PROCEEDINGS OF WORKSHOP ON

SCHEDULING TIMBER HARVEST FOR

HYDROLOGIC CONCERNS

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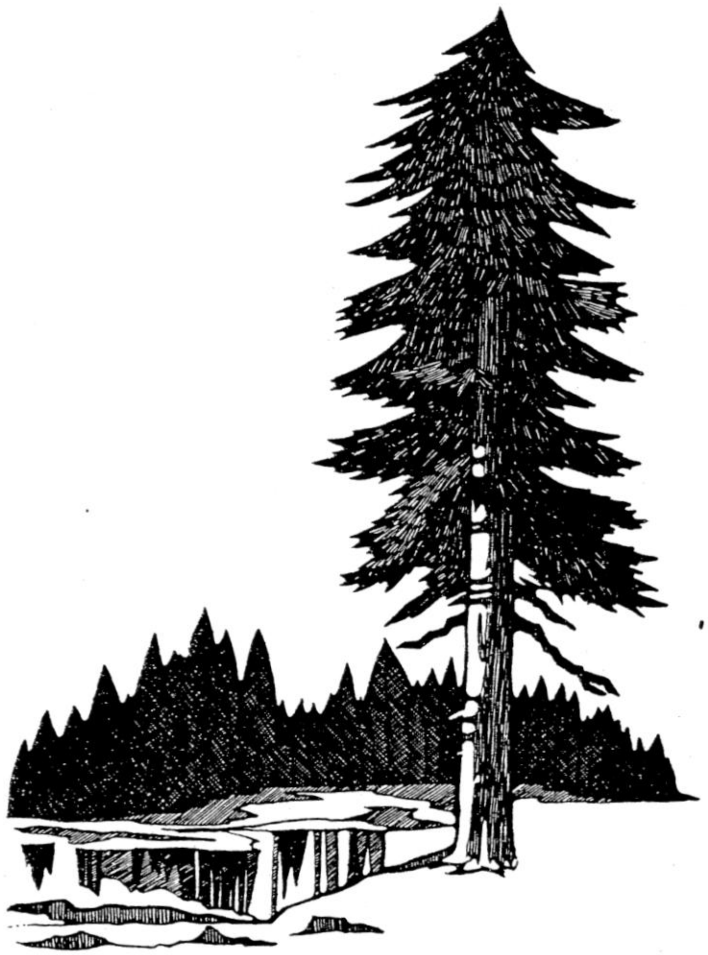

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PREFACE

The workshop was initiated over the concern that timber harvesting in certain watersheds may be upsetting the "hydrologic balance," and consequently there is a need to be able to schedule timber harvest in a manner that protects watershed resource values. Therefore, a workshop sponsored by Region 6 and the Pacific Northwest Forest and Range Experiment Station was held in Portland, November 27-29.

The papers contained herein were presented at the workshop which was entitled "Scheduling Timber Harvest for Hydrologic Concerns".

The purpose of the workshop was to present and evaluate concepts and procedures which may be of potential use in scheduling timber harvest relative to watershed values. Included were considerations of the limitations of the procedures, how to use the procedures, discussions of their reliability, and recommendations for future procedures.

The scope of the workshop was restricted to the following general areas:

Management action - timber harvest.

Resource values - water yield (emphasis on timing), water quality (erosion and sedimentation), stream channel stability (processes, not effects).

Geographic - Region 6, western part of Region 1, northern part of Region 5.

Not all papers presented at the workshop were available for publication. Also, this is a limited publication, therefore, additional copies are not available beyond initial distribution.

A summary of the workshop conclusions is planned for presentation at the Interior West Watershed Management Symposium April 8-10, 1980 in Spokane, Washington.

Effects of Timber Harvest on Water Yield and Timing of Runoff - Snow Region

by

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Introduction

The hydrologic cycle (Figure 1) represent a complex series of process interactions which result in the translation of precipitation and energy inputs into, among other things, liquid and vapor outputs. The potential effect that various timber harvesting practices could have on water yield can be anticipated by evaluating the impact that the proposed activity can have on the processes involved with the translation of energy and water into the products of the hydrologic cycle.

The purpose of this paper is to evaluate the effects that timber harvesting has on water yield in areas where a significant portion of the precipitation input is in the form of snow. Most simply stated, forest harvesting directly modifies the evapotranspirational demands of the vegetation, usually reducing it, and the savings become water potentially available for streamflow. When snow is a significant form of the input, the change in the aerodynamics and energy balance of the stand, also associated with timber harvest, can alter the distribution of the input as well as the timing of its availability to the system. The form of the precipitation input greatly controls the nature and timing of timber harvest impacts on water yield. In this paper, we will consider the effect of timber harvest on water yield from the snow zones in the Rocky Mountain/ Intermountain, Pacific Coast, and Central Sierra Regions. The following describes the snow conditions we are dealing with in those regions (Troendle and Leaf, 1980).

The Rocky Mountain/Intermountain region covers parts or all of South Dakota, Wyoming, Montana, Colorado, New Mexico, Arizona, Utah, and Idaho. Most of the water for the region comes from snowpacks which accumulate in winter and melt in summer. In general, winter temperatures are very cold, snow is dry, and snowpacks have a thermal gradient. That is, snow temperatures at the soil surface approach those of the soil itself (32°F or 0°C). Temperatures from the soil to the snowpack surface decrease, until at the air-snow interface they reach air temperature. However, this region is far from homogenous and the climatic differences affecting snowpack performance should be recognized.

The entire region is subject to summer thunderstorms which can cause disastrous flooding and assist in recharging the soil water supply. The entire area is usually subject to snow deposition as a result of high winds and dry snow, except for two major transition zones -- (1) northern New Mexico, southwestern Colorado, northern Arizona, and (2) northern Idaho. These are transition zones between the dry, low temperature snowpacks and continental frigid winter climate of the true Rocky Mountain chain, and the warm climate, wet snowpacks of the Pacific Coast. Dependent upon the direction from which the storms and air masses come, the snowpacks in these transition areas will be representative of one of the other major provinces all year; or they may resemble one province

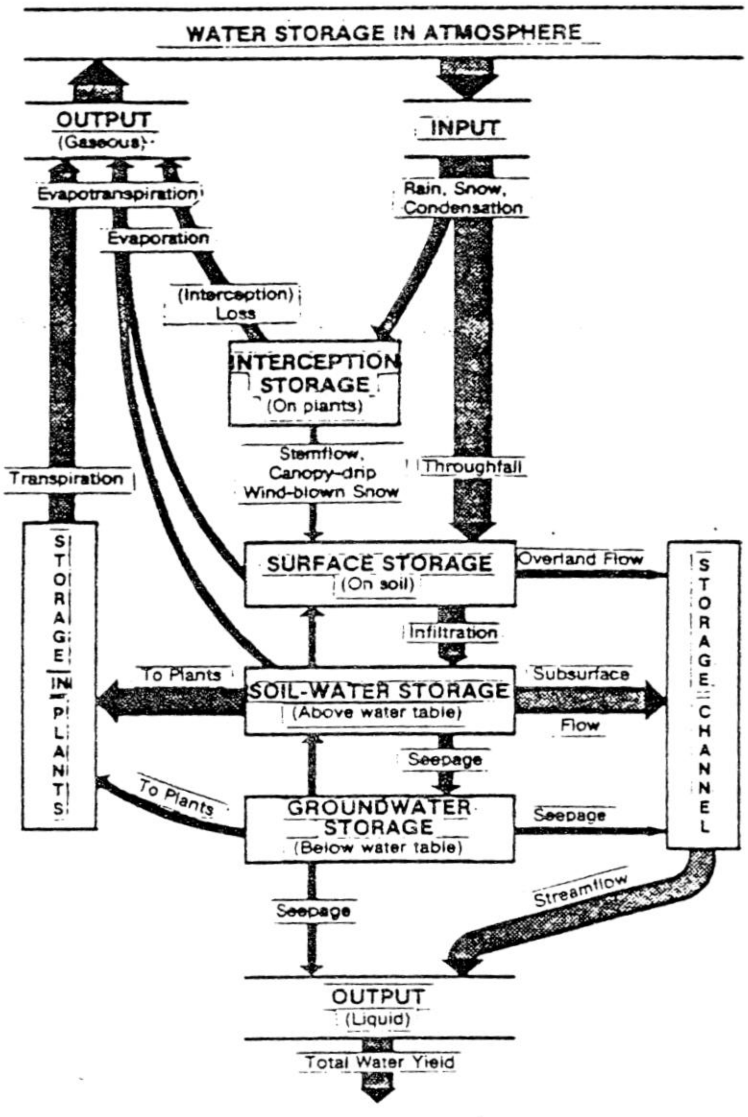

Figure 1 - The hydrologic cycle consists of a system of water storage compartments and the solid, liquid, or gaseous flows of water within and between the storage points (Anderson and others 1976).

during part of the year and resemble the other during another part of the year.

In western Montana and in Wyoming plains and rolling hills, there is enormous displacement and redeposition of snow. This affects evapotranspiration and tree growth since it removes the scanty snow cover from vast areas and concentrates it in a few locations. Obviously, this favors increased plant growth and water use in these sites. Evaporation (sublimation) loss from blowing snow is extensive.

Snows in the Rocky Mountains of Wyoming and Colorado and in the Wasatch Mountains are dry and cold. Wind redeposition is extensive in large, open areas. Particularly in Colorado, much of the mountain chain lies in the Alpine Zone. Snowpacks mature and melt in response to "ground heat" from below and to warm air temperatures and increased solar radiation in the spring. The thermal gradient in such packs creates unstable snow layers; frequent avalanching occurs from this cause and from melting snow sliding over wind slab formations. Since most melt occurs from the surface of the pack downward, the pack largely wets up from the surface. Most melt water goes directly into the soil. Since the packs are "cold," first melt goes to satisfying the thermal demand needed to bring the snowpack to a thermal equilibrium (32°F or 0°C) throughout the pack.

The shallow snows in northern Arizona frequently are redeposited by wind. Because of the lower latitude and higher insolation in winter, however, midwinter melt is often sufficient to wet the surface and prevent further movement.

Southwestern Colorado, northern Idaho, and the Rocky Mountains of western Montana receive wetter snows and even occasional rain. These cause some limited ice layering in the snow in southwestern Colorado.

The Pacific Coast region begins in the San Bernardino Mountains of southern California, continues northward through the Sierra Nevada of California, the Cascades of Washington and Oregon, and includes the mountain ridges and peaks of western and central Nevada. The same type of snowpacks occur northward through British Columbia and into southeastern Alaska, at least to Anchorage.

The maritime climate in the winter is warm and wet. Summers vary depending upon the particular portion of the province, but generally they are dry with little or no summer precipitation. Summer thunderstorm activity is extensive over the southern Sierra Nevada, adding some water to that area, largely in the relatively treeless alpine area. The remainder of the Pacific Coast province, with the exception of parts of Washington, receives little summer precipitation.

Fall and winter precipitation is normally snow, but extensive rainstorms sometimes occur up to 2436 m (8,000 ft) elevation in the Central Sierra. Significant snow falls at elevations down to 1218 m (4,000 ft), and, on rare occasions, significant amounts fall to 610 m (2,000 ft). Rains remove snowpacks up to 1827 m (6,000 ft) elevation and infrequently remove significant parts of the packs to over 2132 m (7,000 ft).

Snowpack depth is extremely variable and has been measured at maximum pack from 91 cm (36 in) to over 700 cm (275 in).

Snow redistribution normally does not occur due to the wetness of the snow.

Snow metamorphism continues all winter as a result of the warm climate, and frequent ice lenses occur throughout the packs, particularly on south, open slopes. Temperatures normally remain at 0°C throughout the packs. When rain falls on packs significantly lower than 0°C, serious flooding can occur from rain and melt water flowing over the frozen layer (Smith 1974).

Snowpack configuration of these warm, wet snows typically consists of a mixture of heavy and light density layers having different maturation schedules and water-holding capacities. The configurations vary dramatically by aspect and by forest cover (Smith 1974, 1975).

Because of warm climate, frequent rains, and melting snow, snowpacks in the subalpine are usually wet and remain at thermal equilibrium throughout the snow season. Frequent snowfalls keep the albedo high (80-90) until spring melt out is well under way, at which time albedo drops to about 45 percent. Major winter melt is caused more from absorption of solar radiation by the rocks, trees and shrubs standing above the snow than from direct solar radiation to the pack. These, in turn, heat up and radiate sensible heat to the pack. This creates the major melt until late season low albedos of the snow increase radiation absorption by the pack.

Because of the isothermal, wet condition of the snow, forest cover change can be used to direct heat into or away from the snow. Melt out date can be moved forward or backward 2 weeks to 1 month by increase or decrease of forest cover (Smith 1974, 1975).

While wind distribution plays little role in this province, differential melt is substantial. The greater amount of snow in forest openings on the west-south walls were once thought to be the result of distribution; it has since been found to be the result of greater melt on the north and east side of the opening (Smith 1974).

There are more problems associated with evaluating the hydrologic responses of snow covered basins to timber harvest than those subject to rainfall.

Snowfall redistributes the precipitation in time and occasionally in space. Snow falling in the Rocky Mountains is not reflected in the soil moisture or streamflow until spring melt. In the Pacific Coast province it may appear as soil moisture or streamflow within a few days, or it may not appear until spring. Due to lack of ice lenses, melt or rain falling on snow in this region may enter the soil under a forest growing on a south slope. Removal of the forest may result in ice lens formation in the pack, and rain or melt may flow through the snow to the stream and never reach the soil to provide water for satisfaction of soil water deficit.

The Fool Creek Experiment

Anderson et al. (1976) summarized the findings of numerous watershed experiments designed to evaluate the effects of forest harvesting on streamflow. Most of those reported experiments were conducted on "rain dominated" watersheds as there is a paucity of information, by comparison, for "snow dominated" watersheds. One experiment, Fool Creek, in the Colorado subalpine, stands out because of its longevity and completeness. I will try to update the results of the Fool Creek experiment with respect to the effects of timber harvest on the timing and quantity of streamflow and at the same time compare or contrast those findings with others in the snow zone region of the western United States.

The Fool Creek Experiment is a classic paired watershed study that has been ongoing at the Fraser Experimental Forest since the early 1940s. The streamgage on Fool Creek, the 289 ha (714 acre) treatment watershed, was built in 1941 while the gage on the companion East St. Louis Creek, the 803 ha (1984 acre) control watershed, was built in 1943. The watersheds were calibrated until 1952 when the timber harvest access system was built on Fool Creek. Approximately 14 ha (35 acre) of the 289 ha watershed was impacted by roads and log decks. The watershed was harvested in 1954, 1955 and 1956. Approximately 40 percent of the watershed was harvested using alternating cut and leave strips which varied from 1 to 6 tree heights wide (Figure 2). The treatment itself has been thoroughly described by Goodel (1959), Leaf (1975), and Alexander and Watkins (1975).

The objective of the experiment was to determine the impact, if any, that forest harvesting had on total precipitation input to the watershed, the distribution of input with respect to openings and opening size within the watershed, and the effect that harvesting has on total yield and timing of streamflow. Snow courses were monitored on both watersheds annually from 1943 to 1954 to "calibrate" the relationship of peak water

Figure 2 - Fool Creek watershed, Fraser Experimental Forest. East St. Louis Creek, the 1,984-acre control watershed, is to the right of Fool Creek (Leaf, 1975).

equivalent on the two watersheds. Postharvest data was collected in 1959, and from 1966 to 1978. Figure 3 presents the pre- and post-treatment estimates of peak water equivalent on Fool Creek plotted over that for East St. Louis. A covariance analysis of the slopes of the pre- and post-treatment relationships indicates no significant change in the relationship occurred following harvest. It can be noted however, that the estimate of the average water equivalent on Fool Creek increased by over 5 cm (2 in) following harvest. The inference that can be drawn is that although the distribution and dissipation of input was altered by harvest, the total input, on a watershed scale, was not significantly altered. It should also be noted that a re-evaluation of the data from Wagon Wheel Gap (Leaf, 1975) also indicated the total input to that watershed was not altered following harvest. There is no indication that timber harvest increases or decreases the total input to the system on a watershed scale. Intensive surveys in the cut and leave strips on Fool Creek were consistent with earlier studies (Wilm and Dunford, 1948) on the forest where it was found that there was a significant increase in snow accumulation in the forest openings. After evaluating the potential interception losses from the canopy as well as evaluating the effect of changing the aerodynamics of the stand through cutting, it was concluded that the increased accumulation in the cut strips was more the result of redistribution than savings in interception (Hoover and Leaf, 1967) and that the size of the strip or opening alters the trapping efficiency. Hoover (1969) felt that for optimal distribution the opening should not exceed 8 tree heights in width. To further refine the estimate of optimal size, data from Fool Creek (Figure 4) imply that the pack in the center of larger openings (6 H) can be scoured. The mirror-like image of the comparison of water equivalent between forest and open (Figure 4) has lead Leaf (1975) to conclude that in the Colorado subalpine the contributing area for the additional snow in the open is an area downwind of the opening and approximately equal in size. Gary (1974) made similar observations at a study site in southern Wyoming.

After numerous re-surveys of the cutting plots reported on by Wilm and Dunford (1948), intensively surveying the cut and uncut strips of Fool Creek, and evaluating other pertinent observations; Leaf (in Troendle and Leaf, 1980) constructed a redistribution relationship for openings in Rocky Mountain subalpine forest. The redistribution (ρ) function is shown on Figure 5 and as can be noted, it implies that a 5 H opening is optimal for maximizing the accumulation of snow. The RHO (ρ) function for the most part represents the current state-of-the-art in understanding the effect of forest harvesting on snow redistribution in the Colorado subalpine. These findings are not necessarily consistent with findings elsewhere in the snow region, however where snow may not be as light. Golding and Swanson (1978) recently reported on observations on replicated plots in lodgepole pine along the James River in Alberta, Canada. They found that 2 - 3H openings were optimal for redistribution. However, their larger openings (5 - 6H) were still nearly as efficient in trapping

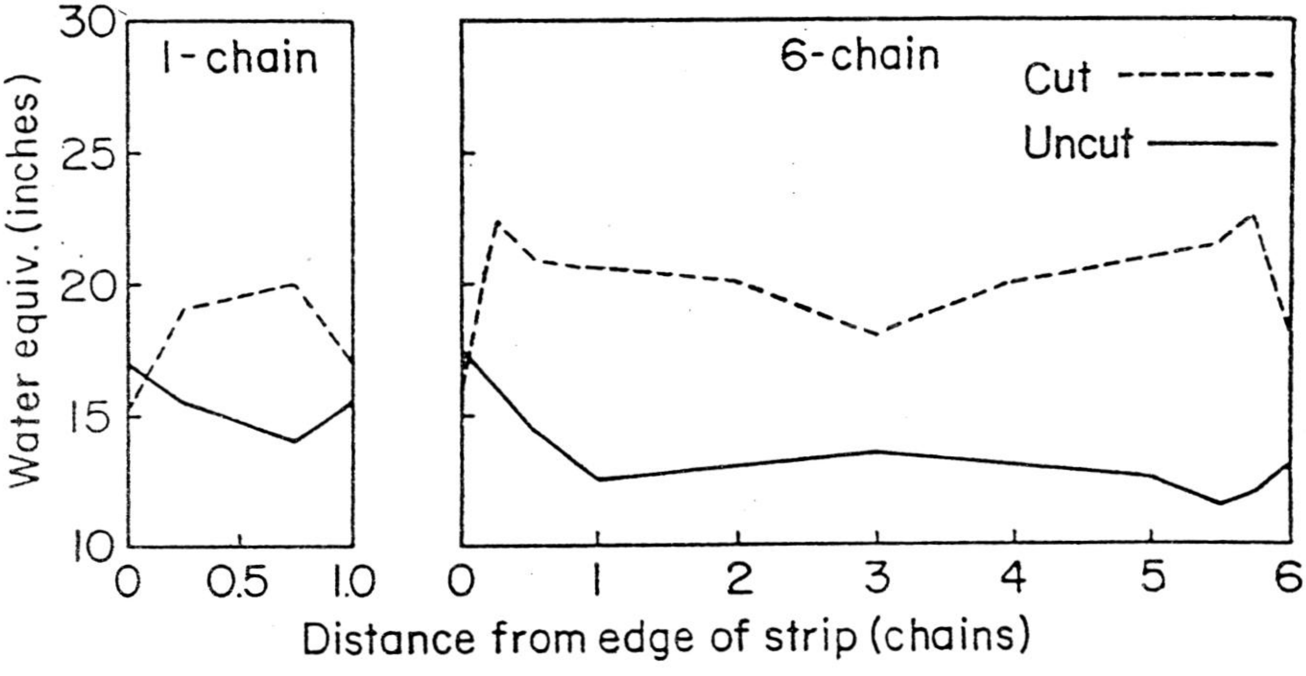

Figure 4 - Comparison of average snow accumulation in one and six tree-height strips on Fool Creek, Fraser Experimental Forest (Leaf, 1975).

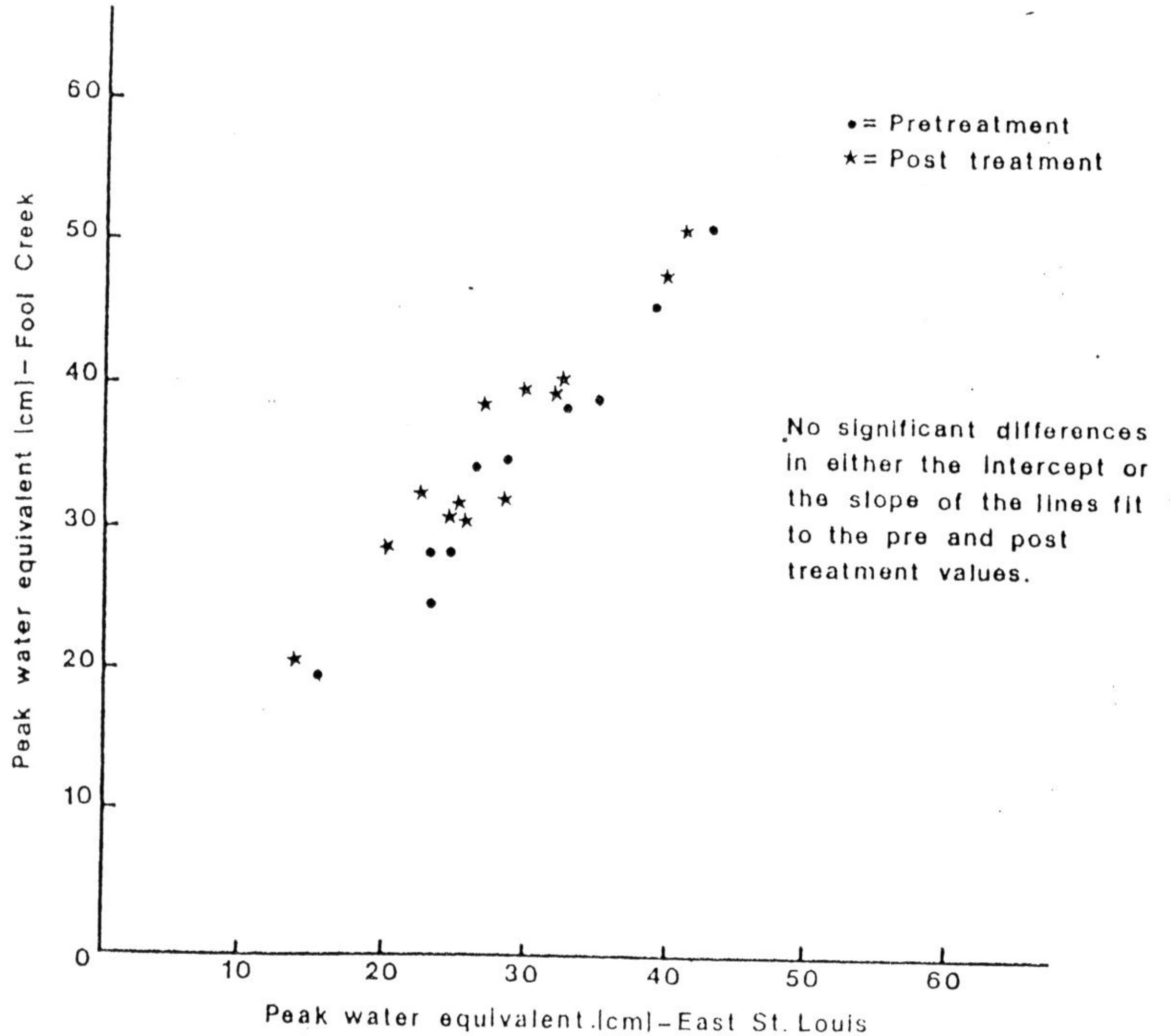

Figure 3. - Peak water equivalent in snowpack on Fool Creek and E. St. Louis Creek under pre and post treatment conditions.

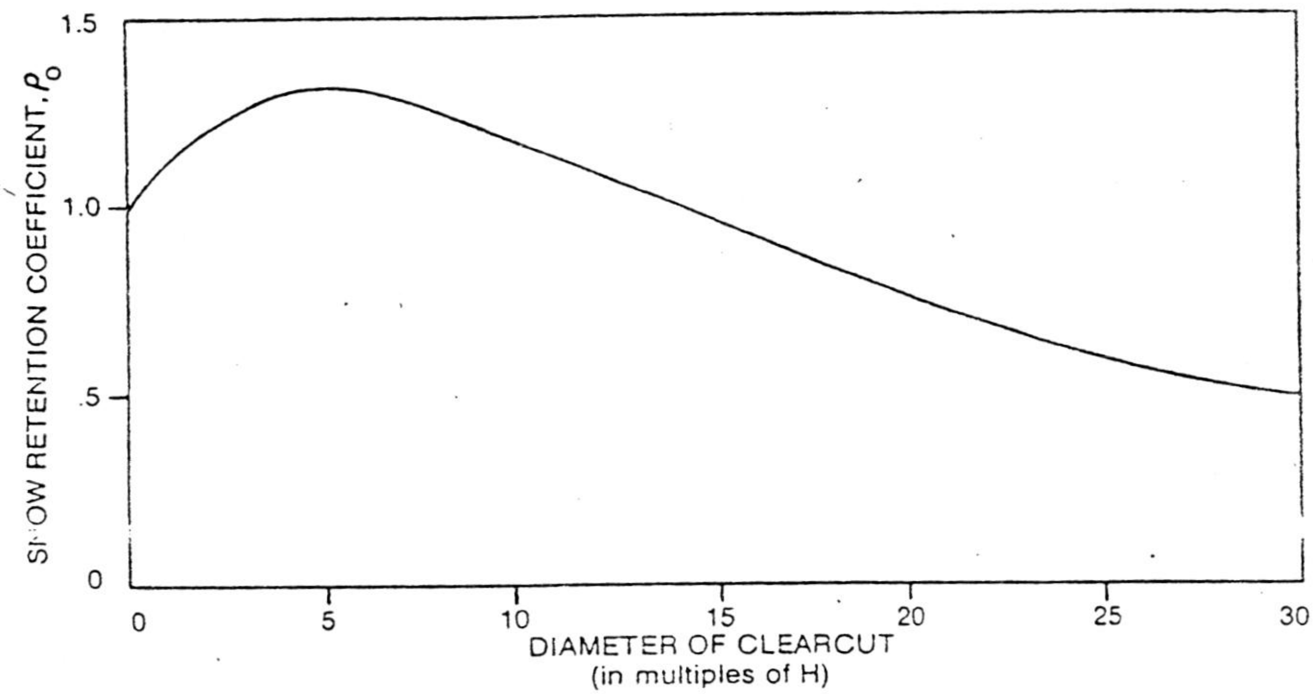

Figure 5 - Snow retention as a function of size of clearcut. H is the height of surrounding trees (from Troendle and Leaf, 1980).

$$Q_{\text{Fool Creek}} = \beta_1 \, Q_{\text{E. St. Louis}} + \beta_2 \, t$$

where

$Q_{\text{Fool Creek}}$ = Annual flow from Fool Creek in cm.

$Q_{\text{E. St. Louis}}$ = Annual flow from the control watershed, East St. Louis, in cm.

t = A linear variable for time, in years, since treatment.

The second model was similar to the first with the exception that a quadratic function for time (t^2) was used. The fit of both models was basically the same. The standard error of the mean for the linear model was 0.3 percent smaller than that for the quadratic model. Complete recovery is estimated as requiring 52 years using the linear and only 35 years using the quadratic model. Neither estimate can be expected to be correct and more will be said about recovery later. Figure 7 shows the pre- and post-treatment relationship of annual flow from Fool Creek and East St. Louis Creek. The annual changes in flow, resulting from the treatment and estimated using the linear function for time are shown in table 1. The average change in flow over the 23 year period was 7.4 cm (2.9-in) but was very heavily dependent on total flow. The expected first year increase in flow (t=1) using the linear function for time and the mean flow for the control watershed (of 34 cm or 13.4 in) during the post-treatment years is 9.4 cm (3.7 in). The reduction in the first year increase that can be attributed to the past 23 years (t=23) of time is 4 cm (1.6 in). We would then expect a 5.3 cm (2.1 in) increase in flow this year (t=24) given the mean flow of 34 cm on the control watershed. However, it should be noted that if 54.3 cm (21.4 in) of flow were to occur on the control watershed next year, (the highest flow during post treatment record) we could still expect a 10.9 cm (4.3 in) increase in flow on Fool Creek. In summary, 40 percent of the watershed was harvested and the increase in flow has been approximately 40 percent. Other experiments in the snow zone, yield somewhat similar results.

At Wagon Wheel Gap in the headwaters of the Rio Grande in Colorado, Bates and Henry (1928) observed accelerated snowmelt rates after clearcutting the aspen-mixed conifer forest from one 81 ha (200-acre) watershed. This effect was apparent in the streamflow hydrograph (fig. 8). Moreover, annual water yields were increased about 22 percent during the 7-year period that records were taken after harvest cutting. Swanson and Hillman (1977) working in West-Central Alberta used the findings at Fool Creek and Wagon Wheel Gap to fashion a predictive procedure to estimate the changes in volume and timing of flow following clearcutting. After comparing nine logged and unlogged catchment pairs, they observed 59%

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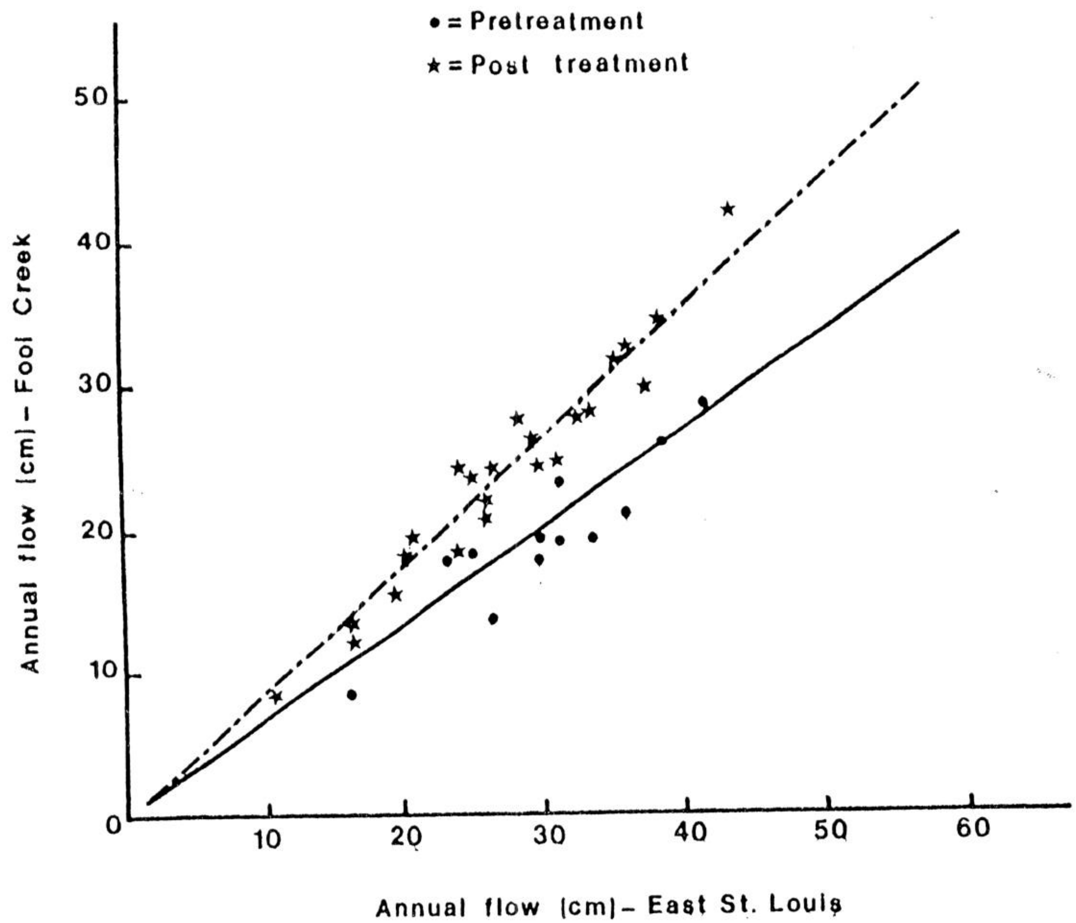

Figure 7. - Annual flow from Fool Creek and E. St. Louis Creek under pre and post treatment conditions.

Table 1. April to September streamflow from Fool Creek and an estimate of the increase due to timber harvest.

Year	Observed Runoff		Estimated[1/] Increase	
	cm	(In.)	cm	(In.)
1956	35.3	(13.9)	10.9	(4.3)
57	52.8	(20.8)	14.7	(5.8)
58	30.5	(12.0)	8.9	(3.5)
59	30.3	(11.9)	7.6	(3.0)
60	34.8	(13.7)	9.1	(3.6)
61	24.4	(9.6)	6.1	(2.4)
62	43.9	(17.3)	12.2	(4.8)
63	10.9	(4.3)	2.3	(0.9)
64	22.9	(9.0)	5.6	(2.2)
65	39.6	(15.6)	10.7	(4.2)
66	17.3	(6.8)	3.6	(1.4)
67	27.9	(11.0)	6.8	(2.7)
68	23.1	(9.1)	6.1	(2.4)
69	30.7	(12.1)	7.9	(3.1)
70	27.6	(14.8)	10.4	(4.1)
71	40.2	(15.8)	9.9	(3.9)
72	29.7	(11.7)	5.7	(2.2)
73	31.0	(12.2)	7.6	(3.0)
74	35.0	(13.8)	7.9	(3.1)
75	26.4	(10.4)	5.6	(2.2)
76	19.6	(7.7)	2.8	(1.1)
77	15.7	(6.2)	1.8	(0.7)
78	32.8	(12.9)	6.1	(2.4)
$\bar{X}$	30.0	(11.8)	7.4	(2.9)

[1/] Estimate of change is made using linear function of time (t=year since harvest) in equation $\Delta Q_{\text{Fool Creek}} = 0.280\ Q_{\text{East St. Louis}} - .180\ t$

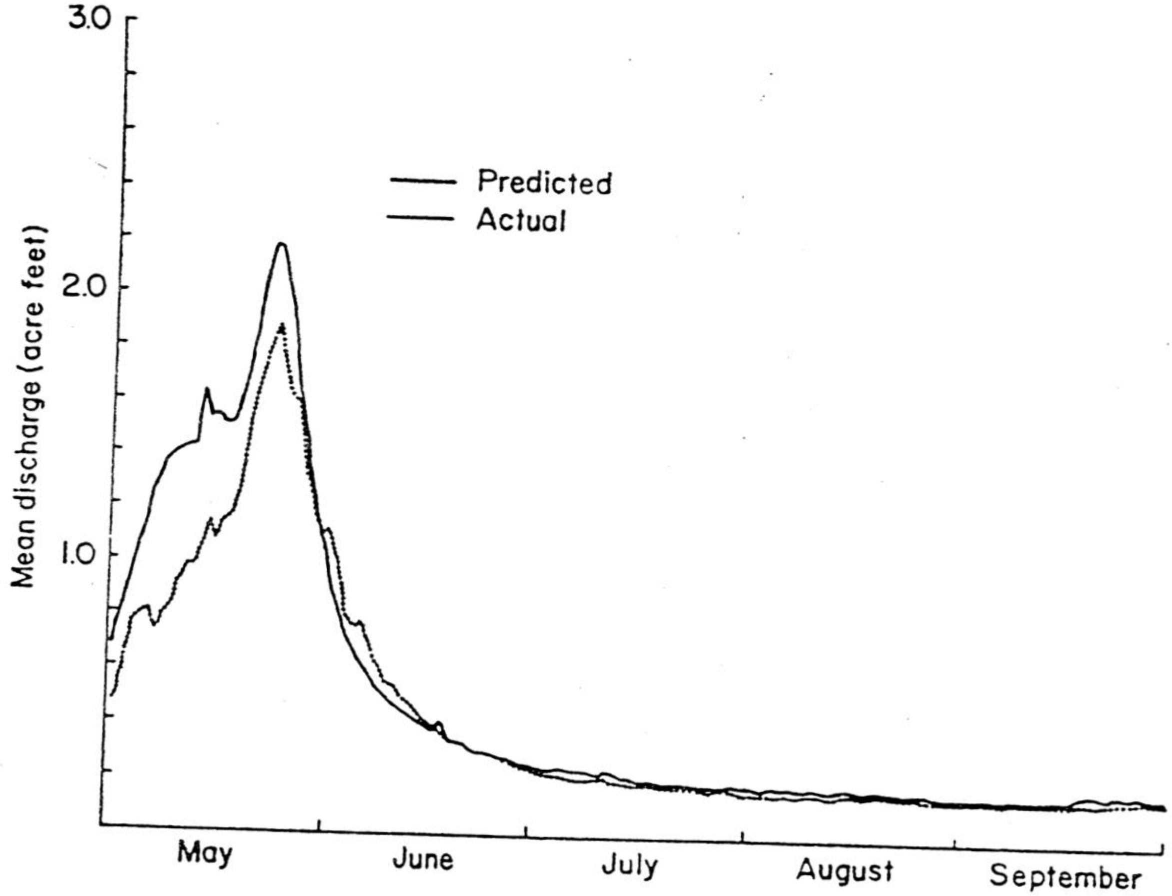

Figure 8 - Average hydrographs for Wagon Wheel Gap watersheds (Bates and Henry 1928). The dotted line is the predicted hydrograph for watershed B if not harvested, based on pre-harvest regression for 1912-19. Solid line is the actual hydrograph for watershed B after timber harvest.

more water in melt runoff, 27% greater yield and 1 1/2 - 2 times greater storm peaks from watersheds where 35 - 85 percent of the area was cut. The nature of the response was similar to that for Wagon Wheel Gap and is shown on Figure 9.

Peak Discharges

A covariance analysis of peak daily discharge between Fool Creek and East St. Louis indicated no significant change. However, the estimate of average peak daily discharge, for after treatment, did increase .02 m^3/sec (1 CFS) from .26 to .28 m^3/sec (9 to 10 CFS/day). Individual rainfall events are so few at Fraser Experimental Forest that unlike the Alberta study (Swanson and Hillman, 1977), detection of changes in storm response cannot be attempted. The pre- and post-treatment relationship in peak discharges for Fool Creek and E. St. Louis is shown on Figure 10. Swanson and Hillman (1977) did observe increases in summer storm hydrographs. Response potential is similar in the "Snow Zone" to that in the "Rain Zone." The most significant difference is the usual lack of rainfall in the snow zones during the growing season.

Summary

In summary, timber harvesting in the "Snow Zone" reduces the evapotranspirational draft. This reduces soil moisture depletion during the growing season and resulting deficits are far less going into the winter than prior to harvest. During the spring snowmelt period, the soil moisture deficit to be satisfied is reduced because of the reduced ET the summer before and more water is available, during the recharge period, for streamflow. As a result, most of the increases in flow observed at Fool Creek or Wagon Wheel Gap were from the spring melt. Since radiation is the chief source of energy to melt snow (Garstka, et al, 1958) opening the stand enhances melt and causes much of the pack to become streamflow very early in the season as noted earlier. In addition to the change in timing, there is an apparent increase in "efficiency" associated with the advanced melt as well. In many portions of the region, more snow is accumulated in the openings either through redistribution (Leaf, 1975) or by savings in interception losses (Haupt, 1979a). The snow in the opening melts earlier, up to a month earlier on high energy sites, and is made available for storage or for streamflow very early and during the time of peak recharge when minimal transpirational draft is occurring. As a result, the efficiency of converting snow pack to streamflow is very great and the melt water has little opportunity to be "lost." Because of this interaction it is difficult to define what portion of the observed changes in flow from "Snow Zones" can be attributed to ET savings and which can be attributed to the "efficiency" of the redistribution of the pack and desynchronization of its melt rate.

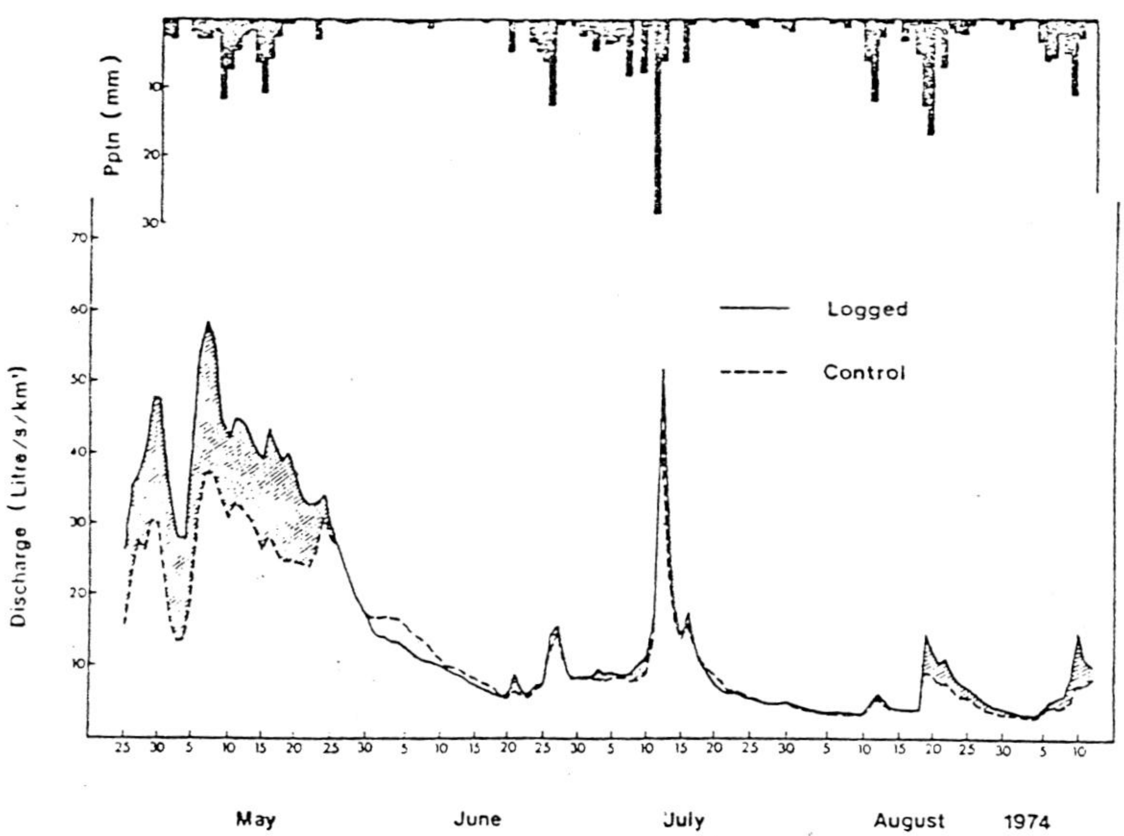

Figure 9 - Composite hydrographs for 1974 from nine logged and nine control catchments on the study area. Shaded portions indicate times when logged yield exceeded control (from Swanson and Hillman, 1977).

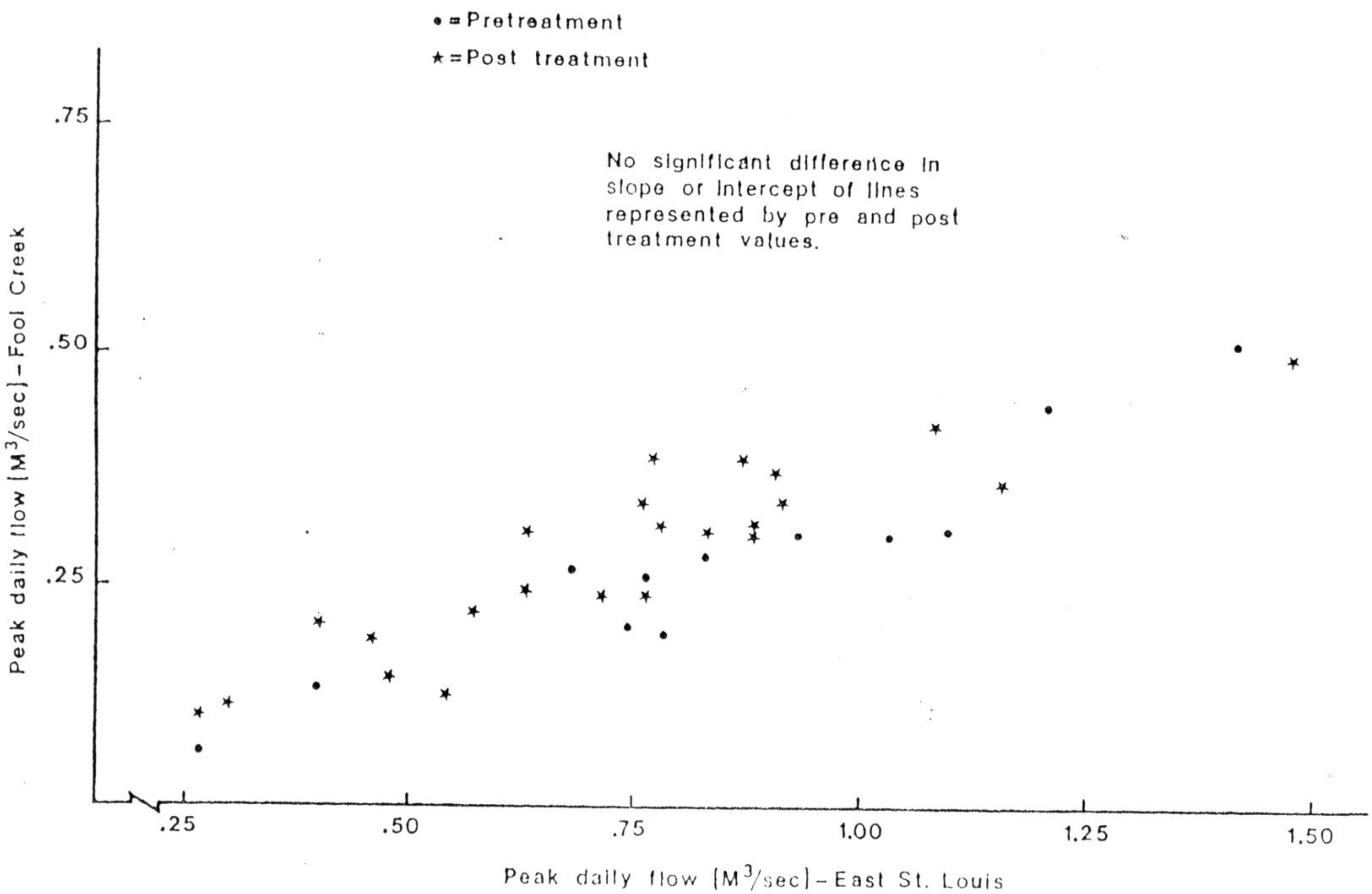

Figure 10. - Peak daily discharge from Fool Creek and E. St. Louis Creek, under pre and post treatment conditions.

As noted earlier, Meiman and Dietrich (1975) concluded that 20 percent of the potential change could be attributed to redistribution in lodgepole pine on the Colorado front range.

Because the redistribution effect can be so long lasting (Gary 1979, Haupt 1979a & b, Swanson and Hillman 1977, Leaf and Alexander 1975), it is difficult to predict the actual longevity of harvesting effects on streamflow. On Fool Creek, for example, a linear time model estimates 52 years are required for recovery while 35 years are estimated if the quadratic function is used. Neither of these can be expected to be correct. What we have evidenced so far in the record is probably only the impact that vegetative recovery has had on the ET process. Whatever was the effect of redistribution itself, is probably still in effect and we can expect it to continue for some time.

The shape of the expected recovery curve, for watersheds such as Fool Creek, is complex. At first the slope of the recovery line will be quite minimal as a new stand establishes. In the case of Fool Creek the first 17 years of post harvest record did not express a significant trend in the reduction of increased flow (Leaf, 1975). This establishment period is then followed by a period of rapid reduction. This period should also tail-off and reflects what is being observed now on Fool Creek. We can expect that the effect of redistribution will hold the curve above zero for quite sometime into the future.

Predictive Techniques

Within the "snow zone," only one "complete" hydrologic model has been demonstrated to be a useful management tool in the region as a whole. Leaf and Brink (1973a, 1973b) have developed a comprehensive hydrologic model which simulates the water balance in several hydrologic subunits within a subalpine watershed on a continuous year-round basis, and compiles the results from up to 25 subunits into a "composite overview" of the entire drainage. The model has been specifically designed to simulate watershed management practices and their resultant effects on hydrologic system behavior.

Leaf and Alexander (1975), and Leaf (1975) have described the application of the model to timber scheduling decisionmaking in the lodgepole pine and spruce-fir types of the subalpine. Alexander and Watkins (1975) have described a pilot study on Deadhorse Creek, Fraser, Colorado, which is intended to verify the simulated results.

However, the model may be too data demanding for everyday use in planning activities. The level of expertise required to operate it is also quite high. As a result models like the Sub-Alpine Water Balance Model (WATBAL) are tools that we need available to us but are ones that may see limited practical application. However, WATBAL is one of the models used to develop WRENS (Troendle and Leaf, 1980) techniques for hydrology. Gordon Snyder will discuss this effort in detail as it represents one way that the knowledge gained from research can be organized into a series of predictive techniques, more useful to the manager, than the simulation models themselves.

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EFFECTS OF TIMBER HARVEST ON STREAMFLOW IN THE RAIN-DOMINATED PORTION OF THE PACIFIC NORTHWEST

by

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CONVERSION TABLE

1 mm	=	0.04 in
1 cm	=	0.39 in
1 m	=	3.28 ft
1 km^2	=	0.386 mi^2 or 247 acres
1 liter/sec·ha	=	10.93 $ft^3/sec \cdot mi^2$

EFFECTS OF TIMBER HARVEST ON STREAMFLOW IN THE RAIN-DOMINATED PORTION OF THE PACIFIC NORTHWEST

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ABSTRACT

Research results from experimental watersheds and plot-level studies in 11 major locations from British Columbia to north coastal California have illustrated the magnitude of changes in streamflow after timber harvest. Annual water yields have increased up to 62 cm, some summer low-flows have quadrupled, and size of peak flows have increased, decreased, or remained unchanged in small headwater basins. Increases in summer flow have disappeared after 4-5 years, and annual water yield increases have diminished as revegetation has proceeded. Although increases in annual water yield and summer flows are probably most readily predicted, neither has any influence on channel erosion processes in the rain-dominated portion of the Pacific Northwest. Our capability of predicting changes in the higher flows directly involved in channel erosion processes is poor and is hindered considerably by our incomplete understanding of subsurface flow of water and runoff production during winter storms, of the mechanics of snowmelt from shallow snowpacks during rainfall, and how each of the foregoing is affected by timber harvest activities.

INTRODUCTION

Each year some 54 million cubic meters (12 billion board feet) of timber are harvested from about 170,000 ha (420,000 acres) of forest land in western Oregon and western Washington alone. Because timber harvest activities have the potential for altering streamflow characteristics in forested watersheds, USDA Forest Service land managers are attempting to schedule harvest in these watersheds over a number of years to minimize the impact on water quality and aquatic ecosystems.

The responsibilities and obligations of the USDA Forest Service in managing National Forest lands have been stated in the Multiple Use-Sustained Yield Act of 1960, the National Environmental Policy Act of 1969, and, more recently, the National Forest Management Act of 1976. Under these Acts the Forest Service is directed to "manage all the various renewable surface resources of the National Forest...without impairment of the productivity of the land...to provide for methods to identify special conditions or situations involving hazards to the various resources," and to "ensure that timber will be harvested from National Forest System lands only where soil, slope, or other watershed conditions will not be irreversibly damaged [or] where protection is provided for streams [streambanks]."

To help the USDA Forest Service fulfill these management obligations requires that everyone responsible for management decisions and actions affecting streamflow have a common and accurate perception of natural forest hydrologic systems and how they are affected by timber harvest activities. Helping to achieve that common understanding of hydrologic systems is a major purpose of not only this paper but also the workshop of which this paper is a part. The objectives of this paper are: (1) to review our understanding of the function of rain-dominated hydrologic systems, (2) to discuss what research has learned about the effects of timber harvest activities on these hydrologic systems, and (3) to examine our capability of predicting effects of harvesting activities on the quantity and timing of streamflow.

Many of my examples and much of my supporting data will be from watershed studies conducted by the Pacific Northwest Forest and Range Experiment Station. These data are most familiar to me and are probably more extensive than data from other areas.

Before I go further, I would like to qualify the title of this paper. When the workshop organizing group met to decide on workshop agenda and structure, it arbitrarily divided the broad subject of "effects of timber harvest on hydrologic systems" into two parts: (1) snow-dominated systems described by Troendle and Leaf,[1/] and (2) rain-dominated systems. Whether or not a hydrologic system is rain or snow-dominated probably is best illustrated by the distribution of annual runoff relative to annual precipitation. Where annual runoff closely follows annual precipitation, the system clearly is dominated by rain. Many west-side systems fall into this category which is illustrated by the runoff pattern of the North Fork Alsea River in figure 1. Where most precipitation occurs during winter but major runoff does not occur until spring, the system is obviously dominated by snow. Most east-side systems are in this category which is illustrated by the runoff pattern of the Colville River in figure 1.

Of course, all natural systems cannot be categorized so simply. Many watersheds, because they span either a wide elevational range or a relatively narrow range at higher elevations, exhibit a pattern of

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[1/] Troendle, Charles A. and Charles F. Leaf. Effects of timber harvest on water yield and timing of runoff--snow region. Paper presented at Workshop on Scheduling Timber Harvesting for Hydrologic Concerns, Portland, Oreg., November 27-29, 1979.

