0 | .57 | 61.45 | | | |
| 71 | 2 29 64 | 13.5 | .30 | 7.53 | | | |
| 72 | 3 11 64 | 45.0 | .56 | 49.01 | 1435.89 | 1392.00 | 2827.89 |
| 73 | 9 30 64 | 3.5 | .22 | 1.21 | | | |
| 74 | 11 2 64 | 24.5 | .41 | 3.33 | | | |
| 75 | 11 4 64 | 14.0 | .27 | 2.82 | | | |
| 77 | 12 1 64 | 28.0 | .51 | 62.91 | | | |
| 76 | 11 24 64 | 32.0 | 1.13 | 55.96 | 5326.16 | 2173.41 | 7499.57 |
| 78 | 12 22 64 | 59.0 | 1.26 | 126.19 | | | |
| 79 | 1 3 65 | 27.0 | .34 | 23.66 | 529.72 | 795.75 | 1325.47 |
| 80 | 1 6 65 | 33.0 | .21 | 23.66 | | | |
| 81 | 1 11 65 | 24.0 | .15 | 15.36 | 158.34 | 615.03 | 773.38 |
| 82 | 1 25 65 | 55.5 | .73 | 32.55 | | | |
| 83 | 1 28 65 | 36.5 | 1.16 | 183.00 | 9455.23 | 1836.17 | 11291.40 |
| 84 | 3 1 65 | 35.5 | .36 | 10.75 | | | |
| 85 | 4 19 65 | 18.5 | .62 | 13.35 | | | |
| 86 | 10 5 65 | 4.5 | .63 | 4.83 | | | |
| 87 | 10 27 65 | 6.0 | .28 | 1.57 | | | |
| 88 | 11 3 65 | 13.5 | .84 | 13.35 | 58.22 | 40.86 | 99.08 |
| 89 | 11 12 65 | 27.0 | .59 | 16.46 | 307.49 | 324.17 | 631.66 |
| 90 | 11 22 65 | 51.5 | .35 | 12.87 | | | |
| 91 | 12 1 65 | 4.0 | .21 | 6.22 | | | |
| 92 | 12 4 65 | 20.5 | .39 | 12.44 | 226.88 | 371.15 | 608.03 |
| 93 | 12 24 65 | 15.0 | .72 | 21.58 | | | |
| 96 | 1 5 66 | 9.0 | .14 | 42.43 | | | |
| 97 | 1 15 66 | 38.0 | .32 | 32.55 | 727.84 | 1134.75 | 1862.59 |
| 98 | 1 19 66 | 5.0 | .31 | 11.34 | | | |
| 94 | 12 27 65 | 43.5 | 1.01 | 104.97 | 3637.54 | 1799.86 | 5437.40 |
| 95 | 1 3 66 | 63.0 | .70 | 78.27 | 3364.28 | 2499.00 | 5863.28 |
| 99 | 3 9 66 | 26.5 | .88 | 106.44 | 2487.79 | 1338.30 | 3826.09 |
| 100 | 3 16 66 | | | 18.00 | | | |
| 101 | 4 11 66 | 8.5 | .26 | 3.73 | | | |
| 102 | 10 21 66 | 60.0 | 1.04 | 21.58 | 617.50 | 342.50 | 960.00 |
| 103 | 11 11 66 | 34.0 | 1.16 | 68.76 | | | |
| 104 | 11 14 66 | | | 25.05 | | | |
| 105 | 12 4 66 | 17.5 | .64 | 85.95 | 2595.89 | 2455.68 | 5051.57 |
| 106 | 12 6 66 | | | 34.40 | | | |
| 107 | 12 13 66 | 37.0 | .50 | 54.86 | 1387.74 | 1251.15 | 2638.89 |
| 108 | 1 5 67 | 49.5 | .40 | 22.64 | | | |
| 109 | 1 13 67 | 23.5 | .53 | 24.51 | 869.06 | 717.06 | 1586.12 |
| 110 | 1 27 67 | 39.5 | .88 | 109.73 | 4038.02 | 1959.78 | 5997.80 |
| 111 | 1 29 67 | | | 72.79 | | | |
| 112 | 2 13 67 | 8.0 | .58 | 14.96 | | | |
| 113 | 2 17 67 | 19.0 | .16 | 24.51 | | | |
| 114 | 3 15 67 | 22.5 | 1.02 | 89.24 | 2904.06 | 1314.00 | 4218.06 |
| 115 | 4 13 67 | 25.0 | .57 | 18.29 | | | |
| 116 | 10 3 67 | 11.0 | .78 | 19.53 | 259.09 | 91.74 | 350.84 |
| 117 | 10 11 67 | 7.5 | .33 | 4.86 | | | |
| 118 | 10 21 67 | 4.0 | .43 | 8.67 | | | |
| 119 | 10 22 67 | 6.0 | .34 | 13.17 | | | |
| 120 | 10 24 67 | 2.0 | .24 | 15.91 | | | |
| 121 | 10 27 67 | 21.0 | .97 | 89.24 | 1681.81 | 795.11 | 2476.92 |
| 122 | 12 3 67 | 41.5 | .60 | 70.22 | 3570.59 | 2718.46 | 6289.04 |
| 124 | 12 23 67 | 45.5 | .62 | 24.50 | 799.04 | 823.97 | 1623.01 |
| 125 | 1 9 68 | 30.0 | .78 | 40.60 | | | |
| 126 | 2 3 68 | 47.0 | .41 | 54.86 | 1514.57 | 1746.36 | 3260.93 |
| 127 | 2 19 68 | 22.5 | 1.23 | 92.17 | 5070.56 | 1302.07 | 6372.63 |
| 128 | 3 16 68 | 25.0 | .28 | 32.92 | | | |
| 129 | 3 28 68 | 36.0 | .18 | 19.53 | | | |
| 130 | 5 25 68 | 10.5 | .56 | 12.07 | | | |
| 131 | 6 2 68 | 24.5 | .59 | 25.35 | | | |