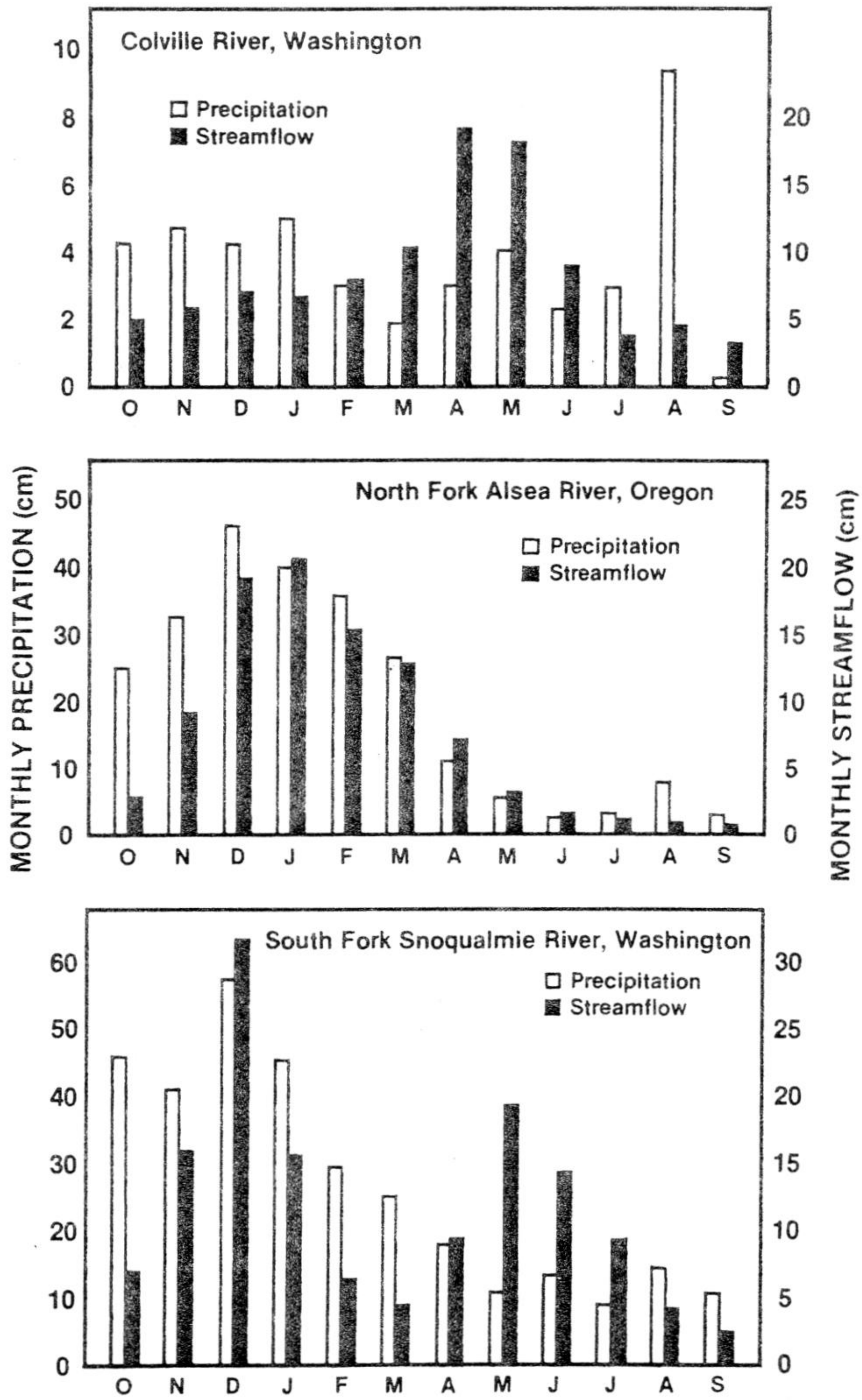

Figure 1—Distribution of annual precipitation and streamflow during 1976 for the Colville, North Fork Alsea, and South Fork Snoqualmie Rivers.

annual runoff with two peaks. The first peak results from fall and early winter rain and the second results from spring melt of winter snow. These watersheds, such as the South Fork Snoqualmie River in figure 1, have been placed in the rain-dominated category, but some of what Troendle and Leaf[1/] described is applicable to these watersheds during spring snowmelt.

The rain-snow dominance question is clouded even further by the rapid melting of shallow snowpacks during rainfall--the so-called rain-on-snow phenomenon. A particular system may fall easily into the rain-dominated category as defined earlier, but several important geomorphic processes--such as soil creep, earthflow, and channel erosion--may be dependent on snowmelt during rainfall although, on the average, less than 5% of total annual precipitation may fall as snow. Thus, in a sense, some parts of apparently rain-dominated systems actually may be dominated by snowmelt, and rain domination may be just a myth of forest hydrology for much of the Pacific Northwest.

For the purposes of this workshop, the rain-dominated hydrologic systems are found from British Columbia to northern California (fig. 2). In Oregon, they are found west of the Cascade Range below about 1500 m elevation and about 1200 m in northern Washington and 1400 m in southern Washington.

RESEARCH HISTORY

Study of the watershed level of natural forest hydrologic systems in western Oregon began in 1946 with the establishment of the Willamette Basin Snow Laboratory in the Blue River drainage by the U.S. Army Corps of Engineers (fig. 2). Soon after the H. J. Andrews Experimental Forest was established in 1948 in the Lookout Creek drainage immediately south of Blue River, parts of it were used for watershed-level experiments by USDA Forest Service Research to determine natural hydrologic characteristics and how they are affected by logging activities. Measurements of streamflow began in three small, low-elevation watersheds (designated HJA-1, 2, 3) in October 1952.

In 1957 USDA Forest Service Research began the Fox Creek Watershed Study in three small basins (designated FC-1, 2, 3) within the city of Portland's Bull Run municipal watershed. Also in October 1957, Oregon State University began the cooperative Alsea Watershed Study in three small watersheds (Needle Branch, Flynn Creek, and Deer Creek) to evaluate effects of roads and clearcut logging on aquatic resources in the Oregon Coast Ranges.

USDA Forest Service watershed management research was expanded in the 1960's to include studies in watersheds in somewhat different climatic and vegetation zones. Hydrometeorological records began in the Coyote Creek watersheds (designated CC-1, 2, 3, 4) in 1964 to determine effects of several silvicultural systems on water resources in the mixed conifer

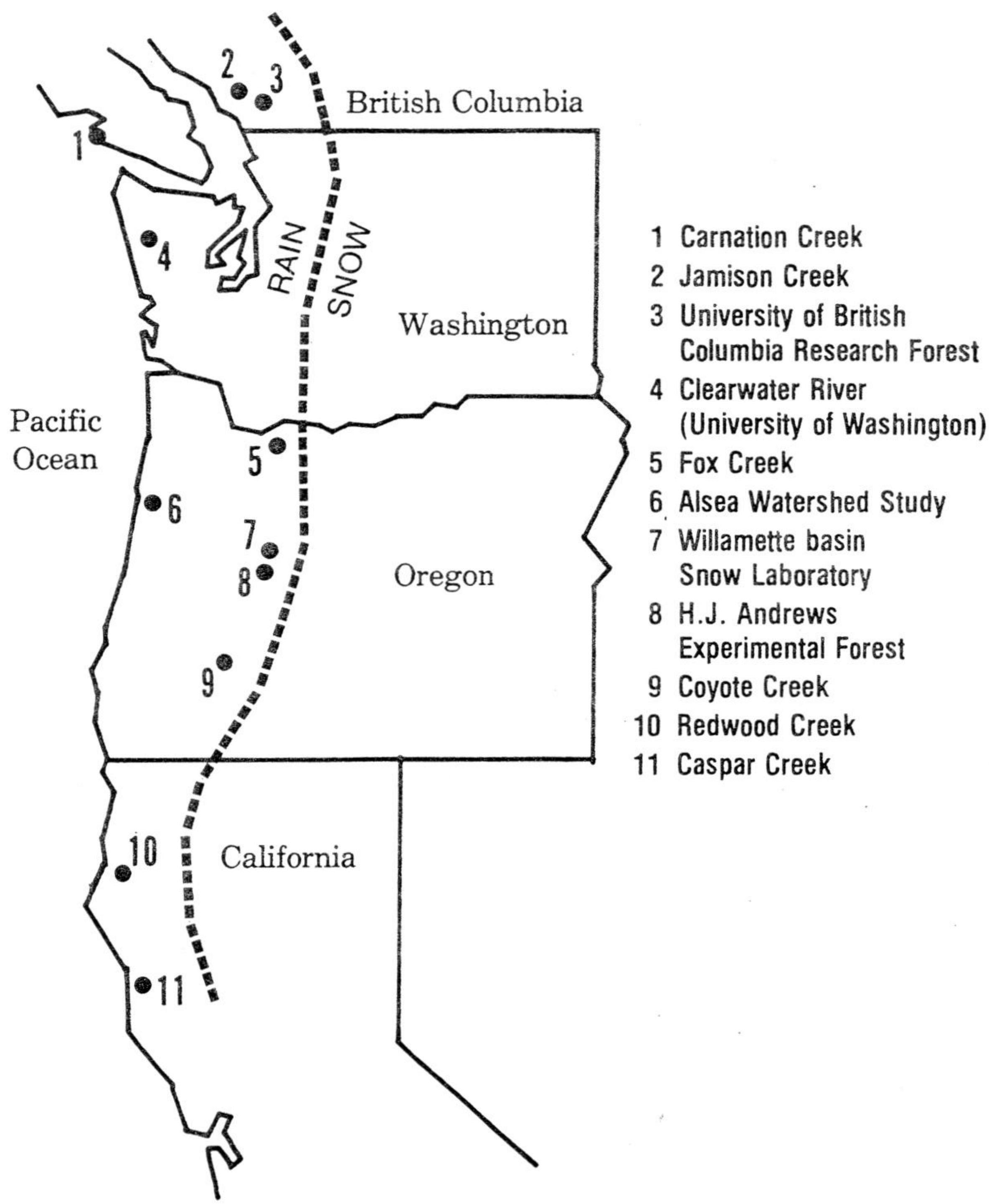

Figure 2--Approximate boundary of rain-dominated portion of the Pacific Northwest. Also shown are locations of major forest hydrology research areas.

zone of southwestern Oregon. Also in 1964, a study was begun in watersheds HJA-6, 7, and 8 in the H. J. Andrews Experimental Forest high elevation watersheds containing second-growth timber. More recently two small, low-elevation watersheds (HJA-9, 10) became the sites of intensive hydrometeorological and ecological studies as part of the International Biological Program's Coniferous Forest Biome.

With the exception of the Alsea Watershed Study which terminated in 1973, all the other watershed-level studies listed above are still in progress. Results from these active studies have been supplemented by data from the Canadian Forestry Service's Carnation Creek Watershed Study on western Vancouver Island, from studies by the University of British Columbia at Jamison Creek north of Vancouver and at the UBC Research Forest near Haney, from the USDA Forest Service Research's Caspar Creek Experimental Watersheds and the U.S. Geological Survey's Redwood Creek studies in north coastal California, and from studies by the University of Washington on the west side of the Olympic Peninsula in Washington.

THE REGION

In this workshop, we are particularly interested in hydrologic processes that can be sufficiently altered by timber harvest activities to cause changes in the quantity or timing of streamflow. We would also like to understand why various processes vary throughout the region because such variability of hydrologic processes hinders interpretation of research data and makes difficult the extrapolation of research findings to other areas for the purpose of accurately predicting the effects of timber harvest activities on quantity and timing of streamflow.

The climate of the Pacific Northwest is characterized by heavy fall and winter precipitation and relatively dry spring and summer periods. Winter weather is dominated by a westerly flow of moist air with a procession of fronts and low pressure areas; 75-85% of annual precipitation generally occurs between October 1 and March 31 (fig. 3). Less precipitation occurs in April and May, and during the June-September period the cyclonic activity characteristic of the winter is greatly reduced. This annual pattern is controlled by the seasonal position of the north Pacific subtropical anticyclone. In winter its southerly position allows storms to enter the Pacific Northwest, but in summer its northerly migration pushes storm tracks to the north. The general climate of the Pacific Northwest is characterized further by mild temperatures with prolonged cloudy periods, muted annual temperature extremes, and relatively narrow diurnal temperature fluctuations. Winters are cool with average January temperatures of 2-5°C (35-41°F) and average minimum January temperatures of -2-2°C (28-35°F) over most of the region. July temperatures average 15-22°C (59-72°F) with average maximum July temperatures of 20-32°C (68-90°F).

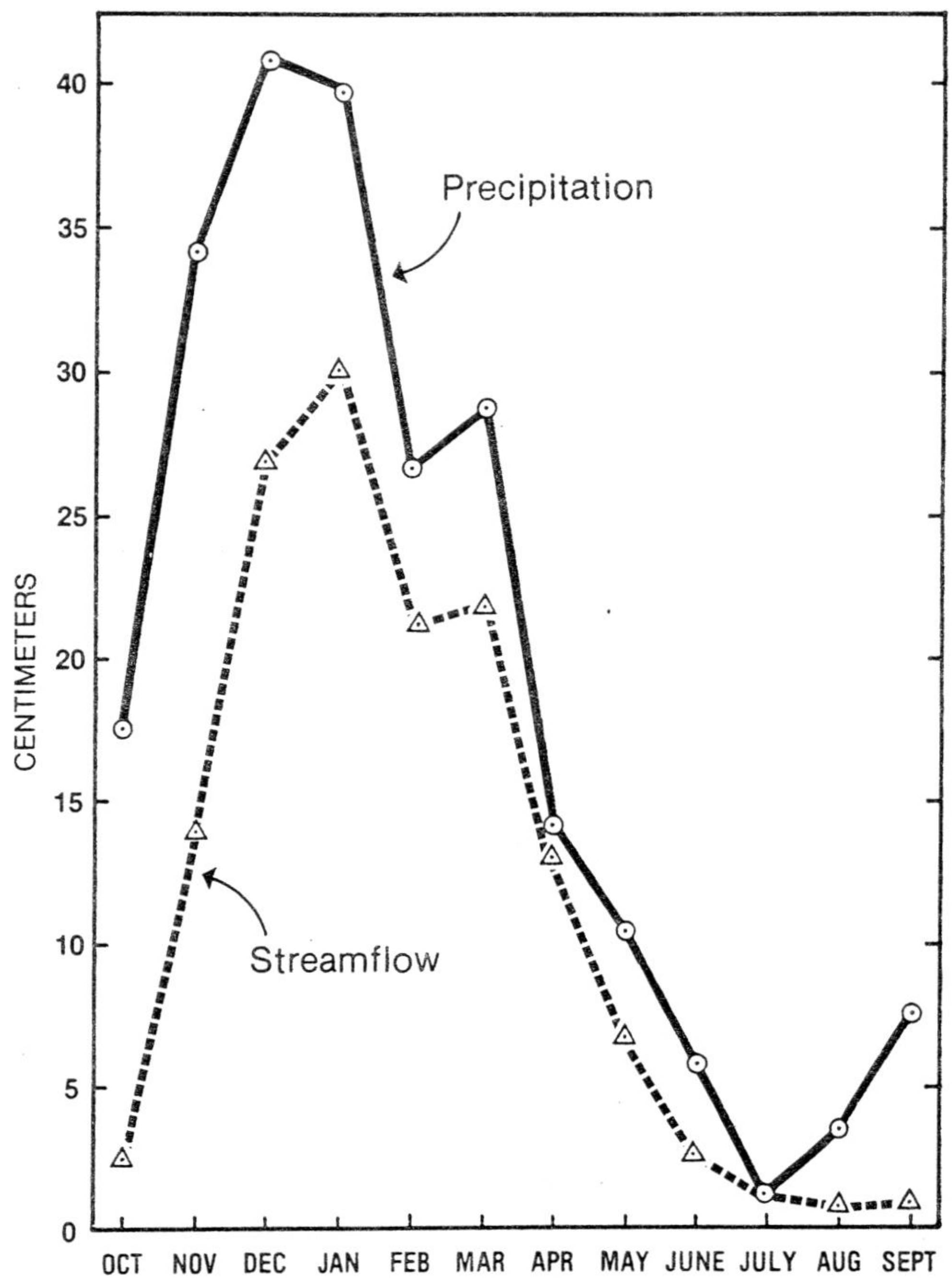

Figure 3--Mean monthly precipitation and streamflow at watershed HJA-2, H. J. Andrews Experimental Forest, Oregon, 1953-77.

Generally speaking, the systems we have classified as rain-dominated receive annual precipitation ranging from about 100 cm along the margins of both the Willamette Valley in Oregon and the Puget Trough in Washington to more than 300 cm along the windward side of the Cascades, the Olympics,

Table 1--Average annual precipitation and 24-hr precipitation for selected stations in western Washington and Oregon

Station	Elevation	Average annual precipitation[1/]	24-hr precipitation[2/] for return periods of		
			2 yr	5 yr	25 yr
	m	cm			
Washington:					
Forks	107	296	14	17	22
Quinault	67	338	15	19	24
Quilcene	37	139	10	12	15
Shelton	7	163	10	12	17
Darrington	168	204	10	13	17
Randle	274	154	7	9	12
Wind River	350	256	11	14	18
Oregon:					
Astoria	2	168	9	11	14
Newport	47	180	8	10	13
Valsetz	352	321	17	19	24
Powers	70	159	12	14	17
Estacada	125	151	9	11	14
Oakridge	389	117	6	9	11
Sexton Summit	1 170	93	8	10	13

[1/] National Oceanic and Atmospheric Administration (1977a, 1977b).

[2/] Miller et al. (1973a, 1973b)

and the Oregon Coast Ranges (table 1). At upper elevations, snowpack depth may reach 150 cm in some years but generally is 60-90 cm. At elevations between 400 m and 1000 m in western Oregon and 350 m and 650 m in western Washington, snowpacks are transient in most years; they rarely remain longer than 1-2 weeks and usually melt in 3-4 days during rainfall.

Precipitation is characterized by long duration (12-72 hr) storms of low to moderate intensity (generally <6 mm/hr) as illustrated by 24-hr precipitation amounts with return periods of 2-5 yr (table 1). According to the precipitation-frequency atlases for Washington and Oregon (Miller et al. 1973a 1973b) average intensity during 6-hr precipitation with a 25-yr return period ranges from 9 to 12 mm/hr over most of the region, although some local average intensities may be more than 18 mm/hr.

For the most part, forest lands in western Washington and Oregon are characterized by steep, extensively dissected topography. In the Olympic and northern Cascade Mountains of Washington, glaciation has strongly influenced many landforms; major river valleys are broad and U shaped, with steep sideslopes. On the other hand, glaciation has been negligible in most of rain-dominated western Oregon. Downcutting by streams and subsequent mass wasting of oversteepened sideslopes has created rugged topography with steep slopes and knifelike ridges. These conditions are particularly characteristic of the Coast Ranges, the Klamath Mountains, and the middle portion of the Western Cascades in Oregon. Drainage densities during the winter rainy season are high over most of the rain-dominated region of the Pacific Northwest, in some cases over 6 km/km^2. Steep slopes and high drainage densities greatly influence the movement of water through a watershed. In general, watershed responses to changes in rates of water input are directly related to slope steepness and drainage density.

Soils in the region have derived from a variety of parent materials, but texture of most surface horizons tends to be loamy, ranging from clay loams to sandy and gravelly loams. Some local areas, however, do exhibit clay surface horizons. Because of cementing of primary soil particles by organic matter and other agents, surface soils have large amounts of secondary porosity and wide ranges of pore sizes. Subsurface horizons are generally less permeable because of lower porosity, particularly in the macropore size range. The soil profile as a whole not only is capable of accepting and rapidly transmitting rain and snowmelt water, but also can store 30-40 cm in its top 1.2 m of depth.

The so-called rain-dominated region of the Pacific Northwest contains dense forests which represent the maximum development of temperate coniferous forests in the world. Forest vegetation influences several portions of the forest hydrologic system within certain limitations imposed by climate and physiography as will be described in the next section.

HYDROLOGIC PROCESSES

In this section I will review the various processes of the natural forest hydrologic system to identify processes that can be altered by timber harvest activities. Such a review will aid in the subsequent discussion of changes in streamflow which have been observed after logging, as well as in the review of our capability of predicting changes in streamflow throughout the rain-dominated portion of the Pacific Northwest.

INTERCEPTION

Interception of precipitation has been measured most extensively in the old-growth forests of Douglas-fir. At the Willamette Basin Snow Laboratory annual interception averaged 46 cm during a 4-yr period when annual precipitation averaged 325 cm (U.S. Army Corps of Engineers, 1956). Near Watershed HJA-2 in the H. J. Andrews Experimental Forest, Rothacher (1963) measured 46 cm of interception when annual precipitation was 213 cm during a 1-yr study under 61-m high trees with average canopy density of 89%. Rothacher also found that stemflow on old-growth Douglas-fir and hemlock had a negigible effect on net precipitation. Krygier (1971) measured 28 cm of interception when annual precipitation was 100 cm in a study under a stand of second-growth Douglas-fir 37 m high with an average canopy density of 99%.

Amount of rain interception loss is dependent on storm size. Rothacher (1963) found very little summer rainfall penetrated the crown canopy until about 1.3 mm of rain had fallen. For summer storms of 25 mm, 50 mm, and 90 mm, interception losses were 5 mm, 10 mm, and 16 mm, respectively. During winter rainy periods, interception losses were also dependent on amount of precipitation but were relatively less than in summer. During storms of 50–100 mm, interception loss averaged about 12% (6–12 mm); for storms of 100–150 mm, it averaged 7% (7–10 mm); and for storms greater than 200 mm, slightly more than 4% (9 m).

Where it has been measured, snow interception has not differed greatly from rain interception. At the Willamette Basin Snow Laboratory snow interception in water equivalent averaged 22 cm compared with 24 cm of rain interception. Snow interception is dependent not only on storm characteristics, such as amount of snow and air temperature, but also on melt conditions immediately after snowfall and on branching habit of forest trees (Smith 1974).

In some local areas, interception of clouds or fog may increase precipitation. For example, Isaac (1946) found annual precipitation owing to fog interception and drip under the forest canopy near the Oregon coast was 252 cm, 52 cm more than in the open. In the Bull Run Municipal Watershed near Portland cloud drip may add significantly to annual precipitation under the forest canopy.[2/]

INFILTRATION

One of the most important characteristics of the forest hydrologic systems in the Pacific Northwest is the capability of surface soil to accept rain and snowmelt water. The result is that overland flow is extremely rare under natural conditions and is confined to intermittent stream channels, bare rock, areas of extremely shallow soil, or frozen soil. Many surface soils in the Pacific Northwest can accept more than a hundred times more water than they are likely to receive from precipitation and snowmelt. For example, Dyrness (1969) reported percolation rates of more than 500 cm/hr for surface horizons of soil on watersheds HJA-1, 2, and 3 in the H. J. Andrews Experimental Forest.

[2/] Harr, R. Dennis. Streamflow after patch-cut logging in small drainages within the Bull Run municipal watershed, Oregon. Unpublished manuscript on file at Forestry Sciences Laboratory, Corvallis, Oregon.

Working with soil from watershed HJA-10, Ranken (1974) measured saturated hydraulic conductivities in excess of 800 cm/hr. Yee (1975) measured conductivities in excess of 300 cm/hr for soil of the Oregon Coast Ranges.

SUBSURFACE FLOW

Once in the soil, water is subject to gravitational and capillary forces that cause it to move and frictional forces that tend to restrict movement. Because of the steep slope of most forest land and because soil permeability generally decreases with depth, water begins to move downslope as it also moves deeper into the soil. The nature of this downslope movement is one of the most poorly understood processes in forest hydrology.

At least two types of subsurface flow exist on forested slopes in the Pacific Northwest. One type consists of flow through the soil matrix by a displacement process described by Hewlett and Hibbert (1967), in which water stored in the soil is displaced by water from precipitation. The second type consists of flow through interconnected soil channels extending from the forest floor through mineral soil. This second type has been described in detail for other parts of the United States by Whipkey (1969) and Aubertin (1971).

Water may move through the soil matrix either as unsaturated flow or saturated flow. In studies by Yee and Harr (1977) and Harr (1977) unsaturated flow dominated although occasional saturated zones were detected. In the latter study, saturation occurred in the soil mantle where there was an abrupt decrease in vertical permeability associated with a reduction in relative amount of macropores. Although other less abrupt decreases in macroporosity with soil depth did not cause saturation, they were instrumental in giving soil water movement a sizable downslope component. Results of these two studies generally support the displacement theory of Hewlett and Hibbert (1967). Between storms, soil profiles remained wet so that they were able to respond quickly to subsequent rainfall; even 1 meter below the forest floor, soil water movement increased greatly during rainfall.

Indirect evidence of flow through interconnected channels has been obtained in forested watersheds in south-coastal British Columbia. Because hydrologic response of soil at 70 cm and near bedrock was faster than horizons closer to the forest floor, Chamberlin (1972) concluded that open drainage routes must exist between the surface organic layer and basal soil horizons. Cheng et al. (1975) also found that water reached the B horizon before it reached horizons closer to the surface, indicating nonuniform wetting or wetting of soil from below. Water apparently was transported rapidly through interconnected channels to lower horizons. Flow through such channels may also occur elsewhere in the Pacific Northwest.

EVAPOTRANSPIRATION

Several measurements have been made of daily evapotranspiration from Douglas-fir forests of various heights in the Pacific Northwest using the energy budget approach (McNaughton and Black 1973, Gay and Holbo 1974), but no measurements of annual evapotranspiration are available. Because so little energy is available for evaporation from soil under a dense forest canopy, most all evapotranspiration consists of only transpiration. Estimates of annual actual evapotranspiration (excluding interception loss) have been about 40-50 cm (U.S. Army Corps of Engineers 1956, Luchin 1973).

Estimates of evapotranspiration can be obtained from long-term measurements of precipitation and streamflow in forested watersheds. At watershed HJA-2 in the H. J. Andrews Experimental Forest, for example, annual precipitation averaged 230 cm during the 1953-78 period, and annual streamflow averaged 142 cm. This leaves 88 cm for evapotranspiration which, in this case, includes interception loss. If 40-45 cm is subtracted for interception, the remainder of 43-48 cm represents largely transpiration, quite similar to the 42 cm estimated at the Willamette Basin Snow Laboratory using the Thornthwaite method (U.S. Army Corps of Engineers 1956). At Coyote Creek watershed CC-4, evapotranspiration plus interception loss averaged 61 cm during the 1966-76 period (Harr et al. 1979). Because overstory canopy density here is less than half of that where Rothacher (1963) conducted his interception study and because there is less annual precipitation at Coyote Creek, interception loss is estimated to be only 20-25 cm. Thus, evapotranspiration at Coyote Creek is estimated to be 36-41 cm. At Needle Branch in the Alsea Watershed Study, evapotranspiration plus interception loss averaged 59 cm during the 7-yr prelogging period and about 43 cm at the nearby Flynn Creek and Deer Creek watersheds. Because Flynn Creek and Needle Branch watersheds were forested primarily with red alder which is leafless during the time of fall and winter rains, annual interception in these watersheds was probably much less than that measured in old-growth Douglas-fir by Rothacher (1963). I estimate that interception loss was 15-20 cm and evapotranspiration was 30-45 cm in these coastal watersheds.

STREAMFLOW

For any time period, streamflow is the difference between precipitation and losses to interception and evapotranspiration plus or minus any change in soil water storage. On an annual basis, streamflow amounts are generally high (table 2) owing to high annual precipitation in the Pacific Northwest. Highest annual streamflows are found on the Olympic Peninsula and lowest annual streamflows are found in southwestern Oregon.

Most small headwater streams in the region respond quickly to precipitation (fig. 4). Soon after rainfall begins, streamflow begins to increase and the source area of streamflow expands and contracts

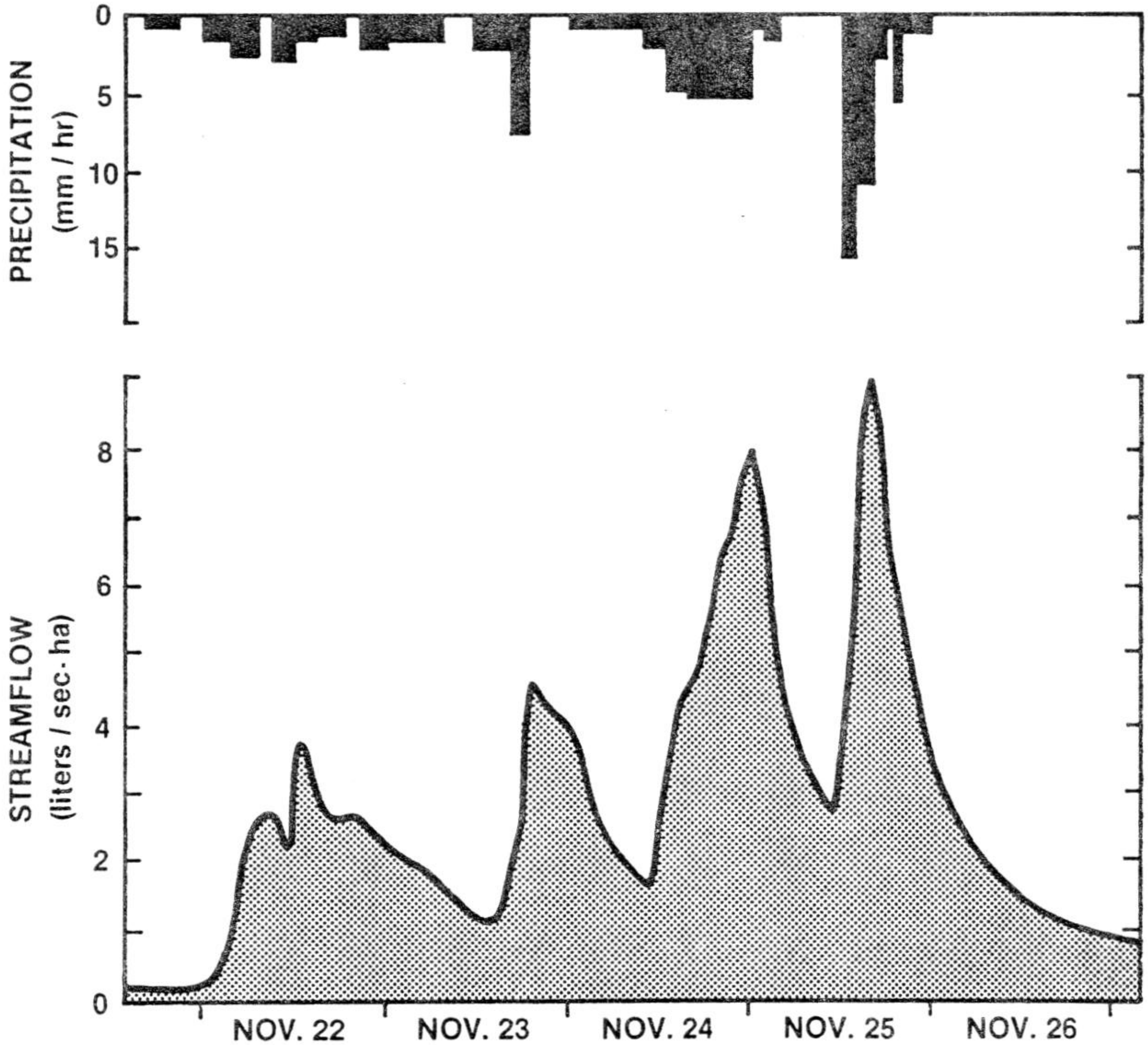

Figure 4--Precipitation and streamflow at watershed HJA-9, H. J. Andrews Experimental Forest, Oregon, November 21-26, 1977.

according to rainfall characteristics and the capability of the soil mantle to store and transmit water (Harr 1976b). This phenomenon is called the variable source area of streamflow (fig. 5). Initially, storm runoff results from channel interception and rainfall on the wet areas adjacent to stream channels. If a storm continues, an increasingly greater proportion of the watershed contributes to storm runoff, and eventually the channel network grows to many times its minimum perennial dimensions. As perennial streams lengthen and flow appears in intermittent channels, drainage density increases, and the watershed becomes more efficient in producing runoff. If rainfall continues at a relatively high rate, streamflow will also continue at a

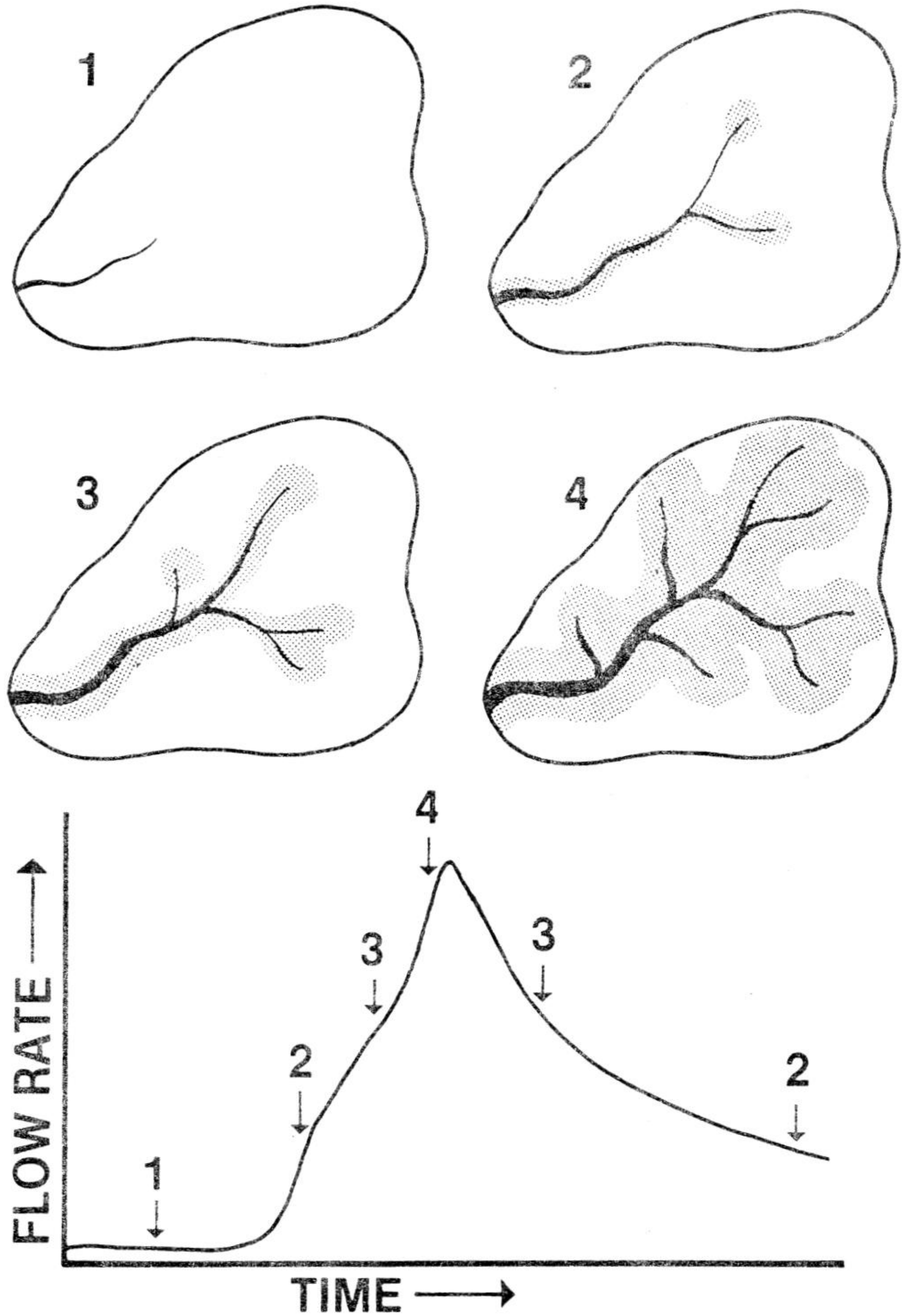

Figure 5--Time-lapse view of a watershed with variable source area of streamflow. The time of each source area condition relative to storm runoff is shown by the location of numbers on the storm hydrograph.

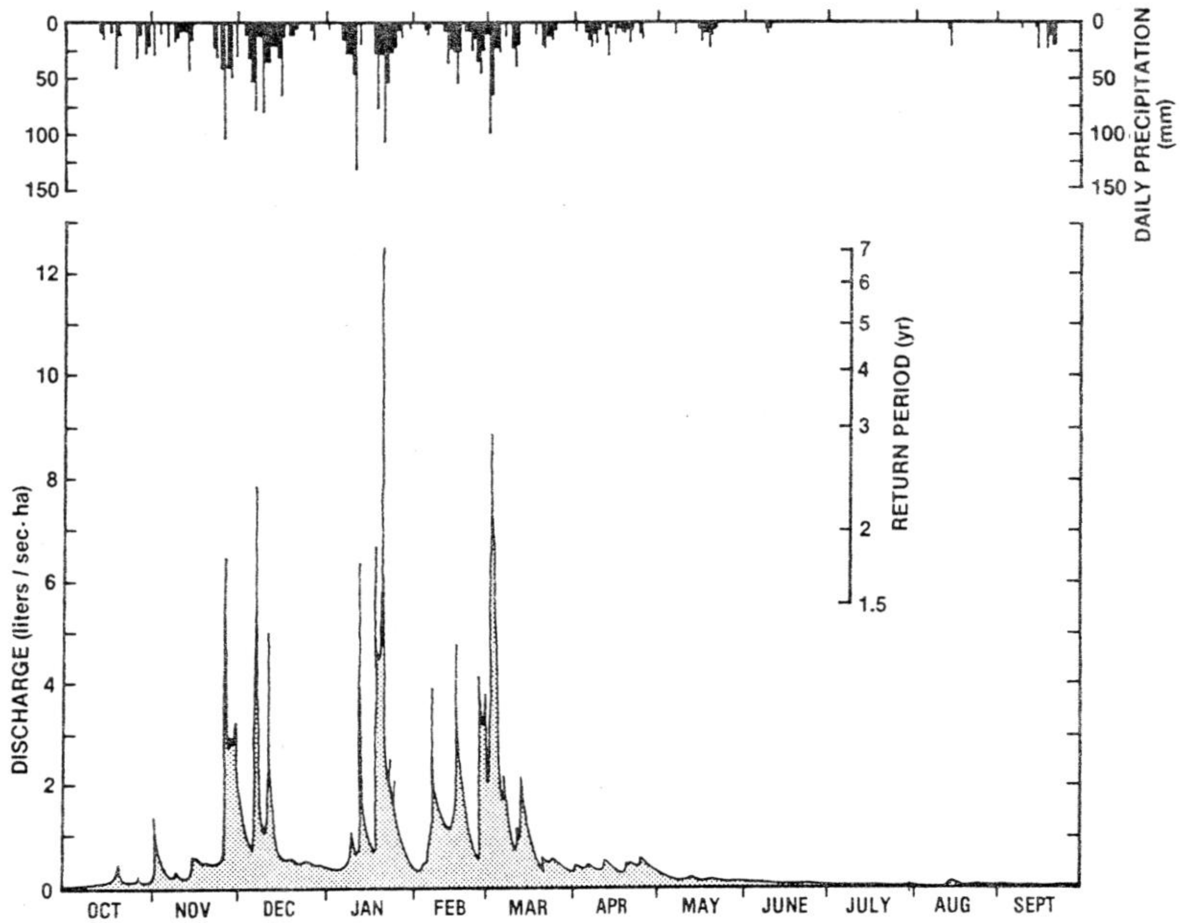

Figure 6--Daily precipitation and instantaneous streamflow at watershed HJA-2, H. J. Andrews Experimental Forest, Oregon, 1972 water year.

high rate. Conversely, if rainfall rate decreases or rainfall ceases altogether, then streamflow will peak almost immediately (fig. 4) and then begin to decrease rapidly as permeable soils on steep slopes drain quickly (Harr 1977).

Over the course of the rainy season, the sequence described above may occur 10-20 times or more, depending on the frequency of storms entering the region from the Pacific Ocean. In 1972 at HJA-2, for example, there were 16 storms which deposited at least 50 mm of precipitation (fig. 6). Eight of these caused peak discharges >4 liters/sec·ha, and three caused peak discharges greater than the estimated mean annual peak of 7.5 liters/sec·ha. Between stormflow periods, discharge decreased to only 2-4 liters/sec·ha, depending on length of time soil was allowed to drain in the absence of rainfall.

Because of steep sideslopes, highly permeable soils, and the rapid response of streams to changes in rainfall rate, high rates of streamflow are short lived. This is illustrated by the flow duration curve (fig. 7) constructed from the streamflow data plotted in figure 6. During the 1972 water year, flows greater than the estimated mean annual peak occurred less than 1% of the time in watershed HJA-2. About half the time, flow was less than the 0.3 liters/sec·ha baseflow which occurred between storm runoff periods in winter.

Maximum flows of nearly all streams in the Pacific Northwest have resulted from rapid snowmelt during prolonged, heavy rainfall. In western Washington streams, maximum flows generally have occurred in November or December (table 2). In western Oregon, maximum flows have occurred most frequently in December and January.

The timing of minimum flows of record has been much more variable, ranging from August to December for the streams listed in table 2. In most years, minimum flows occur between mid-July and early September. Flow ceases in many small headwater basins during the summer dry period.

Dividing maximum flows of record by minimum flows of record (table 2) shows the range of flows that can be experienced at one location in the Pacific Northwest. For large basins, maximum flows of record are up to several thousand times larger than minimum flows of record. The range is much greater for small streams. At watershed HJA-2 in the H. J. Andrews Experimental Forest, maximum flow is more than 17,000 times greater than minimum flow of record. Of course, in any one year ratios of maximum to minimum flows are less than those derived from table 2;

Table 2--Mean annual, maximum, and minimum streamflows for selected watersheds of western Washington and Oregon through the 1978 water year

Stream	Drainage area	Length of record	Mean annual yield[1]	Maximum streamflow of record		Minimum streamflow of record	
	km^2	yr	mm	liters/sec·ha	month	liters/sec·ha $\times 10^{-3}$	month
Washington:							
Wynoochee River	192	52	3 387	34.8	Dec.[2]	84	Sept.
Duckabush River	172	39	2 159	14.8	Nov.[2]	74	Sept.
Snoqualmie River	971	47	2 399	17.8	Nov.[2]	2.8	Aug.
South Fork Cedar River	15.5	35	2 208	42.7	Dec.[2]	35	Nov.
Stetattle Creek	57	46	2 885	42.6	Nov.[2]	45	Nov.
Oregon:							
Siletz River	523	58	2 695	22.2	Nov.	26	Sept.
Alsea River	865	38	1 585	13.6	Dec.	15	Sept.
Flynn Creek	2.03	15[3]	1 949	19.2	Jan.	15	Oct.
South Santiam River	451	42	1 637	17.3	Dec.	14	Dec.
Lookout Creek	62	20	1 850	30.5	Dec.	29	Nov.
HJA-2	0.603	26	1 410	16.6	Dec.[2]	0.95	Sept.
HJA-8	0.214	15	1 295	19.2	Dec.[2]	1.3	Sept.-Oct.
HJA-9	0.085	10	1 311	14.1	Jan.	3.3	Aug.-Sept.
South Umpqua River	1 163	39	801	14.6	Dec.	4.9	Sept.
CC-4	0.486	13	578	14.4	Dec.	2.9	Aug.

1/ Mean annual yield expressed as a uniform depth over entire watershed area.

2/ Streamflow frequently has a secondary annual peak during spring snowmelt.

3/ Streamflow measurement discontinued at the end of the 1973 water year.

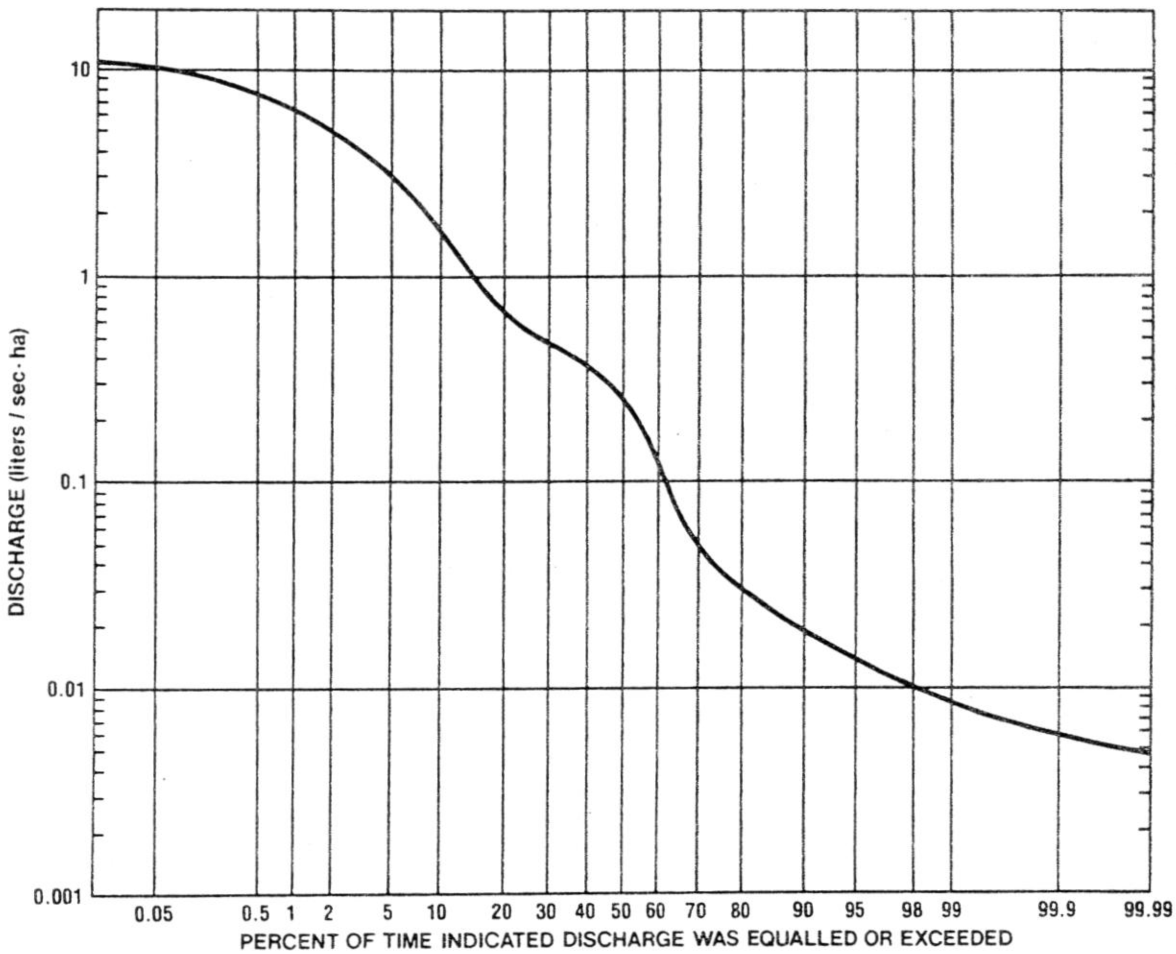

Figure 7--Duration curve of streamflow at watershed HJA-2, H. J. Andrews Experimental Forest, Oregon, 1972 water year.

for the 1972 water year shown in figure 6 the ratio is 1495 to 1. Thus, little can be gained toward understanding winter flow conditions simply by observing stream channels during the summer when drainage densities are at their lowest.

SNOWMELT

Because maximum streamflows in the so-called rain-dominated portion of the Pacific Northwest are usually caused by melting of shallow snowpacks during rainfall, a brief review of snowmelt processes should be helpful at this point. There are several major differences in snow hydrology between western Washington and Oregon and other parts of the United States.

Snowpacks in western Oregon and Washington, like those in the Sierra

Nevada of California, are classified as "warm" in contrast to the "cold" snowpacks of the central Rocky Mountains or the Northeast (Smith 1974). A warm snowpack's interior temperatures remain at or near 0°C throughout the pack's existence. This temperature is hydrologically important because relatively little energy is required to initiate melting. A warm pack can yield water quickly during a period of high air temperature, rainfall, or both, once the pack's storage capacity for liquid water has been satisfied. In many instances, snowpacks at lower elevations (350–1000 m) of western Washington and Oregon are shallow enough to be melted completely during rainstorms.

The heat transfer processes described by Troendle and Leaf[1/] operate to melt snow in western Washington and Oregon as they do elsewhere. The relative importance of these various processes constitutes the second major difference in snow hydrology in this region. Incoming shortwave radiation, the major source of energy for melt in most of the United States, is a minor source of energy for melt during rainfall in western Washington and Oregon. According to the U.S. Army Corps of Engineers (1960), snowmelt during rainfall (commonly referred to as rain-on-snow) is a special situation for which certain simplifying assumptions can be made in the snowmelt equation so melt can be estimated by several indices listed in table 3.

The relative importances of melt resulting from the various sources of energy are shown graphically in figure 8 for 24-hr average air temperatures (T_a) of 2°C and 10°C. At T_a = 10°C (fig. 8B) and P_r = 8 cm, convection-condensation melt (M_{ce})—i.e., melt resulting from warm air moving across the snow surface and from heat released as water vapor condenses on the snow surface—is the major component of total melt; 45% of total melt results from convection-condensation. Second is

Table 3--Snowmelt indices for 24-hr melt during rainfall under forest conditions (adapted from U.S. Army Corps of Engineers 1956)

Source of melt	Equation for 24-hr melt[1/]
Short-wave radiation	M_{rs} = 0.18 cm/day
Ground heat	M_g = 0.05 cm/day
Long-wave radiation	M_{rl} = 0.133 T_a cm/day
Convection-condensation	M_{ce} = 0.206 T_a cm/day
Rainfall heat	M_p = 0.0126 P_r T_a cm/day

[1/] T_a = average 24-hr air temperature (°C); P_r = 24-hr rainfall (cm).

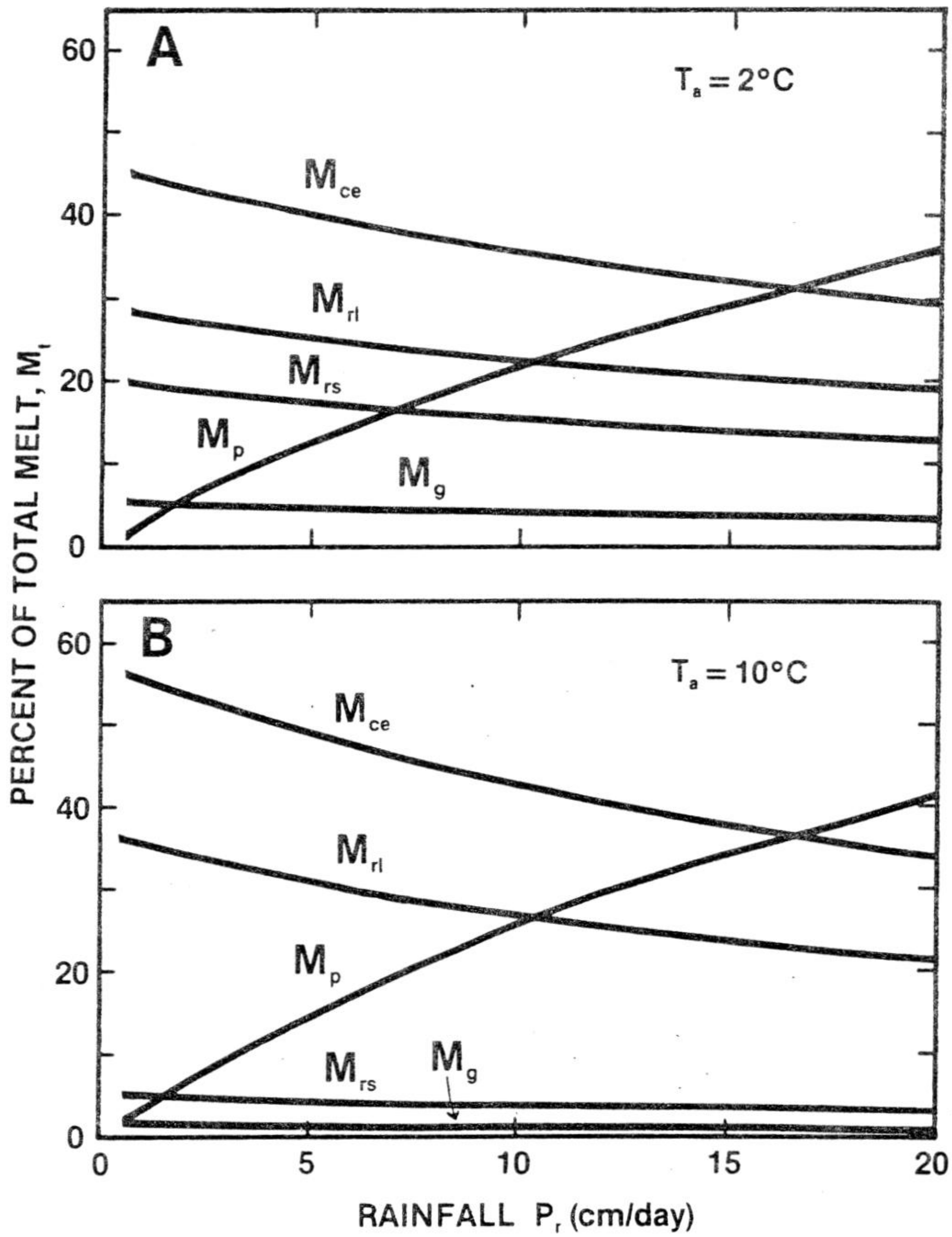

Figure 8--Proportion of total snowmelt caused by various components of melt during rainfall at mean daily air temperatures of 2°C and 10°C. Melt components are defined in table 3 (adapted from U.S. Army Corps of Engineers 1956).

long-wave radiation melt (M_{rl}) followed by melt caused by heat contained in rain (M_p). Although the phrase "rain-on-snow" implies snow is melted by warm rain, this is not entirely the case. Warm rain is the greatest source of energy for melt only when 24-hr rainfall (P_r) is more than 17 cm. This is a very important point because such rainfall rates are infrequent over much of the region; for most conditions, rain is only the third greatest source of energy for snowmelt. Shortwave radiation accounts for less than 5% of total melt during rainfall. Of course, figure 8 and the indices given in table 3 cannot be used to estimate snowmelt during sunny periods.

EFFECTS OF TIMBER HARVEST ON STREAMFLOW

Research elsewhere in the United States in the 1930's and 1940's had shown that forest cutting and forest growth could have a major influence on water yield and that the undisturbed forest provides the maximum opportunity for controlling runoff from flood-producing storms. Watershed management research was begun in the Pacific Northwest in the late 1940's to determine the effects of timber harvest on streamflow characteristics under the climatic, physiographic, and vegetative conditions of this region. Questions to be answered: (1) Can logging increase annual water yields? (2) Does logging affect floods? (3) Can the timing of runoff be altered by logging so as to improve the naturally poor annual distribution of streamflow? These questions have been answered to some degree for a few locations in the Pacific Northwest under certain conditions. There have been, however, several misconceptions about what has been learned and how it can be applied to other areas in the Pacific Northwest. And there are other important questions yet to be answered about the effects of logging on streamflow. What follows is a review of research findings concerning the effects of timber harvest on streamflow in the so-called rain-dominated region of the Pacific Northwest.

Much of what is known about the effects of timber harvest on streamflow has come from studies using paired experimental watersheds. One watershed of each pair is the control or unlogged watershed, and the second is the treated (logged or altered in some other way) watershed. For a time before treatment, streamflow characteristics are measured at each watershed. During this calibration period, linear regression is used to develop a relationship for a streamflow characteristic such as annual water yield, minimum flows, and peak flows between the control watershed (dependent variable) and the watershed to be treated (independent variable). After treatment, a new relationship is determined and compared to the calibration relationship, and the difference between relationships is attributed to the treatment.

ANNUAL WATER YIELD

There have been five studies that have illustrated the range of increases in annual water yield after timber harvest in the Pacific Northwest. These studies have utilized 18 experimental watersheds, all of which are located in western Oregon. Characteristics of these

Table 4—Summary of watershed characteristics for watershed-level studies in the Pacific Northwest

Watershed study[1/]	Mean annual precipitation	Mean annual streamflow at control	Type of precipitation	Area	Aspect	Elevation range	Average slope	Parent material	Forest vegetation	
									Type	Age
	cm	cm		ha		m	%			yr
HJA-1, 2, 3	233	141	Rain	60–101	NW	440–1 080	53–63	Altered volcaniclastics	Douglas-fir W. hemlock	300–500
HJA-6, 7, 8	215	129	Rain, snow	13–21	S	830–1 100	27–31	Relatively unaltered volcaniclastics	Douglas-fir	120–130
HJA-9, 10	233	165	Rain	8.5–10	SW	425–715	65–70	Altered volcaniclastics	Douglas-fir W. hemlock	300–500
FC-1, 2, 3	272	175	Rain, snow	59–253	W–NW	840–1 070	5–9	Igneous glacial till	Douglas-fir W. hemlock	300–500
CC-1, 2, 3, 4	133	58	Rain	49–69	N–NE	730–1 065	23–38	Altered volcaniclastics	Douglas-fir Mixed conifer	100–300
Alsea (AL-1, 2, 3)	243	196	Rain	70–303	S	135–485	34–40	Sandstone	Alder Douglas-fir	120
Jamison Creek (JC)	391	–[2/]	Rain, snow	298	SE	300–1 300	48	Igneous glacial till	W. red cedar W. hemlock Douglas-fir	300–500
UBC-1, 2	229	–[2/]	Rain	23–44	S	145–455	12–20	Igneous glacial till	W. hemlock W. red cedar Douglas-fir	300–500
Caspar Creek (CA-1, 2)	112	–[2/]	Rain	424–508	W–SW	90–365	30	Sandstone	W. hemlock Douglas-fir Redwood	70–90

[1/] HJA = H. J. Andrews Experimental Forest, FC = Fox Creek watersheds, CC = Coyote Creek watersheds, UBC = University of British Columbia Research Forest.

[2/] Not available or not measured.

watersheds, along with other research watersheds in the region, are shown in table 4. Table 5 summarizes timber harvest activities by experimental watershed.

The longest period of postlogging measurement of increases in annual water yields is associated with the study at HJA-1 and HJA-3. Logging began in HJA-1 in late August 1962, but, because of operational problems with the new Wyssen fixed skyline system, logging was not completed until 1966.[3/] Heavy slash was broadcast burned in 1966. In 1965, after the watershed had been 90% clearcut, annual water yield increased nearly 54 cm (fig. 9), only about 60% of the total evapotranspiration and interception losses described earlier. In general, there has been a decreasing trend since 1965 although this trend has been less apparent during the last 8 years. For the entire 1965–78 period 68% ($r^2 = 0.68$) of the variation in yield increases is accounted for by the equation,

$$Y = 52.2 - 2.05X_1; \qquad (1)$$

where X_1 is the number of years after logging, and the year 1966 = 1, 1967 = 2, etc. In other words, 68% of total variation in yield

[3/] Mention of commercial names does not constitute an endorsement by the U.S. Department of Agriculture.

Table 5—Summary of timber harvest activity by watershed

Watershed[1/]	Activity (see key at right)[2/]	Key	
HJA-1	CC, CY-100, BB-100	UC -	Uncut
HJA-2	UC, UB	CC -	Clearcut
HJA-3	R, PC-30, CY-30, BB-30	PC -	Patchcut
HJA-6	R, CC, CY-93, TY-7, BB-100	SC -	Shelterwood cut (percent basal area removed)
HJA-7	SC-60, CY-40, TY-60, BB-100	R -	Permanent haul road
HJA-8	UC, UB	CY -	Yarding by a cable system
HJA-9	UC, UB	TY -	Yarding by tractor
HJA-10	CC, CY-100, UB	UB -	Residue unburned
AL-1[3/]	R, CC,[4/] CY-72, TY-10, BB-82	BB -	Residue broadcast burned
AL-2	UC, UB	CPB -	Residue piled by cable and burned
AL-3	R, PC-25, BB-8	TPB -	Residue piled by tractor and burned
AL-32[5/]	R, PC-30, CY-30, UB		
AL-33[5/]	R, PC-65, CY-65, UB		
AL-34[5/]	CC-90, CY-90, UB		
FC-1	R, PC-25, BB-25		
FC-2	R, UC, UB		
FC-3	PC-25, CY-19, TY-6, UB		
CC-1	R, SC-50, UB		
CC-2	R, PC-30, CY-16, TY-14, CPB-16, TPB-14		
CC-3	R, CC, CY-77, TY-23, CPB-77, TPB-23		
CC-4	UC, UB		
UBC-1	R, CC-75, CY,[6/], TY,[6/], UB		
UBC-2	UC, UB		
CA-1	R, CC[5/], TY-100, UB		
CA-2	UC, UB		

[1/] HJA = H. J. Andrews Experimental Forest, FC = Fox Creek watersheds, CC = Coyote Creek watersheds, UBC = University of British Columbia Research Forest, CA = Caspar Creek watersheds.

[2/] Except where noted, numbers refer to percentages of watershed area where activities were carried out.

[3/] AL-1, 2, 3 refer to Needle Branch, Flynn Creek, and Deer Creek watersheds, respectively.

[4/] Only 82% clearcut during study. Additional 18% in the headwaters of Needle Branch was logged in the early 1950's.

[5/] AL-32, AL-33, and AL-34 are subwatersheds of AL-3.

[6/] Percentages of watershed yarded by cable and tractor are not available.

[7/] Selectively logged in three stages over 3 years. At the end of the period, the watershed was in a clearcut condition.

increases is related to time since logging, a gross index of revegetation and increasing water loss through interception and transpiration.

The effect of annual precipitation on size of yield increases is also apparent in figure 9. In general, wetter years exhibited higher increases in yield and vice versa. Indeed, if annual precipitation is taken into account the predictive equation or model becomes:

$$Y = 31.41 - 2.08X_1 + 0.091X_2; \qquad (2)$$

where X_2 is annual precipitation. Adding annual precipitation to the model accounts for a statistically significant portion of total

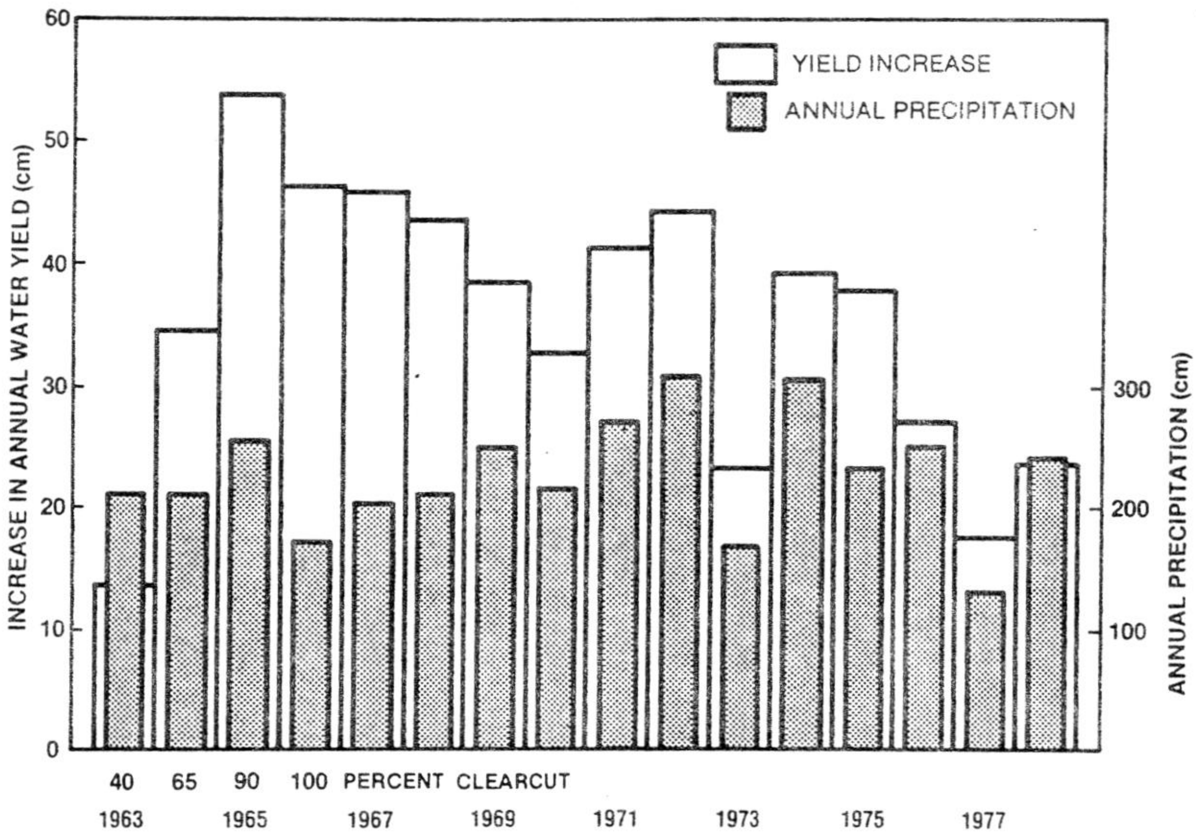

Figure 9—Annual precipitation and increases in annual water yield at watershed HJA-1, H. J. Andrews Experimental Forest, Oregon.

variation in yield increases. The model described by equation 2 accounts for 87% of total variation in yield increases at HJA-1.

Yield increases for all clearcut experimental watersheds are shown in figure 10. Largest increases were noted at AL-1 (Needle Branch) in the Oregon Coast Ranges (Harris 1977) where water yields increased more than 60 cm 3 and 5 years after logging. Yield increases at AL-1 appear also to be influenced by annual precipitation, but, because the Alsea Watershed Study terminated in 1973, the strength of this influence could not be determined. (An undetermined amount of this yield increase is due to road drainage water that flowed into AL-1 from an adjacent logged area.) Why maximum increases at AL-1 and HJA-10 did not occur until the 3rd year after clearcutting is not known.

Yield increases have been smaller at patch-cut HJA-3 than at clearcut HJA-1 because the watershed was altered less by timber harvest (fig. 11). During road construction in 1958, 8% of watershed HJA-3 was cleared. After patch-cutting in three units in late 1962, cleared area totaled 30% of watershed area. Logged units were burned in September 1963. Water yield increases at HJA-3 show a general decreasing trend

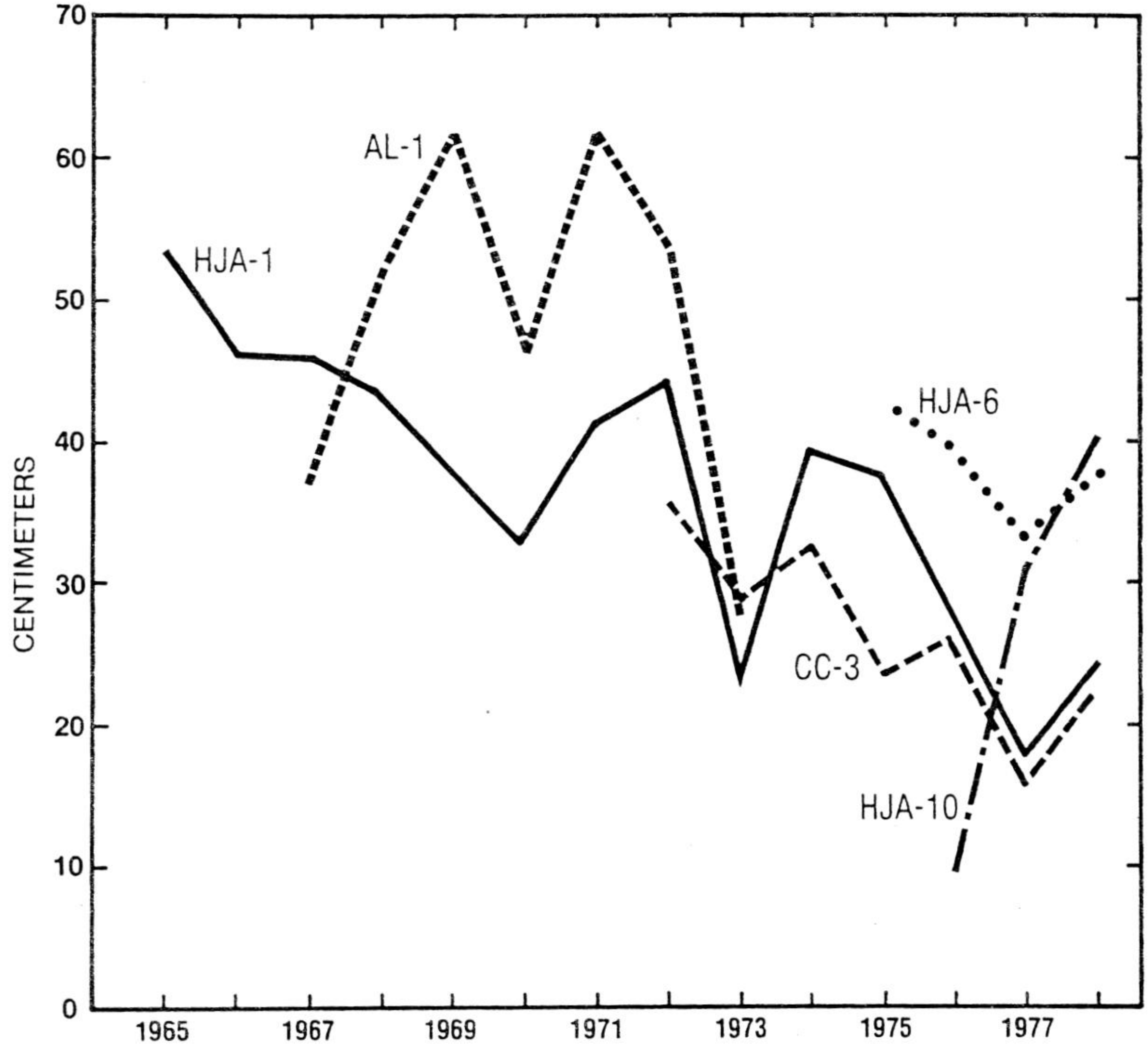

Figure 10--Increases in annual water yield at five clearcut watersheds in western Oregon. Part of the increases at AL-1 are due to road drainage water flowing into the watershed from an adjacent logged area. See tables 4 and 5 for watershed descriptions.

over time but a significant relationship with time was not found. As at HJA-1, greatest increases have tended to occur during wettest years, although this tendency is less apparent at HJA-3 than at HJA-1. Also, at HJA-3 annual precipitation did not account for a significant portion of total variation in annual water yields as it did at HJA-1.

Yield increases for all partially logged experimental watersheds are shown in figure 12. HJA-3, AL-3, CC-1, and CC-2 all contain roads, HJA-3, CC-1, and CC-2 were patchcut, and CC-1 and HJA-7 were logged with

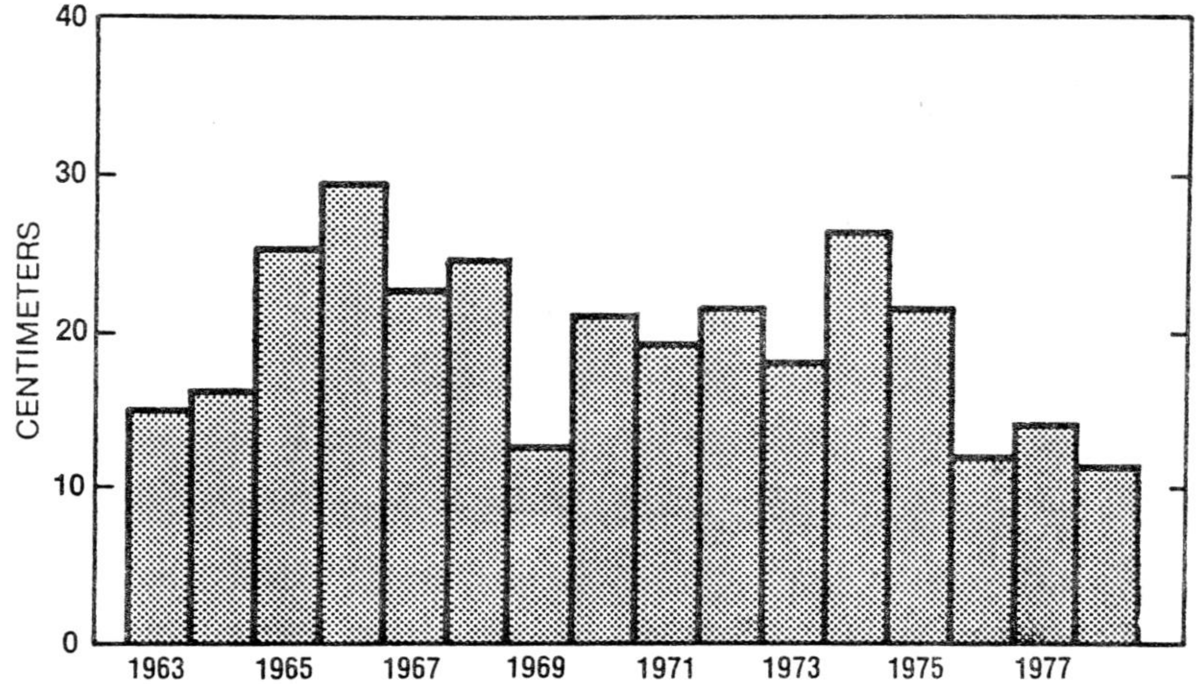

Figure 11--Increases in annual water yield after patch-cutting in watershed HJA-3, H. J. Andrews Experimental Forest, Oregon.

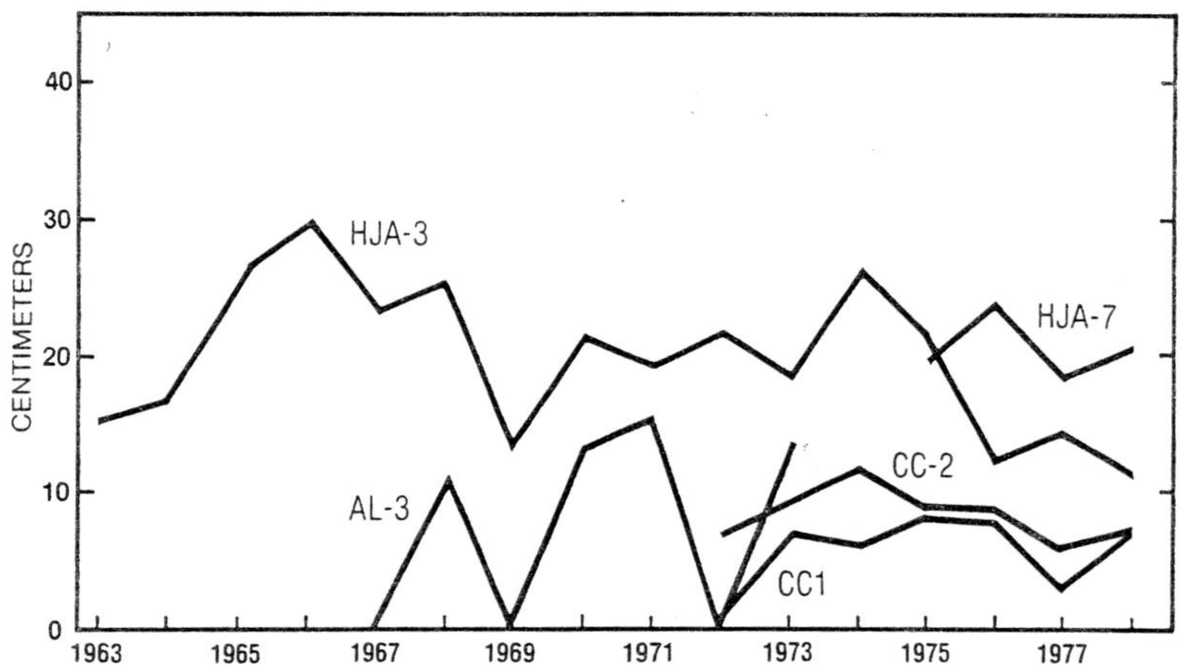

Figure 12--Increases in annual water yield at five partially logged watersheds in western Oregon. See tables 4 and 5 for watershed descriptions.

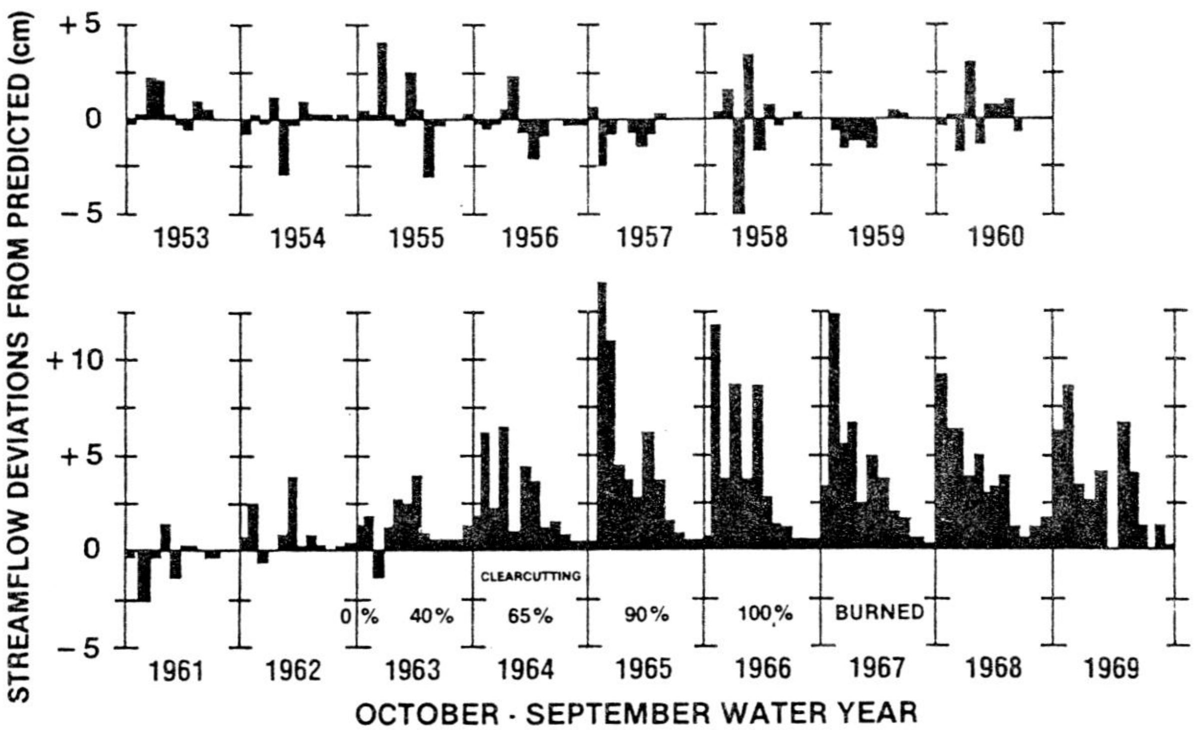

Figure 13--Changes in monthly water yield after logging in watershed HJA-1, H. J. Andrews Experimental Forest, Oregon (Rothacher 1971).

a shelterwood cut. Not included in figure 12 are data from FC-1 and FC-3, patch-cut watersheds where annual water yields decreased slightly though not significantly after logging (see footnote 2). Yield decreases (or at least lack of expected increases) at FC-1 and FC-3 are thought to be related to reduced fog interception after logging.

Seasonal analyses of yield increases have been made only at HJA-1 and 3 and CC-1, 2, and 3 (Rothacher 1970, Harr et al. 1979). At both locations most of each year's increase in water yield occurred during the October-March rainy season (figs. 13-14). Part of this rainy season increase is due to reduced transpiration in a clearcut during the growing season. Wetter soils at the end of the growing season require fewer fall rains for recharging soil water and are able to yield more water to streamflow. Another portion of the rainy season increase in yield is due to reduced interception loss after removal of forest vegetation.

Implications of Water Yield Increases

Certain characteristics of water yield increases combine to make such increases in headwater basins of little consequence downstream. First, increases tend to diminish over time so that only a fraction of a

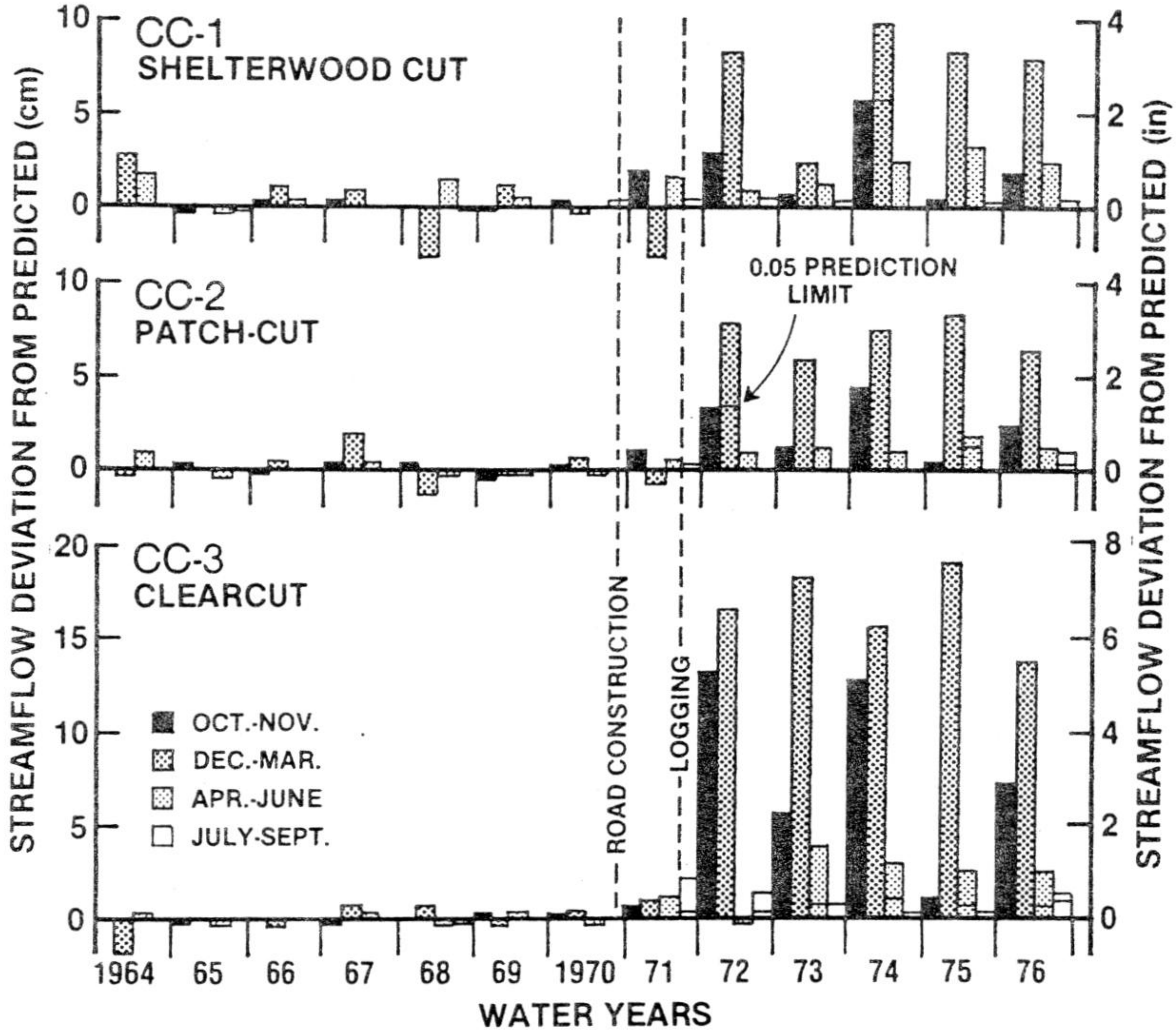

Figure 14--Changes in seasonal water yields after road construction and logging in the Coyote Creek experimental watersheds, Oregon (Harr et al. 1979).

watershed managed for sustained production of timber products will be in a condition to yield appreciably more water. The remainder will yield normal or nearly normal flows which tend to mask increased flows from freshly logged upland areas. Examples used by Rothacher (1970), Bethlahmy (1974), and Harr et al. (1979) show that forest cutting in large watersheds--about 100 km^2--probably would be only about 4-6%, an amount well within the normal accuracy of streamflow measurement for the large watershed. Management under nonsustained yield of timber products, however, could result in somewhat greater water yields for a large watershed.

A second characteristic of water yield increases that bears on the value or utility of increases downstream is their timing. Substantial increases during the fall-winter rainy season will do little to satisfy summer demand for water. This timing, coupled with the fact that water yield increases tend to occur during wet years, further limits the real benefits commonly attributed to increased water yield after timber cutting. To use these increases would require storage facilities, and if storage facilities were present, storage of yield increases would be of miniscule importance compared with storage of normal winter runoff for release during the summer dry period.

Perhaps the major implications of water yield increases demonstrated by these watershed studies lie in the area of erosion by soil creep and earthflow processes. Water yield increases are caused by, and are indices of, higher soil water contents from reduced interception and transpiration. Most of the downslope movement of soil in creep and earthflow terrain occurs during the fall and winter when maximum soil water contents occur (Swanson and Swanston 1977). Reduced interception and transpiration after logging, by increasing the amount of water entering the soil and decreasing its rate of withdrawal from the soil, may cause higher soil water contents that may cause higher rates of slope movement or longer periods of time soil water contents remain conducive for soil creep or earthflow. Prolonged periods of active creep or earthflow movement during a single rainy season or reactivation of dormant creep and earthflows may be the result (Swanston and Swanson 1976). The effects of such landslides can be felt far downstream as well as in the upland areas where the landslides occur.

In forested watersheds of western Oregon and Washington there is no relationship between increases in annual yield and increases in size of peak flows. In a recent summary of changes in streamflow after logging in western Oregon, yield increases and size of peak flow increases appeared to be independent of one another (Harr 1976a). Thus, changes in annual water yield are of no value in predicting changes in maximum flows in this region.

LOW FLOWS

Although yield increases in absolute terms are greatest during fall and winter months, greatest increases in relative terms have occurred during the summer. At HJA-1, for example, measured summer low flows were four times greater than predicted the first 2 years after logging and three times greater than predicted the year after slash was burned (fig. 15). Because of rapid growth of alder, willow, and other riparian vegetation, increases in yield largely disappeared within 2-3 years. Since 1974, 7 years after slash burning, measured summer flows have been consistently slightly less than flows predicted by the calibration regression equation.

At Coyote Creek, relative increases in summer low flows were similar to those observed during the first few years after logging at HJA-1 (Harr et al. 1979). At CC-3, measured summer flow was three times greater

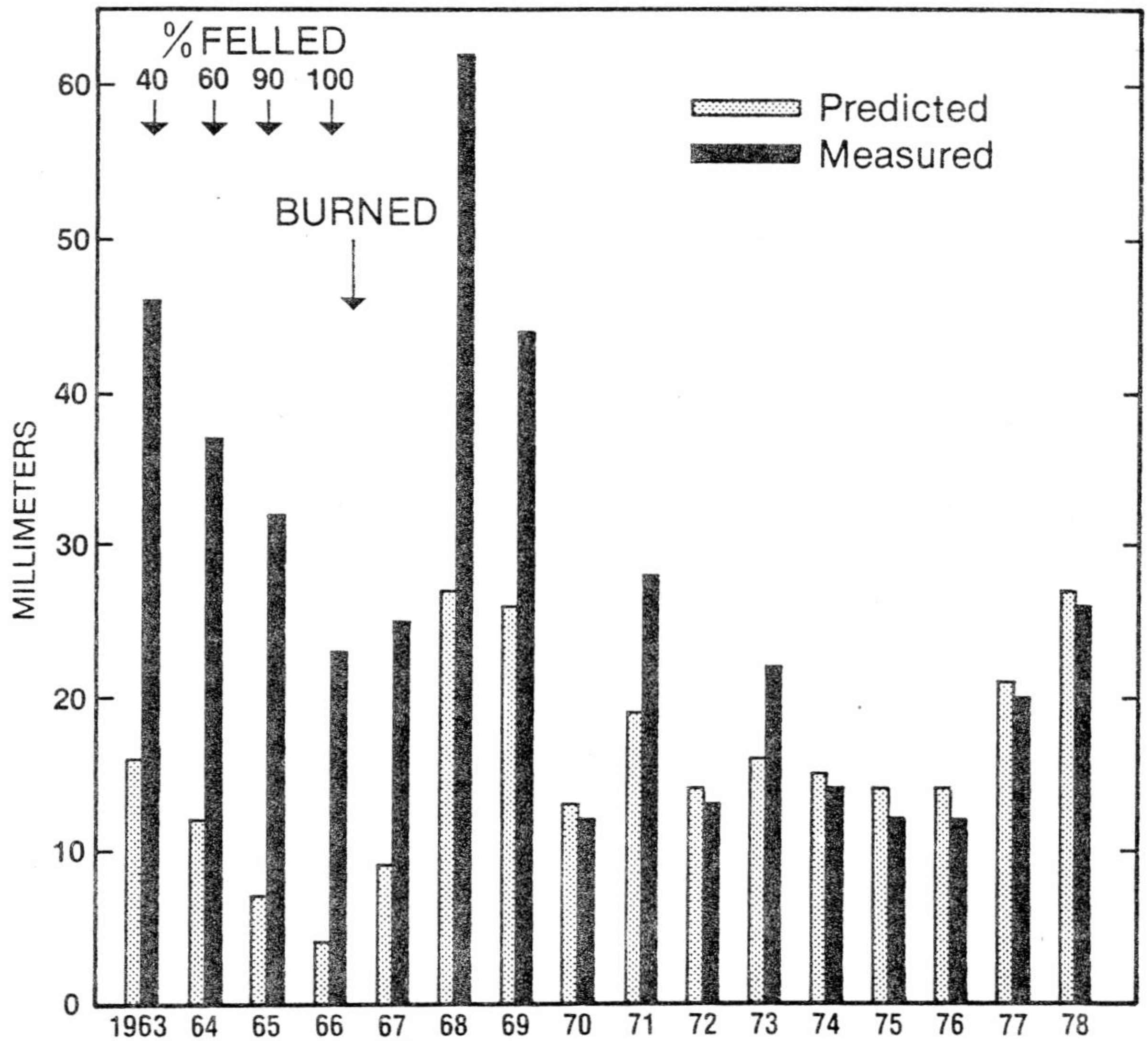

Figure 15--Increases in July-September streamflow at watershed HJA-1, H. J. Andrews Experimental Forest, Oregon.

than predicted the 1st year after clearcutting but, because of rapid growth of alder, willow, and other riparian vegetation, relative size of summer increases have diminished quickly here also. In 1977 and 1978, relative increases in summer flow were only 4% and 16%, respectively. At CC-1 and CC-2, the partially logged watersheds nearby, relative increases in summer flows have been generally much smaller than at CC-3.

In the Alsea Watershed Study in the Oregon Coast Ranges, the number of low-flow days (i.e., days flow was below 0.11 liter/sec·ha) decreased (low flows increased) after AL-1 was 82% clearcut and burned (Harr and Krygier 1972). The effect of patch-cutting 25% of AL-3 on low-flow days was less pronounced. Since this study was discontinued in 1973, longevity of summer increases is unknown.

Summer low flows have not increased after logging in all watershed studies. At FC-1 and FC-3 in Portland, Oregon's Bull Run municipal watershed, summer low flows were significantly reduced following patch-cut logging (see footnote 2). Reduction in low flows tentatively has been attributed to reduced fog drip from late spring to early fall.

PEAK FLOWS

For several decades there have been controversy and speculation about the effects of timber harvest on floods in the Pacific Northwest. Resultant property damage from flooding during 1977 and 1978 in western Washington did not lessen the controversy. The first analysis of the effects of logging on maximum flows in the Pacific Northwest was published in 1959, although concern about these effects had begun long before. After analyzing peak flow data for several large watersheds in western Oregon, Anderson and Hobba (1959) concluded that logging had increased the size of peak flows caused by rain alone and by rain with snowmelt.

Results from a number of studies on experimental watersheds in the Pacific Northwest in recent years suggest that a simple generalization cannot be made about the effects of timber harvest on peak flows. Although research results may appear inconsistent, the change in size of peak flows after logging generally can be explained in terms of what portion of the forest hydrologic system was altered by logging activities and to what degree.

The most common cause of increased size of peak flows has been wetter, hydrologically more responsive soils after timber cutting. Because of wetter soils in logged areas, less rainfall is required to recharge soil water so that more rainfall can be translated into storm runoff. For example, at HJA-1 initial measured peak flows of the fall were up to 200% greater than flows predicted by the prelogging peak flow relationship (Rothacher 1971, 1973). In other studies in the region (Harr et al. 1975, Ziemer[4/]), as well as elsewhere in the United States (Reinhart 1964, Hornbeck 1973), similar larger peak flows have been noted after logging when differences in soil water contents existed.

On the other hand, Rothacher (1973) found the large winter-season peak flows were unaffected by logging activities in watershed HJA-1. After sufficient rainfall had fallen to recharge soil water storage on forested slopes, logged and unlogged areas responded almost identically. Because surface soils are usually only slightly disturbed during yarding

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[4/] Ziemer, Robert R. Influence of roadbuilding and logging on stormflow in small coastal watersheds. Unpublished manuscript on file at Redwood Sciences Laboratory, Arcata, California.

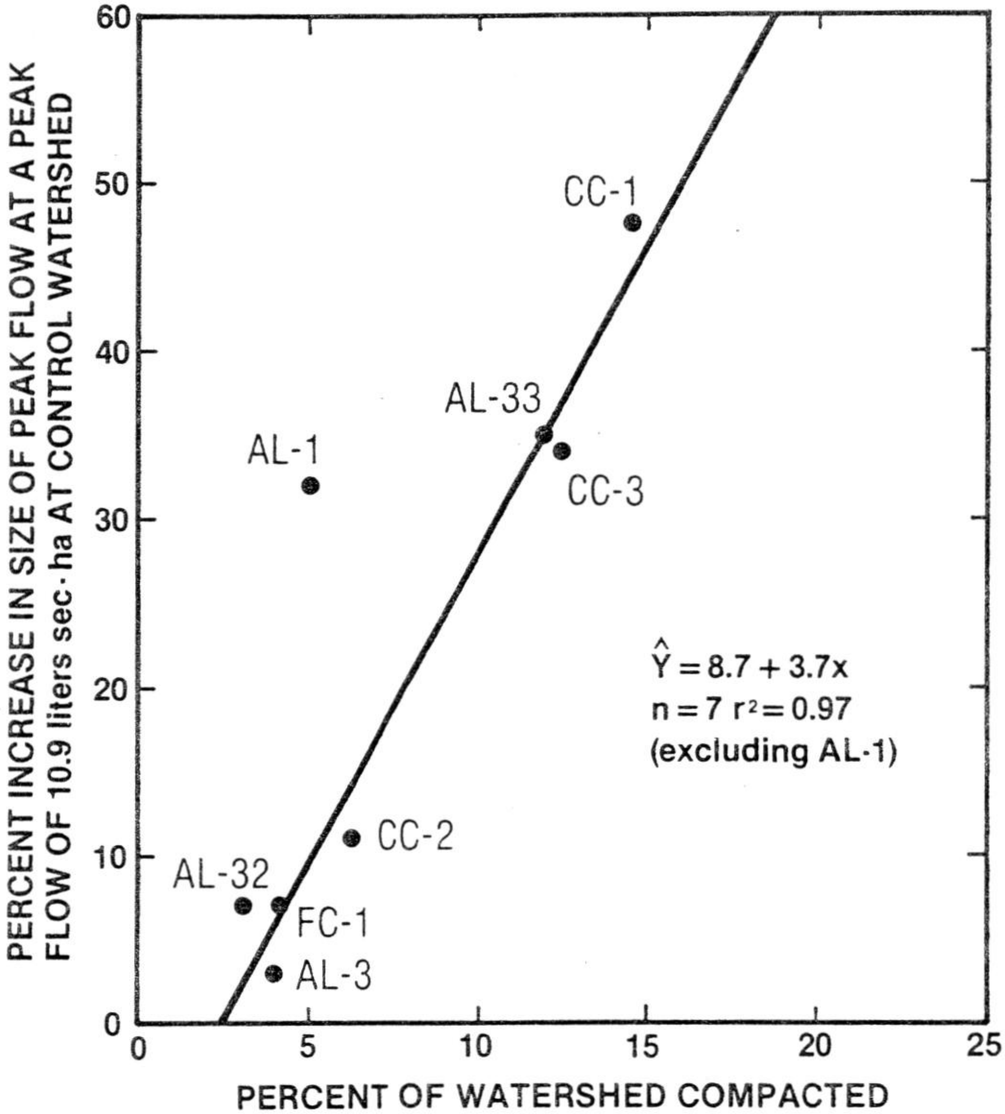

Figure 16--Apparent relationship between soil compaction and increase in size of peak flow. AL-1 has been excluded from the relationship because an undetermined amount of road drainage water flowed into the watershed from an adjacent logged area. See tables 4 and 5 for watershed descriptions.

by cable systems (Dyrness 1965, 1967), soils on HJA-1 were still able to accept all precipitation, and overland flow did not occur.

Winter season peak flows, however, were significantly larger after logging in some watersheds in two other studies in the Pacific Northwest. In the Alsea Watershed Study, Harr et al. (1975) reported larger winter peak flows after logging in AL-33, a small watershed where roads, cutbanks, fillslopes, and landings occupied 12% of total watershed area. Smaller increases were noted at watersheds with less soil compaction. Winter peak flows were larger after shelterwood cutting in CC-1 and clearcutting in CC-3, two small watersheds in the South Umpqua drainage of southwestern Oregon (Harr et al. 1979). In CC-1, compacted soil from permanent roads, skidroads, and landings occupied nearly 15% of total watershed area, and in CC-3, compacted soil occupied about 12% of total area. At CC-2 where compacted soil occupied only 6% of total watershed area, increases in size of peak flows were proportionately smaller than at either CC-1 or CC-3.

An apparent relationship between soil compaction and peak flows is shown in figure 16. Of course, this relationship is oversimplified because it ignores other factors, such as proximity of compacted areas to streams, continuity of compacted areas so that overland flow can reach streams, interception of subsurface water by road cuts and ditches, and watershed soil and physiographic characteristics. In other words, all areas of compacted soil do not contribute toward increased runoff to the same degree.

In two watershed studies in the Pacific Northwest, peak flows were delayed and reduced in size after timber harvest. At watershed UBC-1 near Haney, British Columbia, soil disturbance during yarding apparently disrupted fast flow through water-transmitting pores and forced water through slower routes in the soil which caused delayed, smaller peak flows after clearcut logging (Cheng et al. 1975). At HJA-10, delay and reduced size of peak flows after clearcut logging were attributed mainly to differences in short-term accumulation and melting of snow (Harr and McCorison 1979). Size of annual (return period of about 2 yr) peak flows caused by rain with snowmelt was reduced 36%. Collectively, peak flows resulting from rain with snowmelt were delayed an average of 12 hr. No significant changes were detected in size or timing of peak flows that resulted from rainfall alone.

Taken collectively, results of watershed studies indicate that size of peak flows may be increased, decreased, or remain unchanged after logging. Whether or not a change occurs depends on what part of the hydrologic system is altered, to what degree, and how permanent the alteration is.

Snowmelt During Rainfall

The potential influences of forests on snowmelt have been known for some time, but actual effects have not been clearly established for mountainous, forested terrain typical of western Washington and Oregon. This is particularly true where snowpacks are shallow and transient during the winter.

According to snow hydrology work done by the U.S. Army Corps of Engineers (1960), clearcut logging could increase the rate of snowmelt during rainfall because turbulent transfer of energy and water vapor to the snow surface would be increased after removal of forest vegetation.

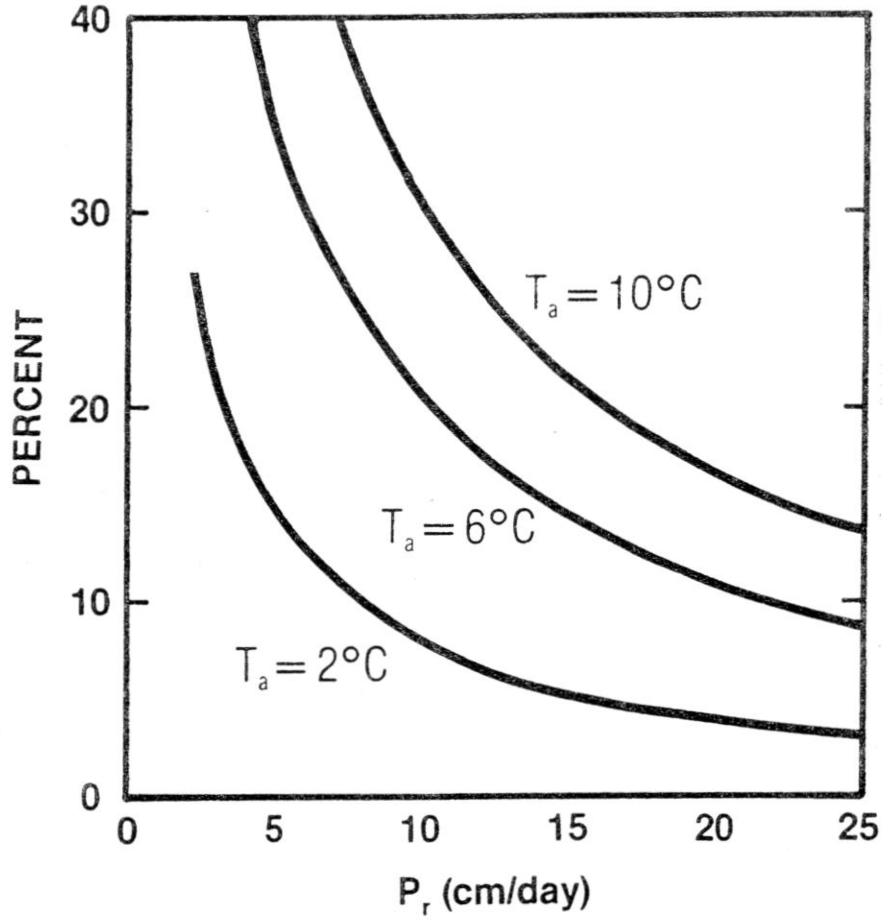

Figure 17--Percent increase in 24-hr water input following timber removal. Increase is a function of average 24-hr air temperature (T_a) and 24-hr rainfall (P_r) and is expressed as a percentage of melt that would have occurred had timber not been removed (adapted from U.S. Army Corps of Engineers 1956).

The equation for convection-condensation melt in table 3 would be replaced by $M_{ce} = 0.086\ V\ T_a$; where V = wind velocity in m/sec 15 m above the snow surface. At a wind velocity of 7.5 m/sec, an average air temperature (T_a) of 6°C, and 24-hr rainfall (P_r) of 10 cm, total melt would be increased about 90% and total 24-hr water input to soil about 20% (fig. 17). In other words, the weather and snowpack conditions which, under forested conditions, would produce a water input event with a return period of about 2 yr, could produce a water input event with a return period of about 10 yr[5/].

[5/] Harr, R. D. Some characteristics and consequences of snowmelt from shallow snowpacks during rainfall in western Oregon. Unpublished manuscript on file at Forestry Sciences Laboratory, Corvallis, Oregon.

At present the effects of timber removal on snowmelt during rainfall are poorly understood and arguments presented here are speculative. Nevertheless, most major runoff and many erosion processes in the Pacific Northwest have been associated with snowmelt during rainfall, and changes in melt under certain circumstances could cause higher runoff than would occur under forested conditions and could adversely affect channel stability. Conversely, depending on weather conditions during snow accumulation and melt, clearcutting may reduce the size of some peak flows as was observed in watershed HJA-10 (Harr and McCorison 1979).

That a potential increase in runoff exists because of changes in snowmelt during rainfall after logging does not mean that all stream channel segments would be adversely affected. Consider two first-order streams which join to form a second-order stream. Assume the two watersheds drained by the first-order streams respond the same to snowmelt during rainfall so that their peak flows are additive at their confluence. If logging one watershed was to speed up snowmelt, its peak flow might occur earlier enough to desynchronize with the peak flow from the other watershed. Thus, peak flow below the confluence would be less than if both watersheds were forested. Increased runoff in the logged watershed could adversely affect the stream channel in that watershed, but below the confluence channel erosion could be less than if logging had not occurred.

That a generalization cannot be made about effects of timber harvest on snowmelt during rainfall, on size of peak flow, and on channel erosion can be illustrated by a second situation which is as plausible as the first. If flows from the two watersheds described above were not synchronized before logging, increased runoff caused by changes in snowmelt during rainfall might synchronize the flows--or it might desynchronize them further. Without understanding the rain-on-snow phenomenon and how it is affected by timber harvest, we have little chance of understanding how streamflow and erosion processes might be affected by timber harvest.

PREDICTING CHANGES IN STREAMFLOW

Whether or not the effects of timber harvest on the quantity and timing of streamflow in the Pacific Northwest can be predicted is of prime importance to forest land managers. This question is basic to the whole harvest scheduling idea and, of course, to this workshop. If we cannot reliably predict the consequences of our harvest activites on streamflow, then scheduling harvest activities according to some formal procedure designed to "maintain hydrologic balance" will be largely an academic excercise and probably will be ineffective in west-side Washington and Oregon.

A first step in formulating a procedure that could be used to help schedule timber harvesting for channel stability purposes is the realization that channel erosion processes are dependent on the magnitude and duration of high flows. Implied in this step is the realization that there is no relationship between increases in annual water yield and increases in size of higher peak flows in western Washington and Oregon (Harr 1976a). It is true that increases in annual water yield after logging in experimental watersheds have generally been accompanied by higher peak flows in early fall and in spring and by relatively large increases in summer low flows. Neither change in streamflow, however, is involved in channel erosion processes.

Although the lack of relationship between annual yield and channel erosion in west-side Washington and Oregon has been well established, it has been either poorly communicated to land managers or not widely accepted by them. Consequently, annual water yield has been given much more than its fair share of importance and, as a result, may have been somewhat of a hindrance in understanding the effects of timber harvest on streamflow and channel erosion processes in this region. Possibly, the emphasis on annual water yield in both research and National Forest administration has stemmed from its emphasis in other regions, such as the Southwest (Barr 1956), the central Rocky Mountains (Goodell 1967), as well as the humid East (Hewlett and Hibbert 1961, Hewlett 1966, Hibbert 1967).

A number of computer models have been developed to simulate annual water yield. Even if these models could simulate yield changes, and few of them can, the relative accuracies of yield increases predicted by them or by the water yield analysis procedures of the type used in Region 1 (Galbraith 1973) would be irrelevant for west-side Washington and Oregon because of the aforementioned lack of linkage between water yield and channel erosion processes.

It should be apparent then that we must concentrate our efforts on predicting the effects of timber harvest activities on higher flows; for example, those above about 4 liters/sec.ha in figure 6. These flows are shaping channels in headwater basins in the Pacific Northwest. Also, synchronization of these levels of storm runoff from subwatersheds is most important in size and duration of high flows in higher order streams of parent watersheds. Once the processes controlling storm runoff in headwater basins are understood, we will stand a better chance of accurately predicting the effects of harvesting on the streamflow characteristics directly involved in channel erosion processes.

Unfortunately, we are not yet at that level of understanding. For a variety of reasons, studies of experimental watersheds have not included enough plot-level studies of processes conducted concurrently with watershed-level studies, so we still have only crude ideas about how a watershed produces streamflow and about what has caused observed changes in storm runoff after logging. We have circumstantial evidence linking increased size of peak flows to soil compaction which suggests, albeit roughly, that perhaps we should limit soil compaction—of the type found on haul roads, primary skidroads, and landings--to less than 10% of total watershed area. But the answer is not that simple, for compaction on less than 10% of total watershed area could also increase size of peak flows if it were located on critical runoff-producing areas. And interception of subsurface water by roadcuts and ditches most likely is involved too. Logically, this could also route water to stream channels faster than natural subsurface flow processes do; thus, a given set of storm conditions that would produce a maximum flow insufficient to cause appreciable channel erosion in an undisturbed watershed could produce after roadbuilding a higher maximum flow sufficient to erode the channel.

To complicate the picture even more, there is the potential of increasing rate of snowmelt during rainfall by clearcut logging. Data from experimental watersheds in western Oregon show the importance of snowmelt during rainfall on peak flows and the occurrence of landslides (see footnote 5). Although snowmelt indices developed by the U.S. Army Corps of Engineers (1956, 1960) suggest that widespread removal of forest vegetation by clearcutting could increase rate of water input to soil and amount of storm runoff, effects of clearcutting on snowmelt from shallow packs during rainfall have not been demonstrated.

If this discussion of our present capability of predicting effects of timber harvest on streamflow characteristics most involved in channel erosion processes sounds negative to you then I have made my point well. I do not believe we can predict changes in size or duration of these high flows at this time. This lack of predictive capability stems primarily from our lack of understanding of (1) subsurface movement of water, (2) snowmelt from shallow snowpacks during rainfall, and (3) how each of these is influenced by timber harvest activities. This lack of predictive capability, however, must not be interpreted to mean certain timber harvest activities are not capable of damaging soil and water resources. For example, we cannot say that clearcutting in the zone of transient snowpacks will not increase size of peak flows caused by snowmelt during rainfall with any more confidence than we can say that clearcutting will increase the size of these flows.

There are some indications that eventually we should be able to predict the effects of timber harvest activities on the channel-eroding higher flows but when and to what extent we will be able to do this are unknown. Recent computer hydrology models have been able to simulate stormflow reasonably well. Simulated volume of storm runoff and size of peak flows in a small watershed in West Virginia averaged 89% and 96% of their respective measured values (Troendle 1979). A model developed for small watersheds in the H. J. Andrews Experimental Forest simulated storm hydrographs and would have fit measured data much better if a more accurate snow accumulation-melt submodel were available (Overton and White 1978). The subsurface routing mechanisms were critical parts of both models. Conceivably, improvements in such models could provide a framework for predicting changes in storm runoff provided, of course, we know how harvest activities change processes of the hydrologic system that are critical to storm runoff and can express these changes in such a way that they can be included in the simulation models. We must know where and when road cuts and ditches will intercept subsurface flow of water, under what conditions soil compaction will affect peak flows, and how timber harvest affects rate of snowmelt during rainfall. These, I believe, are crucial to the success of any attempt to schedule timber harvest to protect soil and water resources. We must also keep in mind that how and where an activity is carried out may be much more important than if or when it is carried out.

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CHANNEL STABILITY AND CHANNEL EROSION PROCESSES

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INTRODUCTION

What is a stable channel? How do we evaluate channel stability and how does it relate to land use practices? These are tough questions that have no absolute answers. Various scientists have dealt with the problem besides the Forest Service, including geomorphologists and engineers. Each of these disciplines has made contributions to the general knowledge of channel stability that are pertinent to the concerns of the Forest Service. The main concern of the Forest Service has been to conduct land use activities on forest lands without causing adverse effects on channel stability. They have attempted to do this by developing a channel stability classification system which is then incorporated into watershed analysis procedures to define acceptable levels and/or types of land uses. In this paper, I would like to point out some of the important concepts in the field of geomorphology and engineering that relate to channel stability. These concepts are then used to review and discuss the efficacy of the Forest Service procedures available for review and discussion at this conference. In so doing, the intent is not to cast doubt on the utility, value or validity of the procedures but rather to point out areas where improvement could possible strengthen the final result. If this paper stimulates some constructive discussion of the overall problem of channel stability and condition in relation to forest land uses, it will have served its purpose.

THE GEOMORPHOLOGISTS APPROACH

> "During graded and steady time, (a duration of a few hundred years versus a week or two respectively*) channel morphology reflects a complex series of independent variables, but the discharge of water and sediment integrates most of the other independent variables; and it is the nature and quantity of sediment and water moving through a channel that largely determines the morphology of stable alluvial channels." (Schumm, 1971, p. 4-14)

If the discharge of water and sediment is relatively uniform over a period of years, the stream tends to develop a graded or equilibrium condition. Leopold and Bull (unpublished) stress some of the specific variables influencing channel morphology in their definition of equilibrium as follows:

> "a graded stream is one in which, over a period of years, slope, velocity, depth, width, roughness, pattern and channel morphology delicately and mutually adjust to provide the power and efficiency necessary to transport the load supplied from the drainage basin without net aggradation or degradation of the channels."

All streams tend toward equilibrium over time. However, actual attainment and maintenance of equilibrium conditions is difficult because a variety of changes in the independent variables of the fluvial system

*my italics

often interact to prevent it. The picture is further clouded because the independent variables often change at different rates. For example, the response time for changes in relief caused by tectonic activity might be 10^4 years whereas the response time for climatic or human changes might be 10^2 or 10^1 years respectively.

Bull (1979) presents a new approach to the equilibrium concept that helps explain the interrelations between form and process in fluvial systems. He introduces the principal of the threshold of critical power which separates the different modes of operation of the fluvial system. The treshold of critical power is defined as:

$$\frac{\text{Stream Power}}{\text{Critical Power}} = 1.0$$

Stream power is defined by Bagnold (1977) as ability of the stream to do work by maintaining fluid flow against flow resistance and by transporting bedload. Stream power per unit width of stream, ω, is calculated as follows:

$$\omega = \frac{QS}{\text{width}} = \gamma dS\bar{u}$$ where:

γ = unit weight of water
Q = discharge
S = energy gradient of the stream
d = flow depth
$\bar{u}$ = average flow velocity

Stream power represents the energy available to transport sediment. Increases in any of the components of stream power cause increased sediment transport. In comparison, critical power represents the amount of energy needed to transport the sediment load supplied to the given stream reach. Critical power is a function of those variables that when increased, tend to cause decreased sediment transport including total sediment load, sediment particle size, channel roughness and channel width, depth and velocity as they affect channel roughness. Both stream power and critical power can change rapidly in time in response to changes in the variables affecting them. It is the ratio of the two that governs the state of the system. Stream power is most responsive to changes in discharge whereas critical power responds rapidly to changes in amount and size of sediment.

As long as stream power is greater than critical power, there is a tendency for channel erosion. Upon passing through the threshold of equality the situation reverses and channel deposition occurs. Variations in the stream power/critical power ratio over time for a given reach of channel are shown in Figure 1 (Bull, 1979).

The figure also illustrates the difference between the concepts of equilibrium and threshold of critical power. The threshold point marks the difference between the mode of operation of the fluvial system (i.e. a transition from aggradation to degradation or visa versa) whereas equilibrium marks periods of no change. Although the figure is not based on real data, it does illustrate the tenuous nature of equilibrium. Generally, the system is adjusting to some change in the driving variables so that equilibrium is short lived.

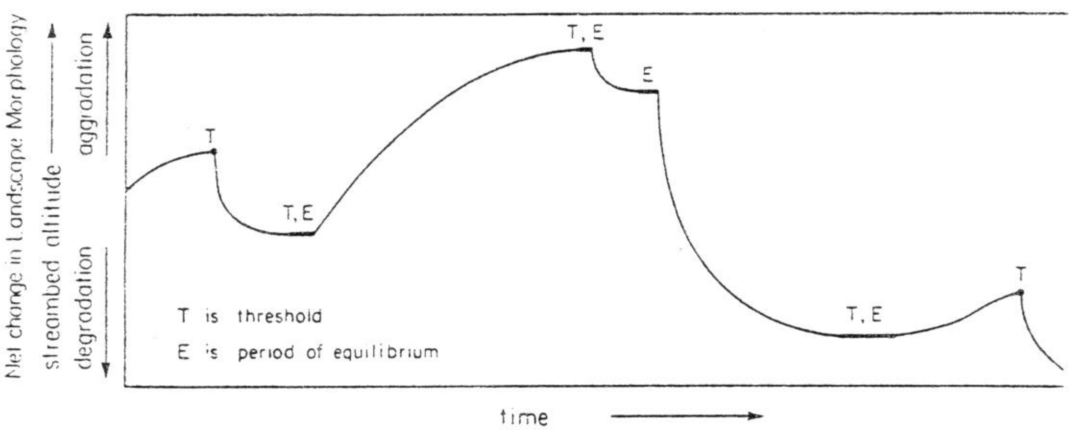

Figure 1. Variations in the stream power/critical power ratio over time.

The threshold of critical power concept is useful for considering channel morphology changes along the channel as well as at a given reach. Bull (1979) illustrates this effect for an ephemeral drainage system in the southwest U. S. (Figure 2). In headwater areas, stream power is greater than critical power so downcutting occurs resulting in V shaped valleys. Further downstream, both stream power and critical power are decreasing but are equal resulting in an equilibrium situation that tends to promote some lateral channel cutting. At the lowest reaches, stream power drops rapidly as flows infiltrate into valley alluvium whereas critical power drops only slightly. The critical power ratio is now reversed and continued alluviation occurs in the area.

The state of the channel system (i.e. eroding, equilibrium or depositing) provides a logical criterion for classifying channel stability although most geomorphologists have not taken this approach. Schumm (1971) has made an attempt at it for alluvial channels. Alluvial channels are those that are free to adjust their dimensions, shape, pattern and gradient in response to hydraulic changes, and flow through a channel with bed and banks composed of material transported by the stream under present flow conditions. This is in contrast to bedrock controlled channels which are those channels that are so confined between outcrops of rock that the material forming their bed and banks determines the morphology of the channel. For the most part, lower order channels in forested areas in the mountain west are bedrock controlled. They represent the situation shown by Bull for low order streams where stream stream power exceeds critical power (Figure 2). Such channels tend to be relatively high gradient with frequent bedrock controls on the banks and/or in the bed. These streams are downcutting and accordingly are found in V shaped valleys.

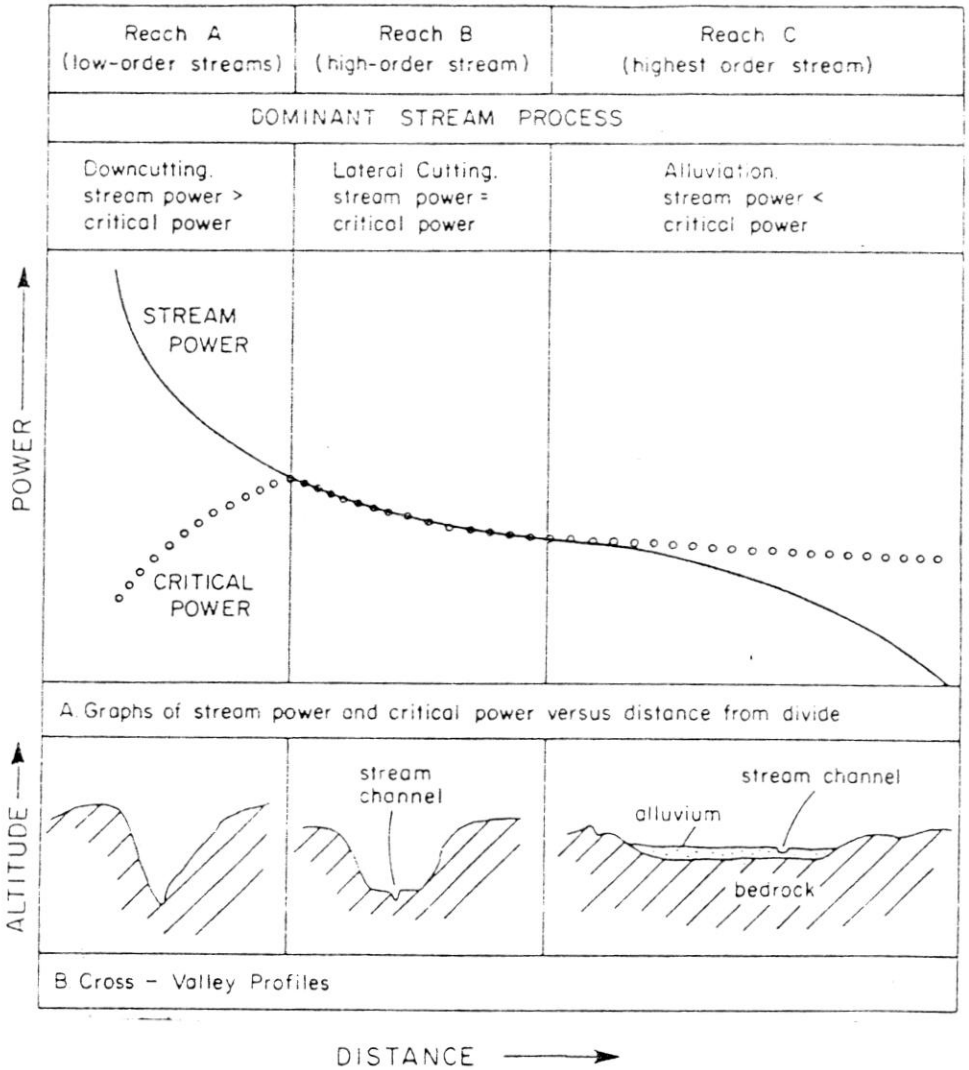

Figure 2. Diagrammatic sketches and graphs of stream power and critical power for an arid, rocky drainage basin.

Localized channels or channel reaches in the mountain west may exhibit characteristics of alluvial channels because of changes in geologic structure or glaciation. In such situations, Schumm's classification might be applied (Table 1). Three classes of channel stability are recognized based on the critical power ratio being greater than, equal to or less than 1.0. The type of sediment transport and the percentage of silt and clay in the channel perimeter are used to discriminate between channels. Unfortunately, this system does not fit the Forest Service concept of channel stability too well, especially for stable channels. For example, a stable bedload channel has a width to depth ratio over 40 according to Schumm. This puts it in the poor channel class of the Forest Service stream channel classification guide

Table 1. Classification of Alluvial Channels

Mode of Sediment Transport and Type of Channel	Percent Silt and Clay in Channel Perimeter	Bedload (% of Total Load)	Channel Stability		
			Stable (Graded Stream)	Depositing (Excess Load)	Eroding (Deficiency of Load)
Suspended Load	>20	< 3	Stable suspended-load channel. Width-depth ratio less than 10; sinuosity usually greater than 2.0; gradient relatively gentle.	Depositing suspended load channel. Major deposition on banks cause narrowing of channel; initial stream-bed deposition minor.	Eroding suspended-load channel. Streambed erosion predominant; initial channel widening minor.
Mixed Load	5-20	3-11	Stable mixed-load channel. Width-depth ratio greater than 10 less than 40; sinuosity usually less than 2.0 greater than 1.3; gradient moderate.	Depositing mixed-load channel. Initial major deposition on banks follow-ed by streambed deposition.	Eroding mixed-load channel. Initial streambed erosion followed by channel widening.
Bedload	< 5	>11	Stable bedload channel. Width-depth ratio greater than 40; sinuosity, usually less than 1.3; gradient relatively steep.	Depositing bedload channel. Streambed deposition and island formation	Eroding bedload channel. Little streambed erosion; channel widening predomi-nant.

in spite of Schumm's classification of "stable." Likewise, I suspect the opposite is also true -- namely, that many channels considered "stable" according to the Forest Service stream classification guide are actually downcutting channels similar to those shown for low order streams by Bull (1979). This is not meant to imply one system or the other is wrong; it simply points out that the criteria for defining stability or instability are not compatible.

In summary, the geomorphic approach provides generally accepted concepts to help understand the interactions of process and form over time. However, most of the concepts are too general to be of practical use and they are not readily quantified. Finally, their terminology often does not fit our biases as to what is a stable or unstable channel.

THE ENGINEER'S APPROACH

Engineers have helped to fill the quantification gap left by the geomorphologists. For the most part, they have been concerned with quantifying the amount of channel change rather than developing some sort of channel stability classification system. Considerable effort has been devoted to devising ways to calculate the rate of sediment transport utilizing a variety of measured flow parameters. Various approaches have been developed over the years ranging from very elaborate accounting of the energy available for transport to relatively simple empirical analyses. Shen (1971) presents an excellent discussion that places the various sediment transport formulae into perspective. The big point Shen makes is summarized as follows:

> "The best that a sediment transport equation based on river flow condition can do is to predict the sediment transport capability of a given flow for a certain sediment mixture."

This is equivalent to the way Bull uses the stream power concept -- it represents the potential for transport but not necessarily the actual transport.

Shen illustrates this point by plotting sediment transport capability for a given discharge rate and the supply of sediment available for transport against sediment particle sizes (Figure 3).

The intersection of the two curves is at point A where the sediment size is d_s^*. The rate of sediment supply from upslope (either from within the channel or from the watershed slopes) is greater than the transport capability of the stream for all sediment sizes greater than d_s^*. Therefore, deposition of a portion of these larger particles occurs. In this instance, a sediment transport equation based on the sediment transport capability of the river agrees with the actual sediment transport. For sediment sizes less than d_s^*, the transport capability of the stream is greater than the rate of supply of sediment. In this case, sediment transport equations are in error because the amount of transport is a function of supply rather than energy available. The only way to accurately predict sediment transport in this instance is to develop an accurate prediction of the rate of supply. In summary, the best an equation for sediment transport that is based on some measure of streamflow can do is to predict sediment transport rates for sediment sizes equal to or greater than d_s^*.

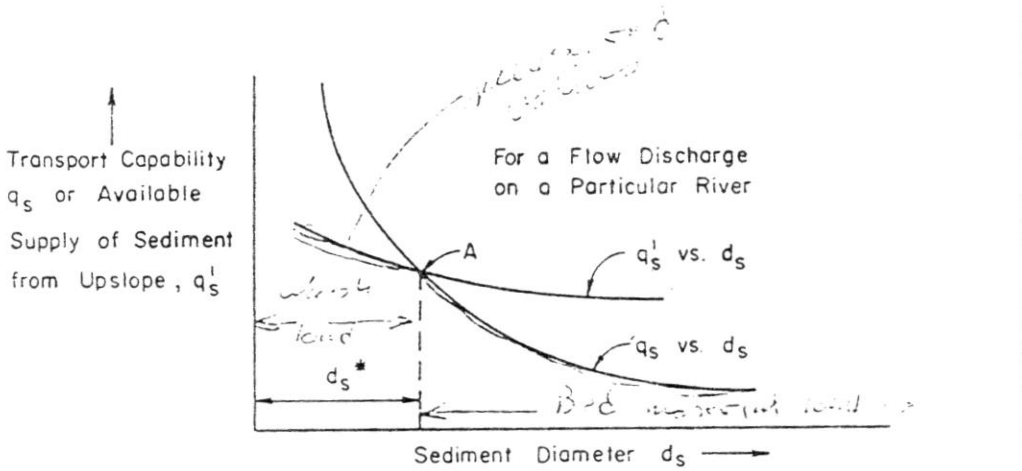

Figure 3. Sediment transport capability and availability of sediment supply from upslope vs sediment diameter d_s^* for a given water discharge.

This brings up another problem; namely that there is considerable variation in the results obtained from sediment transport equations even when their use is appropriate (i.e. the system is not supply limited). Many equations were developed in flumes and/or under restricted conditions such as limited sediment particle sizes, or small ranges in flow, or slope gradients and may not be applicable elsewhere. Also, there is inherent error in the development and testing of any procedure regardless of its environment. The amount of variation can be extreme (Figure 4). This particular data set was taken from Yang (1974). A number of common procedures for estimating sediment transport were applied to measured sediment data taken for the Niobrara River in Nebraska. Notice that an order of magnitude difference between predicted and actual is common depending on the estimation technique selected. Of course, Yang's predictions agree very well or he wouldn't have presented it. This is not an endorsement for Yang's procedure over any of the others; it simply illustrates the amount of variation that can be expected between sediment transport predictions.

The margin of uncertainity can be reduced somewhat by applying the most appropriate equation to the situation at hand. Guidelines are available (eg. American Society of Civil Engineers, 1975, Sedimentation Engineering, pp. 190-209.) for helping the user to select and use the best sediment transport formula for his own application. However, even in this instance, results may vary considerably. To illustrate, the Meyer-Peter and Muller equation was determined to be the best equation to calculate transport of granitic sediments in both Idaho and on the east side of the Sierra-Nevadas in California and Nevada. Neilson (1974) reports good results with the procedure in Idaho whereas Nadolski (1979) found the equation overestimated sediment yield by up to three orders of magnitude. Nadolski felt that debris in channels was the primary cause of lack of agreement. The debris caused discontinuities in channel gradient that did not allow accurate determination of the slope of the energy gradient for the channels. Another possible cause might be that Nadolski was working in lower order, steep mountain drainages similar to those described by Bull that have a stream power to critical power ratio greater than one. Such drainages are commonly supply limited and as such tend to cause over estimates of sediment yield when using bedload transport equations. Similar problems did not exist in Idaho because the study stream was located in a flat meadow land area in the bottom of a structural basin.

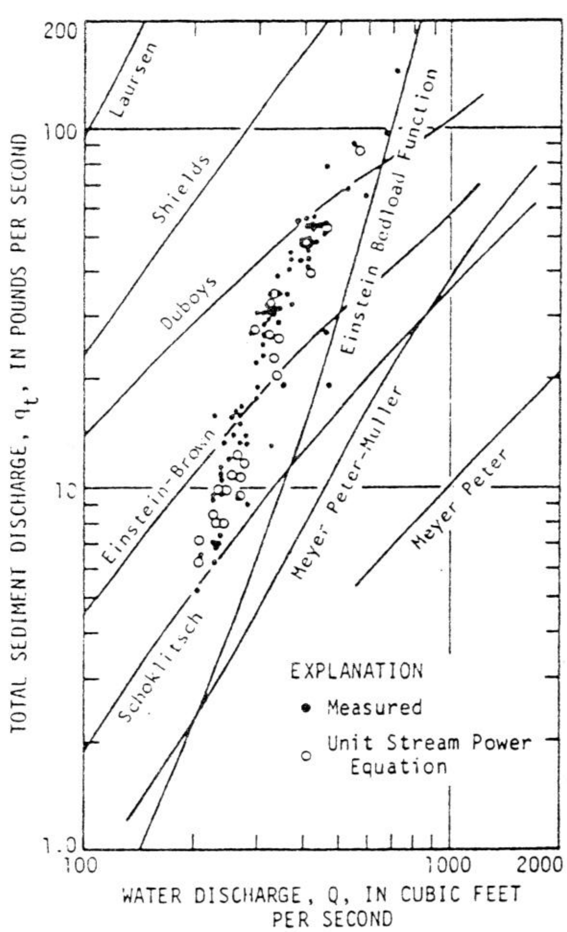

Figure 4. Measured total sediment discharge for Niobrara River near Cody, Neb., compared with that computed by using various sediment transport equations. (from Yang, 1974).

This brings up a whole additional subject -- namely, the effects of debris on sediment transport and storage. Other than to point out the problem of Nadolski, I will leave further discussion of this subject for Fred Swanson.

THE FOREST SERVICE APPROACH

The Forest Service has developed a classification system to inventory present stream channel conditions and to help develop guidelines for future land management activities in the contributing basin. The original channel stability classification was developed by Megahan (1965) to assess channel conditions in the Sevier River Basin of southern Utah as a part of the U. S. Department of Agriculture river basin surveys being conducted at that time. The original system was expanded by Pfankuch (1978) for use in the northern Rocky Mountains for inventory and monitoring purposes and to serve as an integral part of an overall watershed analysis system (USDA Forest Service, N.D.).

A second type of approach to incorporate stream channel conditions into an overall watershed analysis system has been through the use of the equilibrium concept. This was done on the Clearwater National Forest because of difficulties encountered using systems developed elsewhere (Bennett and Wilson, 1975).

THE CHANNEL STABILITY CLASSIFICATION SYSTEM

Rather than to evaluate the time sequence of forces influencing channel morphology (the geomorphic approach) or to calculate the amount of channel erosion or deposition (the engineering approach), the Forest Service has developed a rating system utilizing a number of indicators of upper bank, lower bank and bottom conditions to index the relative state of the channel system with respect to channel stability. Indicators were selected to reflect the present stability of the channel and include such things as bank erosion and evidence of cutting or deposition of the bottom. In addition to direct indicators, the system also includes some indicators that have a potential for influencing channel stability such as the gradient of the upper banks and the potential for development of debris dams.

The system has some definite advantages. It is simple and easily applied using the available field guide. Users indicate that ratings tend to be quite repeatable, thus relative uniformity in application is likely. Most of the indicators used are logical and would be expected to vary with changes in channel stability. Accordingly, the system should be well suited for inventory purposes and for monitoring gross changes at specific channel reaches over time. Because of the number and variety of indicators used, the system may be useful for indexing other channel associated responses such as bedload sediment transport or fishery values.

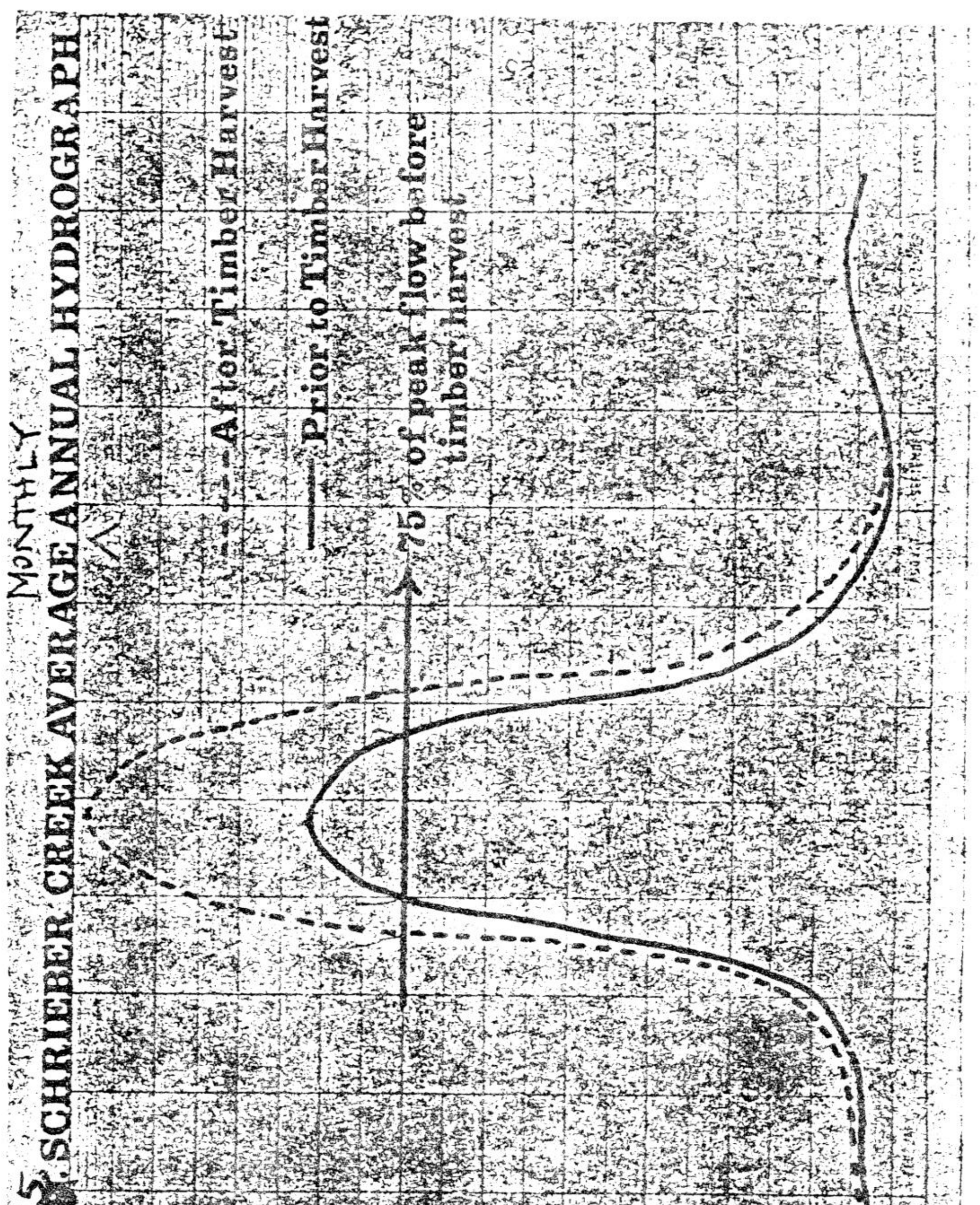
fig. 5 SCHRIEBER CREEK AVERAGE MONTHLY ANNUAL HYDROGRAPH
After Timber Harvest
Prior to Timber Harvest
75% of peak flow before timber harvest
ACRE - FEET

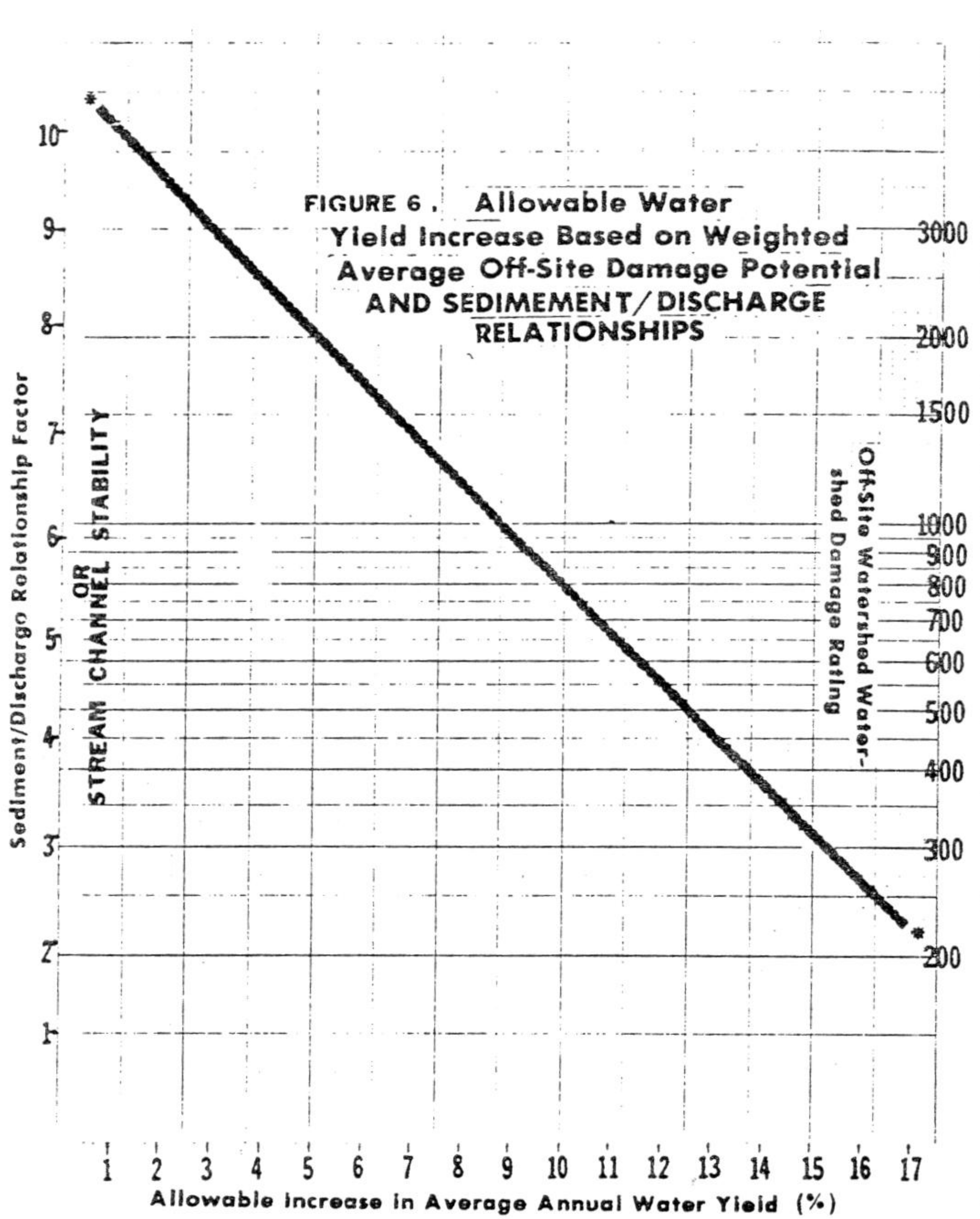
FIGURE 6. Allowable Water Yield Increase Based on Weighted Average Off-Site Damage Potential AND SEDIMEMENT/DISCHARGE RELATIONSHIPS
Sediment/Discharge Relationship Factor
STREAM CHANNEL OR STABILITY
Off-Site Watershed Watershed Damage Rating
Allowable Increase in Average Annual Water Yield (%)
10
9
8
7
6
5
4
3
2
1
3000
2000
1500
1000
900
800
700
600
500
400
300
200
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17

The system does have limitations. For example, it does not define cause and effect so additional detailed studies of watershed functions are needed to define the management implications of a particular stream rating. Because of wide natural variations in the factors influencing channel morphology (as discussed in the geomorphology section) common application of ratings between streams may be hazardous. Although the procedure was developed for 2nd to 4th order streams in the northern Rocky Mountains, the implications are that they are suitable for other locations and stream orders as well. This can be very hazardous because of natural variations in indicators by stream orders or for differing geologic, climatic or biological regimes. One example was pointed out earlier when Schumm's stable bedload stream was shown to have a width-depth ratio contrary to what would be expected in the channel stability guides. Leopold et al (1964) illustrate the problem further by pointing out that width-depth ratio is a function of stream order. Another example is angularity of bed particles -- this can easily be more a function of the bedrock type or glacial history of an area than it is an indicator of channel stability. Changes of the above indicators within a given stream reach may be excellent indicators of changes in channel stability -- it is only when the indicators are applied uniformly over a broad range of stream orders or locations that problems may arise.

APPLICATION OF CHANNEL CONDITION TO WATERSHED ANALYSIS

Broad application and use of the channel stability rating system by many professional hydrologists in the Forest Service suggests the procedure has merit for evaluating the effects of timber harvest on channel conditions. Unfortunately, the use of the channel stability rating in the overall watershed analysis system presented for review by this workshop is questionable. This is because predicted changes in mean monthly flows are used to simply measure changes in channel stability. The procedure is illustrated on Figure 5. The figure is taken from Forest Hydrology Part II and illustrates the mean monthly flows for an example watershed before and after timber harvest. The predicted increase in annual volume of runoff is 72 percent for this example. (This value is very high but won't be disputed here.) The increase is distributed over the annual hydrograph based upon percent of monthly flow rate to give a post harvest hydrograph (again won't be disputed here). Flow rates equal to or greater than 75 percent of the peak monthly flow for the prelogging period are considered to be responsible for most of the erosive power of the stream. The duration of such flows is defined as the channel impact period.

The predicted increase in flows following logging lengthen the channel impact period, thereby decreasing channel stability according to the analysis procedure. In the example, the channel impact period was increased 50 percent. This is the rationale for the development of guidelines of allowable increases in annual water yields in relation to channel conditions (Table 2, Figure 6).

Table 2. Allowable increases in annual flow for levels of channel stability.

Channel Stability Rating	Maximum Probable Increase in Annual Flow
38 - 50	16% - 14
51 - 76	14% - 12
77 -114	12% - 8
115 +	8% or less

I would like to take a few minutes to consider the validity of this approach. A stream channel is developed in response to flow rates that are large enough to cause significant bedload sediment transport and occur often enough to have a major effect on channel form. The flow rate equivalent to bankfull meets these criteria. Leopold et al (1964, p. 219, 320) found that the return frequency for instantaneous bankfull flows was about 1.5 years using data from a number of streams throughout the United States. Nielsen (1974) did a study of sediment transport on Capehorn Creek in southern Idaho for the stream in slightly greater than bankfull conditions (2 year return interval). Sediment transport did not even begin until approximately 65 percent of the peak flow of 400 cfs was attained (Figure 7). Above this rate, bedload sediment transport increased rapidly. At first glance, this 65 percent flow value appears tolerably close to the 75 percent of peak flow value used in the Forest Service watershed analysis guide. However, it is important to note that both Nielson and Leopold et al are referring to instantaneous flow rates while mean monthly flows are used in the watershed analysis guides. The significance of this is illustrated in Figure 8. The figure shows the recurrence interval for annual maximum peak flows for various durations ranging from instantaneous to 365 days on an experimental watershed on the Reynold's Creek Study area (courtesy Jeff Smith, USDA Science and Education Administration, Boise, Idaho). Assuming a log-normal distribution, the mean recurrence interval for any maximum flow duration would occur at 2.33 years. Entering Figure 8 at 2.33 years, we find an annual maximum flow for the average 30 day peak flow duration used by the Forest Service to be about 2.1 $m^3 sec^{-1}$. Seventy-five percent of this flow rate would be about 1.6 $m^3 sec^{-1}$. In contrast, the instantaneous flow for the 2.33 year return interval is about 14.5 $m^3 sec^{-1}$. If we assume sediment transport conditions similar to what Nielson found on Capehorn Creek, bedload sediment transport would not even begin until flows were equal to 65 percent of the 2 year return flow or about 8.1 $m^3 sec^{-1}$. Thus, bedload sediment transport does not even begin until 8.1 $m^3 sec^{-1}$ whereas the Forest Service procedure predicts that flows greater than 1.6 $m^3 sec^{-1}$ "are responsible for most of the erosive power of the stream." At these low levels, no reasonable increase in monthly peak flows caused by logging would have measurable influence on sediment transport.

Obviously, the sediment transport capabilities of Capehorn Creek and the flow frequencies for Reynold's Creek can not be universally extrapolated. However, they are real data that provide a good example

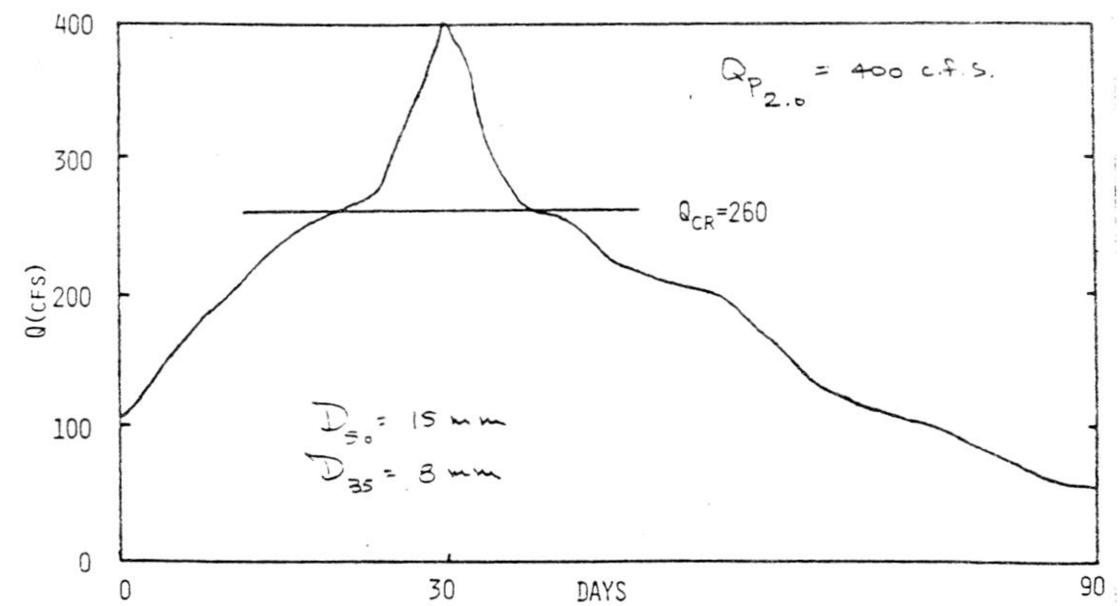

Figure 7. Snowmelt hydrograph for Capehorn Creek (2 year return) showing the flow rate needed to initiate bedload sediment transport.

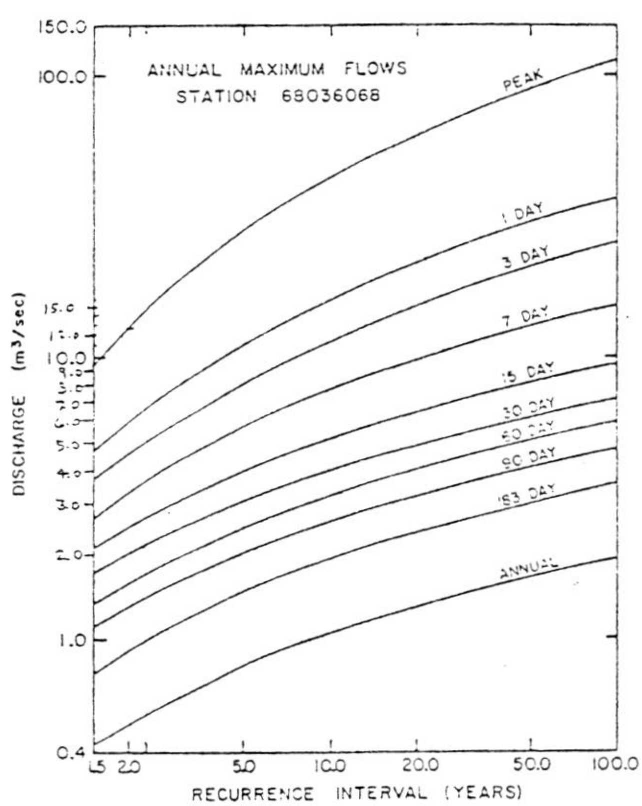

Figure 8. Recurrance interval of maximum discharge rates for various durations for a study watershed on the Reynold's Creek Experimental Watershed. (Courtesy of Jeff Smith, USDA, S.E.A., Boise, Idaho)

of problems arising from the use of average flow values to predict channel conditions. The logical response at this point would be to say let's develop frequency curves similar to Figure 8 and convert mean monthly to instantaneous peak flows. This would indeed help, however, as discussed earlier in the geomorphology and engineering sections, channel erosion and deposition are caused by the combined effect of many factors in addition to flow rate. Many of these may be affected by timber harvest. For example, channel geometry may change by adding or removing debris in channels or by direct channel encroachment and most importantly, total sediment storage and transport can change greatly in response to accelerated surface and mass erosion. All of these factors combine with changing flows to influence channel morphology.

The channel stability guides provide a logical method for indexing channel conditions before and after disturbance. However, their present use in the watershed analysis system is questionable because changes in average annual monthly peak flows have no meaningful effect on sediment transport. For this reason, the present tables of allowable increases in annual water yields in relation to channel condition are suspect. They imply a cause and effect relationship that does not exist. The tables may well be valid in that they probably reflect empirical observations of what happens to channel conditions with increased intensity of timber harvest. However, the impact on channel conditions is the combined effect of short term flow rates and the full spectrum of other factors influencing channel stability. It is important to account for all these factors if a meaningful guideline is to be developed.

APPLICATION OF CHANNEL EQUILIBRIUM TO WATERSHED ANALYSIS

The Clearwater National Forest has recognized some of the limitations of the channel condition-water yield increase approach described above. They have incorporated estimates of changes in sediment production (defined in terms of the percent change in sediment yield or "impact units") with changes in streamflow to help define allowable levels of timber harvest. This approach is theoretically more acceptable because it considers an additional important factor influencing channel erosion and deposition -- namely sediment. It does this by comparing the undisturbed sediment delivery efficiency of the watershed levels (the inherent watershed stability) to the estimated sediment delivery for alternative land use activities (total impact units). These two values are then used to evaluate alternative land management activities on the basis of channel equilibrium (Figure 9). As used here, channel equilibrium was defined on the basis of evidence of channel:

1. Aggradation
2. Degradation
3. Bank cutting
4. Temporary sediment storage by debris, culverts, etc.
5. Location changes

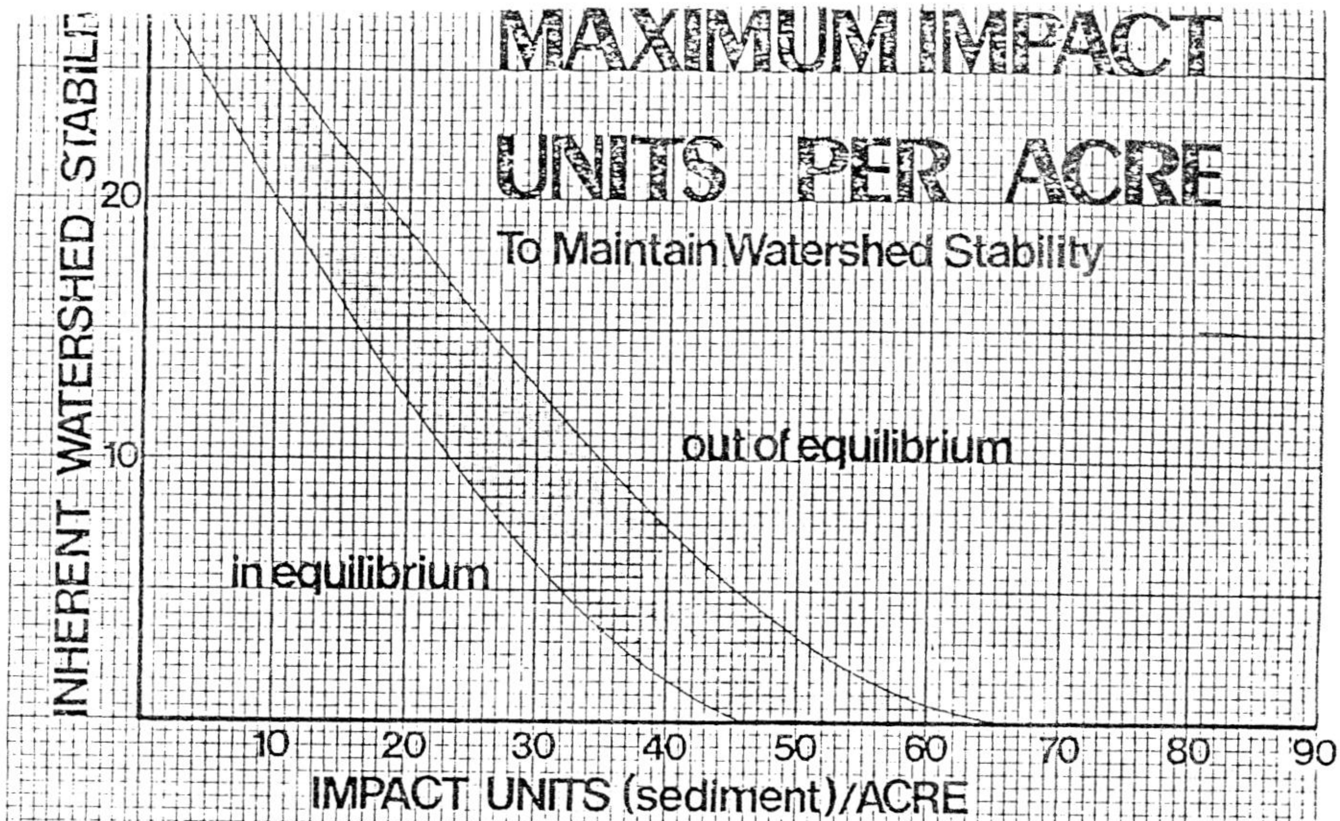

FIGURE 4
Watershed stability curve developed for the Clearwater National Forest

Channels exhibiting extensive areas of one or more of these characteristics were considered to be out of equilibrium, otherwise the channels were in equilibrium.

The overlap between the criteria used to define equilibrium and the indicators used for the channel condition classification are obvious. It would seem logical to combine the two systems in some manner in order to avoid confusion and duplicity of effort. Also there may be some problems in the definition of the term "equilibrium" as used in the Clearwater approach in comparison to the use by Bull and other geomorphologists. It should be possible to resolve these problems by redefining terms.

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LANDSLIDE PREDICTION and ASSESSMENT

INTERPRETING STABILITY PROBLEMS FOR

THE LAND MANAGER

BY

D. N. Swanston

INTRODUCTION

Soil mass movements, that is, downslope movement of a portion of the land surface under the direct application of gravitational forces constitute one of the most common but least investigated processes of natural erosion and slope reduction in mountainous areas of western North America.

In its undisturbed state, the forest floor on steep mountain slopes is in a state of equilibrium between resistance of a soil to failure and gravitational forces tending to move the soil downslope. Any disrupting influence, whether it be natural catastrophic events such as fire, earthquake, or storm, or the cultural activities of man, is a potential initiator of a more active erosion cycle.

The areas of greatest landslide severity lie within the circum-Pacific Mountain belt and the western cordillera (Rocky Mountains, Coast Ranges, and Cascades). These are regions of high relief, characterized by steep slopes and narrow intervalley ridges. Glacial erosion, tectonic uplift, and severe weathering processes have further steepened the slopes, frequently above the angle of internal friction (stability angle) of the soils on them. Periodic storms producing locally saturated soil conditions are also common to most of these areas.

With increasing demand for lumber and pulpwood more of these steep mountain watersheds are being directly influenced by forest operations. The resulting disruption of natural slope stability characteristics has accelerated slope failure in many logged areas, producing excess sediment loads in streams, causing extensive damage to structures and roads, and effectively removing portions of the watershed from immediate reforestation.

It thus becomes essential, for effective forest land management, to be able to recognize and define these unstable areas, to determine primary mass erosion processes operating on the slope, and to identify and understand the interaction of principal and contributing factors controlling slope failure. This requires, first of all, a basic knowledge of the geology and geologic history of the area being managed and at least a rudimentary understanding of the landscape components that control or contribute to unstable conditions. Analytical interpretation and technical evaluation should then be performed, whenever possible, in close cooperation with the engineering geologist, civil engineer and soil scientist.

This paper summarizes published information and concepts dealing with soil mass movement occurence, controling factors, management impacts and identification and assessment techniques. More detailed discussions are available from the principal source documents Swanston, 1976; Swanston and Swanson, 1976; Swanson and Swanston, 1977; Swanston, Swanson and Rosgen, in press).

PRINCIPAL PROCESSES AND MANAGEMENT IMPACTS

Downslope movement of soil materials by mass wasting processes results primarily from direct application of gravitational stress. It may take the form of: 1) single particle erosion involving transport of soil particles and aggregates by rolling, sliding, and bounding (dry ravel): 2) pure reological flow with minor mechanical shifting of mantle materials over large areas (creep), and 3) failure, both along planar and rotational surfaces, of finite masses of soil and forest debris (debris avalanche-debris flow and slump-earthflows). When material from such failures on a slope enter a confining channel carrying storm runoff, a debris torrent may develop.

Slope gradient, soil depth, soil water content, and intrinsic soil properties, such as cohesion and coefficient of friction, control the mechanics and rates of movement of these processes. Geological, hydrological, and vegetative factors determine occurrence and relative importance of mass wasting processes in a particular area.

DRY RAVEL

Dry ravel, or dry creep and sliding, is characterized by single particle movement of coarse, cohesionless materials on steep, sparsely vegetated or recently denuded hill slopes (fig. 1a, b). This is a common erosion process on steep, unvegetated slopes in all mountainous regions, caused by loss of frictional resistance between individual soil particles due primarily to freeze and thaw, and wetting and drying cycles. In areas characterized by steep slopes, coarse textured soils, and extended summer droughts, dry ravel may be a particularly important process. Deforestation and surface cover removal on steep slopes have a strong influence on initiation and acceleration of this process. Recent observations in the San Gabriel Mountains of southern California, indicate this to be the dominant process during the dry summer season, particularly where natural chaparral cover has been removed causing the destruction of stabalizing root systems. Increases in annual sediment production from dry creep and sliding of 10 to 16 times following wildfire has been reported (Krammer, 1965; Rice, et. al. 1969).

A

B

Figure 1.--Cones of loose, granular soil material produced by dry ravel or dry creep and sliding.

a. Dry ravel during the summer drought along a forest road near Shelton, Washington.
b. Dry ravel into a perennial stream in the semi-arid San Gabriel Mountains of southern California.

SOIL CREEP

Soil creep is defined as the slow, downslope movement of soil mantle materials as the result of long term application of gravitational stress. The mechanics of soil creep have been investigated experimentally and theoretically (Terzaghi, 1953; Goldstein and Ter-Stepanian, 1957; Saito and Uezawa, 1961; Culling, 1963; Haefeli, 1965; Bjerrum, 1967; Carson and Kirkby, 1972). Movement is quasi-viscous, occuring under shear stresses sufficient to produce permanent deformation but too small to result in discrete failure. Mobilization of the soil mass is primarily by deformation at grain boundaries and within clay mineral structures. Both interstitial and absorbed water appear to contribute to creep movement by opening the structure within and between mineral grains, thereby reducing friction within the soil mass. Creeping terrain can be recognized by characteristic rolling, hummocky topography with frequent sag ponds, springs, and occasional benching due to local rotational slumping. Local discrete failures, such as debris avalanches and slump-earthflows, may be present wtihin the creeping mass (fig. 2).

Natural creep rates monitored in different geological materials in the western Cascade and Coast Ranges of Oregon and northern California, indicate rates of movement between 7.1 and 15.2 millimeters per year, with the average about 10 millimeters per year (Swanston and Swanson, 1976) table 1). The zone of most rapid movement usually occurs at or near the surface, although the zone of significant displacement may extend to variable depths associated with incipient failure planes or zones of ground water movement. The depth over which creep is active is quite variable and is largely dependent on parent material origin, degree and depth of weathering, subsurface structure, and soil water content. Most movement appears to take place during the rainy season when maximum soil water levels occur (fig. 3a), although creep may remain constant throughout the year in areas where the water table does not undergo significant seasonal fluctuation (fig. 3b). This is consistent with Ter-Stapanian's (1963) theoretical analysis which shows that the downslope creep rate of an inclined soil layer is exponentially related to piezometric level in the slope.

There have been no direct measurements of the impact of deforestation on creep rates in the forest environment, mainly because of the long periods of record needed both before and after a disturbance. There are, however, a number of indications that creep rates are accelerated by harvesting and road construction.

In the United States, Wilson (1970) and others have used inclinometers to monitor accelerated creep following modification of slope angle, compaction of fill materials, and distribution of soil mass at construction sites. The common occurence of shallow soil mass movements in these disturbed areas and open tension cracks along roadways at cut and fill slopes suggests that similar features along forest roads indicate significantly accelerated creep movement.

On open slopes where deforestation is the principal influence, impact on creep rates may be more subtle, involving modifications of hydrology and root strength. Where creep is a shallow phenomenon (less than several meters), the loss of root strength due to deforestation is likely to be significant. Reduced evapotranspiration after clearcutting (Gray, 1970; Rothacher, 1971) may result in longer duration of the annual period of

Figure 2. An example of soil creep and slump-earthflow processes on forest lands in northern California. The entire slope is undergoing creep deformation, but note the discrete failure (slump-earthflow) marked by the steep headwall scarp at top center and the many small slumps and debris avalanches triggered by surface springs and road construction.

Table 1.--Examples of Measures Rates of Natural Creep on Forested Slopes in the Pacific Northwest

(Swanston and Swanson, 1976)

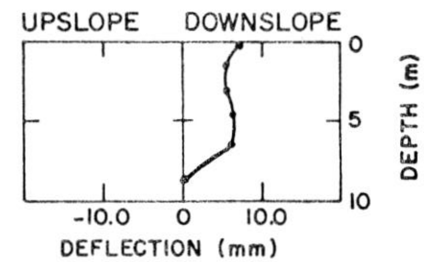
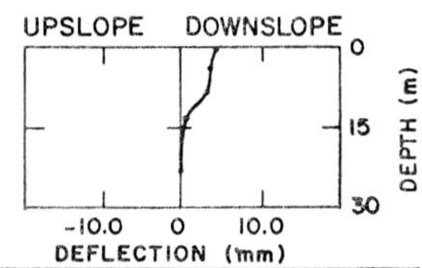
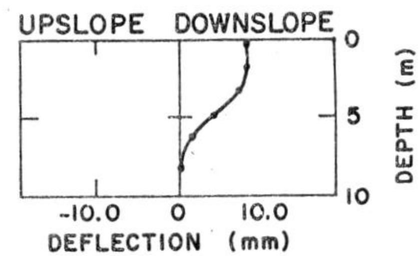
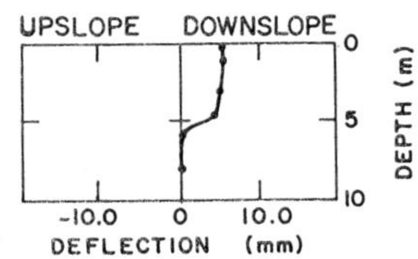
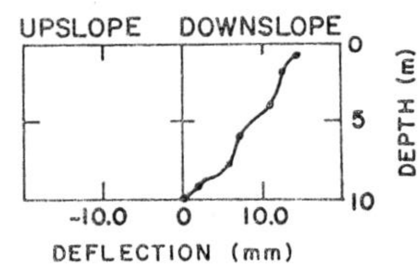
Location	Data Source	Parent Material	Depth of Significant Movement (m)	Maximum Downslope Creep Rate: Surface (mm/yr)	Maximum Downslope Creep Rate: Zone of Accelerated Movement (mm/yr)	Representative Creep Profile
Coyote Creek South Umpqua River Drainage Cascade Range of Oregon Site C-1	Swanston[1/]	Little Butte volcanic series Deeply weathered clay-rich andesitic dacitic volcani-clastic rocks	7.3	13.97	10.9	
Blue River Drainage - Lookout Creek H. J. Andrews Exp. Forest Central Cascades of Oregon Site A-1	Swanston[1/]	Little Butte series Same as above	5.6	7.9	7.1	
Blue River Drainage IBP Experimental Watershed 10 Site No. 4	McCorison[2/] and Glenn	Little Butte volcanic series	0.5	9.0	----	

Table 1.--Examples of Measured Rates of Natural Creep on Forested Slopes in the Pacific Northwest

(continued)

Baker Creek Coquille River Coast Range, Oregon Site B-3	Swanston[1/]	Otter Point Formation Highly sheared and altered clay-rich argillite and mudstone	7.3	10.4	10.7	
Bear Creek Nestucca River Coast Range, Oregon Site N-1	Swanston[1/]	Nestucca Formation Deeply weathered pyroclastic rocks and interbedded, shaley siltstones and claystones	15.2	14.9	11.7	
Redwood Creek Coast Range, Northern California Site 3-B	Swanston[1/]	Kerr Ranch Schist Sheared, deeply weathered clayey schist	2.6	15.2	10.4	

1/ Douglas N. Swanston, unpublished data on file at Forestry Sciences Laboratory, USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Corvallis, Oregon, USA.

2/ F. Michael McCorison and J. F. Glenn, data on file at Forestry Sciences Laboratory, USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Corvallis, Oregon, USA.

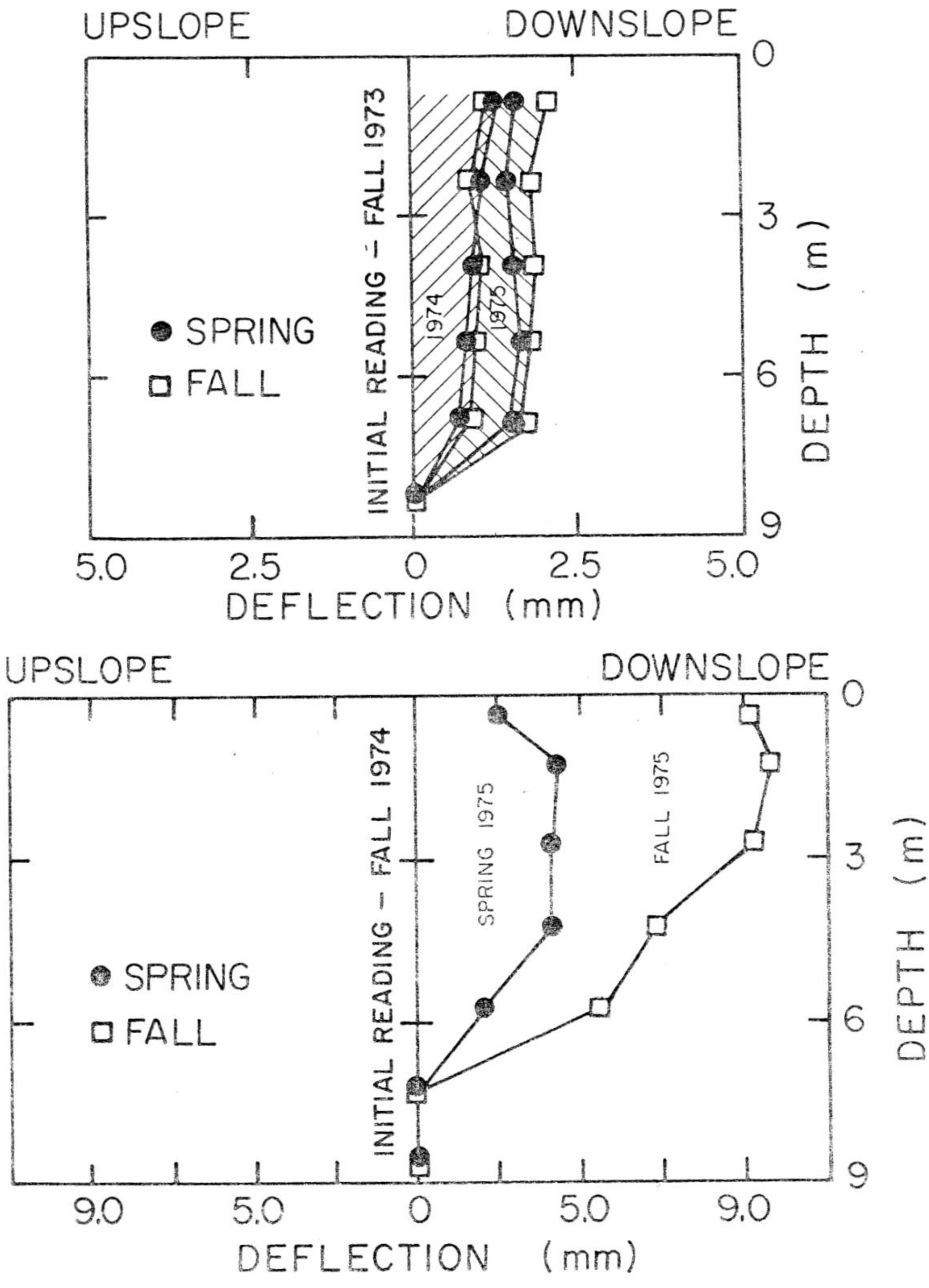


Figure 3.--Deformation of inclinometer tubes at two sites in the southern Cascade and Coast Ranges of Oregon. (Swanston and Swanson, 1976)

a. Coyote Creek in the southern Cascade Range showing seasonal variation in movement rate as the result of changing soil water levels. Note that the difference in readings between spring and fall of each year (dry months) is very small.

b. Baker Creek, Coquille River, Oregon Coast Ranges, showing constant rate of creep as a result of continual high water levels.

creep activity and, thereby, the annual creep rate.

SLUMP-EARTHFLOWS

Where creep displacement has exceeded the shear strength of soil, discrete failure occurs and slump-earthflow features (Varnes, 1958) are formed. Simple slumping takes place as a rotational movement of a block of earth over a broadly concave slip surface and involves little breakup of the moving material. Where the moving material slips downslope and is broken up and transported either by a flowage mechanism or by gliding displacement of a series of blocks, the movement is termed slow earthflow (Varnes, 1958) (fig. 4). Geologic, vegetative, and hydrologic factors have primary control over slump-earthflow occurrence. Deep, cohesive soils and clay-rich bedrock are especially prone to slump-earthflow failure, particularly where these materials are overlain by hard, competent rock (Wilson, 1970; Swanson and James, 1975). Earthflow movement also appears to be sensitive to long term fluctuations (weeks, months, or annually) in the amount of available soil water (Wilson, 1970; Swanston, 1976).

Because earthflows are slow moving, deep-seated, poorly drained features, individual storm events probably have much less influence on their movement than on the occurence of debris avalanches and torrents. Where planes of slump-earthflow failure are more than several meters deep, weight of vegetation and vertical root-anchorage effects are insignificant.

Movement rates of earthflows vary from imperceptibly slow to more than a meter per day in extreme cases. In parts of Northwestern North America, many slump-earthflow areas appear to be inactive (Colman, 1973; Swanson and James, 1975). Where slump-earthflows are active, rates of movement have been monitored directly by repeated surveying of marked points and inclinometers.

Figure 4.--Slump and earthflow in deeply weathered volcaniclastic rocks of the western Cascades Range, Oregon. The slump occurred following exceptionally heavy rain and formed an earthflow mass which temporarily dammed Canyon Creek. Much of the earthflow lobe has been removed from the foreground area by heavy machinery.

and by measuring deflection of roadways and other inadvertent reference systems. These methods have been used to estimate the rates of earthflow movement shown in table 2 (Swanston and Swanson, 1976).

The areal occurrence of slump-earthflows is mainly determined by bedrock geology. Fore example, in the Redwood Creek basin, northern California, Colman (1973) observed that, of the 27.4 percent of the drainage which is in slumps, earthflows, and older or questionable landslides, a very high percentage of the unstable areas are located in the clay-rich and pervasively sheared sedimentary rocks. Areas underlain by schists and other more highly metamorphosed rock are much less prone to deep-seated mass erosion. The areal occurrence of slump-earthflows in volcanic terrains has also been closely linked to bedrock (Swanston and Swanson, 1976). At a study site in the western Cascade Range of Oregon, for example, approximately 25.6 percent of areas underlain by volcaniclastic rocks are included in active and presently inactive slump-earthflows. Less than 1 percent of areas of basalt and andesite flow rock have undergone slump-earthflow failure.

Engineering activities which involve excavation and fills frequently have a dramatic impact on slump-earthflow activity. There are numerous examples of accelerated or reactivated slump-earthflow movement after forest road construction on the western U.S.A. (Wilson, 1970). Undercutting of toe slopes of earthflows and piling of rock and soil debris on slump blocks are common practices which influence slump-earthflow movement. Stability of such areas is also affected by modification of drainage systems, particularly where road drainage systems route additional water into the

Table 2.--Observations of Movement Rates of Four Active Earthflows in the Western Cascade Range, Oregon, (Swanston and Swanson, 1976)

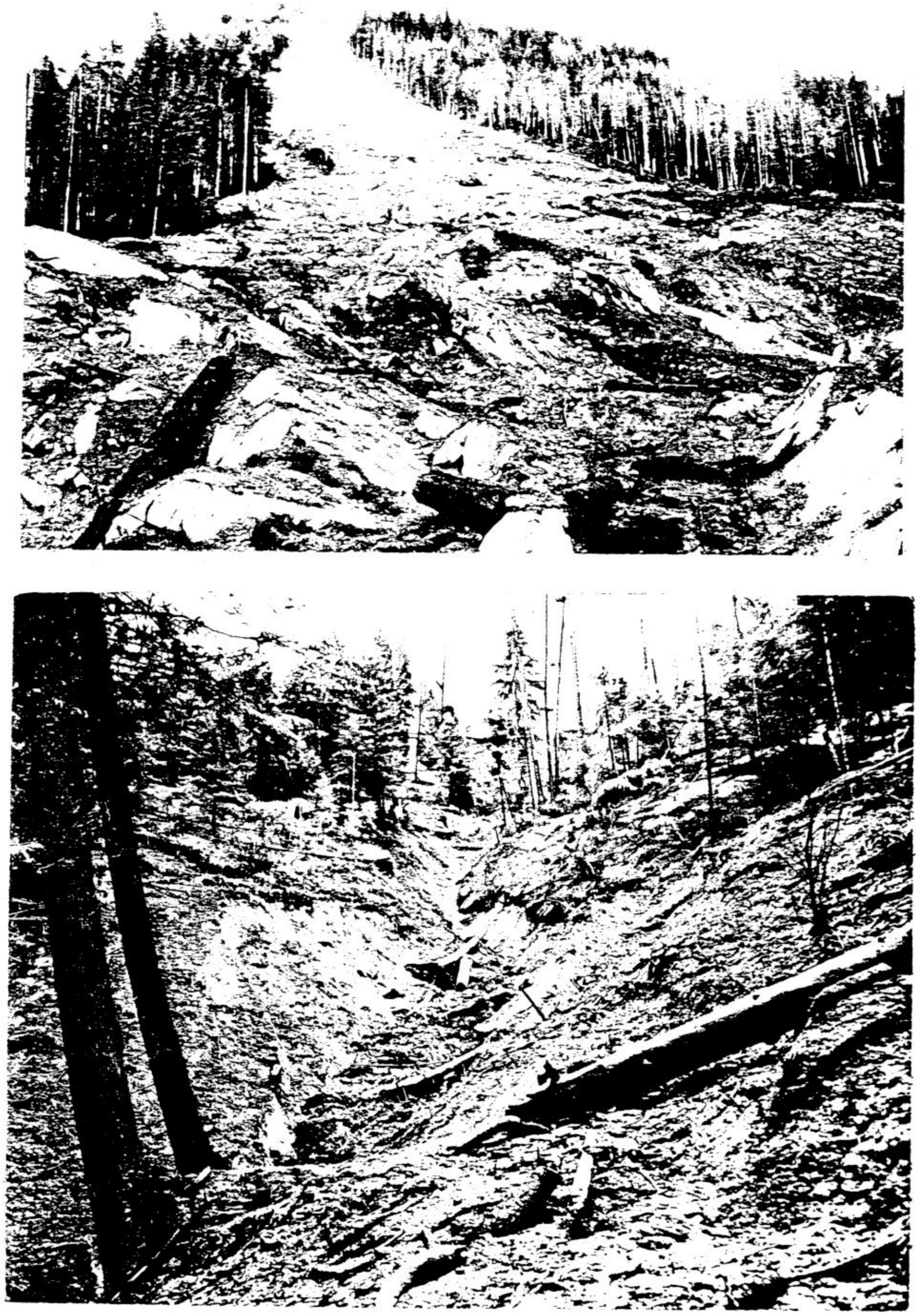
Location	Period of Record (yr)	Movement Rate (cm/yr)	Method of Observation
Landes Creek (Sec 21 T22S R4E)	15	12	Deflection of road
Boone Creek (Sec 17 T17S R5E)	2	25	Deflection of road
Cougar Reservoir (Sec 29 T17S R5E)	2	2.5	Deflection of road
Lookout Creek (Sec 30 T15S R6E)	1	7	Strain rhombus measurements across active ground breaks

slump-earthflow areas. These disturbances may increase movement rates from a few millimeters per year to many tens of centimeters per year or more. Once such areas have been destabilized, they may continue to move at accelerated rates for several years.

Although the impact of deforestation alone on slump-earthflow movement has not been demonstrated quantitatively, evidence suggests that it may be significant. In massive, deep-seated failures, lateral and vertical anchoring of tree root systems is negligible. Hydrologic impacts of deforestation, however, appear to be important. Increased moisture availability due to reduced evapotranspiration will increase the volume of water not used by the vegetation. This water is therefore free to pass through the rooting zone to deeper levels of the earthflow.

DEBRIS AVALANCHE-DEBRIS FLOWS

Debris avalanches are rapid, shallow soil mass movements from hillslope areas. Here we use the term "debris avalanche" in a general sense encompassing debris slides, avalanches, and flows which have been distinguished by Varnes (1958) (fig. 5a) and others on the basis of increasing water content. From a land management standpoint, there is little purpose to differentiating among the types of shallow hillslope failures since the mechanics and the controlling and contributing factors are the same. Debris avalanche-prone areas are typified by shallow, noncohesive soils on steep slopes where subsurface water may be concentrated by subtle topography on bedrock or glacial till surfaces. Because debris avalanches are shallow failures, factors such as root strength, anchoring effects, and the transfer of wind stress to the soil mantle are potentially important influences. Factors which influence



A

B

Figure 5.--Debris avalanche and debris torrent development on steep forested watersheds in Northwestern North America.

a. Debris avalanche developed in shallow cohesionless soils on a steep, forested slope in coastal Alaska.

b. Debris torrent developed in a steep gully, probably caused by failure of a natural debris dam above trees in foreground.

antecedent soil moisture conditions and the rate of water supply to the soil during snowmelt and rainfall also have significant control over when and where debris avalanches occur.

The rate of occurrence of debris avalanches is controlled by the stability of the landscape and the frequency of storm events severe enough to trigger them. Therefore, the rates of erosion by debris avalanching will vary from one geomorphic-climatic setting to another. Table 3 (Swanston and Swanson, 1976) shows that annual rates of debris avalanche erosion from forested study sites in Oregon and Washington in the United States and British Columbia in Canada range from 11 to 72 $m^3/km^2/yr$. These estimates are based on surveys and measurements of erosion by each debris avalanche occurring in a particular time period (25 years or longer) over a large area (12 km^2 or larger).

An analysis of harvesting impacts in the Western United States (table 3) reveals that timber harvesting commonly results in an acceleration of erosion by debris avalanches by a factor of 2 to 4. Roads appear to have much more profound impact on erosion activity. In the four study areas listed in table 3, road-related debris avalanche erosion was increased 25 to 340 times the rate of debris avalanche erosion in forested areas. The great variability of the impact of roads reflects not only differences in the natural stability of the landscapes but also, and more important from an engineering standpoint, differences in site location, design, and construction of roads.

DEBRIS TORRENTS

Debris torrents involve the rapid movement of water-charged soil, rock

Table 3.--Debris Avalanche Erosion in Forest, Clearcut, and Roaded Areas (Swanston and Swanson, 1976)

Site	Period of Record (yr)	Area Percent	Area (km^2)	Number of Slides	Debris Avalanche Erosion ($m^3/km^2/yr$)	Rate of Debris Avalanche Erosion Relative to Forested Areas
Stequaleho Creek, Olympic Peninsula, Washington, U.S.A. (Fiksdal, 1974):						
Forest	84	79	19.3	25	71.8	x 1.0
Clearcut	6	18	4.4	0	0	0
Road	6	3	0.7	83	11825.	x165
			24.4	108		
Alder Creek, Western Cascade Range, Oregon, U.S.A. (Morrison, 1975):						
Forest	25	70.5	12.3	7	45.3	x 1.0
Clearcut	15	26.0	4.5	18	117.1	x 2.6
Road	15	3.5	0.6	75	15565.	x344
			17.4	100		
Selected Drainages, Coast Mountains, S.W. British Columbia, Canada:[1]						
Forest	32	88.9	246.1	29	11.2	x 1.0
Clearcut	32	9.5	26.4	18	24.5	x 2.2
Road	32	1.5	4.2	11	282.5[2]	x 25.2
			276.7	58		
H. J. Andrews Experimental Forest, Western Cascade Range, Oregon, U.S.A. (Swanson and Dyrness, 1975):						
Forest	25	77.5	49.8	31	35.9	x 1.0
Clearcut	25	19.3	12.4	30	132.2	x 3.7
Road	25	3.2	2.0	69	1772.	x 49
			64.2	130		

1/ Calculated from O'Loughlin (1972, and personal communication[2]), assuming that area involving road construction in and outside clearcuts is 16 percent of area clearcut.

2/ Colin L. O'Loughlin, presently located at Forest Research Institute, New Zealand Forest Service, Rangiora, New Zealand.

and organic material down steep stream channels.

Debris torrents typically occur in steep, intermittent, and first- and second-order channels. These events are triggered during extreme discharge events by debris avalanches from adjacent hillslopes which enter a channel and move directly downstream or by the breakup and mobilization of debris accumulations in the channel (fig. 5b). The initial slurry of water and associated debris commonly entrains large quantities of additional inorganic and living and dead organic material from the streambed and banks. Some torrents are triggered by debris avalanches of less than 100 m^3 but ultimately involve 10 000 m^3 of debris entrained along the track of the torrent. As the torrent moves downstream, hundreds of meters of channel may be scoured to bedrock. When a torrent loses momentum, there is deposition of a tangled mass of large organic debris in a matrix of sediment and fine organic material covering areas of up to several hectares.

The main factors controlling the occurrence of debris torrents are the quantity and stability of debris in channels, steepness of channel, stability of adjacent hillslopes, and peak discharge characteristics of the channel. The concentration and stability of debris in channels reflect the history of stream flushing and the health and stage of development of the surrounding timber stand (Froehlich, 1973). The stability of adjacent slopes is dependent on a number of factors described in previous sections on other mass erosion processes. The history of storm flows has a controlling influence over the stability of both soils on hillslopes and debris in stream channels.

Although debris torrents pose very significant envirionmental hazards in mountainous areas of Northwestern North America, they have received little study (Fredriksen, 1963, 1965; Morrison, 1975; Swanson et al., 1976). Velocities of debris torrents, estimated to be up to several tens of meters per second, are known only from verbal and a few written accounts. The occurrence of torrents has been systematically documented in only two small areas of the Pacific Northwest, both in the western Cascade Range of Oregon (Morrison, 1975; Swanston and Swanson, 1976). In these studies, rates of debris torrent occurrence were observed to be 0.005 and 0.008 events km^2/yr for forested areas (table 4). Torrent tracks initiated in forest areas ranged in length from 100 to 2 280 m and averaged 610 m of channel length. Debris avalanches have played a dominant role in triggering 83 percent of all inventoried torrents. Mobilization of stream debris not immediately related to debris avalanches has been a minor factor in initiating debris torrents.

Deforestation appears to dramatically accelerate the occurrence of debris torrents by increasing the frequency of debris avalanches. Although it has not been demonstrated, it is also possible that increased concentrations of unstable debris in channels during forest harvesting (Rothacher, 1959; Froehlich, 1973; Swanson et al., 1976) and possible increased peak discharges (Rothacher, 1973; Harr et al., 1975) may accelerate the frequency of debris torrents.

The impact of clearcutting and road construction on frequency of debris torrents (events km^2/yr) may be compared to debris torrent probability under natural conditions. In the H. J. Andrews Experimental Forest and the Alder Creek study sites, Oregon, timber harvesting appeared to increase

Table 4.--Characteristics of Debris Torrents wtih Respect to Debris Avalanches and Land Use Status of Site Initiation in the H. J. Andrews Experimental Forest[1/] and Alder Creek Drainage (Morrison, 1975)

Site	Area of Watershed (km^2)	Period of Record (yr)	Debris Torrents Triggered by Debris Avalanches	Debris Torrents with no Associated Debris Avalanche		Total (No./km^2/yr)	Rate of Debris Torrent Occurrence Relative to Forested Areas
			--------------Number	-----------------			
H. J. Andrews Experimental Forest, western Cascades, Oregon U.S.A.:							
Forest	49.8	25	9	1	10	0.008	x 1.0
Clearcut	12.4	25	5	6	11	0.036	x 4.5
Road	2.0	25	17	-	17	0.340	x 42.0
Total	64.2		31	7	38		
Alder Creek Drainage, western Cascade Range, Oregon, U.S.A.:							
Forest	12.3	90	5	1	6	0.005	x 1.0
Clearcut	4.5	15	2	1	3	0.044	x 8.8
Road	0.6	15	6	-	6	0.667	x133.4
Total	17.4		13	2	15		

1/ Fredrick J. Swanson, unpublished data, on file at Forestry Sciences Laboratory, U.S. Department of Agriculture Forest Service, Pacific Northwest Forest and Range Experiment Station, Corvallis, Oregon, U.S.A.

the occurrence of debris torrents by 4.5 and 8.8 times; and roads were responsible for increases of 42.5 and 133 times.

Although the quantitative reliability of these estimates of harvesting impacts is limited by the small number of events analyzed, there is clear evidence of marked acceleration in the frequency of debris torrents as a result of forest harvesting and roadbuilding. The histories of debris avalanches in the two study areas clearly indicate that increased debris torrent occurrence is primarily a result of two conditions: debris avalanches trigger most debris torrents (table 4), and the occurrence of debris avalanches is greatly increased by deforestation and road construction (table 3).

FACTORS CONTROLLING AND CONTRIBUTING TO LANDSLIDE OCCURRENCE

It is essential for effective management of steep mountain lands to be able to identify and understand the interaction of principal and contributing factors controlling slope failure. This requires, first of all, a basic knowledge of the geology, hydrology, and pedology of the area being managed and at least a rudimentary understanding of the principal mechanisms of movement. Thus, local bedrock type and structure, frequency and intensity of storm events, depth and degree of weathering, and basic soil characteristics determine the type of process and the individual failure mechanism. External factors, primarily rooting structures of trees and understory vegetation, and the influences of man modify these mechanisms and have been shown to contribute substantially to the inherent stability of the site.

MECHANICS OF MOVEMENT

An adequate understanding of the mechanisms of failure can best be obtained using simplified concepts of soil mechanics.

Direct application of soil mechanics theory to analysis of mass movement processes is difficult because of the heterogeneous nature of soil materials, the extreme variability of soil water conditions, and the related variations in stress-strain relationships with time. The theory does, however, provide a convenient framework in which to discuss the general mechanism and complex interrelationships of the various factors active in development of soil mass movements on mountain slopes.

In simplest terms, the stability of soils on a slope can be expressed as a ratio between shear strength, or resistance of the soil to sliding, and the downslope pull of gravity or gravitational stress. As long as shear strength exceeds the pull of gravity, the soil will remain in a stable state (Terzaghi, 1950; Zaruba and Mencl, 1969).

It is important to remember that soil mass movements result from changes in the soil shear strength-gravitational stress relationship _in the vicinity of failure_. This may involve a mechanical readjustment among individual particles or a more complex interaction between both internal and external factors acting on the slope.

The following figure (fig. 6) shows the geometrical relationship of these various factors acting on a small portion of the soil mass. Any increases in gravitational stress will increase the tendency for the soil to move downslope. Increases in gravitational stress result from

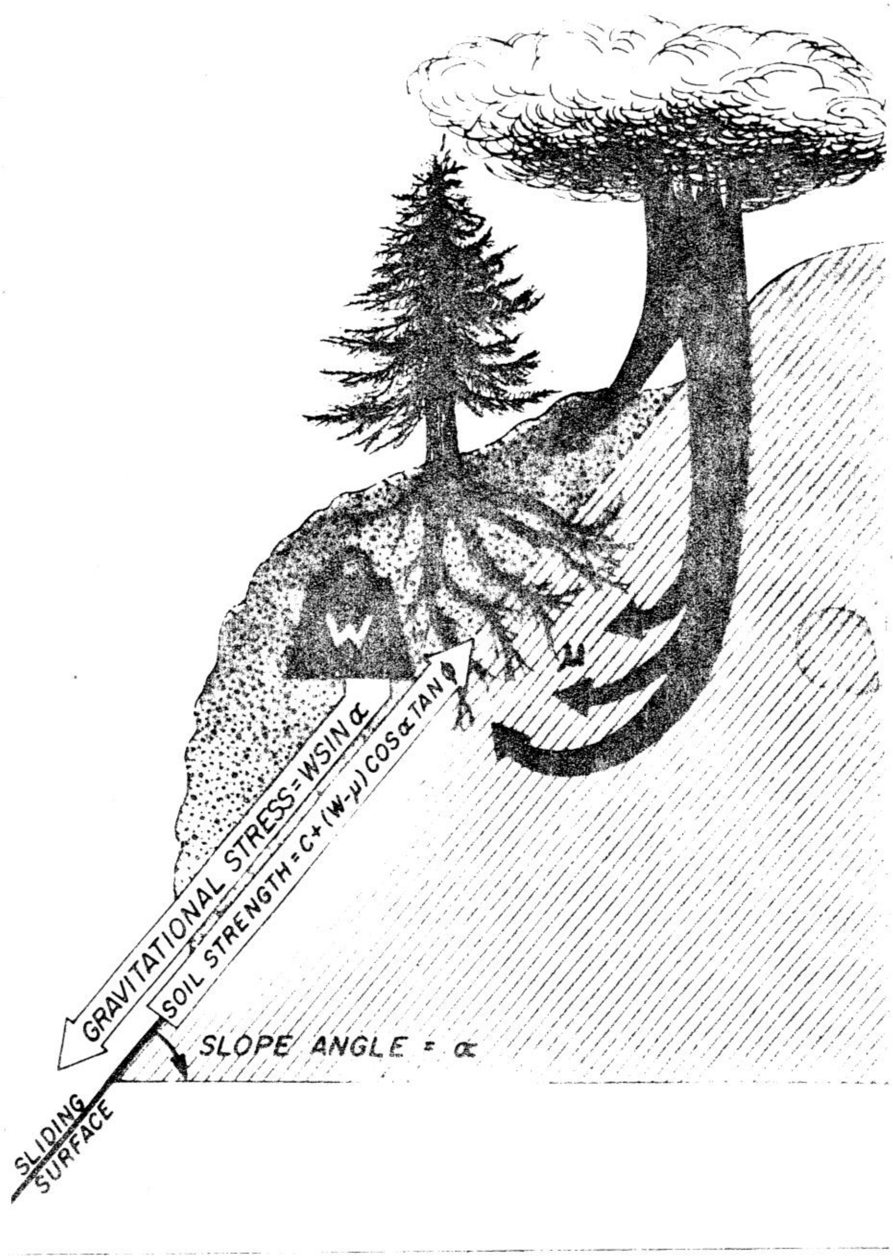


Figure 6.--Simplified diagram of forces acting on a mass of soil on a slope. (Swanston, 1976)

increasing inclination of the sliding surface or increasing unit weight of the soil mass. Stress can also be augmented by (a) the presence of zones of weakness in the soil or underlying bedrock produced by bedding planes and fractures, (b) application of wind stresses transferred to the soil through the root systems of trees, (c) strain or deformation in the soil produced by progressive creep, (d) frictional "drag" produced by seepage pressure, (e) horizontal accelerations due to earthquakes, and (f) removal of downslope support by undercutting.

Shear strength is governed by a more complex interrelationship between the soil and slope characteristics. Two principal forces are active in resisting downslope movement. These are: (1) cohesion (c) or the capacity of the soil particles to stick or adhere together--a distinct soil property produced by cementation, capillary tension, or weak electrical bonding of organic colloids and clay particles; and (2) the frictional resistance ($W \cos \alpha \tan \phi$) between individual particles and between the soil mass and the sliding surface. Frictional resistance is controlled by the angle of internal friction (ϕ) of the soil--the degree of interlocking of individual grains--and the effective weight [$(W-\mu) \cos \alpha$)] of the soil which includes both the weight of the soil mass and any surface loading plus the effect of slope gradient and excess soil water.

Pore water pressure--pressure produced by the head of water in a saturated soil and transferred to the base of the soil through the pore water--acts to reduce the frictional resistance of the soil by reducing its effective weight. In effect, its action causes the soil to "float" above the sliding surface.

CONTROLLING AND CONTRIBUTING SITE CHARACTERISTICS

Particle size distribution (which governs cohesion), angle of internal friction, soil moisture content, and angle of slope are the controlling factors in stability of a steepland soil. For example shallow coarse-grained soils low in clay-size particles have little or no cohesion, and frictional resistance determines the strength of the soil mass. Frictional resistance is in turn strongly dependent on the inherent angle of internal friction of the soil and the degree of pore-water pressure development. A low angle of internal friction relative to slope angle or high pore pressures can reduce soil shear strength to negligible values.

Slope angle is a major indicator of the stability of those soils. Slopes at or above the angle of internal friction of the soil indicate a highly unstable natural state.

Soils of moderate to high clay content take on a much more complex character wtih resistance to sliding determined by both cohesion and frictional resistance. These factors are controlled to a large extent by clay mineralogy and soil moisture content. In a dry state, clayey soils have a high shear strength with the internal friction angle quite high ($>30°$). Increasing water content mobilizes the clay through adsorption of water into the clay structure. The angle of internal friction is reduced by the addition of water to the clay lattices (in effect reducing "intragranular" friction) and may approach zero in the saturated state. In addition, water between grains--interstitial water--may open the structure of the soil mass. This permits a "remolding" of the clay fraction, transforming it into a slurry, which then lubricates the remaining soil mass. Some clays are more susceptible to deformation than others, making clay mineralogy an important consideration in areas characterized by quasi-viscous flow deformation or "creep." Swelling clays of the smectite group are particularly unstable because of their tendency to adsorb large quantities of water and the loosening effect of alternate expansion and contraction during periods of wetting and drying. Thus, clay-rich soils have a much higher potential for failure given excess soil moisture content. Under these conditions, failures are not directly dependent on sliding surface gradient as in cohesionless soils but may develop on slopes with gradients as low as 2 or 3°.

Parent material type has a major effect on the particle size distribution, depth of weathering, and relative cohesiveness of a steepland soil. It can frequently be used as an indicator of relative stability or potential stability problems if local climatic conditions and relative age of the geomorphic surface on which the soil is developed are known. In humid regions where chemical weathering predominates, transformation of easily weathered primary minerals to clays and clay-size particles may be extensive. Siltstones, clay stones, shales, nonsiliceous sandstones, pyroclastics, and serpentine-rich rocks are the most easily altered and are prime candidates for soil mass movements of the creep and slump-earthflow type. Conversely, in arid or semi-arid regions, slopes underlain by these rocks may remain stable for many years due to slow chemical weathering processes and lack of enough soil moisture to mobilize existing clay minerals. On steeplands, underlain by resistant rocks, especially those at high altitude or latitude where mechanical weathering prevails, soils are usually coarse and low in clay-size particles. Such areas are more likely to develop soil mass movements of the debris avalanche or debris flow type.

Parent material structure is a critical factor in stability of many shallow soil slopes. Highly jointed bedrock slopes with principal joint planes parallel to the slope provide little mechanical support to the slope and create avenues for concentrated subsurface flow and active pore-water pressure development as well as ready-made zones of weakness and potential failure surface for the overlying material. Sedimentary rocks with bedding planes parallel to the slope function in essentially the same way with the uppermost bedding plane functioning as an impermeable boundary to subsurface water movement--a layer restricting the penetration and development of tree roots and an active failure surface.

Vegetation cover in general helps control the amount of water reaching the soil and the amount held as stored water against gravity, largely through a combination of interception and evapotranspiration. The direct effect of interception on the soil water budget is probably not large, especially in areas of high total rainfall or during large storms when most soil mass movements occur. The small storms where interception is effective probably have little influence on total soil water available for activating mass movements.

In areas of low rainfall, the effect of evapotranspiration is much more pronounced but is particularly dependent on region and time. In areas characterized by warm, dry summers, evapotranspiration withdrawals of soil moisture have a significant effect in reducing the degree of saturation resulting from the first storms of the fall recharge period. This effect is reduced as soil water deficit is satisfied. Once the soil is recharged, the effect of previous evapotranspirational losses becomes negligible. Conversely, in areas of continuous high rainfall or those with an arid or semi-arid climate, evapotranspirational effects are probably negligible. Also of importance is the depth of evapotranspirational withdrawals. Deep withdrawals may require substantial recharge to satisfy the soil water deficit, delaying or reducing the possibility of attainment of saturated soil conditions necessary for major slide-producing events. Shallow soils, on the other hand, will recharge rapidly, possibly attaining saturated conditions and maximum instability during the first major storm.

Root systems of trees and other vegetation may act to increase shear strength in unstable soils. Such an external shear strength factor can result from roots:

1. Anchoring through the soil mass into bedrock fractures in the rock.
2. Providing continuous long fiber cohesive binders to the soil mass.
3. Tying slope together, across zones of weakness or instability, or stable soil masses.
4. Providing downslope support to an unstable soil mass.
5. Interlacing wtih other vegetation, providing a network of stability through their own strength.

In shallow soils, all five items may be important. In deep soils, the anchoring effect of roots becomes negligible, but the other parameters will remain important. In some extremely steep areas in Western North America, root anchoring may be the dominant factor in maintaining slope equilibrium of an otherwise unstable area (Swanston and Swanson, 1976).

Snow cover increases soil unit weight through surface loading and affects delivery of water to the soil through retention of rainfall and delayed release of large water quantities during spring melt. Delayed release of melt water, coupled with unusually heavy storms during a spring warming trend have been identified as the principal initiating factor in recent major landslide activity on forest lands in central Washington.

Hazard Identification and Assessment

A basic understanding of mass wasting processes and controlling and contributing factors is essential to effective identification, prediction and control of soil mass movements on forest lands. Once he has accomplished this the land manager has several options available to him. He can (1) identify problem areas and avoid operations on unstable terrain; (2) identify and attempt to control operational effects or (3) identify and assess the hazard relative to various forest operations and downstream impacts.

In highly unstable areas or areas of questionable economic value, avoidance of all operations is probably the best and least expensive solution. Controlling operational effects is a much more difficult approach which at best will probably be only partially successful. It is applicable in high value areas of questionable soil stability or where other considerations override a desire for stability maintenance. Assessment of the relative hazard of soil mass movement activity and damage from proposed forest harvest operations provides the most useful approach for the land manager, allowing a comparison of the impacts of various alternatives and selection of the best management approaches to protect watershed values.

Accurate models and the substantial body of input data necessary for the quantitative prediction of failure risk and magnitude of contributions to stream courses over broad areas is currently lacking. Quantitative engineering techniques for site-specific stability analyses exist (based on the Mohr-Columb Theory of Earth Failure) and are quite accurate in assessing the strength-stress relationships in a small area. These techniques, however, require accurate measurement of the engineering properties of the soils involved and specific knowledge of the geology and groundwater hydrology at the site. Such data must be generated at considerable expense and are extremely variable from site to site, even under the same geologic and climatic setting making this mechanistic approach impractical for broad areal risk assessment at the present time.

Given these limitations, a more practical approach is to combine:

a) a subjective evaluation of the relative stability of an area using soils, geologic, topographic, climatilogic and vegetative indicators obtained from aerial photos, maps and field reconnaisance,

b) a limited strength-stress analysis of the unstable sites using available or easily generated field data, and

c) estimates of sediment delivery to streams based on failure type, distance from the stream channel and certain site variables such as slope gradient and slope irregularities.

Together, these data can be integrated to provide a measure of landslide hazard and the level of sediment contributed to adjacent stream channels.

Such an approach has been developed in Chapter V, Soil Mass Movement, Water Resources Evaluation Non-Point Sources-Silviculture Handbook (Swanston, Swanson and Rosgen, in press) and in the Watershed Analysis Procedure, Clearwater National Forest (Bennett and Wilson; 1975).

While the results of this approach are largely qualitative in nature they do provide a viable means of assessing the impacts of various harvest practices on the stability of a watershed and estimation of sediment delivery to channels by mass movement processes.

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SURFACE EROSION[1/]

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ABSTRACT

Surface erosion from undisturbed forest areas in the Pacific Northwest is uncommon since the infiltration capacity of the forest soils generally exceeds any experienced rainfall intensity. Soil compaction and disturbance caused by such forest practices as tractor yarding, road construction, and mechanical pile and burn can increase the potential for surface erosion by removing the protective litter layer and reducing the infiltration capacity and subsoil permeability. Management alternatives such as preplanning skid trails, skyline yarding systems, revegetation of cut and fill slopes, and non-burning alternatives for site preparation are discussed as possible erosion control measures. Utilization of the universal soil loss equation (USLE) for prediction of surface erosion from forest lands is considered.

INTRODUCTION

RELEVANCE OF THE PROBLEM

The significance of surface erosion on forest lands can best be relized by examining some of the on-site and off-site potential impacts. One of the most important on-site impacts is the decrease in site productivity due to losses of nutrient-rich surface soil. Although under most acceptable forest management practices the rate of surface erosion is much less than on conventional agricultural lands, under certain man-induced and natural stresses surface erosion on forest land may become significant. Decreased tree growth due to the loss of eroded topsoil may be less apparent than the agricultural analogy where crops are harvested annually. As a result, long-term low levels of surface erosion could be permitted to persist without any management related action taken, resulting in substantially longer rotations or reduced volume growth. Another on-site impact occurs when surface eroded sediment is deposited in upland draws or pockets in relatively steep terrain. These depressions are highly susceptible to future surface erosion or mass wasting, such as sluice-outs, and tend to have low site productivities as well as being potential sediment transporting links.

In steep or sparsely vegetated terrain, surface eroded sediment may

[1/]Prepared for U. S. Forest Service Workshop on Scheduling Timber Harvesting for Hydrologic Concerns, November 27 - 29, 1979, Portland, Oregon.

be transported off-site and into stream systems where fisheries' habitats can be adversely affected. Stream studies in the Pacific Northwest, (Hall and Lantz, 1969), and southeast Alaska, (Meehan and Swanston, 1977), have shown that porous streambed gravels provide an efficient trap for fine sediment. These and other studies have indicated that this entrapped sediment can significantly reduce the survival of salmon and steelhead eggs by decreasing oxygen flux within the streambed and by presenting a physical barrier for young fry emergence. Sediment which remains suspended in streams can be lethal to fish if high levels persist for long periods of time (Herbert and Merkens, 1961, and Cordone and Kelley,1961). Under these conditions, fine sediment accumulates on the gill filaments and prevents oxygen transfer to the blood. A final fisheries related impact of sedimentation is the effect of turbidity on angling success. Since salmon and trout are primarily sight feeders, turbid water is not productive for these species, (Phillips, 1971).

Sediment loads in stream systems can have a variety of negative impacts on such downstream users as municipalities, industries, agriculture, recreational users, and domestic water supplies. In many parts of the Pacific Northwest first and second order forest streams merge and flow through irrigated agricultural bottomland within relatively short distances. Pumping sediment laiden water can considerably shorten the life of irrigation equipment, not to mention the possible reduction of infiltration capacity of land continually irrigated with such water. Municipal, industrial, and dometsic water supplies dependent upon surface water are particulary conscious of sediment levels. High concentrations of sediment may require expensive filtration or tertiary treatment processes.Another downstream impact of sedimentation is the transport of absorbed nutrients into estuaries or reservoirs where they may initiate or accelerate the eutrophication process. Although the relative costs of most of these downstream impacts are difficult to assess, it is usually the downstream user who must bear the financial burden. Thus, it is important that best management timber harvest practices are implemented to minimize surface erosion from managed forest land.

THE BASIC SURFACE EROSION PROCESS

In an undisturbed forest environment typical of the Pacific Northwest, rainfall feeds stream systems largely by underground movement through soil macropores or by flowing along the soil-bedrock interface, especially in the shallow soils often found in steep, forested terrain. These macropores which include such things as freeze-thaw cracks, decayed root channels, inter-aggregate spaces, earthworm passageways, and small animal burrows, permit rapid movement of water and nutrients through the soil, especially during nearly saturated conditions, (Aubertin, 1971; Sidle and Kardos, 1979). Since the infiltration capacity of these undisturbed forest soils is almost always higher than any experienced rainfall rate, the entire amount of water falling on the forest floor moves into the soil and overland flow rarely occurs. Thus, under natural forested conditions surface erosion is almost nonexistent. However, when forests are managed for commercial timber production certain harvesting, road building, and site preparation practices may cause soil disturbance and soil compaction which tend to reduce this high native infiltration capacity of forest soils.

Surface erosion begins with the detachment of individual soil particles from the soil mass at these disturbed and compacted sites. Individual particles are then transported downslope some distance depending on their size and energy of flowing water. Finally, sediment is deposited on the slope or in the streambed. Surface erosion should not be confused with mass soil movement, another form of erosion on forest lands. Mass wasting events, such as landslides and slumps, tend to be large and often occur rather spontaneously during extended precipitation periods.

SOIL DISTURBANCE AND COMPACTION

Soil sisturbance occurs when the forest litter layer is removed, exposing the underlying bare mineral soil to the erosive forces of raindrop impact. More severe disturbance involves the breakdown or alteration of this mineral soil structure. "Splash erosion" on a sloping bare soil surface can gradually move substantial sediment downslope. In addition, when this exposed soil is subjected to raindrop impact, soil aggregates or structural units tend to break down and fine particles often filter into interaggregate spaces, thus reducing infiltration capacity. Soil compaction involves the densification of the soil mass as the result of an applied mechanical load. Compaction decreased the number of macropores and thus restricts water and nutrient movement through the soil. Although the potential for soil disturbance increases with increasing soil moisture content, soil compaction potential is a maximum at moisture contents much less than saturation, depending on soil texture. Thus, even during the drier summer months many subsoils would be highly susceptible to compaction.

When soil disturbance and compaction have reduced infiltration rates to the point that rainfall rates commonly exceed them, overland flow can occur. With the exception of the more subtle process of "splash erosion", overland flow over exposed soil initiates surface erosion. As overland flow moves downslope it concentrates and its velocity increases leading to the formation of rills and gullies on the exposed sites.

IMPACT OF FELLING AND YARDING

During timber felling, minor on-site compaction may occur due to the weight of trees falling on the soil surface; however, increases in surface erosion caused by timber felling alone are generally negligible. An exception to this is when felling occurs into stream channels or draws. In such instances the stream bank is disturbed and sedimentation may increase. Yarding logs out of streamside areas will cause an even greater erosion potential. Streamside buffer strips of "leave areas" in which no trees are harvested insure protection of accelerated stream bank erosion caused by indiscriminate timber felling. Buffer strips must be properly designed in terms of wind protection to insure survival (Steinblums, 1977). Harvesting commercial trees near streams can be accomplished with a minimum impact on the stream bank by using directional felling techniques such as hydraulic jacks and cable assisted felling.

The particular method of timber yarding can have a significant impact on the amount of soil disturbance and compaction incurred at a given site. Table 1, summarized by Swanston and Dyrness (1973) shows impacts from four yarding methods used in clearcut operations in the Pacific Northwest. Comparative figures for tractor, highlead, skyline, and balloon yarding show that tractor logging produces more than twice the soil disturbance as highlead yarding and almost six times the disturbance as balloon logging. Soil compaction among the various yarding methods varies even more dramatically, with tractor logging causing about three times the soil compaction as highlead yarding and about eight times the compaction as skyline yarding.

Since tractor logging causes far greater soil disturbance and compaction than other yarding methods it is important to investigate the causes of these impacts so that their effects can be minimized. Tractor logging is generally done either with rubber-tired skidders or crawler tractors on slopes up to 35%. On-site impacts created by the use of this equipment depend greatly on operation conditions. During relatively dry summer periods both types of skidders can be used with minimal soil disturbance. Soil compaction, on the other hand, can occur during summer logging since the subsoil often retains enough moisture to be highly susceptible to compaction. For instance, tractor logging on clayey soils such as the Apt, Honeygrove, Jory, and Slickrock series found in the Coast Range and Cascades can cause subsoil compaction even when the surface soil appears relatively dry. At depths greater than 6 inches the moisture content of these soils rarely drops below levels needed for maximum compaction.

Crawler tractors tend to compact soil less severely than rubber-tired skidders due to their weight distribution over a larger area of soil. On the other hand, crawler tractors have a greater potential for soil disturbance than rubber-tired skidders, especially during slightly moist periods. Tractor grousers or cleats churn deeply into the soil during turns and uphill operations causing the more easily erodible mineral soil to be exposed. Rubber-tired skidders may lose traction on steeper slopes during slightly moist conditions requiring chains for most efficient operation. During wet conditions both types of skidding should be avoided on clayey or silty soils to prevent extensive soil disturbance.

Equipment operators have a great deal of control over the extent to which the soil is disturbed and compacted during skidding operations. Operators can greatly minimize the areal extent of soil compaction by utilizing the same skid trails many times over. This can best be accomplished by pre-planning and flagging skid trails to insure operator recongnition for repeated entry. The tractor should stay on the skid trails at all times. Trees should be felled into the direction of the skid trail for ease of removal. Logs are then winched up to the tractor and skidded out to the haul road. By doing this, skid trails actually become part of the permanent road system and the areal extent of compaction and site degradation is minimized. Initial costs incurred by using a preplanned skidding system in a partial cut in Northern California were approximately 29% greater than conventional tractor skidding; however, the areal extent of skid roads was reduced from 22% to 4%, (Bradshaw, 1979).

Operators can avoid creating excessive soil disturbance simply by keeping the tractor blade off the ground at all times, except when pushing logs. The blade should not be used as a braking mechanism when going down steep slopes and likewise whould not be used by rubber-tired skidders to improve traction going up steep slopes. Operators should avoid equipment passage in upland swales or intermittent streams when at all possible. Even when dry, these areas are a direct sediment transporting link to lower lying streams. Surface erosion from these areas will occur during the wet winter months if they are disturbed and compacted during logging operations. Another site where operators should avoid using tractors is in or around stream channels. Equipment operation in these areas drastically disturbs stream banks and bottoms providing an immediate sediment source to flowing water.

In order to avoid excess soil disturbance and compaction it is a good rule of thumb to restrict tractor yarding to slopes less than 35%. On steeper slopes cable logging methods should be used to minimize these erosional impacts. Skyline systems are particularly effective means of minimizing soil disturbance and compaction on very steep sensitive sites, since logs are either partially or totally suspended above the soil surface during much of the yarding process. Since skyline yarding distances are much greater than highlead methods, road requirements may be substantially less (Wooldridge, 1960 and Dyrness, 1967). Aerial logging methods such as helicopter and balloon provide harvesting capabilities with minimal environmental impact in steep isolated areas too hazardous for conventional cable systems. These more expensive harvesting methods can sometimes be used successfully during salvage operations, such as following fire or insect infestation, in areas where road systems are minimal. On more gently sloping sites, the use of low ground pressure vehicles should be considered as an alternative to conventional logging on compactible soils. Decreased compaction and soil disturbance has been observed (Froehlich, 1978) using these flexible-tracked vehicles.

Uphill cable yarding is more desirable from the standpoint of surface erosion protection than downhill yarding. Cable roads in a downhill system tend to converge at one point downslope, thus concentrating any overland flow that is generated from these areas. Uphill systems, on the other hand, tend to disperse water across the slope (in the downslope direction) by the nature of their road layout.

IMPACT OF ROAD BUILDING

Roaded areas, by and large, are the greatest source of surface eroded sediment from managed forests. This is especially true during the first year following road construction. One of the factors which influences the extent of surface erosion from roaded sites is the resistance of the bare soil material on cuts, fills, road surfaces, and ditches to detachment and transport (known as soil erodibility). Generally, forest soil erodibility index has been significantly correlated with vegetative cover, parent material, aspect, slope, and elevation in a study in the southern Sierra Nevadas, (Willen, 1965). Soils of the silty to fine sandy textures tend to be most erodible, while those with higher clay and organic matter contents are less erodible. Another factor that influences the extent of surface erosion from roaded areas is the amount and energy of flowing water. This erosive energy of flowing water is increased with increasing road and slope gradients. Also, lower lying roaded sites on hillslopes tend to collect more water due to the larger upslope contributing drainage area. Aspect can also influence the amount of water available for runoff, but this effect is often complicated by local storm patterns and surface vegetative cover. Finally, the amount of water that flows to roaded sites can be greatly affected by seepage from road cuts. Studies on shallow, coarse-textured soils in the Idaho Batholith indicate that cut bank interception can constitute greater than seven times the water produced from road surface runoff, (Megahan, 1972). A third factor that influences erosion from roaded areas is the sediment trap efficiency of the land between the road system and the downslope streams. Dense understory vegetation, such as encountered in the Coastal Range, will tend to trap some of the surface eroded sediment from roaded sites and prevent immediate transport into the stream. The sediment trap efficiency of the more sparsely vegetated slopes in eastern Oregon and Washington and the Idaho Batholith is much lower.

Since roaded areas represent potential erosion sites, it is important to recognize the amount of land utilized for roads by various logging systems. Comparative summarized data by Froehlich (1978), for haul roads is given in Table 2. Ground-based logging systems including crawler tractor and rubber-tired skidder, utilized considerably more land area in their haul road systems than highlead or skyline systems. Jammer logging, a special type of short span cable system previously popular in Idaho and Montana, devotes the largest amount of land to its haul road system.

Careful road construction practices must be undertaken in steep forested terrain to insure adequate stream protection from surface erosion. During the initial clearing phase of road construction, attempts should be made to minimize the extent of soil disturbance and special attention paid to weather conditions. On steep erodible sites in high rainfall areas, it is important to construct a temporary drainage system during clearing to minimize water flow over disturbed areas. Brush cleared from the road rights-of-way can be piled at slope breaks to act as sediment filters. Earthwork should immediately follow clearing operations in order to minimize the time period of maximum site disturbance. Durings storms or periods of excessive soil moisture, earthwork operations should be curtailed and measures taken, such as slash piling, to protect partially completed work. In addition, it is important that sidecast material be kept away from stream flood plains.

Following road construction many portions of these sites remain susceptible to surface erosion and require special corrective measures. One major source of surface eroded sediment from road systems is exposed cut and fill slopes, which are often very steep and difficult to revegetate. Erosion features, such as rills and small gullies, indicate that these areas are major sediment contributors. Erosional losses from bare steep granitic road fills in Idaho Batholith averaged 3.4 metric tons/km^2 over a 3-year period (Megahan, 1978). Special measures, such as hydroseeding, mulching, and fertilizing, may need to be implemented to revegetate steep cut and fill slopes in certain areas so as to prevent surface erosion and allow seeded grasses and legumes time to establish. For example, on steep cut slopes (greater than 1:1) in western Oregon and Washington receiving 40-60 inches of precipitation per year, a possible seed mixture would be annual ryegrass, creeping red fescue, birdsfoot trefoil, New Zealand white clover, and tall fescue seeded at rates of 5, 5, 2, 2, and 10 pounds per acre, respectively, (Berglund, 1976). A typical fertilizer application on such newly seeded sites would be 250 pounds per acre of ammonium phosphate (16-20-0). Some acid sites may require liming. In order to control erosion during the first winter and allow seedling establishment, straw or fiber mulch should be applied at a minimum of 2,500 pounds per acre on the steep slopes, (Kay, 1979).

Benches and terraces on long steep cut slopes, especially at drier sites, provide a more suitable environment of seedling establishment and reduce the velocity of overland flow. The natural roughness of the soil surface after the soil material is sidecast or wasted will often be a suitable seedbed for more gently sloping sites. When gullies have developed on bare portions of fill slopes, their further development may be impeded by installing porous check dams constructed from brush (Rains, 1977) or rock (Heede, 1978) which tends to catch sediment and some debris, while allowing water to pass through.

Another source of surface eroded sediment is unpaved or unrocked road surfaces, which concentrate water due to their compacted nature. When wet, road surfaces are highly susceptible to disturbance by traffic. Thus, it is desirable to divert water off road surfaces as quickly as possible by either crowning the road or sloping it inward or outward. Soil-aggregate or asphalt surfacing of haul roads greatly reduces this erosion problem. Water diversion from skid trails can be accomplished by water bars. Water bars should be compacted with a relatively non-erosive fill material to insure their functioning longevity. Proper maintenance is an essential part of minimizing erosion from road surfaces. Road grading during dry periods and limiting access in very wet weather are a few ways of accomplishing this. A special problem in many areas is the operation of off-road vehicles, such as 4-wheel drives and dirt bikes on logging roads during the wet season. Unless these activities are curtailed by limiting access, they can provide a substantial source of surface eroded sediment as well as deteriorate the haul road system. Extensive erosional losses have also been attributed to the operation of these vehicles in "off-road" situations during relatively dry periods. (Stull, et al, 1979).

Road drainage systems can be another source or cause of surface erosion. Severe scouring of drainage ditches can occur if water is allowed to reach high enough velocities. Fine sandy and silty soils are most susceptible to ditchline erosion with coarse gravels, cobbles, and bedrock being least susceptible. Ditchline erosion on the inslope portion of forest roads can be minimized by installing an adequate number (and size) of cross drains, thus not allowing water to build up excessive velocities in ditches. Highly erodible sites require special measures including armoring ditches with rock, concrete, or asphalt and orienting culverts at oblique angles to the ditchline to control erosion. Since some ditchline sedimentation will occur, it is desirable to install some type of simple catchment structure or riser at the inlet of relief culverts. Relief culvert and ditchline cleaning are an essential part of the maintenance program for forest roads. Cross drain outfalls should extend out over erodible fill and should be protected by riprapping or by using water energy dissapators such as downspouts. Discharge from relief culverts should not be allowed on highly erodible slopes or directly into streams.

A final source of sediment from roaded areas involves stream crossings, such as major culvert installations. During installation the operator should minimize equipment contact with stream channels. Fill material should be adequately compacted by the operator in order to firmly seat the culvert. In some cases, upstream face protection of the culvert fill such as armoring may be needed to curtail erosion. Outfall protection such as riprapping may be desirable to impede excessive stream bottom scouring.

A foresighted approach to watershed protection is through the advanced planning of road systems. It is desirable to minimize both the mileage of raods built in a timber harvest unit as well as the number of steep grades. Of course these two concepts are not always compatible and trade-offs must be made in the interests of timber harvest and watershed protection. Road grades in steep terrain should be varied, especially in conformence to natural slope contours to reduce water velocity on road surfaces and in drainage ditches. In the advance layout of a road system it is desirable to stay clear of natural drainages whenever possible. Road location plans should take advantage of natural log landing areas on slopes, so as to reduce the amount of soil disturbance needed to construct such sites. Finally, the importance of adequate drainage design pre-planning cannot be emphasized too strongly.

IMPACTS OF SITE PREPARATION

Site preparation can also have a major impact on surface erosion. Slash burning and mechanical scarification are two common site preparation practices in the Pacific Northwest. Slash burning is conducted by foresters following logging, and prior to replanting to remove excessive debris from the soil surface. Scarification is practiced to prepare favorable soil physical conditions for new seedling survival. While these two practices may offer benefits for regeneration, the extent to which they are implemented can greatly affect the potential for surface erosion.

The amount of surface erosion generated by slash burning is generally proportional to the severity of the burn. During a relatively hot or severe slash burn, hydrophobic or water-repellent conditions are created in the surface soil greatly reducing the infiltration rate. Research conducted in the Oregon Cascades, (Dyrness, 1976), found that wildfire in a lodgepole pine stand increased the water repellency of the soil at depths of 1 to 9 inches for up to 5 years after the fire. In addition to the formation of this hydrophobic condition, portions of the litter layer are entirely consumed by fire, exposing much of the underlying bare mineral soil to the forces of raindrop impact and overland flow. During extremely hot slash fires, some of the organic matter within the mineral soil, which acts as a cementing agent for soil aggregates, is destroyed. As a result, soil particles can be easily detached and eroded away under these disturbed surface conditions. In addition to increasing the rate of surface erosion, hot slash fires tend to upset the balance of nutrient cycling and cause a measurable loss of soil nutrients (especially nitrogen) during the first few years following the burn, (Brown, et al, 1973).

One method of slash burning commonly practiced in the Pacific Northwest is the broadcast burn. From the standpoint of surface erosion, broadcast burning has the potential to disturb large areas of the watershed. Studies in Oregon's Coast Range, (Brown and Krygier, 1971; Beschta, 1978) and western Cascade Range (Fredriksen, 1970) have shown significant increases in suspended sediment loads of streams for up to 5 years following severe broadcast burns on clearcut units when compared to unharvested watersheds. The most effective way to minimize the severity of a broadcast burn is to burn when the litter layer and organic soil layers are moist. This will prevent complete destruction of the protective litter layer and minimize the organic matter volatilization from the soil. Single-grained soils, such as those derived from granitic material, are generally most susceptible to surface erosion following burning.

Another site preparation procedure is to pile and burn slash. Although this method limits the extent of ground area that is disturbed by severe burning, the equipment used for piling slash often disturbs and compacts surrounding areas, thus leaving the site in a highly erodible condition. If piling is done, it should be accomplished with light machinery or by hand to reduce soil disturbance and compaction.

Consideration should be given to non-burning alternatives for site preparation. High utilization of felled timber will tend to leave some smaller slash distributed over the soil surface to provide erosion protection and at the same time removing larger debris that inhibits replanting. Brush competition can be controlled with appropriate herbicide applications when necessary. In cases where excessive large debris have accumulated in steep upland draws following logging, it is desirable to cable yard some of this material out of these critical mass erosion sites.

The practice of mechanical scarification in site preparation may have either a positive or negative effect on surface erosion. Deep ripping of the soil is normally accomplished by pulling a multi-tonged ripper behind a crawler tractor. Although infiltration rates are initially increased in the ripped areas (Hickey and Dortignac, 1963) additional compacted areas are produced by the heavy equipment tracks. Light scarification is commonly accomplished with a brush blade on a crawler tractor. Again, compaction may occur depending on the size of the equipment. Excessive ripping or scarification in areas where the forest litter layer is still intact may ultimately increase surface erosion. Although some light scarification and selected ripping can be beneficial in terms of regeneration, the ultimate impacts on surface erosion are questionable when using conventional equipment. The use of lower ground pressure machinery should be considered for such operations on gentler slopes.

PREDICTION OF SURFACE EROSION- USLE

The universal soil loss equation (USLE) developed by Wischmeier and Smith (1965) was designed to predict sheet and rill erosion on agricultural land. The soil loss predicted by the equation is that soil moved off the particular slope segment represented by the selected topographic factor. The equation does not account for deposition of sediment in depressions within the unit or at slope breaks. Thus, soil loss values obtained from the equation do not represent sediment yield from a given unit of land.

The USLE groups variables affecting sheet and rill erosion into six factors.

$A = RKLSCP$

where, A = the average soil loss for a given time interval per unit area

R = rainfall factor (usually the annual EI value which is based on the 2 year, 6 hour rainfall event)

K = soil erodibility factor

L = slope - length factor

S = slope - gradient factor

C = cropping - management factor
P = erosion - control practice factor

Since this empirical relationship was derived using runoff plot data from agricultural land, the extension of this equation to forest land would appear to be tennous. For instance, the upper limit for slope gradient used to calibrate the USLE was approximately 20%. Estimates of C factors for woodland have recently been published (Wischmeier, 1974); however, these are very general in nature and would not reflect the uneven patterns of soil disturbance commonly encountered in timber harvesting operations. Also, the extremely high infiltration capacities and permeabilities of undisturbed forest soils are not specifically handled by any predictive factor in the equation.

In order to predict soil loss from a watershed-sized area using the USLE, the watershed must be subdivided into areas for which representative values of the six factors can be defined (Wischmeier, 1976). Soil loss estimates from individual subunits of the drainage must be compensated for deposition and the routed to the outlet. A sediment delivery ratio can be used for given land types as a lumped accounting for sediment load changes below the units for which gross soil loss is computed. This method will not predict sediment contributions from mass wasting or channel erosion, thus independent estimates of these must be made to compute total sediment delivery.

At the present time use of the USLE for predicting surface erosion from forest land should be exercised with caution. Additional research is needed to quantify the effects steep slope gradients (>20%), various forest vegetative ground covers, and routing of sediment in steep forest terrain.

SUMMARY AND CONCLUSIONS

We have seen how surface erosion can be initiated by forest practices such as timber harvest, road construction, and site preparation. A variety of management and control measures to minimize this erosion have been examined. Basically, surface erosion is generated by soil and operational conditions that are conducive to or cause disturbance and compaction. By using good operational and management techniques to minimize the extent to which disturbance and compaction occur, we can significantly reduce the amount of surface erosion from managed forest lands and insure high standards of water quality as well as protecting our forest land base for future timber production.

TABLE 1. Relative impacts of four yarding methods on soil disturbance and compaction[2/]

YARDING METHOD	% BARE SOIL	% COMPACTED
Tractor	35	26
Highlead	15	9
Skyline	12	3
Balloon	6	2

2/ Adapted from Swanston and Dyrness (1973). Stability of Steep Land Journal of Forestry, Vol. 71 (May) for Pacific Northwest conditions.

TABLE 2. Land utilized for haul roads by various logging methods[3/]

LOGGING METHOD	% AREA IN HAUL ROADS
Skyline	2 - 3.5
Highlead	6 - 10
Tractor	10 - 15
Jammer	18 - 24

[3/] Adapted from Froehlich (1978). The physical effects of timber harvesting on forest soils. Proc. Soc. Am. For. Nat. Convention. Albuquerque, NM. for Pacific Northwest conditions.

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WORKSHOP NOTES

TIMBER HARVEST SCHEDULING AND SEDIMENT ROUTING

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Studies of complex natural systems, such as ecosystems, have taught us that all parts of such systems are connected to all others, and that it is difficult, if not misleading, to analyze a system by looking at only one fragment. The purpose of this section of the workshop is to at least raise the issue of considering the entire soil/sediment routing system in forest watersheds. The term "sediment routing" refers to the full range of erosion processes and soil and sediment storage sites that are involved in the movement of soil and sediment through watersheds from ridge top to the sea. We can view sediment routing as the transfer of materials from one temporary storage site to another. The sediment routing regime thus involves both storage sites and transfer processes. Although it is convenient to distinguish hillslope and channel sites and processes for the sake of discussion, it is necessary to recognize that they are closely linked in an overall sediment routing context.

Erosion from hillslopes is accomplished by a group of processes that interact in complex fashion. Some processes are episodic, while others operate more continuously. Some processes operate in chain reaction fashion, such that acceleration of one process may lead to increased soil transfer by successive processes. Processes are also superimposed in space, in that a particular column of soil may be subjected to soil transfer by creep, root throw, surface erosion, and other processes simultaneously. Because of this complexity, it is commonly difficult to pick out a single erosion process or group of processes to focus on in order to assess the impact of management activities on hillslope erosion. For example, we may analyze debris avalanche erosion and assess short term (decade) increase in erosion rate following clearcutting. However, long term (several rotations) effects of cutting may be keyed more to those processes that resupply temporary storage sites that repeatedly, but infrequently, fail by debris avalanche. In this case, an overview of sediment routing provides a basis for distinguishing long term from short term impacts of management practices. Evaluation of management impacts may vary substantially depending on the time scale on which the system is viewed.

Sediment transport through channel systems also involves complex interactions among storage sites and transfer processes. For example, coarse sediment breaks down to finer particles during transit and deposits of coarse particles form storage sites for finer material. Large organic debris in many small forested streams dominates hydraulics and sediment transport by forming steps which dissipate stream energy and trap sediment. Removal of logs from a channel as part of a logging operation may release large quantities of sediment which entered the channel under conditions of natural vegetation. I raise this issue to point out that forest practices may affect storage sites as well as the transfer processes we typically measure in assessing management impacts.

To say harvest scheduling and sediment routing in the same breath suggests that we can practice a form of even flow, sustained yield of sediment. This thought raises three questions: Can we do this? If so, how? Should we? The first two questions can be considered in light of two limitations: (1) foreclosed options in lands already extensively entered, and (2) lack of knowledge of sediment routing systems needed to interpret effects of harvest scheduling. Perhaps by the time we have cut 30 to 50% of a forested landscape, most future decisions concerning cutting patterns are determined by history of past decisions. Placement of new cuts may be determined by existing patterns of cuts and roads and subsequent mortality due to blow down, pathogens, and other factors. Of course, we could never actually practice "even flow" of sediment yield, because in most steep, forested terrain sediment production and yield are regulated predominantly by infrequent, extreme storm events, regardless of the character of management activities. However, in forested ecosystems typified by infrequent, catastrophic wildfire natural sediment routing regimes may have been much more "flashy" than routing regimes in the same landscapes under conditions of managed forests. This leads back to the "should we?" question. One can argue that some ecosystems have experienced wide spread, catastrophic disturbance in the past. So, if we have some success in practicing "even flow" of sediment yield, we may significantly alter the natural sediment routing regime of a geomorphic system by reducing some of the extreme periods of sediment movement.

What are our overall sediment management objectives: mimic nature or smooth both natural and man-imposed variations in sedimentation? What is the role of roads in this scenario? If vegetation disturbance influences the sedimentation effects of major storms, managed forests will have less variation in long-term sediment yield than natural forests subject to periodic, extensive wildfire (assuming roads are of minor importance in the managed forest). The managed forest of large drainages on Federal land contains stands of a broad age distribution up to the rotation age. Natural forests in the same area may have contained stands of only a few age classes and may have been largely freshly burned when some major storms occurred.

To interpret effects of scheduling on sediment routing it is necessary to understand (1) downstream effects of individual activities, (2) cumulative effects of multiple activities, and (3) important thresholds or feedback mechanisms which may trigger abrupt shifts in system behavior. In general, our poor understanding of each of these matters limits our ability to prescribe harvest scheduling to regulate sediment routing. However, several specific examples in which scheduling may affect sediment movement do come to mind.

Rapid mass movements down channels, termed debris torrents, are potential off-site consequences of timber harvest in some areas of steep hillslopes and channels. We have some ability to identify critical sites which will be points of origin of torrents that can move from first- to third- or fourth-order channels (Swanson and Lienkaemper 1978). Since freshly clearcut areas have the highest probability of torrent occurrence, we may wish to schedule cutting so that only a small proportion of critical sites in a large watershed are in young clearcuts at any particular time. In this way we distribute impacts over time and space.

Scheduling may also be effective in minimizing impacts of timber removal on slumps and earthflows--slow, deep-seated mass movement features. Removal of vegetation reduces evapotranspiration, thereby increasing soil water availability which may lead to increased movement of seasonally active slumps and earthflows. This hypothesized link between forest cutting and accelerated movement has not been convincingly demonstrated. If cutting does lead to accelerated slump and earthflow movement, hydrologic effects of forest removal could be minimized by scheduling cutting in the earthflow area and on any adjacent land that drains into the earthflow terrain. Cutting could be scheduled so that the evapotranspiration potential of the entire watershed area influencing the earthflow never falls below a particular value.

The extremely high sediment producing basins of northwestern California provide examples of sediment routing systems in which harvest scheduling might have been of some value. Naturally, very high sedimentation rates in the Van Duzen River (Kelsey 1977) and Redwood Creek (Janda 1978) basins have possibly been increased by forest management practices that have included extensive impacts of roads and continuous cutting over large areas. During the December 1964 flood and some subsequent floods sediment from upper basin source areas was deposited in some main stem reaches. This aggradation of sediment from upstream sources triggered local bank cutting, channel widening, mortality of streamside vegetation, and entrainment of sediment that had previously been stored in floodplain deposits. Apparently, some threshold of stability was exceeded along some main stem reaches triggering negative feedback mechanisms. Perhaps these sequences of events could be avoided by harvest scheduling to distribute management impacts over longer time periods.

Effects of increased sediment availability are conspicuous in these particularly sediment-rich systems. These effects are more subtle and more difficult to document in most other systems. Even in the northern coastal California areas where land use practices of the 1950's and 1960's were much rougher than today, the degree of management impact on observed channel changes has been hotly debated. Were the channel changes due to the flood alone? So harvest scheduling for sediment management may be difficult to sell to hesitant customers.

CONCLUDING COMMENTS

Here are some personal feelings and tentative assumptions from a west-side, steep forest land perspective. They are offered as points for discussion.

1. Increased sedimentation following logging is generally due more to increased sediment availability than to increased peak or total flows. If so, hydrologic arguments for harvest scheduling may be weaker than some other arguments. Can we, and should we, distinguish systems where sediment yield is flow limited from those that are sediment supply limited?

2. If harvest scheduling were deemed useful and possible, prescriptions for scheduling to regulate sediment routing may vary substantially between landscapes with contrasting sediment routing regimes. Sediment-rich and sediment-poor systems may vary greatly in the problems and possibilities each presents for management of sediment routing by harvest scheduling. Earthflow dominated landscapes may need a different approach than areas where debris avalanches are very important. Do these different types of systems require different approaches to scheduling or just different degrees of the same basic approach?

3. Much of our detrimental impact on habitat and sedimentation in small- and intermediate-sized streams may be due to management practices which reduce streamside vegetation and large organic debris in channels rather than practices that alter hydrology and sediment supply in upstream areas. Live and dead vegetation helps stabilize stream banks, creates diverse habitats, especially pools, provides cover, and performs other functions. If so, harvest scheduling will have only a secondary effect in protecting this part of the aquatic habitat.

4. We do not know enough about sediment routing to say how harvest scheduling affects it. How should we be thinking about and monitoring soil/sediment movement and storage in

watersheds so we can determine effects of harvest scheduling and other management activities?

The answer to this question is crucial to successful management of sediment with scheduling techniques.

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CLEARWATER WATERSHED MANAGEMENT GUIDELINES

By

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Editor's note: The following paper was part of the Clearwater guidelines. These other guidelines are not included with these proceedings.

Clearwater Watershed Management Guidelines

In order to provide a reproducible and efficient assessment and evaluation of current watershed conditions, and the potential relative impact of various management activities, the Clearwater Watershed Management Guidelines computer simulation was developed.

The primary concern of watershed management on the Forest is sediment loading and transport and their effect on water quality, stream condition, and fish habitat. The program objectives are directed toward evaluating these concerns with a given inventory and map base leading to an indication of trends, comparing alternatives, and providing a "flag" indicating where more detailed analysis is necessary. The program is intended to be a tool for the resource manager. The natural variability of any wildland system, the complex interaction of many processes, and a limited data base precludes the possibility of any model predicting watershed response with absolute certainty. Therefore, the program should not be used as a decision criteria. It can, however, provide support and direction in the management process.

The program addresses three major variables that control the response of streams to watershed management:

1. the slope stability of the system in terms of mass erosion;

2. the surface erosion and sediment delivery from slopes to the stream system; and

3. the water balance of the watershed system. The three components are handled within the program nearly independently There is some interaction at this time in the area of slope hydrology. This is one area of refinement in the program that is under study.

The slope stability component is generally discussed in Wilson, Bennett, Megahan, and Russell, "A Systematic Watershed Analysis Procedure for Residual Landforms in the Northern Rocky Mountains," (1975). It was developed using a detailed inventory of off-site sediment sources (mass failures and surface erosion) and measured stream sediment loads. The erosion hazard has been related to specific landtypes (see USDA - R1, "Land Systems Inventory Guide," 1976) that occur on the Forest. The delivery potential and risk of various management activities on these landtypes have been estimated. The program stratifies a watershed system by its landtypes to determine its "inherent stability" and to evaluate the impact of past management and proposed management on slope stability and sediment delivery.

The results of this component of the program yield a relative risk factor of sediment loading from the watershed slopes. Guidelines have been established that provide the manager with the element of risk management activity has on the catastrophic degradation of stream channel. Further interpretations can be made relative to sediment delivered from slopes in terms of percent changes in supply. Additional guidelines are then established with consideration of the resource objectives, quality criteria, and interrelationships with the modification in run-off response.

The surface stability component is similar to the slope stability component with the emphasis on surface erosion and the fluvial delivery process. The technique is in development with a R1-R4-INT task force. The current erosion-sediment data base is from studies in the Idaho Batholith and other similar sites.

The third program component uses essentially the same data as the sediment components. It first simulates the unmanaged ("natural") hydrograph of a watershed in terms of average annual flows, average distribution of flows in the water year, and the peak flows. With past management inventory information and with proposed activity data, the program then simulates the changes in the unmanaged annual hydrograph. Guidelines are established for acceptable risk relative to changes in peak flow magnitude and peak discharge duration period. These have been established by comparison of stream systems with various changes in response and defined channel conditions and stability (see USDA-R1, "Stream Reach Inventory and Channel Stability Evaluation," 1975) to observe channel degradation and changes in sediment loading. Guidelines can be modified for different levels of risk and the resource values.

The water balance component simulates the change in run-off amount and timing as a function of management activity and vegetative recovery. Responses are in terms of average hydrographs, but such responses are reflected in less frequent events.

The program displays the unmanaged, current, and predicted response of the watershed in terms of slope sediment delivery and streamflow. It also computes a flood frequency analysis. The simulated watershed response can also be used for assessing changes in flow patterns, low flow modifications, flood risk, and other characteristics. The program can be a helpful tool in relating to these as well as the primary objectives if the user has a basic knowledge of component parts, assumptions, data base, and limitations. It should be kept in mind that the program is intended to compare alternates and flag potentially unacceptable risk.

The program uses a multi-purpose input format. Four separate sections are filled in. In the event that a section requires more space than is provided for on a single page, the information is continued in the same field on a new page. (See enclosed coding form).

The first section is basically identification information, such as watershed and project name, ranger district, geologic and hydrologic section, channel length, and elevation data.

The second section is an accounting of all the area of the system stratified by land types. An estimate of the precipitation zone is included.

The third and fourth sections have the same format. The third section is an inventory of past management (and wildfire) activity. The fourth is a single proposal description. Both sections stratify the management activities by land type. Additional information relating to road segments, habitat type, yarding systems, slope, cover density, treatment, intensity and date of treatment are required. The program defaults to typical values for much of this information when it is left blank.

The program is under continuous development. However, the input and output formats are expected to remain unchanged. Refinement of the internal models and data base will provide continuous improvement in the reliability and confidence related to the simulations. Guidelines will always be a function of resource values and objectives.

Areas of internal refinement at this time include the utilization of specialized process oriented snowmelt - watershed response models and improvement of the surface erosion, delivery, and slope hydrology aspects of the program. Data from the Clearwater National Forest and the Horse Creek Study watershed are being incorporated in the program.

The program is up and running at FCCC.

A typical example runstream is:

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@XQT Program * CLW.WATBAL

@ADD PROGRAM * CLW. IMPACT

@ADD PROGRAM * D1.CABIN
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The first file is the main program. The second file is an information base that is integral to the program. The third file is a watershed inventory and an example management alternative.

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A COMPUTER MODEL FOR DETERMINING WATER YIELD FROM FOREST ACTIVITIES

IPNF*LIB.H2OY
1977 VERSION

RELEASED BY
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INTRODUCTION

During 1974 Dave Rosgen, Darrel Kenops, and Doris Matz, members of Sandpoint Zone Planning Team, began work on Water Yield Computer Model I. Use by Districts on the IPNF found areas for improvement and the program was revised in 1976 with refinement of runoff data and curve equations. Further use found more areas for improvement and, as a result, the Water Yield Model 1977 Version. (New additions to the Program will be noted throughout this report between ***.)

Dave Thorson, Sandpoint District Watershed Specialist, and Doris Matz, Computer Specialist, have expanded the program with three major changes: (1) refinement of activity codes, (2) runoff curve options, and (3) development of hydrographs. These changes make the Water Yield Model a much better tool to aid land managers in developing timber and land management plans that will be compatible with the needs for preserving environmental quality.

In writing this program we have attempted to combine the outstanding qualities of the manual programs in existence within Region One. Our goal has been to establish one efficient program that is usable by District personnel on their terminals to give them the hydrologic impacts of proposed activities under the constraints they establish for the watershed. A dual goal has been for use by Land Use Planning in establishing resource allocations under land capability restraints.

The Water Yield Model 1977 Version (program name - IPNF*LIB.H2OY) is written in Fortran V and is now operational from the Fort Collins Computer Center. This version will determine the following on existing conditions and/or proposed activity by subdrainage.

1. Existing equivalent clearcut acres by habitat type.

2. Water yield increase volume by habitat type.

3. Percent of original water yield increase.

4. Allowable acres in equivalent clearcut condition under a certain percent allowable water yield increase.

5. Monthly distribution of water yield increases.

6. Hydrograph of Mean Monthly Water Yields of Base, Past Treatment, and Post Treatment.

7. Peak flow increase, percent and acre feet.

*8. Sustained cutting rates by habitat type based on a certain percent allowable water yield increase.

*9. It will indicate, for a desired cutting rate, the year by habitat type in which the allowable water yield increase limit is met.

* The calculations performed use a weighting of habitat type acres to the total subdrainage acres.

This report describes research projects used as background data for this program, watershed objectives and recommendations for enhancing the water resource along with a description of this program including its limitations and points of emphasis.

Procedures previously published were used exclusively or slightly revised from those described by Silvey, 1970, 1974; Delk, 1972; and Galbraith, 1973. Much of this program is developed around the recovery rates established for different habitat types as described for Montana by Pfister, et al, 1972; and reported by Galbraith, 1973. Darrel Kenops, Silviculturist, IPNF, has adjusted and grouped the habitats to match North Idaho conditions. Appendix 6.

A great deal of credit goes to Dave Rosgen for the original idea and work on Model I. Without the continued efforts and knowledge provided by Doris Matz in computer use and programming, this program would not be a reality.

INCREASES IN WATER YIELD FOLLOWING TIMBER HARVESTING (1)

The fact that removal of forest vegetation increases streamflow has been known since the early 1900's. Research conducted across the Nation has verified this fact. Nearly every study in forested zones has shown a pronounced increase in streamflow following forest cuttings or a gradual decrease in streamflow if an area is reforested (Hibbert, 1967). The magnitude of the increase or decrease is a function of climate, topography, vegetation, and other environmental factors.

Annual Water Yield

The first watershed experiment in the United States was conducted at Wagon Wheel Gap, Rio Grande National Forest, Colorado. Clearcutting the Douglas-fir, lodgepole pine, and spruce on a 200-acre watershed increased annual water yield an average of 1 inch, or 16 percent (Bates and Henry, 1928). Wagon Wheel Gap has an average annual precipitation of 21 inches and is at an elevation of 9,000 to 11,000 feet. Average streamflow before cutting was 6.5 inches. Of the increase, 83 percent occurred during the spring peak runoff season.

The most dramatic increases in water yield have been produced on the east and west coasts, where precipitation is greatest. At Fernow Experimental Forest in West Virginia, with an average annual precipitation of about 58 inches, four different harvest methods were tested in gaged hardwood forest watersheds. Clearcutting, three levels of selection cutting, and a control of no cutting were installed, following a 6-year stream calibration period. Increases in streamflow were proportional to the volume of timber cut (Reinhart, Eschner, and Trimble, 1963; Reinhart, 1965). Clearcutting showed the largest change in discharge with up to a 5-inch increase the first year after harvest. However, these increases were short-lived, dropping back to only 1-inch advantage by 7 years after the clearcut and proportionately sooner in the partial cuttings (Lull and Reinhart, 1967). These decreases were directly associated with the increase in height of the forest vegetation.

(1) Reprint of material presented by Herb Garn and published in Hydrology Part II, Region 1, U.S.F.S.

Similar but more substantial results have been obtained from experiments at Coweeta Hydrologic Laboratory in North Carolina (70 inches annual ppt.) after clearcutting mature hardwoods (Hewlett and Hibbert, 1961; Hibbert, 1967). Here, clearcutting increased annual yield 15 inches the first year. This gradually dropped to about 3 inches after 22 years. A second and similar cut at this time produced an increase in flow similar to the first cutting. Increases in north slope yields were nearly always greater than those on the south slopes. After the second cutting, streamflow increases diminished at a much faster rate and appear to be reaching pretreatment levels after just 16 years. (Swank and Helvey, 1970).

Water yields are also increased by thinning trees, but the thinning has to be drastic to produce any long-term effects. A study in the white pine plantation in Massachusetts showed that only the heavy crop tree thinning (reserved 130 trees/acre) produced long-term increases in water yield (Hunt, 1965). Plots thinned lightly (31 percent basal area removed) increased water yield only the first year.

The greatest increases in water yield following logging have been recorded in the Cascade Range of Oregon. A 237-acre watershed in the H. J. Andrews Experimental Forest was completely clearcut, which increased water yield by 18 inches. Significant increases in yield did not occur until 40 percent of the timber had been cut (Rothacher, 1970). Patch cutting 30 percent of a 250-acre watershed increased yields by 6 inches. The area has an average annual precipitation of 90 inches and an annual streamflow of 57 inches.

A study in the Cascades and Sierra Nevadas of California compared strip cutting, block cutting, and diameter-limit selection cutting. On-site water yields increased 35 percent (8.6 inches) for the strip cutting, 25 percent (6.3 inches) for the block cutting, and 13 percent (3.4 inches) for the diameter-limit cutting (Anderson and Gleason, 1960).

Detailed watershed studies near Fraser, Colorado, have provided valuable water yield information for the high elevation coniferous forests of the Rocky Mountain Region. Clearcutting 40 percent of the 714-acre Fool Creek watershed in strips varying from 66 to 400 feet wide increased annual streamflow by 25 percent (Hoover, 1969). The Fool Creek watershed has an average annual precipitation of 30 inches, 75 percent of which is in the form of snow; elevations range from 9,600 to 11,500 feet; major vegetation is lodgepole pine and spruce. Average annual yield before cutting amounted to 12.1 inches.

Plot studies, also at Fraser, showed that cutting lodgepole pine from five-acre plots could increase water available for streamflow by 31 percent (Wilm and Dunford, 1948).

Seasonal Water Yield

Research results from mountainous areas, where the majority of precipitation is in the form of snow and runoff is primarily from snowmelt, have shown that the increased water yield occurs primarily during the snowmelt runoff season (Bates and Henry, 1928; Hoover, 1969; Leaf and Brink, 1972). The Wagon Wheel Gap Study reported that 83 percent of the increase in yield occurred during spring runoff which increased flows during this period by 50-60 percent. The increase in water yield of Fool Creek resulted in the broadening of the base of the hydrograph, with the bulk of the snowmelt runoff occurring at an earlier date. Both of these studies reported that no damage to channels occurred nor was sediment increased significantly. Recession flows, however, remained the same (Leaf and Brink, 1972). It should be emphasized that these studies were only designed to increase total water yields and were not specifically designed to alter the timing of yield.

Studies in areas where precipitation is primarily in the form of rain have shown that removing vegetation can increase late summer streamflow, but timing is largely dependent on the distribution of precipitation. Clearcutting the lower 20 percent of a 102-acre watershed in Pennsylvania resulted in significant increases in water yield. These increases occurred primarily during the growing season months of May to October, with much of this occurring during the critically low flow months of July to September (Lynch, Sopper, and Partridge, 1972). About 85 percent of the annual streamflow increases at the Coweeta Hydrologic Laboratory, North Carolina, occurred during May to October (Swank and Helvey, 1970). Low streamflow normally occurs here in October and high flow in March. Increases in water yield obtained at the H. J. Andrews Experimental Forest in western Oregon increased sharply with the arrival of fall rains, although the increase occurred during all seasons (Rothacher, 1970). Increases remained high during the rainy season so that about 80 percent of the annual increase occurred during the October to March period. Although the remaining 20 percent is small, it is an important increase to the high demand, low flow in the dry summer.

Peak Flows

Peak, or flood, flows and how clearcutting affects them, have recently received increased attention. Early studies conducted at Wagon Wheel Gap and Fraser, Colorado, report no effect on flood peaks or damage to stream channels (Bates and Henry, 1928; Leaf, 1970). Although snowmelt was accelerated in the cutover areas of Fool Creek, snowmelt also occurred earlier, and peak daily streamflow actually diminished slightly after the timber harvesting (Leaf and Brink, 1972).

Logging, under normal conditions, is believed to not significantly increase floods in the Pacific Northwest because logging does not normally decrease infiltration capacity of the soil below the rate of precipitation (Rothacher, 1971). In an analysis of records from Coweeta, Hewlett and

Helvey (1970) concluded that the mean peak flow was increased slightly but that there was no conclusive evidence that clearcutting resulted in an increase in record high peak flows.

There is other evidence, however, that under some conditions, road building and logging may increase peak flows, especially on small drainages.

Clearcutting the lower 20 percent of a 106-acre watershed in central Pennsylvania resulted in a significant increase in quick flow volumes and instantaneous maximum peaks of single storm events (Lynch, Sopper, and Partridge, 1972). These increases were most pronounced during the growing season. The increases, however, occurred primarily at relatively low antecedent flow conditions and therefore do not represent any potential increase in flood threat.

These results are not necessarily conflicting. Even though peak flows may be increased by harvest cutting on the immediate small watershed concerned, this effect is rapidly diminished outside of this small watershed as the flows of many tributaries combine with the main stream (Bethlahmy, 1972). Maximum floods on the main stream result from the synchronization of the flood peaks from its tributaries. Therefore, partial clearcutting of a watershed may reduce the magnitude of peaks when snowmelt from clearcut areas is not synchronized with slower melt from forested tributaries of the watershed. Conversely, the opposite may occur if synchronization is enhanced. Sufficient knowledge is presently available to make it possible to cut timber with no aggravation of peak flows or possibly a reduction of peak flows (Goodell, 1959; Satterlund and Haupt, 1972). This may be accomplished by designing the timber harvesting program to maximize the diversity of snowmelt on the various components of a watershed and to desynchronize the peak flows from tributaries of the watershed.

FACTORS AFFECTING INCREASES IN WATER YIELD AND DIVERSITY OF SNOW ACCUMULATION AND MELT

Forest removal increases water yield because of one or more of the following:

1. A reduction of transpiration.

2. An increase in wind turbulence which results in redistribution of snow and greater local snow accumulations.

3. A reduction of interception.

4. More efficient conversion of the snowpack to streamflow.

Disregarding the aerodynamic effect on snow distribution for the moment, removal of all vegetation would result in a potential increase in water available for streamflow approximately equal to transpiration (assuming precipitation is not limiting). Removal of vegetation also makes more water available for streamflow by reducing interception losses. Evaporative losses from water intercepted by trees are greater than losses from the ground surface under a canopy (Anderson and Gleason, 1960; Rothacher, 1971). As the soil is exposed to greater isolation by removal of vegetation, evaporative losses from the soil are increased. However, these evaporative losses are limited to the surface horizons of the soil, whereas with a vegetative cover soil moisture is depeleted throughout the entire rooting depth by the transpiring vegetation (Herring, 1968; Johnston, 1969, 1970). The overall effect is a reduction in total evapotranspiration by a decrease in transpiration and interception losses, even through evaporation from the soil increases with removal of vegetation (Johnston, 1970).

The magnitude of increase in water yield is dependent upon:

1. Soil and rooting depth - greatest increases in water yield are obtained by removing deep-rooted vegetation from deep soils.

2. Rainfall input compared to energy supply - greatest increases in water yield are obtained from areas having great amounts of precipitation compared to evapotranspiration. Increases in water yield from north aspects are greater than those from south aspects.

3. Amount of vegetation removal - water yield increases are roughly proportional to the percentage of the drainage that is cut.

4. Type of vegetation removal - clearcutting produces maximum increases in yield, selective cutting produces the least increases. Size and geometry of clearcuts also affect amounts and timing of increases in yield.

5. Species differences - increases in water yield may differ between species because of differences in:

   a. rooting characteristics
   b. dormancy
   c. plant size
   d. radiation reflectance
   e. interception

Conifers use more water than deciduous hardwoods.

Topographic and Climatic Effects

Natural diversity in snow accumulation and melt exists by virtue of differences in elevation and slope. Several investigators have established the effect of these factors on snow accumulation and melt. An increase in elevation at a given latitude is associated with an increase in snow accumulation, a delay in snowmelt, and an increase in melt rate (Packer, 1960, 1962, 1971; Anderson, 1963).

Slope and aspect are two other topographic factors that influence snow accumulation and melt, mainly through their influence on radiation intensity and exposure to winds. Packer (1960, 1962) observed that the relation of water equivalent to aspect was quadratic. Slope and aspect effects were best measured and expressed in combined form as solar radiation received at the surface (Anderson, 1963). Snowmelt is delayed and snow accumulation and the melt rate increase with a shift in aspect from south to north. The effect of a change in aspect at high elevations is about four times greater than at low elevations (Packer, 1971). The effect of steepness of slope varies with aspect. On south aspects melt is delayed and rate of melt is increased with a decrease in slope angle. On north aspects, melt is delayed and melt rate is increased with an increase in slope angle (Packer, 1971). These differences with change in slope are also greater at the high elevations and are reduced as aspect shifts to east or west.

Vegetation variables have been found to be of less importance than topographic and climatic variables. Anderson, Rice, and West (1958b) found wind and shade effects to be dominant in controlling snow accumulation in forest stands near openings. Packer (1960) tested snowfall years, elevation, aspect, canopy density, and their interactions as variables in a curvilinear multiple regression. He found that the product of snowfall year and elevation and the product of aspect and elevation were the only two significant interactions; canopy density had the least effect on snow water equivalent. All of these variables explained 91.6 percent of the variation.

Anderson (1967) investigated snow accumulation and its relationship to meterological, topographic, and forest variables. Storm characteristics were found to explain almost all of the variation in snow accumulation, with the solar radiation and advective heat variables explaining the next greatest variation. Several studies have shown that increases in water yield are greatest during periods of abundant precipitation (Hoover, 1969; Lynch, Sopper, and Partridge, 1972; Rothacher, 1970).

Vegetative Effects

The forest effects water yield and snow accumulation and melt by transpiring water extracted from the soil, by intercepting snow, and by influencing meteorological factors such as insolation and wind patterns. Packer (1960, 1961) observed that snow water equivalent increased uniformly 4.2 inches as forest density decreased from 100 to 0 percent. This relation occurred regardless of differences in year, elevation, or aspect, which led him to infer that this increase in water equivalent was due primarily to interception. Lull and Rushmore (1960) plotted snow accumulation and melt against canopy closure and found that water equivalent decreased 1/3 inch for each 10 percent increase in canopy closure. These findings suggest that snow accumulation and melt are linearly related to forest density, which may not be the case as pointed out by Anderson, Rice, and West (1958a). They discovered that snow increased with small increases of hemispherical cover up to 33 percent and then decreased with additional increases in cover.

An increase in forest density delays the time of snowmelt. Snowmelt rates related to increases in forest density are dependent on elevation and aspect (Packer, 1971). At low to intermediate elevations, the snowmelt rate decreases with increases in forest density. The reduction of rate is greater on southerly aspects than on northerly aspects. At higher elevations this relationship held true on south aspects. However, on north aspects, snowmelt rates were reduced with an increase in forest density up to 25 percent; beyond this density snowmelt rates increased with an increase in density. Snowmelt rates on southerly exposures were greatest in clearcut and natural openings. At low to intermediate elevations snowmelt was slowest in dense, completely closed stands. On north aspects at higher elevations, highest snowmelt rates occur under dense stands. Snowmelt rates are lowest under canopy densities of 25-45 percent.

The forest may affect snowmelt rates in two ways. Shade from trees along the southern edge of openings reduces showmelt, whereas radiation from trees on the north edge may increase melt. Anderson (1956) and later Anderson, Rice, and West (1958a) indexed trees to the south by the shade they produced and trees to the north by the ratio of tree height to distance to the tree from the sampling point. They found that shade from the south was related curvilinearly to maximum snow accumulation. Maximum accumulation occurred at 65 percent shade, decreasing on either side of this value.

Anderson (1967) investigated snow accumulation and its relationship to forest variables. Wind influenced the distribution of snow among openings, margins, and forest. Forest margins and openings had the greatest response to storms of different wind velocities. Natural shading affects reached a maximum in openings of high-energy south slopes. The increase in snow accumulation associated with differences in shading averaged 3.8 inches for south slopes and 1.9 inches for north slopes. In forest stands differences in shading from 61 to 100 percent were associated with increases in snow of 1.7 inches on average-energy slopes, 2.1 inches on low-energy slopes, and 1.1 inches on high-energy slopes. Back radiation effects from trees to the north were small except for openings. Back radiation reduced snow by o.3 inches on north slopes, 1.3 inches on average slopes, and 2.5 inches on south slopes. The effect of back radiation in forest and forest margins was less than 0.4 inches. All parts of the forest showed a response to differences in energy received. Low-energy slopes had more snow than high-energy slopes, but this effect was not as great for slopes within the forest.

The type of timber cutting and the size, shape, and orientation of clearcuts are important in determining snow accumulation and melt. More snow accumulates in cutover areas than under forest because of a reduction in interception and an increase in wind turbulence which results in redistribution of snow. Most studies show that interception losses amount to 10 percent or less of actual precipitation (Anderson, 1969). Only part of the total snow intercepted is lost to evaporation (Satterlund and Haupt, 1970; Haupt, 1972). Interception losses may decrease with increasing elevation, as cloud cover increases (Satterlund and Haupt, 1972). The increased snow accumulation in small openings is caused primarily by snow redistribution rather than reduced interception loss (Hoover, 1969). This effect will persist until trees in the small openings approach the height of the surrounding trees. The Fool Creek Study in Colorado increased snow accumulation in the clearcut strips by 25 percent. However, total snow storage on the watershed remained the same (Hoover, 1969).

Anderson (1960, 1969) has investigated the effects of different cutting practices on snow accumulation and melt. Snow persists longer in forested areas than in clearcut openings because of shading by the trees. More snow is deposited in the openings and the melt rate is increased. On south aspects snowmelt begins much earlier in the season than in the forest, and may occur intermittently during the winter. Because of this season-long melt period, snow disappears much earlier in the opening than in the forest. Strip and block cutting also increase snow accumulation but does not increase the melt to the extent of large clearcuts. Maximum snow accumulation occurs in openings 1/2 to 1 tree height in width and snow disappearance occurs at about the same time in the forest.

Snow accumulation is greater in openings on north aspects and melt does not occur until late in the season when it is very rapid. Even with higher melt rates, the snowpack may disappear later in small openings on north aspects than in the forest. Snowmelt may be delayed by designing small openings in the forest to maximize shading and snow redistribution effects of wind (Anderson, 1969).

Anderson and Gleason (1960) compared the effects of three types of logging on water yield. Clearcut strips twice as wide as the height of adjacent trees increased water available for streamflow by 8.6 inches (35 percent). A 17-acre block cutting reduced water losses by 6.3 inches, increasing water available for streamflow by 25 percent. A commerical selection cutting increased water yield by 3.4 inches (13 percent).

Increased water yields from clearcutting have been found to be proportional to the percent of the drainage cleared (Rothacher, 1970). Greater water yields are also obtained from deep rather than shallow soils, and from high precipitation areas (Hewlett and Hibbert, 1961; Lull and Reinhart, 1967). Increases in water yield on north aspects were greater than those on south aspects. The least increases in water yield result from partial cutting of trees. Rothacher (1971) suggests that removing 20 percent or less of the forest cover would not produce a significant change in streamflow.

Vegetative recovery and corresponding decreases in water yield vary considerably. The duration of increases in water yield from logging depends on the persistence of the aerodynamic effect on snow redistribution and the persistence of its effect on soil moisture and other evaporative losses. The only water yield experiment repeated in time was conducted at the Coweeta Hydrologic Laboratory in North Carolina (Swank and Helvey, 1970). Recovery of water yield to pretreatment levels after the first cut was estimated to require 35 years. This estimate held true when the watershed was recut 22 years later. After the second cut recovery occurred at a much faster rate, indicating streamflow will return to pretreatment levels after only 16 years. The logarithmetic reduction of streamflow increases is closely associated with the rapidity of regrowth of vegetation. Regrowth and declines in water yield are most rapid in the humid coast regions where soils are shallow. Roots can rapidly re-occupy the entire soil profile of a shallow soil (Lull and Reinhart, 1967). Recovery is also more rapid in partial cuts than in clearcuts. Increases in water yield from partial cutting diminish to pretreatment levels in usually less than 10 years, and may only take several years (Hunt, 1965; Lull and Reinhart, 1967; Anderson, 1969; Dahms, 1971). Partial cutting has to be quite drastic to produce long-lasting increases in water yields (Hunt, 1965; Dahms, 1971). Water yield from a lightly thinned plot (31 percent basal area reduction) was above pretreatment levels only the first year (Hunt, 1965).

Recovery in the subalpine mountain zones where precipitation is dominantly in the form of snow may take much longer than research has shown in the more productive coastal regions. The increased water yield from Fool Creek, which was cut in 1955, has shown no significant reduction with time (Hoover, 1969). Increases in snowpack accumulation due to the aerodynamic effect of small openings may persist for long periods of time compared to savings in soil moisture. Increases in snow accumulation in five-acre plots laid out in mature lodgepole pine in Colorado have changed little since they were cut in 1940 (Hoover, 1969). This aerodynamic effect will persist until the new crop of trees approach the height of the surrounding trees. In contrast, the savings in evapotranspiration tend to decrease more rapidly, especially under selection cutting. These savings diminished by 50 percent in four years after a selection cutting in California (Anderson, 1969). Zeimer (1964), studying soil moisture changes in a strip clearcut in the subalpine zone of California, estimated that increases in water stored in the soil as a result of cutting would become insignificant after about 16 years.

HYDROLOGIC OBJECTIVES IN TIMBER HARVESTING

A program involving the extensive, unplanned removal of timber from a forested basin may lead to a hydrologic problem. Since the increase in water yield resulting from removal of timber may be beneficial, the major effort related to timber harvesting must be directed towards safe disposition of this increased yield. This goal may be achieved by managing vegetation with the following objectives:

1. Limit increases in spring peak runoff volumes to the capability of stream channels to safely handle this increase, based on channel condition and stability;

2. Desynchronize snowmelt runoff from the components of a watershed by maximizing the natural diversity in the quantity and timing of snowpack accumulation and melt.

Following these objectives will at the same time result in:

1. Broadening the base of the spring flood hydrograph and possibly increasing late summer flows and reducing peak spring flows.

2. Maintenance of stream channel stability.

3. Holding sedimentation to a minimum.

The amount of snowmelt runoff depends largely on the amount of water in the snowpack, the rate of snowmelt, and the capacity of the soil to absorb and store water (Packer, 1962). Snowmelt runoff lossed are integrated values of transmission, evaporation, and ground losses, and are largely a function of the length of time of the snowmelt period (Miller, 1950). On the basis of these factors, investigators primarily interested in maximizing water yields state that this can be achieved by (a) minimizing winter snowmelt; (b) maximizing spring snowmelt rates; (c) minimizing length of the snowmelt period; (d) maximizing snow accumulation; and (e) minimizing lengths of water flow paths (Anderson, 1966; Hansen and Ffolliott, 1968).

Conversely, the opposite effect, that of minimizing increases in water yield may be achieved by (a) maximizing the diversity of snowmelt; (b) reducing snowmelt rates; (c) maximizing the length of the snowmelt period; (d) maximizing the length of water flow paths; and (e) maintaining high use of water by vegetation (Anderson, 1966).

High rates of water use by vegetation may be maintained by favoring timber harvest methods that produce the least increase in water yield, e.g., partial cutting. Length of water flow paths may be maximized by restricting logging to the upper portions of the slopes, strip cutting on contours, and maintaining high soil infiltration rates and deep seepage of water. Management practices to change the length of the snowmelt period and snowmelt rates will vary on different parts of the watershed in order to maximize the diversity of snowmelt.

In order to maximize the diversity of snowmelt and desynchronize discharge from side tributaries, the natural diversity of watersheds will need to be evaluated. Physiographic and climatic factors have the greatest influence on water yield. These may be quickly evaluated from the slope-aspect combinations and elevation components of a watershed. Slope-aspect combinations may be expressed as potential solar radiation received.

Potential solar radiation on the various slope-aspect combinations of a watershed was found to be significantly related to the areal distribution of maximum snow accumulation and snowmelt rates (Garn, 1969). Potential solar radiation on paired high- and low-energy watersheds is also related to the relative timing and magnitude of peak daily runoff from the snowpack (Satterlund and Haupt, 1972). Where elevational ranges are great, temperature effects will also need to be accounted for. Temperature is related to elevation and may be generally evaluated by the diversity in elevation. The remaining factor, forest cover, can be managed by man to enhance or minimize the existing natural diversity.

Although more research is needed for optimum application of these techniques in practical management programs, sufficient knowledge is presently available to at least qualitatively design and evaluate timber harvesting systems with respect to snowpack management objectives. Research is presently being conducted in Arizona to develop forest management guidelines for increasing water yields (Thorud and Ffolliott, 1972). This study will evaluate the effectiveness of forest management practices for maximizing runoff. Maximum increases in water yield may be obtained by locating practices that maximize snow accumulation on portions of a watershed having the greatest runoff efficiency. Studies are also being initiated in northern Idaho by the Intermountain Forest and Range Experiment Station to evaluate the effects of forest management activities on quantity and timing of water yield. Studies such as these will greatly improve the application of research for operational management programs.

Although the application of present research knowledge and the lack of detailed data will result in fairly large prediction errors, it is feasible to design systems of timber harvesting that are compatible with snowpack management objectives. Satterlund and Haupt (1972) provide some general suggestions. Natural diversity would be evaluated by dividing the watershed into homogeneous strata based on elevation, slope aspect and gradient, and prevailing wind direction. Each of the strata would be ranked on the basis of relative water equivalent at maximum accumulation, time of initiation of the melt period, and average rate of melt. Maximizing the diversity of snowmelt and desynchronizing snowmelt runoff from parts of the watershed may be attained by the following management practices:

High Energy Slopes

Objectives

1. Reduce maximum snow accumulation.
2. Advance time of initiation of melt.
3. Lengthen snowmelt period.

A. Low-Intermediate Elevations

Cut moderate-sized patches (less than 20 acres) or use heavy partial cuts (e.g., shelterwood). Minimize shading by trees to the south. Anderson's "wall and step" forest can be applied in reverse.

Sites where soil moisture and soil temperatures may become limiting for tree re-establishment with minimization of shading will need special treatment. Some shading will be beneficial on these sites for reducing water losses and soil temperatures.

B. High Elevations

Similar to lower elevations except that openings may be larger here (up to 40 acres).

Low Energy Slopes

Objectives

1. Delay or maintain time of initiation of melt.
2. Minimize increases in water yield.
3. Reduce rate of melt.
4. Lengthen snowmelt period.

At all elevations, clearcut strips will be oriented parallel to contours and will have wide leave-areas between cuttings.

A. Low Elevations

Cut moderate-sized patches less than 20 acres to initiate earlier melt, reduce melt rates, and lengthen the snowmelt period.

B. Intermediate-High Elevations

Favor single tree or group selection cuttings to reduce density to around 50 percent. Clearcuts should be in small patches or narrow strips 1-5 acres in size, designed to maximize snow accumulation and delay melt.

In addition to the above general guidelines, amount of vegetation removal (or total increase in water yield) will be limited for any given time. The total allowable increase during peak season streamflow will be determined by stream channel condition and stability.

Rate of timber harvesting, once this limit has been reached, will be determined by the rate of hydrologic recovery of previously cut areas.

These guidelines are based on the preceding research conducted primarily in other Regions and were modified to fit local conditions. Because detailed local data are lacking, some broad estimates of various factors will have to be made to develop the details of this procedure.

REASONS FOR HYDROLOGIC GUIDELINES*

The following are some reasons for applying hydrologic guidelines to the water yield increase analysis procedure:

1. Maintain or prevent a degradation of water quality.
2. Maintain compliance with Weeks Law, Organic Act. PL 92-500 and Quality Management Directives.
3. Determine the effects of increased runoff resulting from vegetation manipulation.
4. Develop awareness of water resource and watershed conditions in specific subwatersheds.
5. Reduce the magnitude of natural occurring runoff events.
6. Manage terrestrial ecosystems in harmony with aquatic systems.

*Hydrology Part II, Region One, U.S.F.S.

7. Facilitate the determination of sound vegetational manipulation practices based upon watershed conditions and land capability -- rather than decisions based solely on silvicultural characteristics and public demand for goods.

8. Prevent degradation of stream's ability and water quality parameters irrespective of land ownership boundaries.

9. Quantify and sytematize the effects from water yield increase.

Timber Cutting Guidelines

These guidelines are designed to complement and strengthen the recommendations offered under the preceding section on hydrologic objectives.

1. Proposed timber harvest activities should not develop more than a 10% increase in the mean annual yield of a 3rd to 5th order drainage. This may be adjusted up or down depending upon: (a) channel stability, (b) soil characteristics. A channel stability rating that adequately shows the potential increase will not cause damage must be prepared for proposals that develop over the ten percent guide.

2. The peak flow volume or the highest average monthly yield should not be increased more than 20%.

3. The maximum channel impact period should not be increased more than 20%.

4. Avoid the following:

    a. Concentration of cutting in the same elevation zone on north slopes.

    b. Cutting next to or along both sides of the main drainageway.

    c. Reducing the intervening strip between clearcuts to a width less than 8-10 tree heights.

    d. Cutting within the intervening strip of timber until the adjacent cutting unit has an ECA recovery of at least 60%.

    e. Developing more than 20 to 25% ECA in a 3rd to 5th order drainage.

    f. Clearcutting closer than 3 chains or 250 feet slope distance to a 3rd order or higher drainage channel below 5000 feet elevation. Above 5000 feet, buffer strip may be reduced to two chains. Timber within such leave strips may be partially cut on a salvage basis, but not to exceed 35% crown removal (in a fully stocked stand).

5. Should a "silvicultural emergency" develop, the intervening strip between clearcuts may be partially cut, but not to exceed 30% crown removal from a fully stocked stand.

Alternatives to Meet Established Water Yield Increase Guidelines

1. Increase or decrease the area or size of vegetation to be removed.

2. Modify the method of removal, i.e., clearcut vs. shelterwood harvest.

3. Collect additional soil, geology, and hydrology data, i.e., refine the input data.

4. Modify the harvest by energy slopes to desynchronize the increased water yield.

5. Exceed guidelines after inclusion of mitigation, such as these expensive measures:

   a. Sediment basins
   b. Road stabilization
   c. Debris clearing
   d. Bank stabilization
   e. Progressive revegetation
   f. High-lead logging, etc.
   g. Buffer stips
   h. Channel stabilization
   i. Eliminate spring logging
   j. Modify method of harvest

PROCEDURE USED IN COMPUTER COMPUTATIONS

The mathematics used within the computer program for estimating the effects of planned or existing timber cutting on mean annual and monthly water yield was developed on the Nezperce by Lee Silvey.

The basic premise is based on a local analysis of runoff patterns, volumes, terrain-landform, and channel condition-soil areas; it is assumed that most 3rd through 5th order drainage channels in North Idaho can sustain an increase in average annual runoff that varies from 5% to 17% increase as a result of timber harvesting and road building. This increase varies as the stream channel stability varies with the ability of the channel to handle increased runoff. See Appendix 5.

Option 1

The program assumes the elevation-precipitation curve to be a straight line for a subdrainage. It calculates the precipitation for each elevation, given the minimum and maximum elevation-precipitation, then determines runoff from the SCS runoff-precipitation curve.

Appendix 2 shows the relationship between precipitation and runoff used in the computations by the program. Stations shown in Appendix 2 have average annual precipitation which varies from 12 to more than 100 inches. Drainage areas vary from about 10 to 2,000 square miles. Mean elevation varies from 3,000 to 9,000 feet. Most rocky alpine basins plotted along the high side of the curve. Heavily timbered, deep soil mantle basins plotted along the lower portion of the curve. By determining the average annual precipitation for a watershed and entering this data in Appendix 2 the average annual runoff of most streams could be estimated within 15 percent.*

Option 2

The 1977 Version has the option to use the precipitation-elevation-runoff relationship or a one, two, or three segment elevation runoff curve for drainages which the runoff relationship varies from the SCS runoff-precipitation curve.

The following Nezperce Formula I was developed to express a rapid means of determining a key guideline value known as ECA. The ECA value is the total area in acres within a drainage that can or will be in an "Equivalent Clear-cut" conditon; consisting of clearcuts, partial cuts, roads outside of clearcuts, burns, recent slides, etc. Through application of this formula, it is possible to estimate prior to drainage development, how much of the land area in a drainage can be in an equivalent clearcut condition and not cause an increase in average annual yield values above that which the drainage channel can safely transmit during years when the annual flow volume is average or above.

Formula I.

$$ECA = \frac{A(I)}{F(R)} \qquad \text{where:}$$

A = Average Annual Water Yield in Acre Feet
I = Prescribed Increase Limit for Ave. Annual Water Yield in %.
F = On-site Water Yield Increase Factor in %.
R = Average Runoff for Treated Area in Feet.
A(I) = "B" - Allowable or Calculated Water Yield Volume in Acre Feet.
DA = Drainage area in acres.
ECA ÷ AA = % of Drainage Treated
B ÷ F = Y = Pre-treatment Water Yield of Treated Area, Acre-ft.
A ÷ DA = R in Feet.

H. Lee Silvey, Hydrologist, Region 2, Denver, CO.

The increase in average annual water yield that has resulted from previous development in a drainage may be estimated with use of the Nezperce Formula II. In order to calculate the existing ECA for such a drainage, graphs provided as Figures 10 and 11 allow an estimate of the ECA value for partial cuts and clearcuts older than one year.

*Reprint from material presented by P. E. Farnes and published in Hydrology of Mountain Watersheds, Soil Conservation Service.

Formula II

$$I = \frac{(ECA \times R)\ F}{A} \quad \text{where:}$$

I = Percent Increase in Average Annual Water Yield Due to Vegetative Manipulation.
ECA = Existing Equivalent Clearcut Area in Acres.
R = Ave. Runoff of Treated Area in Feet
F = On-site Water Yield Increase Factor in %.
A = Average Annual Water Yield of Subdrainage in Acre Feet.

$ECA \times R = Y$) = Pretreatment Water Yield of Treated Area in Acre Feet
$\frac{B}{F} = Y$)

Y)F = B = Water Yield Increase Volume in Acre Feet

(R)F = B_1 = Water Yield Increase, Feet-Depth.

Discussion of Formula Components

DA = DRAINAGE AREA - Simply the planimetered area, expressed in acres, of the subdrainage being considered for analysis. Generally subdrainages within a large drainage or drainage area (i.e., PWI Watershed) are delineated on the basis of stream orders. That is, drainage areas of 3rd, 4th, and in some cases 5th order size provide a means of characterizing and dividing a larger drainage in terms of "logical watershed units". Stream orders at this level of analysis are usually based on the degree of channel branching found on the standard USGS topographic map with a distance scale of 2.65 inches/mile. Appendix 1 defines stream orders and describes the method used for delineation.

A = AVERAGE ANNUAL WATER YIELD of the subdrainage. This value is obtained by planimetering the area between runoff isolines or elevation zones, for the local area. For the area between any two isolines, the average runoff value used for volume calculations is the average of the upper and lower isolines.

I = INCREASE LIMIT FOR Average Annual Runoff in percent. This value is a guideline used to equate the magnitude of the impact upon a drainage system that develops from removal of timber vegetation. An average of 10 percent increase in average annual yield for 3rd, 4th, and 5th order drainages is used as a limiting factor. The term average indicates that this value can vary with location, and primarily due to soil type; that is the increase limit may be 5 or even 10 percent higher in stable soil areas with a good to excellent stream channel condition rating. Conversely, the limit could be decreased in certain high-hazard soil areas with unstable or poor stream channel conditions (Appendix 5). The percentage limit is based on the following assumptions: When the estimated or calculated average annual flow is exceeded by more than 10 percent, stream channel damage will begin to occur. This assumption was derived from several on-site analyses conducted in the Region where the water yield increase from an active timber sale was related to accelerated stream channel damage. In addition, the assumption is based on the analysis of local USGS gaging station records where the total annual flow for each year during the period of record is compared with average annual flow in terms of departures upward or downward from the mean.

B = ALLOWABLE OR CALCULATED WATER YIELD INCREASE VOLUME IN ACRE FT. - This value is simply a product of the drainage average annual water yield times the percentage increase limit, expressed in acre feet of water as used in Formula I, or in Formula II a product of the average pre-treatment yield of a treated area times the water yield increase factor, expressed in acre feet.

F = ON-SITE WATER YIELD INCREASE FACTOR IN PERCENT (Appendix 3) - The water yield increase factor is an expression of the increase in the normal or average water yield of any particular land unit that occurs as a result of the removal of vegetation, i.e., timber harvesting. The increase develops from three primary hydrologic sources. The largest part of the increase develops from the significant reduction in loss of moisture from the soil due to transpiration and evaporation, or "ET". This is to say that when the timber is removed from a site, the soil moisture levels on that site are not depeleted through transpiration to the extent that would occur with timber in situ. Thus with the soil moisture reservoir not requiring as much water for recharge from precipitation in order for runoff to be in effect, there is a resulting surplus of precipitation that will normally show up as an increase in runoff.

A second source of water yield increase develops from a redistribution of snow into openings in the forest canopy such as clearcuts. The term "redistribution" refers to the phenomena that occurs when snow carried by the ambient air mass across the top of the canopy is deposited into a clearcut area due to the disruption of the shear plane at the canopy level. In effect, the standing timber around the edge of a clearcut acts as a snow fence, causing more snow than normally would fall into the timber area to settle into the relatively still air in the clearcut unit.

The third source of the water yield increase is a result of the reduction of interception losses that occur with snow or rain deposited on the forest canopy. Elimination of the forest canopy as in a clearcut would provide a significant reduction in above-ground-level evaporative losses, hence causing more moisture deposited at the surface for transfer to soil storage or runoff.

Recent indications from research in North Idaho suggest that for the general area in which timber is harvested on the Nezperce, i.e., 4,000-6,000-foot elevation zone, the maximum increase to water yield from a reduction of transpiration loss can be as high as 6 inches of water; with a range of 3 to 6 inches possible increase depending on soil depths, etc. The redistribution of snow across a watershed and the subsequent increase to water yield may vary from 2 inches to a high of 4 inches of additional water. An increase to water yield due to a reduction of the interception factor can result in additional water in the amount of 1 to 3 inches. Thus, the total amount of water that could be available as additional runoff would range from 6 to 13 inches. Within the Nezperce area, for example, there could be a potential for a water yield increase factor ranging from 30 to 70 percent. For purposes of estimating the water yield increases due to timber cutting, it is assumed the water yield increase factor may vary from about 35 percent at 4000 elevation to 45 percent at 6000 feet. These values seem reasonable when compared with water balance calculations, wherein precipitation for the 4000 to 6000 foot zone is estimated at 38 inches annually; and the annual runoff is calculated at 20 inches, with an estimated water loss to evapotranspiration of 18 inches.

Considering local soil types, precipitation patterns, climate and timber types, it is estimated that on the average there would be about 7 or 8 inches water diverted from the evapotranspiration loss of 18 inches to runoff. This would in effect be the average water yield increase factor of about 40 percent that would be applied to equivalent clearcut area through Formulas I and II in this elevation zone.

Y = AVE. PRE-TREATMENT YIELD OF TREATED AREA IN ACRE FT.
R = AVE. RUNOFF OF TREATED AREA IN FT. - The "Y" value is the average annual water yield of the timber harvest units (clearcut or partial cut) determined by multiplying their area in acres by the average annual runoff value, in feet, for the treated area. The "R" value for the treated area is simply the most representative or closest water yield isoline value converted from inches to feet. For a precise estimate of pre-treatment yield, the isoline value in or adjacent to the unit would be used, with each unit figured separately and their yields totaled for the subdrainage. A close approximation for a rapid estimate may be obtained by totaling the area of the cutting units and multiplying by the average runoff (feet) of the subdrainage in which the units are located.

ECA - EQUIVALENT CLEARCUT AREA (Appendix 4) - This term describes the total area within a particular subdrainage that does or will exist in a clearcut condition. The ECA value is determined by adding the area actually in a clearcut condition with an "equivalent" clearcut area for roads outside of clearcut units, and partial or selective cut units. The graph shown as Appendix 4 provides a means of estimating what percent of a particular partial cut unit to consider as being in an equivalent clearcut condition.

PECA = Probable Equivalent Clearcut Area allowable in the subdrainage at any one time.

FORMULA III

$$\text{PECA} = A \times I = B \div F = Y \div R \text{ or } \frac{A(1)}{F(R)} = \text{PECA}$$

PECA ÷ DA converts PECA to A% value.

This formula makes it possible to <u>estimate</u> how much of the drainage area can be in an equivalent clearcut condition and not create an increase beyond which the increase in mean annual flow will result in channel damage.

Recovery Rates for Past Activities

In Appendix 6 you will find a graph that was prepared for western Montana and revised for northern Idaho conditions. You will also find a table comparing forest habitat types with hydrologic recovery codes.

The recovery rate for past activity is exponential and depends on the same factors that determine the habitat that has been established on the site. For this reason the rate of recovery will vary from site to site depending upon microclimatic conditions. This can be predicted fairly accurately by using its habitat type groupings and field checking to insure there are no outside factors that would change the rate of recovery. An example would be herbicide spraying during the Blister Rust program.

This graph is the basis for recovery within the computer program.

PROCEDURES FOR OBTAINING NATURAL CONDITIONS

1. Prepare a base map of the area suitable for use with overlays, to present graphically the necessary water resource data. The most appropriate appears to be the standard USGS topographic map, 1/24,000 scale at 2.65 inches/mile or this type map reduced to the 2 inches/mile.

   a. Establish the primary area boundary and watershed boundary.

   b. Delineate all stream channels not shown on the topog map, that are within the drainage area. A drainage channel is considered to exist as long as there is a distinct indentation or "V" in the contour line.

   c. On a suitable overlay material, determine the "order" of all stream channels that make up the drainage network. See Appendix 1.

   d. On the base map and using the stream order overlay for reference, delineate subdrainage boundaries (dashed line). For practical use with these procedures, subdrainages should be:

      at least a 3rd, 4th, and, in some cases, a 5th order stream or drainage.

      an "entity", that is, a closed drainage or one that does not include the small "interior" or "front-facing" drainages.

   An example of a "front-facing" drainage area would be one that has its lower boundary a length of 5th or 6th order channel and is drained by 1st order streams. Determine the area of each subdrainage and the total drainage area and tabularize for use in the following data tables.*** The Water Yield Calculation Sheet (Form III, page 29 and Appendix 13) is an excellent form for runoff determinations as well as an excellent data form for the subdrainage watershed file.***

   e. On suitable overlay material, delineate the even 500-foot contour lines, i.e., 2500, 3000, 3500, etc.

   f. Use a Digitizer or Planimeter to determine the area elevation between contours for each subdrainage.

   g. Obtain from your Forest Hydrologist or applicable publications the elevation-precipitation curves for your locality or, if runoff-elevation relationships are available which vary from the SCS precipitation-runoff curve these may be used.

*** Runoff Curves - SCS and Other Options

The 1976 version of the Water Yield Model uses the Precipitation-Runoff Curve from Hydrology of Mountain Watersheds (Appendix 2) in determining runoff from a vegetation manipulation activity. This curve is an excellent curve for many situations over the Northern Rockies, but may not be right for certain drainages.

A runoff curve developed for a particular planning unit fitting the geologic, soil, precipitation, and vegetation characteristics of the area may be quite different than the SCS curve.

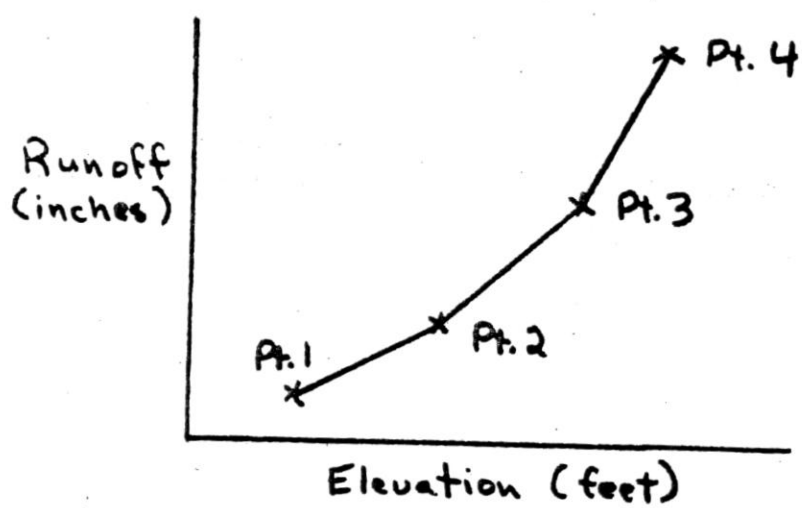
The 1977 Version of the Water Yield Model has the capabilities of using either the SCS curve or the user has the option to insert a curve of his choice. Form I, page 27.

Situation 1: If the user has been using the SCS curve for the runoff calculations, then to be consistent he should continue using the same runoff curve. This option is available in the 1977 Version by inputting the minimum and maximum precipitation and elevation data. This is the same as the 1976 version.

Situation 2: If another runoff curve is used in the determination of total runoff, this curve may be used in determining the water yield increases from vegetation manipulation.

The curve used must be continuous but may have up to three straight line segments.

For example, the runoff may vary in a watershed due to soil moisture holding capacities and vegetation types. A drainage may have its lower elevation in deep soil, heavily timbered areas; its midelevation zones may have shallow soil, sparsely timbered; and its upper elevations may be bare bedrock. The curve then for this drainage may look similar to the following:



A runoff elevation curve may be input if it is either a one segment (straight line) curve, a two segment curve, or a three segment curve. To input these curves the runoff elevation data must be input at the minimum and maximum elevations of all the segments.

If a one segment (straight line) curve is used, two points must be used: the minimum elevation-runoff point and the maximum elevation-runoff point on that line.

If a two segment curve is used, three points of data must be input and if a three segment curve is used, four points must be inserted.

The choice of runoff curves is a "one or the other" type situation. If the SCS curve is desired, you input the precipitation curve and the computer uses the SCS precipitation-runoff curve. If another curve is desired, you input this data on the same line as the precipitation-elevation data with a code 1, 2, or 3 indicating the number of segments in your curve.

For example, if a one segment curve is used it should be inserted as follows:

Runoff Data	Elevation (Feet)	Runoff (Inches)	Code
First Point	2000	20	1
Second Point	6000	60	1

If a two segment curve is used, you continue the lines of data, inserting a third point and coding all lines 2 to indicate two segments.

A three segment curve is input by inputting four points on four lines and coding each point a 3 to indicate a three segment curve.

When inserting a runoff curve do not insert the precipitation curve data.***

h. Determine the weighted average elevation of the subdrainage by multiplying the area in each elevation zone x the elevation and then dividing the total area (Form III, page 29).

$$\frac{\text{sum of (elevations x areas)}}{\text{Total area}} = \text{weighted average elevation}$$

NOTE: For elevation zone - 3000 - 3500 use 3250 feet.

Record on Form I.

2. Determine total runoff for each subdrainage. Multiply area of each elevation zone times runoff figure. Set in this form as an example.

Elevation	Area (Acres)	Runoff (feet)	Water Yield (ac/ft)
2500-3000	50	.5	25.0
3000-3500	150	.8	120.0

Record on Form I

3. Have your timber staff or silviculturist prepare an overlay of the drainage area that delineates the area into the 9 hydrologic habitat groups listed in Appendix 6 and 7. There are different groups for Idaho and Montana.

Record the acreages by grouping in the nine spaces provided on Form I.

***
4. Hydrograph Development

The development of hydrographs is based on the assumption that streams of similar basin characteristics have similar runoff characteristics. The more similar two drainages are in precipitation patterns, vegetation, area, aspects, elevations, and soil and geologic conditions, the more similar the timing of runoff.

Determine the mean monthly runoff from a nearby gaged stream of similar characteristics (USGS Water Resources Data publications) for the years the similar stream was gaged. Input the mean monthly percentages of the annual runoff on Form I for the 12 months of the year. This data is in the following format 12F5.2.***

PROCEDURE FOR DETERMINING EXISTING CONDITIONS

By using Form II, page 28, we record the information needed to build a file of past activities within the drainage.

1. On suitable overlay material, determine past cutting blocks and roads within the drainage. Use your timber stand information as much as possible to determine the history of the individual blocks. This may need some supplementary field work. Fill out one horizontal line for each stand with past activity. Also make entries for roads of different classes. Acreages per mile of road may be obtained from Appendix 8.

   The following information is the same for past and proposed activities.

   a. Stand Number--The 6-digit stand number or a name of a road, fire, or activity such as AGLAND may be used in columns 1-6.

*** b. Activity Codes - Improvements--The 1976 IPNF*H2OY. Model used three activities to determine water yield increases: partial cuts, clearcuts and roads. (These three did not cover all situations. Other activities such as agricultural lands, powerlines, wildfire, or others had to be called either a clearcut, partial cut, or road as these were the activity codes available.) This was not only inaccurate in name, but did not include proper recovery or lack of it on several of these other activities. The Water Yield Model 1977 Version is better able to accommodate the many other types of vegetative manipulation activities that occur in a watershed.

   The 1977 Version has two major changes regarding activities and how they are treated to determine increases in water yields. The first is an increase of six additional activities making a total of nine and second the use of Column 7 to be able to adjust recoveries on certain activities.

Activities which have been included in the 1977 Version in addition to partial cut, clearcut, and roads and the way each is treated are:

Code	Activity	Treated As
4	Wildfire	Clearcut
5	Disease	Partial cut
6	Insects	Partial cut
7	Agricultural lands	Special treatment - see
8	Rights-of-way	additional information
9	Other	regarding Column 7 - must use Column 7.

Column 7 has been utilized to alter recovery on certain individual activities which do not recover as the vegetative-hydrologic recovery curves indicate. For example, agricultural lands do not recover completely but they have vegetation utilizing soil moisture for a good portion of the year. Year after year these lands are planted, the crop raised, and harvested. A particular crop may utilize a specified percent of the available moisture with the remainder adding to the runoff in a watershed. An example might be that this particular crop utilizes 20 percent of the original water yield increase, leaving 80 percent for increases in runoff. An 8 in Column 7 would tell the computer to omit any recovery and would instead multiply the water yield increase by .8, indicating 80 percent of the original water yield increase.

Another example might be a powerline right-of-way which is periodically cut back to a grass-low brush stage in succession which may be 50 percent of the original water yield increase. A 5 in column 7 would eliminate recovery and the result would be that over time this right-of-way contributes 50 percent of the original water yield increase to streamflow.

Another example might be a wildfire or clearcut which had changes in microclimate which resulted in drastic changes in recovery. For example, an extremely hot wildfire may have damaged the soil to a point where essentially little recovery begins for ten years or more. The recovery curve for a hemlock/pachistima habitat type shows 56 percent recovery or 44 percent of the original water yield increase at ten years since the activity, when in reality it may have 80 percent of the original water yield increase due to the lack of recovery. An 8 in Column 7 would fit this particular situation for the wildfire or clearcut better than by using the recovery curves. This, however, would have to be changed in any future runs to indicate the state of the original water yield increase at that date.

The use of Column 7 to indicate a constant percent of the original water yield increase is optional on some activities, essential on others, and forbidden on those treated as partial cuts.

Codes in Column 7 are to be used in the following manner:

	Use of Column 7
1 - Partial cut	Not to be used
2 - Clearcut	Use optional
3 - Road	Use optional
4 - Fire	Use optional
5 - Disease	Not to be used
6 - Insects	Not to be used
7 - Agricultural lands	Must be used
8 - Rights-of-way	Must be used
9 - Other	Must be used

The codes 1 - 9 indicate the following:

Code	1	10% Original Water Yield Increase (90% recovery)
	2	20% Original Water Yield Increase (80% recovery)
	3	30% Original Water Yield Increase (70% recovery)
	4	40% Original Water Yield Increase (60% recovery)
	5	50% Original Water Yield Increase (50% recovery)
	6	60% Original Water Yield Increase (40% recovery)
	7	70% Original Water Yield Increase (30% recovery)
	8	80% Original Water Yield Increase (20% recovery)
	9	90% Original Water Yield Increase (10% recovery) ***

c. Elevation--Record the mid-elevation of all activities. May be recorded to the nearest foot. The elevation on roads may be input as individual sections at various elevations.

*** d. Aspect--Must be recorded on all activities. If stand is on flat ground, record general aspect of watershed - 1-N, 2-NE, 3-E, 4-SE, 5-S, 6-SW, 7-W, 8-NW. ***

e. Year cut or burned--Record year cutting was completed or year slash was burned. May be omitted on roads or activities with constant recovery (use of Column 7).

f. Percent crown removal--Record number, generally 10% intervals.

g. Acres--Record number.

h. Habitat type--Record by habitat group. Appendix 6 and 7. Must be recorded on all activities except roads.

The program will recover past activities up to the date you establish when asked for the year to which watershed status is to be projected.

PROCEDURE FOR PREDICTING IMPACTS OF FUTURE PROPOSALS

If we have correctly entered all the data required for natural conditions and for the past activities, we are now ready to ask some questions on the impacts of future management activities.

The procedure is the same as for the Past Activities.

1. An overlay should be constructed from which data is transferred over to Form II, Proposed Activities, in the same manner as it was presented above for past activities.

2. You can use any combinations of activities from clearcuts to different degrees of shelterwood harvest. You may vary aspects of blocks or elevations and determine the hydrologic impacts of each proposal. Don't forget to add the road impacts for each proposal.

WATER YIELD DATA FORM I

Subdrainage Name____________________ Tributary to ____________________

Subdrainage Acres ____________________ Total Runoff____________________

Weighted Average Elevation____________ Subdrainage Acres by Habitat Type:

1________________ 2________________ 3________________

4________________ 5________________ 6________________

7________________ 8________________ 9________________

Subdrainage Precipitation Data:	Elevation (Ft.)	Precipitation (In.)
Minimum	____________	____________
Maximum	____________	____________

OR

Runoff Data:	Elevation (Ft.)	Runoff (In.)	Code
First point	____________	__________	____
Second point	____________	__________	____
Third point	____________	__________	____
Fourth point	____________	__________	____

Base Hydrograph Data:

Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec

Do you want the water yield increase volume by stand?____________________.

Year to which watershed status is to be projected?____________________.

Percent increase limit for average water yield?____________________.

Do you want the sustained cutting rate calculated?____________________.

Cutting rates? ________ ________ ________ ________ ________ ________.

PAST ________ ACTIVITY INPUT SHEET PROPOSED ________

SUBDRAINAGE NO. ________ SUBDRAINAGE NAME ________________ DATE ________

STAND NUMBER						ACT CODE		ELEVATION					ASP CODE		ACTIVITY YEAR				% CROWN REMOVAL			ACRES				HAB TYPE	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28

WATER YIELD CALCULATION SHEET

Drainage No.: ____________ Data File: ____________ District: ____________

Drainage Name: ____________ Date: ____________ Prepared By: ____________

Elev. Zone (Feet)	Elev. Ave. (Feet)	Total Acres	Wt. Mean Elev.	%	Precip. (in.)	Runoff (in.)	Runoff (ft.)	Acre Ft.
1000-1500	1250							
1500-2000	1750							
2000-2500	2250							
2500-3000	2750							
3000-3500	3250							
3500-4000	3750							
4000-4500	4250							
4500-5000	4750							
5000-5500	5250							
5500-6000	5750							
6000-6500	6250							
6500-7000	6750							
7000-7500	7250							
7500-8000	7750							
TOTAL	A	B	C		D	E	F	G

Base Hydrograph (compared to: ____________ Yrs. Record: ____________)

Month	Jan.	Feb.	Mar.	Apr.	May	June	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
%												
Acre Ft.												

[illegible] ____________
Annual Runoff ____________
Wt. Mean Elev ____________ Total C ÷ Total B=WME

Habitat Acres 1____ 2____ 3____
4____ 5____ 6____
7____ 3____ 9____

Elev. - Precip.
Min. ______ ______
Max. ______ ______

Elev. - Runoff
Pt. 1 ______ ______
Pt. 2 ______ ______
Pt. 3 ______ ______
Pt. 4 ______ ______

Runoff Curve Used: ____________
Precip. Curve Used: ____________
Allowable % Water Yield Increase: ____________
Allowable Water Yield (acre ft.) ____________
Allowable ECA: ____________

REMARKS:

**INSTRUCTIONS FOR PROGRAM OPERATION

Having completed Form I and Form II for each subdrainage the operator can build the data file required for execution of the program. Be sure the bottom of Form I has been completed so that the operator will know what options you would like run. The program will run each subdrainaige for the projected year and then return for another projected year. You may run up to a maximum of five years, then the program automatically stops. You may enter different percent increase limits for average water yield for each subdrainage. A sample run of the program is provided in Appendix 10.

The following commands are necessary to execute the program IPNF*H2OY.MODEL.

```
@ASG,A (DATA FILE)
@ASG,A IPNF*LIB.
@USE 10.,(DATA FILE).
@XQT IPNF LIB.H2OY
DO YOU WANT THE WATER YIELD INCREASE VOLUME BY STAND?  (YES=1.  OR NO=-1.)
XX.
ENTER CURRENT YEAR OR YEAR TO WHICH WATERSHED STATUS IS TO BE PROJECTED,
EG.  1980, NONE=0
XXXX
% INCREASE LIMIT FOR AVERAGE WATER YIELD, EG.  8.0 ?
XX.

DO YOU WISH TO HAVE THE SUSTAINED CUTTING RATE CALCULATED?  (YES=1.  OR NO=-1.)
XX.

ENTER CUTTING RATE (NONE=0.)
XXXX.


etc.
@FREE 10.
@FIN
```

**BEFORE USING THIS PROGRAM IT IS YOUR RESPONSIBILITY TO BE SURE THE CURVES AND ASSUMPTIONS USED IN THIS PROGRAM ARE SUITABLE FOR YOUR AREA!

DATA FILE

The following data card types are required to operate H2OY.MODEL

****

Card Type 1.   This is the subdrainage title card.

Card Column	Description	Format
1 - 80	Subdrainage name.	20A4

****

Card Type 2.   This is the drainage title card.

Card Column	Description	Format
1 - 80	Drainage name.	20A4

****

Card Type 3.   Subdrainage acres card.

Card Column	Description	Format
1 - 9	Subdrainage acres.	F9.0

****

Card Type 4.   Subdrainage runoff card.

Card Column	Description	Format
1 - 9	Total subdrainage runoff in acre-feet.	F9.0

****

Card Type 5   Subdrainage weighted average elevation card.

Card Column	Description	Format
1 - 9	Subdrainage weighted average elevation in feet.	F9.0

****

Card Type 6 Subdrainage acres by habitat type card.

Card Column	Description	Format
1 - 63	Acres by habitat type 1 - 9.	917

****

Card Type 7 Runoff or Precipitation Data. Use A or B only.

****

Card Type 7A1 Minimum precipitation data card.

Card Column	Description	Format
1 - 5	Elevation in feet.	F5.0
6	Blank	
7 - 12	Precipitation in inches.	F6.3

****

Card Type 7A2 Maximum precipitation data card.

Card Column	Description	Format
1 - 5	Elevation in feet.	F5.0
6	Blank	
7 - 12	Precipitation in inches	F6.3

****

Card Type 7B1 First point of runoff line segment 'one'.

Card Column	Description	Format
1 - 5	Elevation in feet.	F5.0
6	Blank	
7 - 12	Runoff in inches.	F6.3
13	Number of line segments inputting (1, 2, or 3)	I1

****

Card Type 7B2 Last point of runoff line segment 'one' and first point of runoff line segment 'two'.

Card Column	Description	Format
1 - 5	Elevation in feet.	F5.0
6	Blank	
7 - 12	Runoff in inches.	F6.3
13	Number of line segments inputting (1, 2, or 3)	I1

****

Card Type 7B3 Last point of runoff line segment 'two' and first point of runoff line sgement 'three', if necessary.

Card Column	Description	Format
1 - 5	Elevation in feet.	F5.0
6	Blank	
7 - 12	Runoff in inches.	F6.3
13	Number of line segments inputting (1, 2, or 3)	I1

****

Card Type 7B4 Last point of runoff line segment 'three', if necessary.

Card Column	Description	Format
1 - 5	Elevation in feet.	F5.0
6	Blank	
7 - 12	Runoff in inches.	F6.3
13	Number of line segments inputting (1, 2, or 3)	I1

****

Card Type 8 Base Hydrograph data.

Card Column	Description	Format
1 - 60	Monthly distribution % of base hydrograph	12F5.2

****

Card Type 9 Stand data card

Card Column	Description	Format
1 - 6	Stand description	A4,A2
7	% of original water yield increase (constant - no recovery)	I1
8	Activity code.	I1
9 - 13	Elevation.	F5.0
14 - 15	Aspect.	I2
16 - 19	Year area was cut or burned.	I4
20 - 22	Percent of crown removal.	F3.0
23 - 26	Acres.	F4.0
27 - 28	Habitat type.	I2

****

Repeat card type 9 as many times as necessary to complete the past sales stand data.

****

Card Type 10A This card signals the end of past sales data and will be followed by proposed sales data.

Card Column	Description	Format
7 - 8	'70'	I2

****

Card Type 10B This card signals the end of each subdrainage in a data file of multiple subdrainages.

Card Column	Description	Format
7 - 8	'80'	I2

****

Card Type 10C This card is used if there is only one subdrainage to be analyzed in the drainage.

Card Column	Description	Format
7 - 8	'90'	I2

****

After card type 10A, repeat card type 9 as many times as necessary to complete the proposed sales stand data. Follow the data with card type 10B or 10C.

After card type 10B, repeat card types 1 - 10., or end of file.

Card type 10C should be followed by end of file.

INTERPRETATION OF THE PROGRAM OUTPUT

The program will print out the heading, year of status, drainage area and the water yield increase for each block of past activity, if this was your selection. This is listed by stand number you input from Form II. Remember this is just the past activities printed at this time. The program will also give you the ECA by habitat type and road impacts along with a print of water yield increase that corresponds to the ECA listed above. ***Each water yield increase is distributed to the six months March through August on the basis of aspect and elevation as shown in Appendix 14, Monthly Distribution of the Water Yield Increase. The hydrographs developed include a base hydrograph, an existing condition hydrograph, and a post sale hydrograph. Use of these hydrographs will tell the land manager how past and proposed activities affect the timing of streamflow, the peak flow, and give an indication of channel impact period.*** The next line is the percent of original water yield increase and the probable equivalent clearcut area allowable for the percent increase limit you indicated to the program at the beginning.

Again remember that the first printout is for past activities. Then the process is repeated for the proposed activity and the next step is a printout of the combined past and proposed activity within the subdrainage.

At this time you may elect to receive a sustained cutting rate by habitat type for an undeveloped area. This subroutine figures the impact of timber removal and the recovery of past harvest by habitat type until a sustained rate is reached that could be carried on yearly with the impact and recovery balancing each other. This could be likened to a sustained yield calculation on the basis of hydrologic impact. This is a good option for use by Land Use Planning in allocating timber yields; however, it has limited use on the project level.

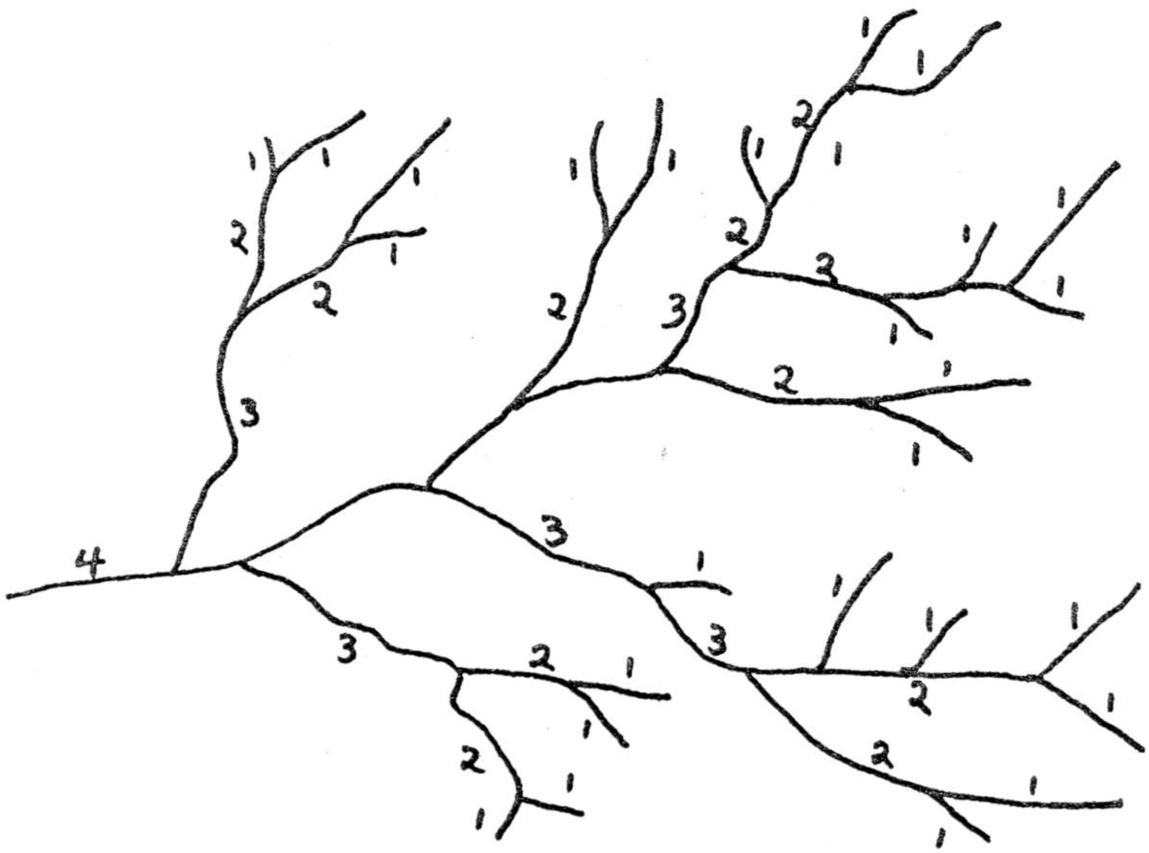
The final option works with the sustained yield option where you input cutting rates and receive a printout by habitat type the years you can harvest at that rate and continue within the water yield limit you have input earlier. This is a good option for Land Use allocations. A "0" year indicates you can cut the amount of acres printed at least 100 years.

Please look at the example program in Appendix 10 for clarification of the output from IPNF*LIB.H2OY.

DETERMINING STREAM ORDERS

Stream order is a term used to characterize the branching of a drainage. A first order stream is any mapable, unbranched tributary. A second order stream is formed when two unbranched first order channels join together; and continues as a second order stream until it meets another second order channel to become a third order channel; or enters a third order or higher channel as a side drainage. A second order channel may have any number of first order channels entering along its length, just as a third order channel may have several second order channels entering from the side, etc.

	Blackline Code
First Order	1
Second Order	2
Third Order	3
Fourth Order	4
Fifth Order	5
Sixth Order	6



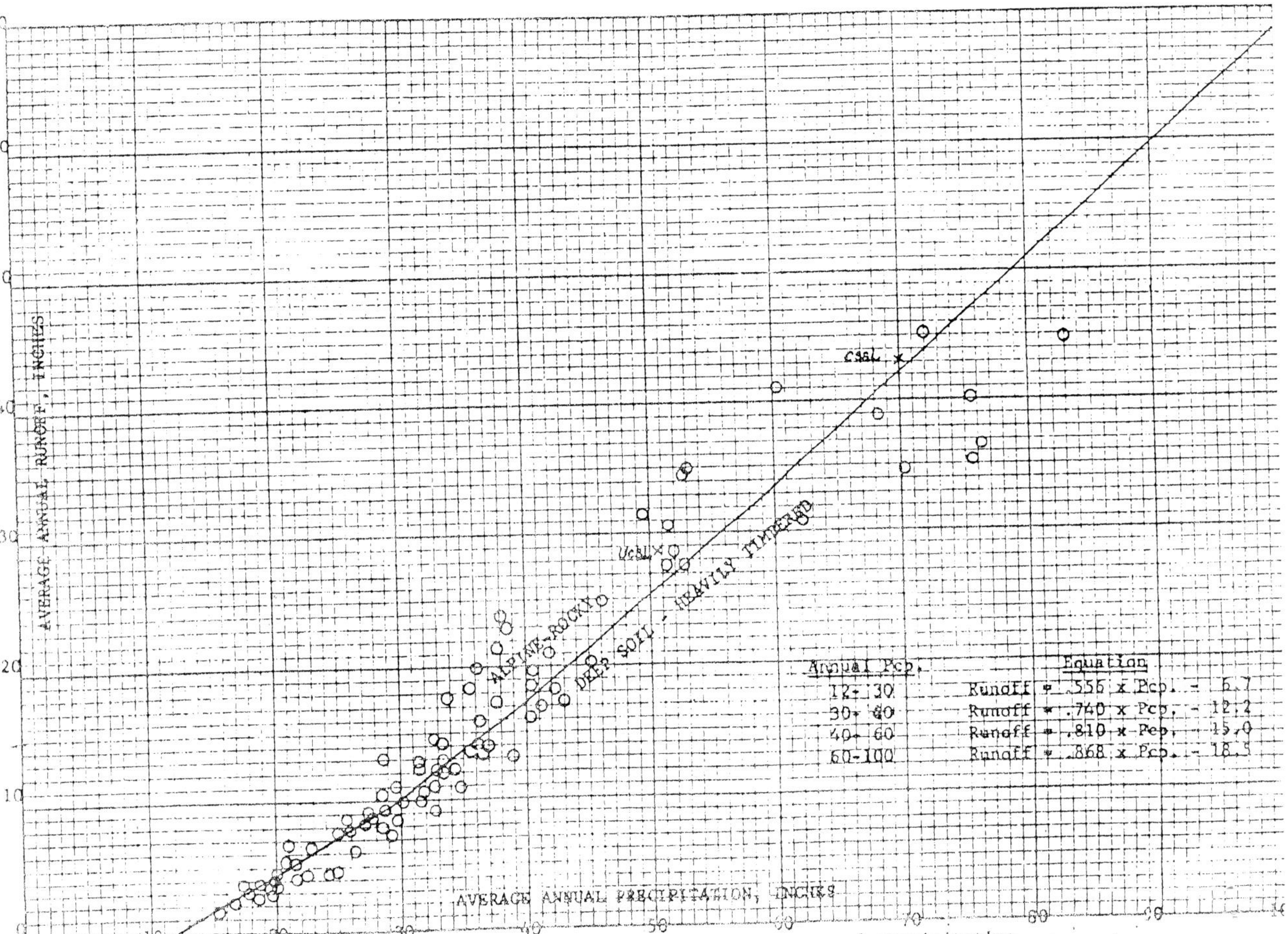
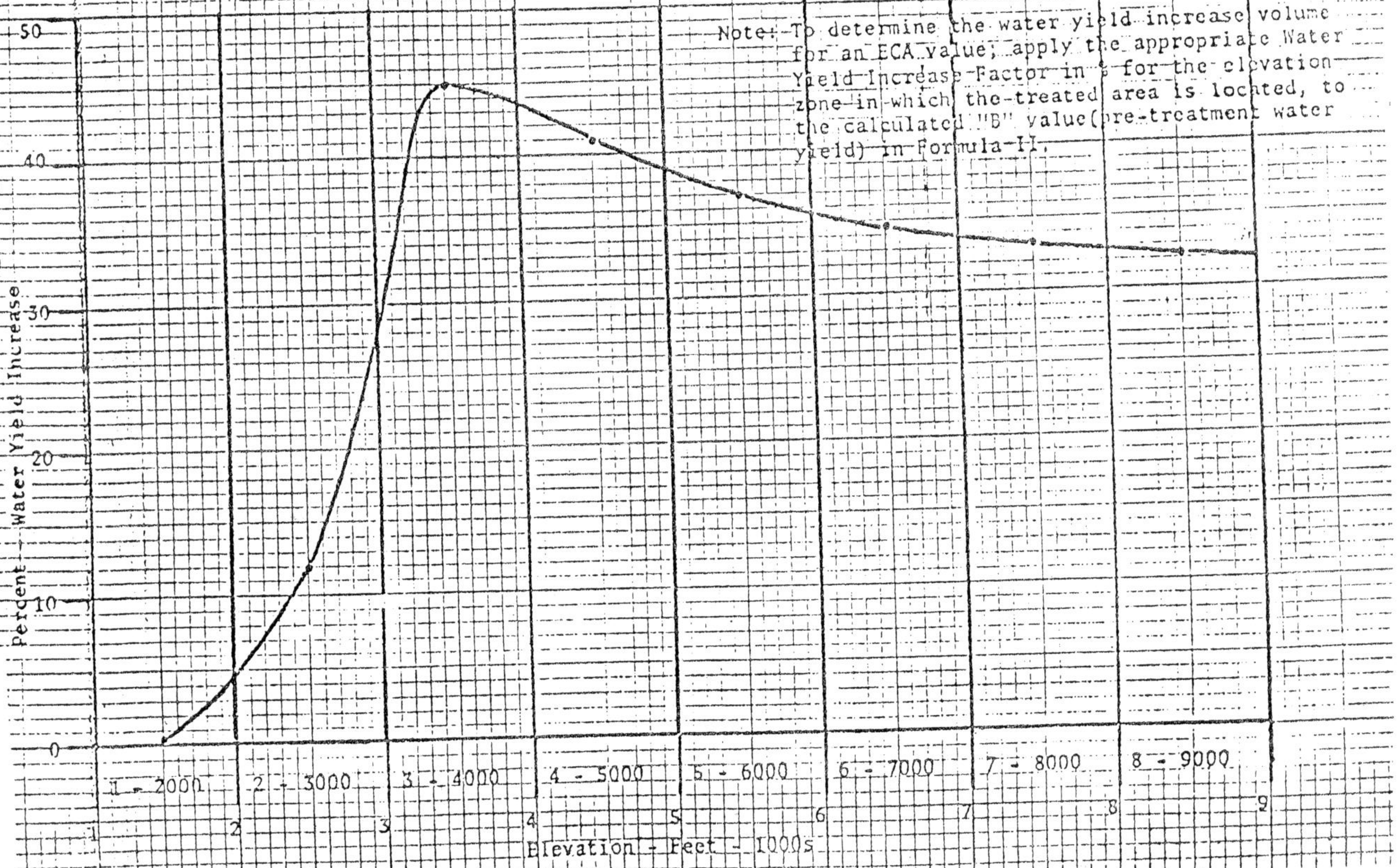


Figure 1. Average annual runoff vs. average annual precipitation.

APPENDIX 2

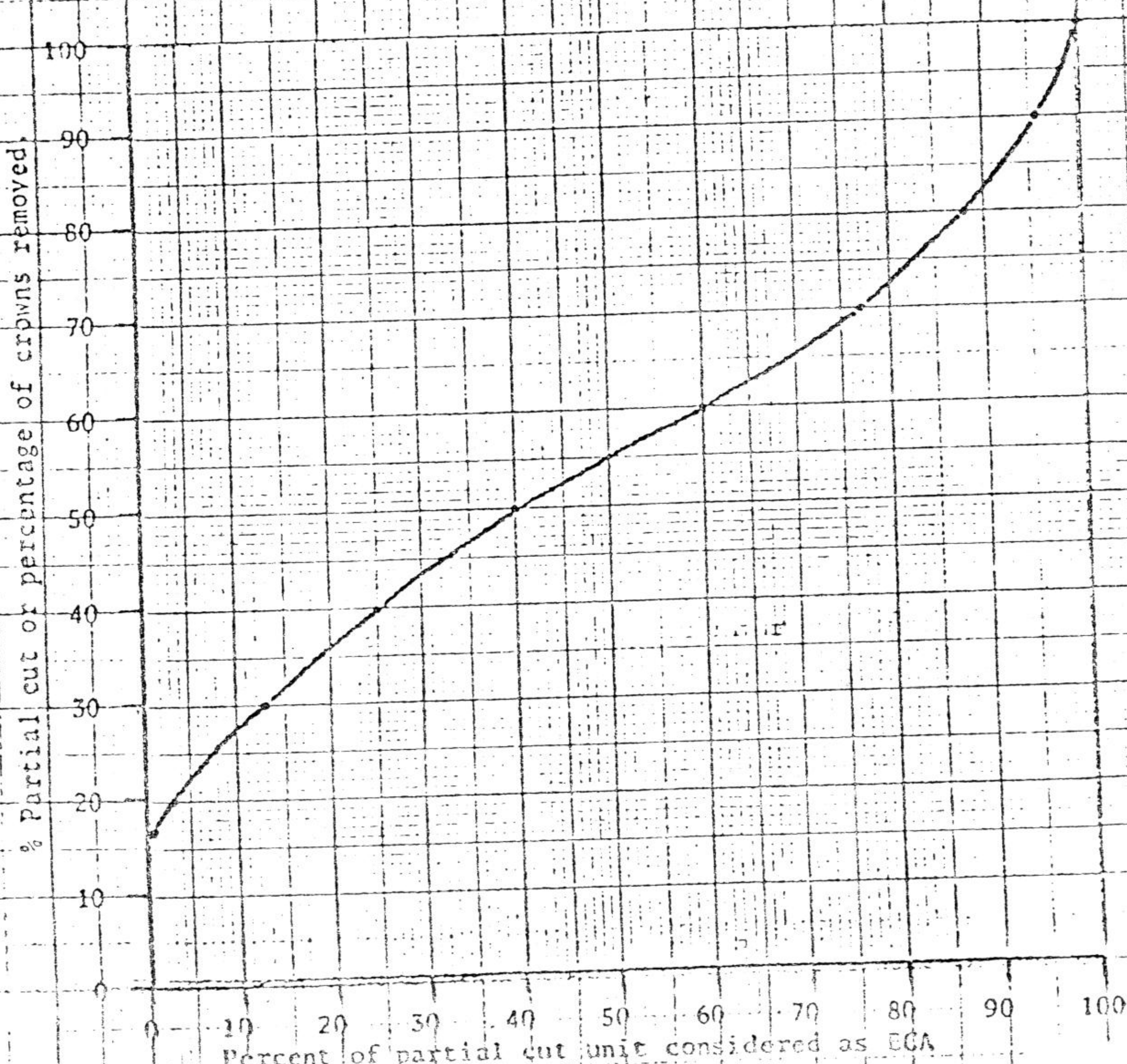
FIGURE 12. Water Yield Increase Factor ("F" value) by Elevation Zones. Based on an Analysis of Water Balance Data for the Nezperce National Forest.



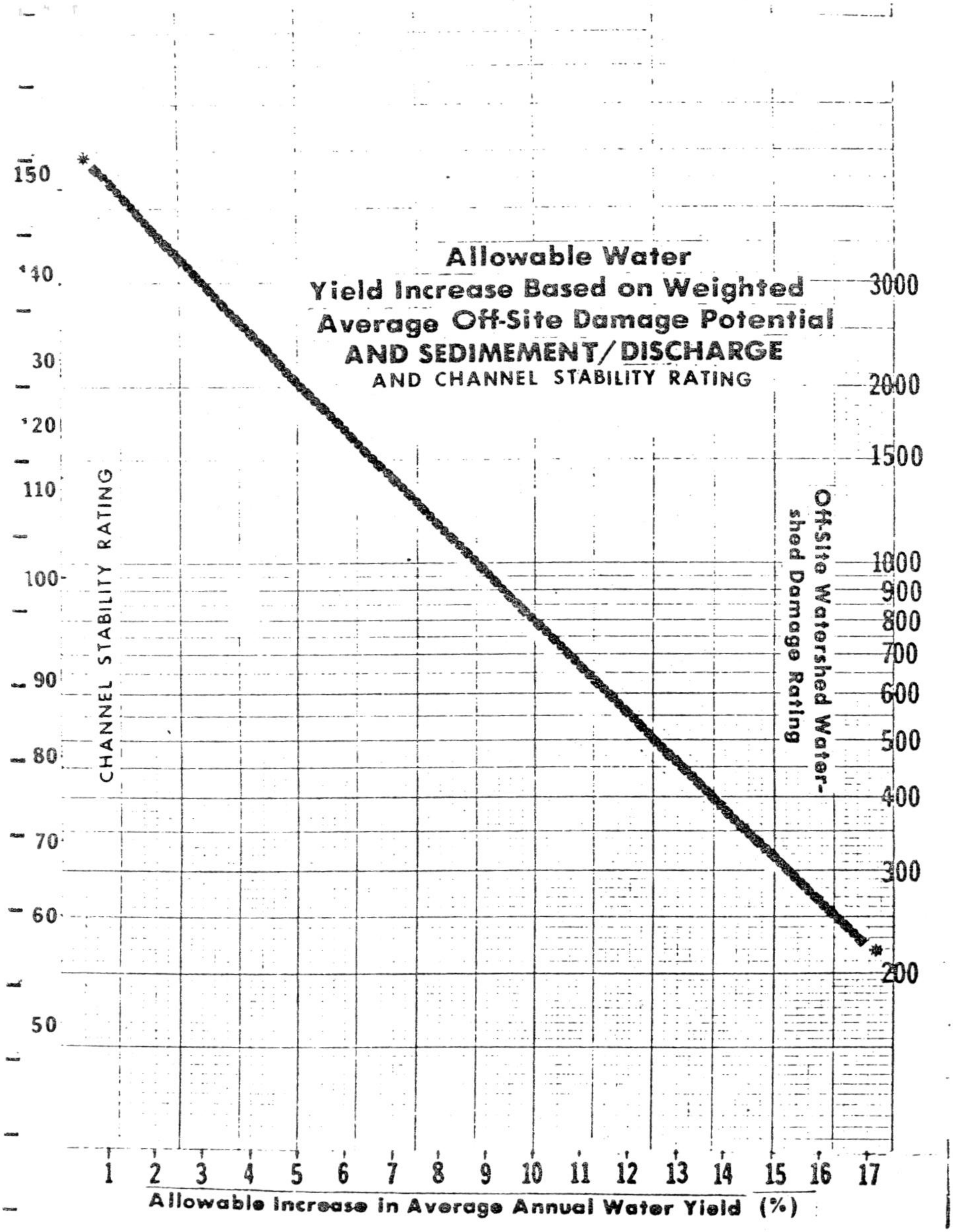
Note: To determine the water yield increase volume for an ECA value, apply the appropriate Water Yield Increase Factor in % for the elevation zone in which the treated area is located, to the calculated "B" value (pre-treatment water yield) in Formula II.

FIGURE 10. Estimating the Percent of a Partial Cut Unit to Consider as ECA. (4500 - 6000 Ft., Nezperce)

Example: An 80 acre partial cut unit with 50% of the crowns removed would have an ECA of 40% or 32 acres.

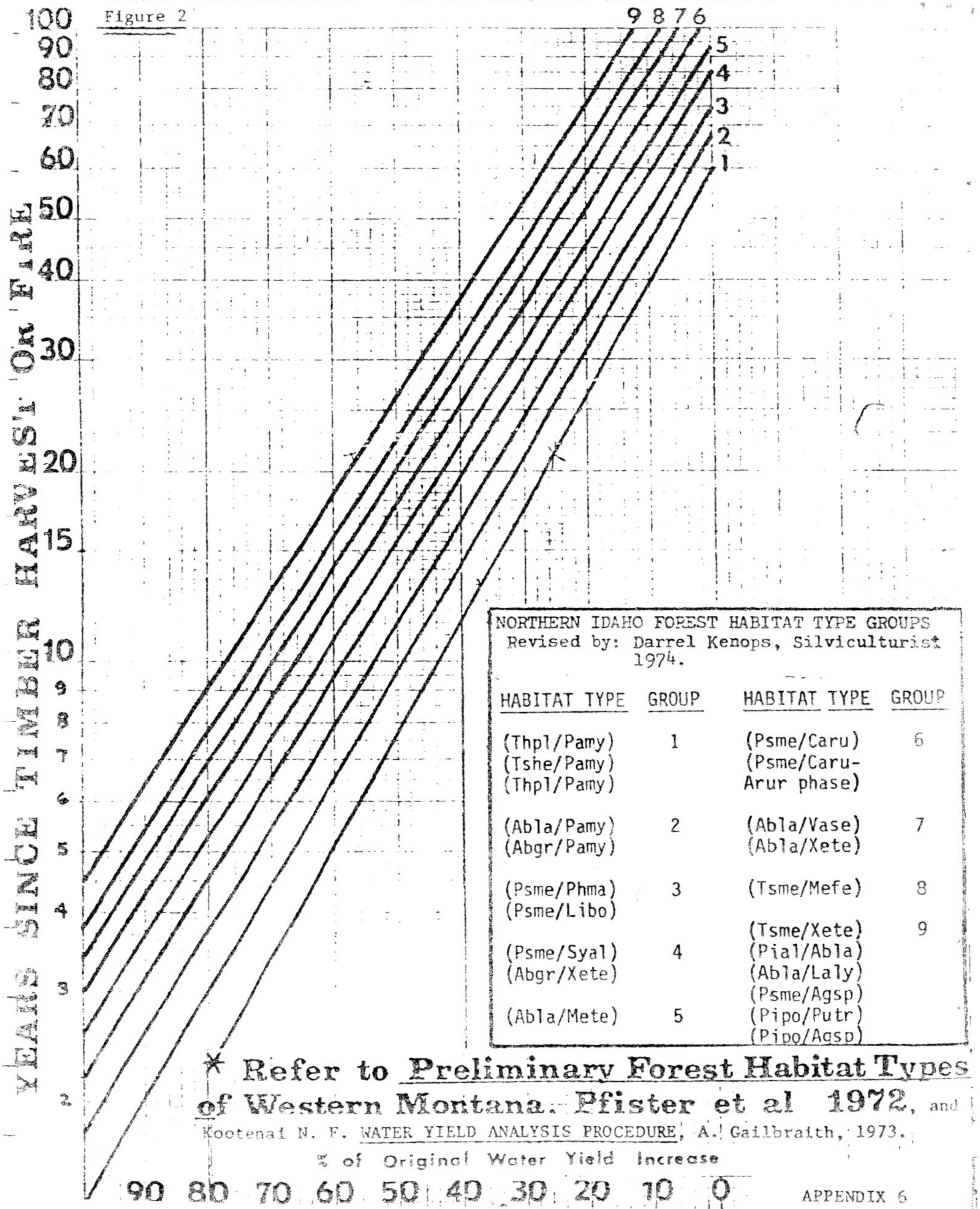


APPENDIX 4


Allowable Water
Yield Increase Based on Weighted
Average Off-Site Damage Potential
AND SEDIMEMENT/DISCHARGE
AND CHANNEL STABILITY RATING
CHANNEL STABILITY RATING
150
140
30
20
110
100
90
80
70
60
50
Off-Site Watershed Water-shed Damage Rating
3000
2000
1500
1000
900
800
700
600
500
400
300
200
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
Allowable Increase in Average Annual Water Yield (%)

VEGETATIVE - HYDROLOGIC RECOVERY

Figure 2



NORTHERN IDAHO FOREST HABITAT TYPE GROUPS
Revised by: Darrel Kenops, Silviculturist
1974.

HABITAT TYPE	GROUP	HABITAT TYPE	GROUP
(Thpl/Pamy) (Tshe/Pamy) (Thpl/Pamy)	1	(Psme/Caru) (Psme/Caru-Arur phase)	6
(Abla/Pamy) (Abgr/Pamy)	2	(Abla/Vase) (Abla/Xete)	7
(Psme/Phma) (Psme/Libo)	3	(Tsme/Mefe)	8
(Psme/Syal) (Abgr/Xete)	4	(Tsme/Xete) (Pial/Abla) (Abla/Laly) (Psme/Agsp)	9
(Abla/Mete)	5	(Pipo/Putr) (Pipo/Agsp)	

* Refer to **Preliminary Forest Habitat Types of Western Montana. Pfister et al 1972**, and Kootenai N. F. WATER YIELD ANALYSIS PROCEDURE, A. Gailbraith, 1973.

Cross Reference Listing of North Idaho Habitat Types

Habitat Type	Daubenmire Code	"New" Idaho Code	Vegetative Recovery Class Code
Festuca & Carex geyerii meadow	05	999	2
Agropyron spicatum meadow	06	999	2
Carex & Scripus meadow	07	999	2
Populus tricocarpa (hardwood)	08	999	2
Alnus sinuata (hardwood)	09	999	2
Pinus ponderosa/Agropyron spicatum	10	130	9
Pinus ponderosa/Festuca idahoensis	11	140	9
Pinus ponderosa/Purshia tridentata	12	160	9
Pinus ponderosa/Stipa comata	13	110	9
Pinus ponderosa/Symphoricarpos albus	14	170	9
Pinus ponderosa/Physocarpus malvaceus	15	190	9
Pinus ponderosa and/or Pseudotsuga menziesii/Scree	18	010	9
Pseudotsuga menziesii/Physocarpus malvaceus, Agropyron phase	19	010	9
Pseudotsuga menziesii/Agropyron spicatum	20	010	9
Pseudotsuga menziesii/Physocarpus malvaceus	21	260	3
Pseudotsuga menziesii/Symphoricarpos albus	22	310	4
Pseudotsuga menziesii/Calamagrostis rubescens	23	320	6
Pseudotsuga menziesii/Calamagrostis rubescens, Arctostaphylos phase	24	322	6
Pseudotsuga menziesii/Physocarpus malvaceus rockland	25	010	9
Pseudotsuga menziesii/Linaea borealis	26	010	3
Abies grandis/Pachistima myrsinites	31	520	2
Abies lasiocarpa/Pachistima myrsinites	32	620	2
Abies lasiocarpa/Xerophyllum tenax	33	690	7
Abies lasiocarpa/Menziesii ferrunginea	34	670	5
Abies lasiocarpa/Vaccinium scoparium	35	730	7
Abies lasiocarpa/Rockland	36	850	9
Abies lasiocarpa/Rockland complex	37	732	9
Abies grandis/Xerophyllum tenax	38	510	4
Thuja plicata/Pachistima myrsinites	41	530	1
Thuja plicata/Athyrium felix-femina	42	540	1
Thuja plicata/Oplopanax horridus	43	550	1
Thuja plicata/Xerophyllum tenax	44	530	1
Thuja plicata/Adiantum pedatum	45	530	1
Tsuga heterophylla/Pachistima myrsinites	51	570	1
Pachistima myrsinites/Rockland complex	52	010	9
Tsuga heterophylla/Xerophyllum tenax	53	570	1
Tsuga mertensiana/Xerophyllum tenax	54	710	9
Tsuga mertensiana/Menziesii ferruginea	55	680	8
Pinus albacaulis/Abies lasiocarpa	66	850	9
Abies lasiocarpa/Parkland (Carex & Festuca)	67	720	9
Abies lasiocarpa/Larix lyallii	68		9
Non-forest	70	999	9
Abies lasiocarpa/Luzula sp.	83	010	9

ROAD - E.C.A. CONVERSION GUIDELINES

When using the procedure to determine hydrologic impacts from vegetation manipulation, it is important to account for the water yield increase attributable to existing and planned roads. The following road conversion procedure to E.C.A. is recommended; however, adjustments can and must be made with this guideline framework for:

1. Revegetation status of road cuts and fills.
2. Type and intensity of road right-of-way clearing.
3. Hydraulic adequacy of stream crossings.
4. Soil erosion hazard.
5. Type of road surface.
6. Type of road drainage.
7. Size of cut and fill slopes.

Guideline

Total road class miles x acres/mile cleared x ECA factor = acres of ECA in roads. The Forest Hydrologist will determine the actual ECA conversion factor.

Road ECA conversion factors vary by class of road. The amount of road surface compaction and surfacing material is a major consideration in determining conversion factors.

Road Class	ECA Multiplier Factor
Skid trail - fire trail	
Temporary spur	
Project road (12' fed)	
Single track system	
1-1/2 track system	
2 track system	
2 track system (paved)	

NOTE: Use of the above factors must be guided by: proximity of road to stream channel; anticipated hydrologic recovery of disturbed areas, if any; the number and type of stream crossings; and road drainage.

The acres of cleared area per mile of road constructed may be arrived at by actual contract figures supplied by Engineering or from the following table that was supplied from actual measurements of recently constructed roads on the Idaho Panhandle National Forests.

Acres of clearing per mile of road adjusted for slope.

Slope of adjacent terrain by 10% classes	Width of road with ditch 12'	14'	16'
10 percent	3.8	3.9	4.0
20 percent	4.3	4.7	5.1
30 percent	4.8	5.3	5.8
40 percent	5.8	6.3	6.8
50 percent	6.0	6.6	7.3

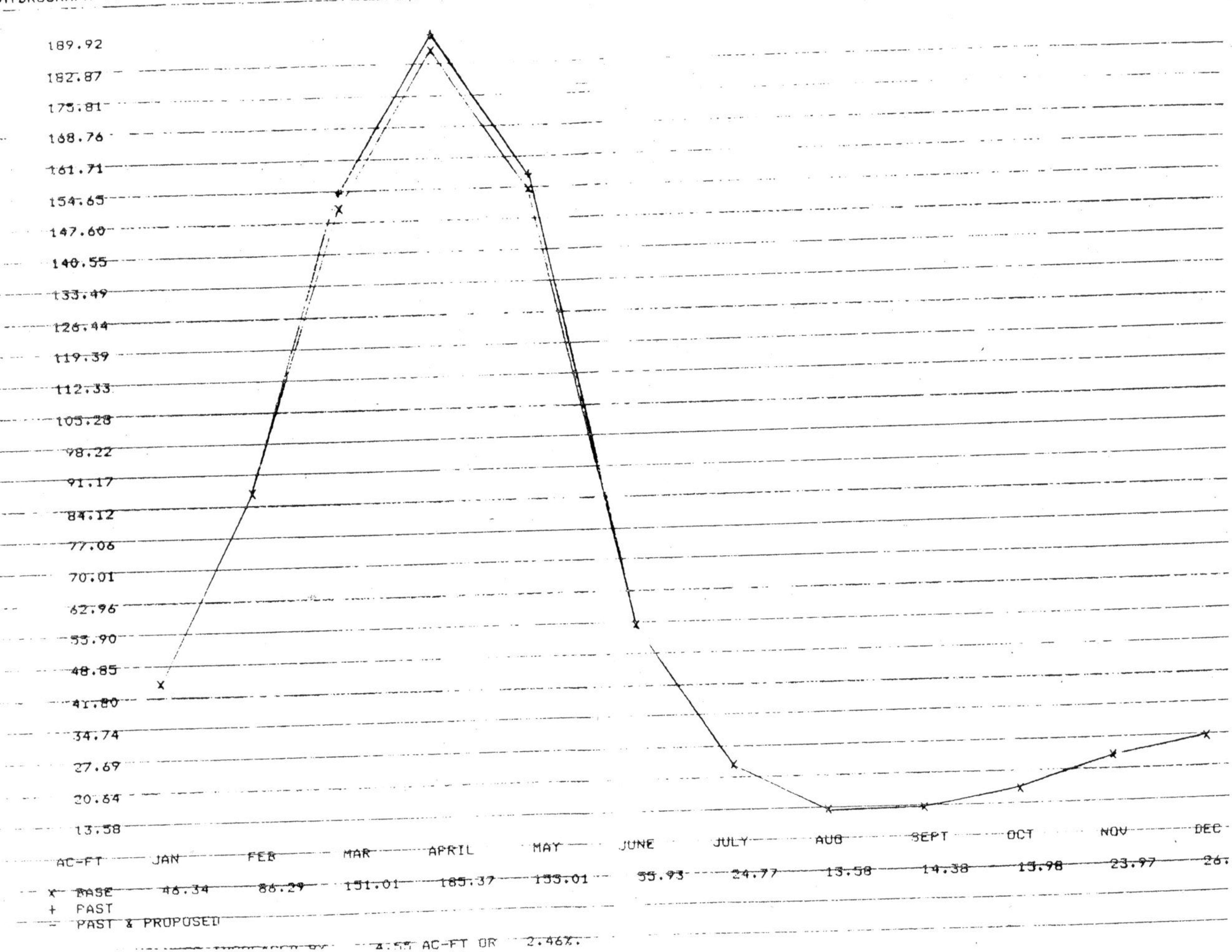
Note that even a narrow road has a large impact on steep slopes.

```
LINES:40 FIELDATA
>@ed,r trout.
READ-ONLY MODE
CASE UPPER ASSUMED
ED 15.00-02/14/77-15:19:26-(0,)
EDIT
0:>inp+
        1:DRY CREEK
        2:TROUT CREEK
        3:1000.
        4:799.
        5:2950.
        6:    500    250    250
        7:2000. 23.
        8:5000. 43.
        9:  5.8 10.8 18.9 23.2 19.4  7.0  3.1  1.7  1.8  2.0  3.0  3.3
       10:AGLAND87 2250 5          100 1
       11:P-LINE48 2500 5           50 1
       12:S-ROAD 3 2500 5           25 2
       13:SW-CUT 1 2250 51970 70 100 2
       14:CLRCUT 2 2400 61978100  35 2
       15:MTPBUG 6 2400 61965 30 200 1
       16:       80
       17:SPRING CREEK
       18:TROUT CREEK
       19:3500.
       20:8645.
       21:4071.
       22:    500   1000                   500                        1500
       23:2000. 10.   3
       24:3000. 15.   3
       25:4500. 30.   3
       26:5500. 60.   3
       27:  3.3  4.1  6.2 13.9 33.7 22.2  4.7  1.3  1.4  2.2  3.4  3.6
       28:SDBURN94 4500 21975     250 9
       29:CLRCUT 2 4000 11979100  60 2
       30:C-THIN 1 3000 11979 40 150 2
       31:S-ROAD 3 4000 11970      50 2
       32:B-RUST 5 4000 11970 50 200 1
       33:CLRCUT92 4500 21970     100 9
       34:       70
       35:CLRCUT 2 4000 21980100 100 5
       36:S-ROAD 3 4000 21980      25 5
       37:SW-CUT 1 4000 21980 70 200 5
       38:CLRCUT 2 5000 11980100 150 9
       39:CLRCUT 2 3000 31980100 150 2
       40:       80
EOF:40
0:>exit
NO CORRECTIONS APPLIED.
>
```

APPENDI[illegible]

```
@asg,a ...out.
READY
>@asg,a 1Pnf*11D.
FACILITY WARNING  000200000000
>@uses
@use 10.,trout.
>@xqt 1Pnf*11D.m209
-@@COMPLETE

                    WATER YIELD MODEL - 1977 VERSION (DAVE THORSON MODIFICATIONS)
                    BE SURE YOUR DATA FOLLOWS THE NEW FORMAT BEFORE PROCEEDING
                    LIST FS*R1.INFORM OR CALL DAVE - (208) 263-5111

 DO YOU WANT THE WATER YIELD INCREASE VOLUME BY STAND?  (YES=1. OR NO=-1.)
>1.
 ENTER CURRENT YEAR OR YEAR TO WHICH WATERSHED STATUS IS TO BE PROJECTED, EG. 1980, NONE=0
>1980

 % INC LIMIT FOR AVERAGE WATER YIELD, EG. 8.0 ?
>12.0

 DATE:021477  TIME:152137

            SUBDRAINAGE DRY CREEK
                  1980

            DRAINAGE TROUT CREEK
            HAVING TOTAL ACRES OF       1000.
            AND TOTAL RUNOFF OF        799.ACRE-FEET.
                                                                      MARCH   APRIL    MAY    JUNE   JULY  AUGUST
 STAND:AGLAND WATER YIELD INCREASE VOLUME IS   3.48 ACRE-FEET.        1.05    1.39     .87    .17    .00    .00
 STAND:P-LINE WATER YIELD INCREASE VOLUME IS   1.68 ACRE-FEET.         .51     .67     .42    .08    .00    .00
 STAND:S-ROAD WATER YIELD INCREASE VOLUME IS   2.11 ACRE-FEET.         .53     .84     .53    .11    .00    .00
 STAND:SW-CUT WATER YIELD INCREASE VOLUME IS   1.62 ACRE-FEET.         .48     .65     .40    .08    .00    .00
 STAND:CLRCUT WATER YIELD INCREASE VOLUME IS   2.08 ACRE-FEET.         .57     .78     .62    .10    .00    .00
 STAND:MTPBUG WATER YIELD INCREASE VOLUME IS    .58 ACRE-FEET.         .16     .22     .17    .03    .00    .00

 TOTAL MONTHLY DISTRIBUTION OF THE WATER YIELD INCREASE VOLUME        3.40    4.55    3.02    .38    .00    .00

                      EXISTING ELA IN ACRES BY HABITAT TYPE
          1       2       3      4      5      6      7      8      9    ROADS    TOTAL
     108.80   68.85     .00    .00    .00    .00    .00    .00    .00    25.00   202.65 ACRES

                      WATER YIELD INCREASE VOLUME BY HABITAT TYPE
          1       2       3      4      5      6      7      8      9    ROADS    TOTAL
       5.75    3.70     .00    .00    .00    .00    .00    .00    .00     2.11    11.55 ACRE-FEET

  PER CENT OF ORIGINAL WATER YIELD INCREASE
         1.44 PER CENT
  PROBABLE EQUIVALENT CLEARCUT AREA ALLOWABLE
        439.06 ACRES

 DO YOU WISH TO HAVE THE SUSTAINED CUTTING RATE CALCULATED? (YES=1. OR NO=-1.)
>-1.
 ENTER CUTTING RATE. (NONE=0.)
>0.
```

HYDROGRAPH YEAR 1980 DRY CREEK



DATE:021477 TIME:152137

SUBDRAINAGE SPRING CREEK
1980

DRAINAGE TROUT CREEK
HAVING TOTAL ACRES OF 3500.
AND TOTAL RUNOFF OF 8645.ACRE-FEET.

	MARCH	APRIL	MAY	JUNE	JULY	AUGUST
STAND:SDBURN WATER YIELD INCREASE VOLUME IS 230.64 ACRE-FEET.	.00	17.30	86.49	92.26	23.06	11.53
STAND:CLRCUT WATER YIELD INCREASE VOLUME IS 54.50 ACRE-FEET.	2.73	10.90	21.80	16.35	2.73	.00
STAND:C-THIN WATER YIELD INCREASE VOLUME IS 13.69 ACRE-FEET.	1.86	4.11	5.48	2.74	.00	.00
STAND:S-ROAD WATER YIELD INCREASE VOLUME IS 45.42 ACRE-FEET.	2.27	9.08	18.17	13.63	2.27	.00
STAND:B-RUST WATER YIELD INCREASE VOLUME IS 31.01 ACRE-FEET.	1.55	6.20	12.40	9.30	1.55	.00
STAND:CLRCUT WATER YIELD INCREASE VOLUME IS 92.26 ACRE-FEET.	.00	6.92	34.60	36.90	9.23	4.61
TOTAL MONTHLY DISTRIBUTION OF THE WATER YIELD INCREASE VOLUME	8.41	54.51	178.93	171.18	38.84	16.14

EXISTING ECA IN ACRES BY HABITAT TYPE

1	2	3	4	5	6	7	8	9	ROADS	TOTAL
34.14	97.50	.00	.00	.00	.00	.00	.00	315.00	50.00	496.64 ACRES

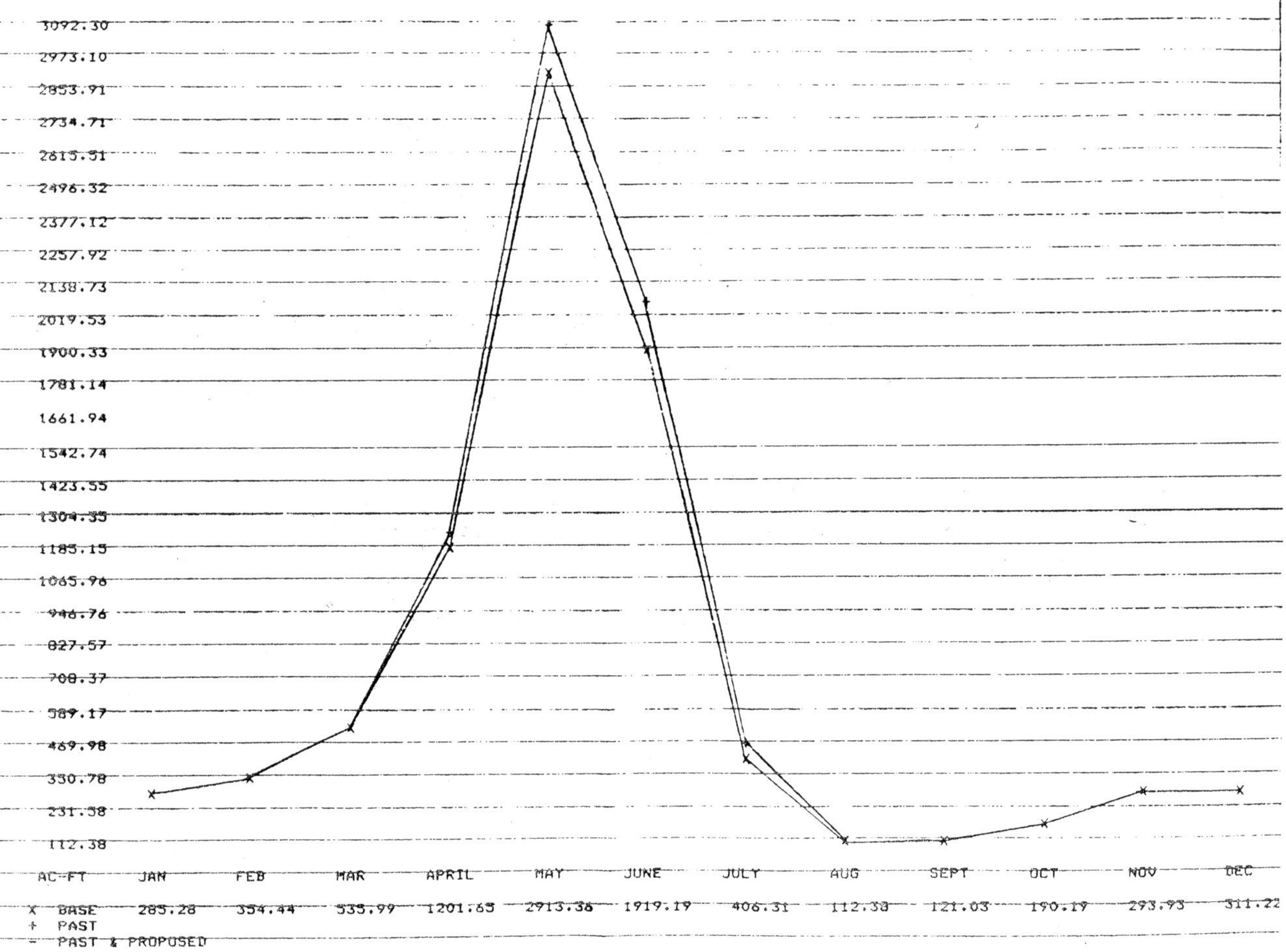
WATER YIELD INCREASE VOLUME BY HABITAT TYPE

1	2	3	4	5	6	7	8	9	ROADS	TOTAL
31.01	68.19	.00	.00	.00	.00	.00	.00	322.90	45.42	467.52 ACRE-FEET

PER CENT OF ORIGINAL WATER YIELD INCREASE
5.41 PER CENT
PROBABLE EQUIVALENT CLEARCUT AREA ALLOWABLE
559.39 ACRES

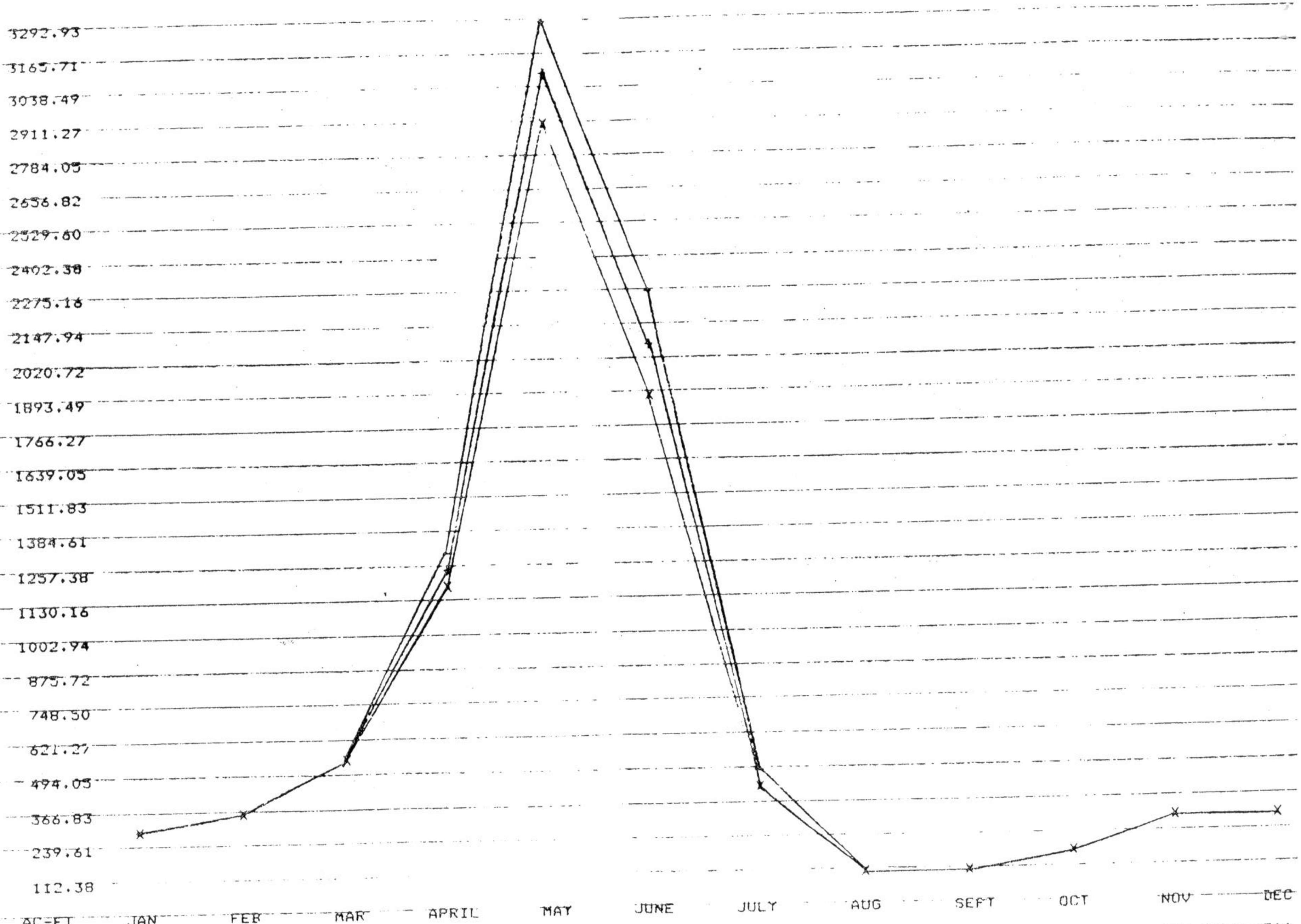
DO YOU WISH TO HAVE THE SUSTAINED CUTTING RATE CALCULATED? (YES=1. OR NO=-1.)
?-1.
ENTER CUTTING RATE (NONE=0.)
?0.

HYDROGRAPH YEAR 1980 SPRING CREEK DATE:021477



```
STAND:CLRCUT WATER YIELD INCREASE VOLUME IS   90.84 ACRE-FEET.        1.82    20.44    36.33    24.98    4.54    .00
STAND:S-ROAD WATER YIELD INCREASE VOLUME IS   22.71 ACRE-FEET.         .45     5.11     9.08     6.25    1.14    .00
STAND:SW-CUT WATER YIELD INCREASE VOLUME IS  137.53 ACRE-FEET.        2.75    30.94    55.01    37.82    6.88    .00
STAND:CLRCUT WATER YIELD INCREASE VOLUME IS  215.89 ACRE-FEET.         .00    10.79    75.56    97.15   21.59  10.79
STAND:CLRCUT WATER YIELD INCREASE VOLUME IS   54.77 ACRE-FEET.        5.48    19.17    24.65     5.48     .00    .00

TOTAL MONTHLY DISTRIBUTION OF THE WATER YIELD INCREASE VOLUME        18.90   140.97   379.57   342.85   72.98  26.94

                          EXISTING ECA IN ACRES BY HABITAT TYPE
               1      2        3       4      5       6       7        8       9    ROADS   TOTAL
 RES       34.14 247.50      .00     .00 251.40    .9S$3*r;+r;r'

                       WATER YIELD INCREASE VOLUME BY HABITAT TYPE
               1      2        3       4      5       6       7        8       9    ROADS   TOTAL
***PARITY ERROR***
           31.01 122.96      .00     .00 228.36     .00     .00      .00  538.78    68.13   989.24 ACRE-FEET
***PARITY ERROR***

 PER CENT OF ORIGINAL WATER YIELD INCREASE
         11.44 PER CENT
 PROBABLE EQUIVALENT CLEARCUT AREA ALLOWABLE
          559.39 ACRES

DO YOU WISH TO HAVE THE SUSTAINED CUTTING RATE CALCULATED? (YES=1. OR NO=-1.)
?-1.
ENTER CUTTING RATE (NONE=0.)
?0.
```

HYDROGRAPH YEAR 1980 SPRING CREEK



	JAN	FEB	MAR	APRIL	MAY	JUNE	JULY	AUG	SEFT	OCT	NOV	DEC
X BASE	285.28	354.44	535.99	1201.65	2913.36	1919.19	405.31	112.38	121.03	190.19	293.93	311

\+ FAST
= FAST & PROPOSED

PEAK FLOW VOLUMES INCREASED BY 379.57 AC-FT OR 13.03%.

DRAINAGE TROUT CREEK
1980
HAVING TOTAL ACRES OF 4500.
AND TOTAL RUNOFF 9444. ACRE-FEET

	MARCH	APRIL	MAY	JUNE	JULY	AUGUST
TOTAL MONTHLY DISTRIBUTION OF THE WATER YIELD INCREASE VOLUME	22.30	145.52	382.59	343.42	72.98	26.94

EXISTING ECA IN ACRES BY HABITAT TYPE

1	2	3	4	5	6	7	8	9	ROADS	TOTAL
142.94	316.35	.00	.00	251.40	.00	.00	.00	465.00	100.00	1275.69 ACRES

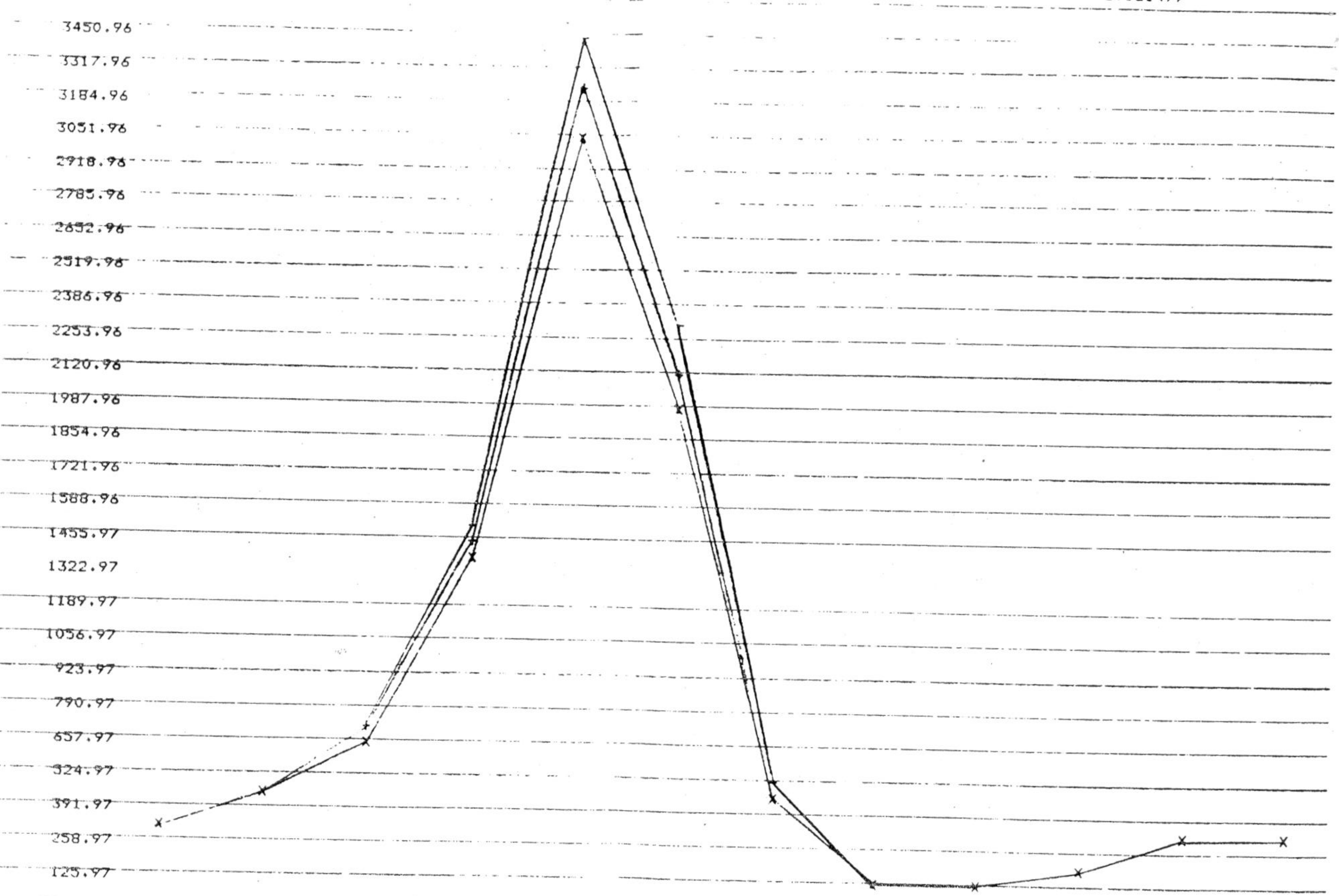
WATER YIELD INCREASE VOLUME BY HABITAT TYPE

1	2	3	4	5	6	7	8	9	ROADS	TOTAL
36.75	126.66	.00	.00	228.36	.00	.00	.00	538.78	70.23	1000.79 ACRE-FEET

PER CENT OF ORIGINAL WATER YIELD INCREASE
10.60 PER CENT
PROBABLE EQUIVALENT CLEARCUT AREA ALLOWABLE
998.45 ACRES

DO YOU WISH TO HAVE THE SUSTAINED CUTTING RATE CALCULATED? (YES=1. OR NO=-1.)
>-1.
ENTER CUTTING RATE (NONE=0.)
>0.

DROQ YE 980 JUT K E:01..7



AC=FT	JAN	FEB	MAR	APRIL	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
X BASE	331.63	440.74	687.00	1387.02	3068.37	1975.12	431.08	125.97	135.41	206.17	317.90	337.59

+ PAST
- PAST & PROPOSED

PEAK FLOW VOLUMES INCREASED BY 382.59 AC-FT OR 12.47%.

PAST ______ ACTIVITY INPUT SHEET PROPOSED ______

SUBDRAINAGE NO. ______ SUBDRAINAGE NAME ______ DATE ______

STAND NUMBER						ACT CODE		ELEVATION					ASP CODE		ACTIVITY YEAR				% CROWN REMOVAL			ACRES				HAB TYPE	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28

WATER YIELD DATA FORM I

Subdrainage Name____________________ Tributary to ____________________

Subdrainage Acres ____________________ Total Runoff____________________

Weighted Average Elevation__________ Subdrainage Acres by Habitat Type:

1_______________ 2_______________ 3_______________

4_______________ 5_______________ 6_______________

7_______________ 8_______________ 9_______________

Subdrainage Precipitation Data:	Elevation (Ft.)	Precipitation (In.)
Minimum	__________	__________
Maximum	__________	__________

OR

Runoff Data:	Elevation (Ft.)	Runoff (In.)	Code
First point	__________	__________	____
Second point	__________	__________	____
Third point	__________	__________	____
Fourth point	__________	__________	____

Base Hydrograph Data:

Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec

Do you want the water yield increase volume by stand?____________________.

Year to which watershed status is to be projected?____________________.

Percent increase limit for average water yield?____________________.

Do you want the sustained cutting rate calculated?____________________.

Cutting rates? _______ _______ _______ _______ _______ _________.

Monthly Distribution of the Water Yield Increase ("B" Value); Expressed as a Percentage of the Total Yield Increase Volume, by Elev. Zones and General Aspect.

	South						North					
Elev. Zone	Mar.	Apr.	May	June	July	Aug.	Mar.	Apr.	May	June	July	Aug.
2-3500	30	40	25	5	0	0	10	30	40	20	0	0
3500-4500	20	30	40	10	0	0	5	20	40	30	5	0
4500-6000	10	20	45	20	5	0	0	5	35	45	10	5
6000-7000	0	10	50	25	10	5	0	5	25	50	15	5
Elev. Zone	West						East					
2-3500	25	35	35	5	0	0	10	35	45	10	0	0
3500-4500	15	25	40	15	5	0	5	25	40	25	5	0
4500-6000	5	15	45	25	5	5	0	10	40	35	10	5
6000-7000	0	5	45	40	5	5	0	5	35	45	10	5
Elev. Zone	Southwest						Northwest					
2-3500	27.5	37.5	30	5	0	0	17.5	32.5	37.5	12.5	0	0
3500-4500	17.5	27.5	40	12.5	2.5	0	10	22.5	40	22.5	5	0
4500-6000	7.5	17.5	45	22.5	5	2.5	2.5	10	40	35	7.5	5
6000-7000	0	7.5	47.5	32.5	7.5	5	0	5	35	45	10	5
Elev. Zone	Southeast						Northeast					
2-3500	20	37.5	35	7.5	0	0	10	32.5	42.5	15	0	0
3500-4500	12.5	27.5	40	17.5	2.5	0	5	22.5	40	27.5	5	0
4500-6000	5	15	42.5	27.5	7.5	2.5	0	7.5	37.5	40	10	5
6000-7000	0	7.5	42.5	35	10	5	0	5	30	47.5	12.5	5

Drainage No.: ____________ Data File: ____________ District: ____________

Drainage Name: ____________ Date: ____________ Prepared By: ____________

Elev. Zone (Feet)	Elev. Ave. (Feet)	Total Acres	Wt. Mean Elev.	%	Precip. (in.)	Runoff (in.)	Runoff (ft.)	Acre Ft.
1000-1500	1250							
1500-2000	1750							
2000-2500	2250							
2500-3000	2750							
3000-3500	3250							
3500-4000	3750							
4000-4500	4250							
4500-5000	4750							
5000-5500	5250							
5500-6000	5750							
6000-6500	6250							
6500-7000	6750							
7000-7500	7250							
7500-8000	7750							
TOTAL	A	B	C		D	E	F	G

Base Hydrograph (compared to: ____________ Yrs. Record: ____________)

Month	Jan.	Feb.	Mar.	Apr.	May	June	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
%												
Acre Ft.												

Total Acres ____________
Annual Runoff ____________
Wt. Mean Elev. ____________ Total C ÷ Total B=WME

Habitat Acres 1____ 2____ 3____
4____ 5____ 6____
7____ 8____ 9____

Elev. - Precip.
Min. _____ _____
Max. _____ _____

Elev. - Runoff
Pt. 1 _____ _____
Pt. 2 _____ _____
Pt. 3 _____ _____
Pt. 4 _____ _____

Runoff Curve Used: ____________
Precip. Curve Used: ____________
Allowable % Water Yield Increase: ____________
Allowable Water Yield (acre ft.) ____________
Allowable ECA: ____________

REMARKS:

Prediction Techniques for Potential Changes in Sediment Discharge Due to Silvicultural Activities 1/ *

David L. Rosgen 2/

Introduction

One of the most significant and widespread "non-point" water quality problems associated with silvicultural activities in the U.S. is that of accelerated inorganic sediment discharge. Prediction techniques which evaluate the potential changes in sediment discharge from silvicultural activities must also evaluate stream morphological conditions, potential changes in timing and amounts of stream flow and changes in introduced sediment. Due to the dynamic nature of streams, a change in one process such as sediment supply from stream adjacent slopes, not only changes sediment discharge but sets up a series of adjustments in the stream channel. In order to predict these changes, a process oriented evaluation technique is needed.

After a review of the various analytical tools available it was determined that a systems approach offers the most productive framework in which to discuss any aspect of potential sediment and stream channel changes including: 1) evaluations of soil loss and transport to stream channels; and 2) in-channel processes which contribute material from the stream channel systems themselves. The major driving mechanism in such a process-type analysis is stormflow and snowmelt runoff. Thus, induced changes from silvicultural activities in slope hydrology and streamflow on various soil-vegetation-landform complexes have a potential for significant changes in stream channel stability and sediment discharge. Procedures for evaluating the hydrologic impacts of silvicultural activities have been presented earlier by Troendle, (27).

1/ Portions of this paper produced under USFS-EPA amended Interagency agreement No. EPA-IAG-DG-0660. 1978.

2/ Forest Hydrologist. U.S. Forest Service. Fort Collins, Colo.

* Presented at the ASCE National Meeting, Pittsburg, PA. April, 1978.

The objective of this paper is to propose a consistent analytical process to quantitatively predict the potential changes in sediment discharge and stream channel response as a result of changes in stream energy and/or sediment supply due to silvicultural activities. Potential changes in sediment discharge associated with direct increases in streamflow, introduced sediment sources, and direct stream channel disturbances will be inferred from the process-oriented analysis procedures presented.

<u>Stream Channel Morphology</u>

Research associated with stream channel morphology, sedimentology, and geomorphology has led many researchers to develop consistent analytical relationships involving stream systems and associated sediment supply and transport. Many of these analysis schemes are presented in the USFS-EPA's State-of-the-Art Assessment of Prediction Analysis Associated with Silvicultural Activities, (29).

Streams are dynamic systems whose configurations are adjusted in response to eight interrelated variables, which include width, depth, gradient, velocity, roughness of bed and bank materials, discharge, concentration of sediment, and size of sediment debris, Leopold, et al., (12). A change brought about through silvicultural operations which influence any one of these variables, either directly or indirectly, initiates sequential adjustments in the stream channel.

Stream channels often reflect the "existing watershed condition." When the concentrations and/or size of erosional debris supplied to the channel exceeds the carrying capacity of the stream, disequilibrium conditions may be created which could result in changes in channel stability. Adjustments associated with a stability shift are associated with change in localized grade, lateral channel migration and associated bank erosion, aggradation, etc. Streams well entrenched in erodable material respond quite differently to increases in sediment supply and/or changes in the flow regime than do streams entrenched in more resistant material.

Changes in channel stability can be affected by man's direct influence on streams such as debris introduction, constrictions due to road fill encroachments, type and number of stream crossings, streamflow amounts and timing, introduced sediment, or direct channel alignment or pattern changes. These channel impacts affect the rate and magnitude of channel change for a given reach, and in turn affect channel erosion through lateral channel migration, change in bed form, and other morphological changes which yield differences in sediment concentration per unit discharge.

The relationship between sediment supply and stream energy is shown diagrammatically by Lane (9), (figure 1) where stream slope and discharge (energy) is proportional to sediment load and sediment size (supply). A change in one or more of the variables produce changes in channel stability, with a net effect of either aggradation or degradation. Shen (23) has indicated that if any one of the variables mentioned above changes, a counteractive change occurs over time in the other variables to prevent continued stream aggradation or degradation.

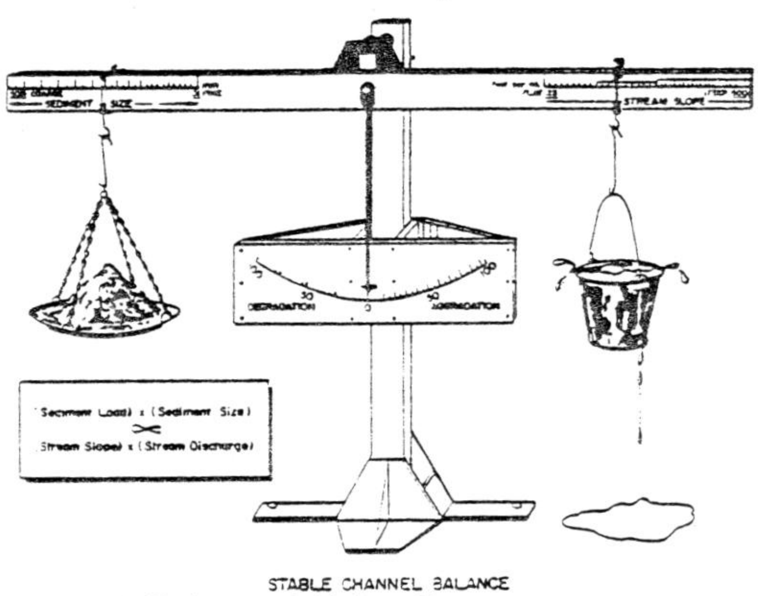


Figure 1.--Diagrammatic relationship of a stable channel balance (after Lane 1955).

Shen and Li (24) describe a relationship where sediment discharge is a function of the supply rate and transport capability of various sized particles under a particular flow regime (figure 2). "Washload" is that portion of the suspended load which is 0.062 mm or smaller (silts and clays).

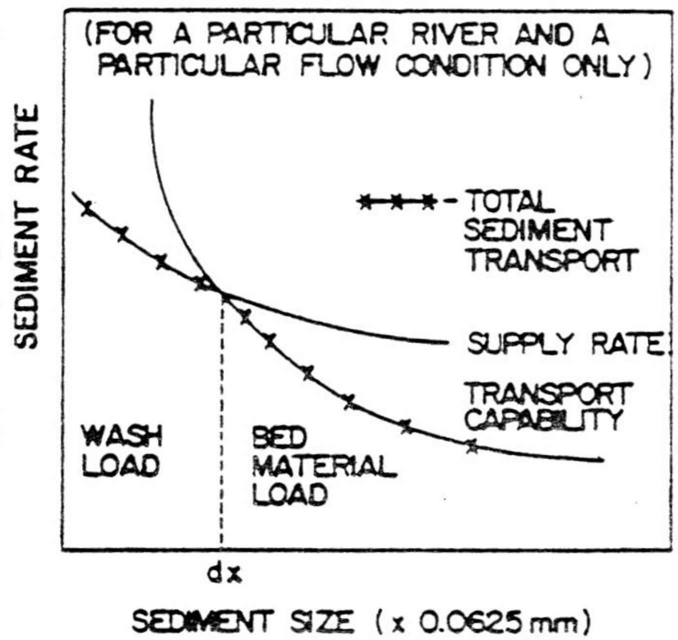


Figure 2.--Relationship of sediment rate and size to supply rate and transport capability (Shen and Li 1976).

The efficiency of streams to adjust to imposed changes varies based on the type of bed and bank materials, the stability of the landform in which the channel is incised, the amount of stored or available sediment in the channel, and the runoff characteristics of the watershed. The stability of natural channels varies by geomorphic province and by reach within the same watershed. The ability to interpret this variance is important when assessing sediment discharge as influenced by channel process.

Suspended Sediment

Since the sediment and water moving through a stream channel are primary variables influencing modern channel morphology, quantitative relations can be established between stream discharge and sediment concentrations. The nature and quantity of sediment and all aspects of channel morphology (channel dimensions, gradient, and patterns) can be related to stream discharge.

The importance of the effects of the size and concentration of suspended sediment available on stream channel geometry is well documented in work by Leopold and Maddock, (13) and Leopold, et al. (12).

Suspended sediment derived primarily from stream channel sources has been documented by researchers and shown to be a significant contributor to total annual sediment discharge (Anderson (1), Striffler (25), Rosgen (17), Flaxman (6), and Piest, et al., (16)). Quantitative predictions of suspended sediment discharge associated with channel sources have been developed using the sediment rating curve approach (Flaxman (6), and Rosgen (19)). The sediment rating curve approach involves depth-integrated sampling for suspended sediment over a wide range of representative flows for various reaches during a water year. The values of measured suspended sediment in mg/l are plotted on log-log paper as a function of stream discharge in cfs. The equation is shown as the log transformed regression:

$$\text{Log } Y = b + n \log Q$$

where: Log Y = Logarithm of suspended sediment concentration in mg/l.

b = A regression constant expressing the intercept of the regression line.

Log Q = Logarithm of instantaneous discharge in cfs.

n = an exponent representing the slope of the regression line.

Significant correlations throughout the United States have been observed between representative flows during various runoff events for a given year and actual sediment concentrations for those flows. Typical sediment rating curves are shown in figures 3 and 4.

Most of the annual sediment discharge results from flows occurring during short duration events. Since streamflow is the primary transport agent, silvicultural activities that influence flow levels or timing directly influence sediment discharge, especially if the stream is not supply-limited. Since flows vary from year to year, time-dependent plots are generally not

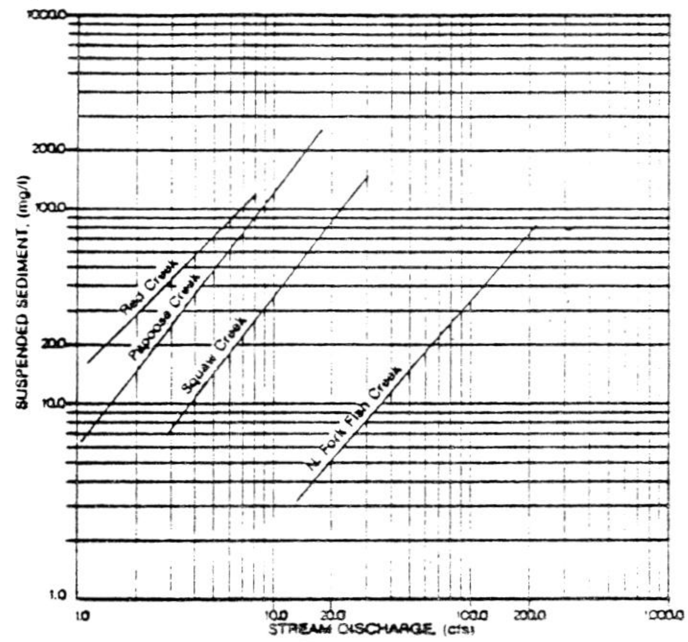


Figure 3.--Sediment rating curves for streams in western Wyoming (Holstrom 1976).

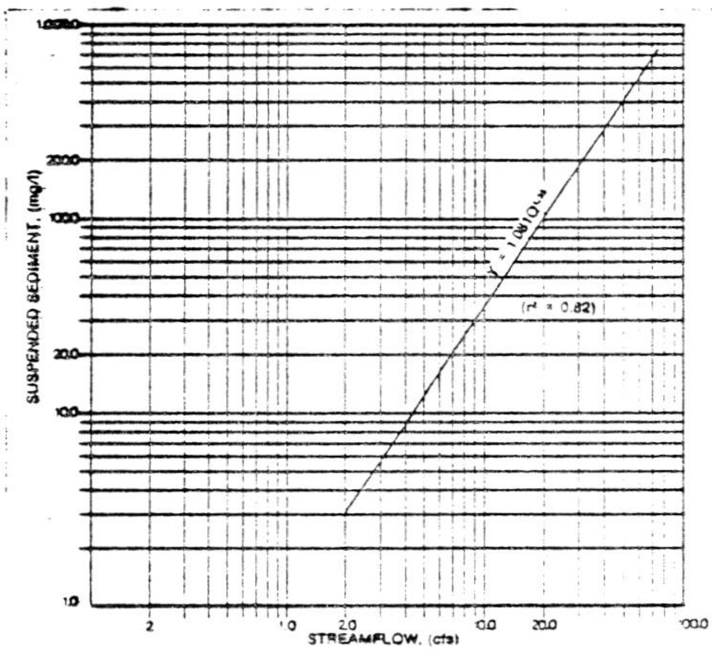


Figure 4.--Sediment rating curve for Needlebranch Creek, Oregon, 1964-1965 water year (Sundeen 1977).

evaluated due to the long-term records required. However, flow-dependent analysis can be reliably determined in one runoff season if "representative flows" have been monitored. "Representative flows" involve collection of suspended sediment throughout the expected range in flow levels. This includes sampling over seasonal conditions to isolate any variability in concentration for the same flow levels. Once the variation is defined, it may be possible to stratify by season, flow level, or both, depending on the variability and number of samples. The actual application of a sampling scheme involves a knowledge of the runoff characteristics of the watershed and its components. Sampling intensity varies within the year depending upon flow variation and anticipated sediment supply changes.

A hysteresis effect on sediment rating curves occurs frequently. When this occurs the effects of various treatments on the rising vs. recession limbs should be evaluated independently to predict individual responses more accurately.

Since sediment rating curves represent relationships between sediment supply and stream energy, the stability relationship in figure 1 can be inferred from sediment rating curves. Measurements have been made that show shifts caused by both natural and man-induced changes that alter the slope (n) and intercept (b) of the regression equation of the sediment rating curve (Flaxman (6)).

Applications by Farnes (5) were designed to identify changes in sediment discharge as a result of upstream changes in land use on selected watersheds in Montana. The technique is presently used as a portion of the analytical prediction technique for determining potential changes in sediment due to timber harvest on some national forests in Montana and Idaho (USDA Forest Service (28)).

Examples of changes in sediment rating curves can be shown to have occurred following a major flood in 1964 which shifted the sediment rating curve a full order of magnitude on the Eel River in northern California (Flaxman, (6)). Thus, an increase in stream channel sediment supply which aggraded many river reaches resulted in major channel adjustments and associated increased sediment discharge (figure 5). For any given flow on the Eel River following the flood, the sediment concentration was exponentially higher, making sediment changes very sensitive to flow increases. Flaxman (6) cited similar results from channel restoration measures applied to streams where channel erosion was a predominant source of the total annual suspended sediment discharge. A shift in the sediment rating curve detected changes in sediment availability and channel adjustments associated with the channel stabilization work.

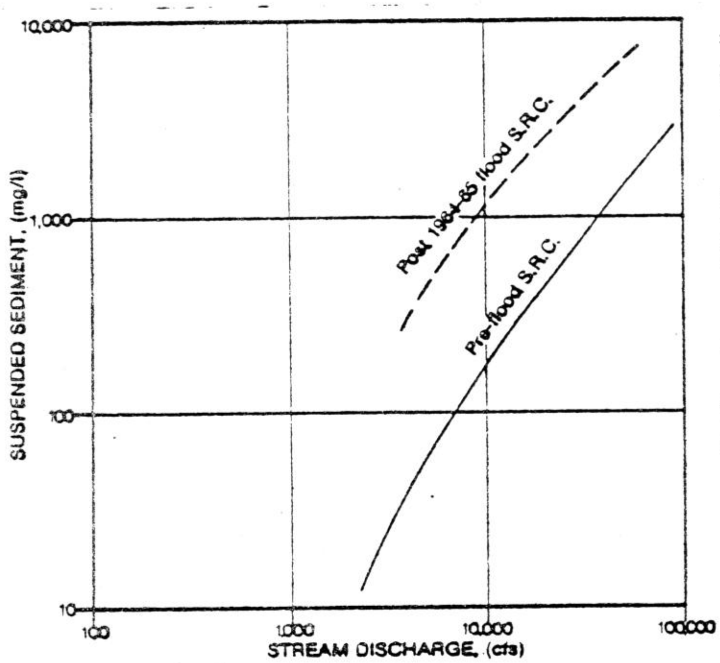


Figure 5.--Change in the sediment rating curve for the Eel River (at Scotia, California) showing increases in sediment concentration per unit discharge when new sediment sources developed during floods (Flaxman 1975).

A recent analysis of the effects of clearcutting on sediment rating curves was recently conducted on the Needle Branch drainage, a portion of the Alsea watershed research studies near the Oregon coast (Sundeen (26)). This analysis indicated a post-condition shift of the regression constants, b and n, of the sediment rating curve following the first year of harvest (figure 6). Even though the highest flood peaks occurred before treatment (due to the 1964 flood), the major shift in the sediment rating curve occurred following timber removal. This was due primarily to a debris slide which delivered considerable soil directly into the stream. There were no roads constructed for the timber removal. The recovery of Needle Branch has been fairly rapid, as indicated by the second year following clearcutting when the sediment rating curve (1967-68) returned nearer the pre-flood condition. The curves represent changes in sediment supply and stream channel adjustments associated with the accelerated sediment debris introduction. Under this condition any further change in duration of bankfull stage and/or magnitude of peak flows due to timber harvesting will produce exponentially higher sediment discharge. These relationships agree closely with those suggested by Flaxman (6).

The sediment rating curve technique has been used to evaluate timber sale impacts in Montana and Idaho (Rosgen (20)). Changes in sediment supply have been linked to individual sources when a surveillance type monitoring program is initiated to show these "shifts" in sediment rating curves. In many instances the major cause for the shifts and change in stability is associated with sediment supply increases by roads, debris slides, and stream channel impacts.

Stream Channel Stability and Sediment Rating Curves

A characterization of stability was developed by Pfankuch (15). This stability evaluation primarily examines: (1) detachability of bank and bed

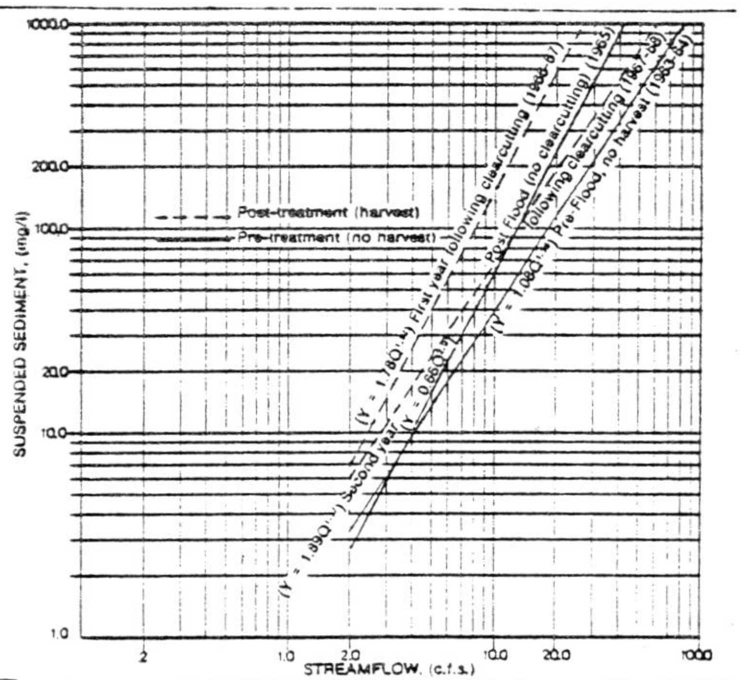


Figure 6.--Change in sediment rating curves for Needlebranch Creek, Oregon, showing the shift in curves due to silvicultural operations (Sundeen 1977).

materials, (2) availability or supply of sediment as a function of degree of entrenchment, stored sediment, and landform adjacent to the stream, (3) direct impacts on the channel, and (4) energy forces available. This evaluation provides a consistent analytical comparison of stability between stream reaches within a given region and has been demonstrated to be a reproducible method of assessing channel characteristics.

In order to provide a link between the morphological characteristics of stream channels as determined by the channel stability rating procedure (Pfankuch (15)) and sediment rating curves, regression analyses were made on over 80 streams in northern and central Idaho and northwestern Montana involving sediment rating curves and channel stability ratings. The relationship is shown in figure 7. The coefficient of determination (R^2) was 0.94 for the "good and excellent" streams (stability rating, 38 to 76), 0.91 for the "fair channel stability" (77 to 114), and 0.94 for the "poor or unstable" channels (115 to 132). A covariance analysis was conducted (Bernath (3)) indicating highly significant correlations (.01 cl) when comparing various populations of sediment rating curves and channel stability. The F values were highly significant at the .01 level.

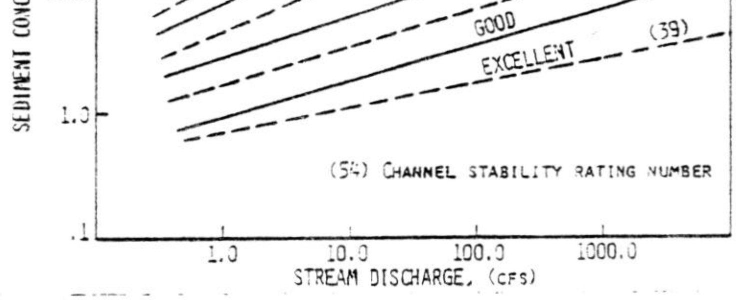


Figure 7.--Relationship of sediment rating curve stream channel stability ratings--Northern Region, USFS (Rosgen 1975).

Work conducted in California has shown widespread application of this technique where 27 streams with sediment rating curves were evaluated using the same stability procedures (Laven (10)). Concentrations are considerably higher for comparable flows in the California streams, but the stability evaluation provides a comparison of the different regression constants and stability ratings within a given locale using the same procedures (figure 8). Similar relationships (figure 9) have been developed where sediment rating curves were related to stability ratings in the Rocky Mountain region of Colorado (Rosgen (21)).

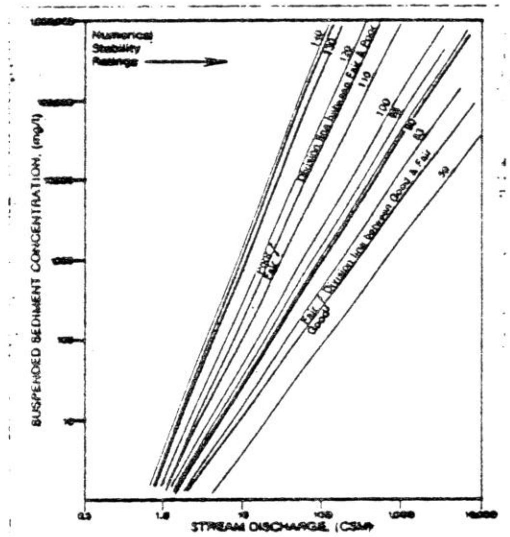


Figure 8.--Relationship of stream channel stability to sediment rating curves for various streams in the Redwood Creek area (Laven 1977).

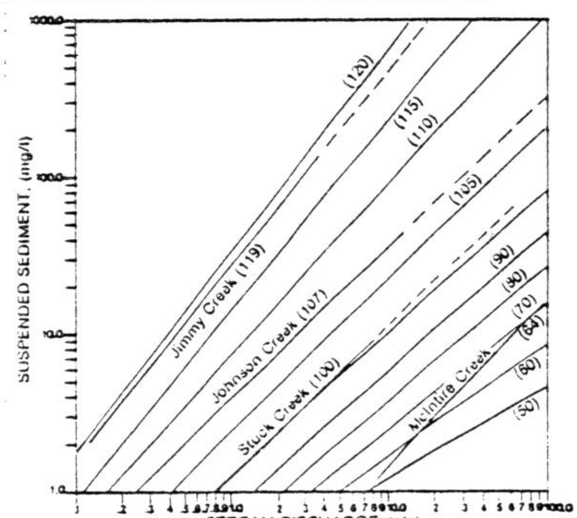


Figure 9.--Relationship of stream channel stability to sediment rating curves in the Central Rockies, Colorado (Rosgen 1977).

Additional validation of this procedure was conducted in Wyoming, Oregon, New Mexico, North Carolina, New Hampshire, and Vermont (Rosgen (22)). Tentative results indicate that this procedure applies to many areas other than where it was developed. This success is due to the application of the process related procedures rather than extrapolation of actual curves or regression equations from region to region. The use of this procedure demands the development of local curves based on actual sediment rating curve data. Once this step has been completed, information can be obtained from many miles of stream reach upstream or adjacent to where sediment data has been collected. Thus the channel stability procedure, if used in a consistent comparative analysis over a wide range of stream types, can be used to infer the regression constants of the sediment rating curves. This would not be as accurate as actual measurements on 100 percent of the stream reaches being evaluated in a subdrainage; however, time and financial constraints might justify this approach once local validation has been accomplished.

Interpretations

An application of the stability rating involves the location of stream reaches where there is considerable sediment storage and/or organic debris accumulation. These conditions may not presently influence downstream reaches since there is insufficient energy to transport the sediment or the stream is in the initial phases of adjustment due to debris jams, etc. Identifying and locating these conditions through the stability rating procedure does, however, indicate potential hazards that may affect channel and water quality response to various runoff changes and/or physical disturbance.

It is difficult to characterize a stream to determine how much of a change in sediment supply and/or change in energy can be absorbed without altering the stream system. Sediment rating curves may be used as a potential indicator of channel changes and adjustments. If the post-treatment sediment supply exceeds the highest observed sediment discharge at bankfull stage, the stream may have to make channel adjustments to accommodate the increased sediment supply. Such adjustments may cause a shift in the sediment rating curve and thereby affect sediment transport rates at all flow levels.

The "stability threshold" of streams can then be interpreted as the lines between the major stability classes as shown in figure 7. This interpretation would be used where either actual or proposed potential suspended sediment discharge for a given flow would plot higher than any of the observed data as measured in the development of these relationships. (A conversion of sediment discharge in tons/day to mg/l is necessary for comparison with sediment discharge at bankfull stage.) If potential introduced sediment is anticipated during periods of lower flow, the same comparison may be made. If the increased supply is higher than the highest pretreatment observed concentrations, or plots well into a different "stability class," a stability change or associated shift in the sediment rating curve may occur.

Bedload Determination

Bedload transport generally becomes a predominant factor during major runoff events where sufficient energy is avalable to dislodge and transport the larged sized particles, generally armored in the streambed or supplied to the stream from the channel sides and slopes. Studies in Idaho have shown bedload to be less than 5 percent of mean annual total sediment discharge when measured concurrently with suspended sediment on first to third order streams (Rosgen (18)). Emmett (4) determined that bedload transport for gravel bed streams in the upper Salmon River area is approximately 1 to 10 percent of the suspended sediment load transported.

Evaluation of the basic processes involved in bedload transport, however, is valuable to determine potential changes in stream channel stability and associated suspended sediment concentrations.

Numerous empirical bedload transport equations are described in the EPA-USFS Non-Point Water Quality Modeling Evaluations (USDA Forest Service (20)). Since few data for validation of natural channels are available to test these bedload transport equations, it is difficult to convert them to quantitative expressions of water quality. In addition, the field data necessary to empirically determine bedload transport is extensive and requires specialized expertise.

To calculate bedload discharge the same principles are applied as in the development of sediment rating curves. Thus, bedload rating curves are obtained from actual field measurements. The objective is to:

- determine the contribution of bedload vs. suspended sediment discharge
- determine the flow related increases associated with bedload transport
- obtain field data to develop bedload transport - stream power relationships for:
    a) extrapolation to other reaches where bedload data is not available
    b) determination of stream channel change potential due to introduced sediment and direct channel impacts

Once bedload rating curves, stream discharge, water surface slope, stream width and particle size in transport are determined, bedload transport - stream power relationships may be obtained.

Bedload transport is calculated as a function of stream power, as developed by Leopold and Emmett (11). A relationship between stream energy and measured bedload transport was developed for natural streams as a function of the size of material being transported (figure 10). At flows approaching bankfull discharge transport rates become directly proportional to stream power, as suggested by Bagnold (2). Stream power is defined as the unit weight of water (1,000 Kg/m^3) times the discharge of water per meter of width over the total stream width ($M^3/M/S$) times the gradient of the stream (M/M) (Leopold and Emmett (11)). (The integration of cross sectional area and velocities assumes rectangular channel banks for the calculation.) This basic approach was applied for two years on 25 different first to third order streams in Idaho (Rosgen (18)). A relationship similar to that of figure 10 was developed for these streams using actual bedload transport rate measurements by means of the Helley-Smith bedload sampler (Helley and Smith (7)) and particle size analysis of the bedload material. The variables required to calculate stream power were also measured at each site. Extrapolation of the bedload transport curves presented beyond the measured reach requires data on the mean bed material size that is present immediately below the downstream point of channel bars, and the dominant surface particle size on point bars at bankfull stage. Surface water slope and stream width at bankfull stage must also be obtained.

The comparison of the Leopold-Emmett data (figure 10) and the Idaho bedload data (figure 11) reveals a definite separation between particle size transport under the same stream powers. This could be due to either the larger size of the bedload material in the Idaho streams which affects the energy available to transport the sands between the larger rocks or a change in sand size availability (Leopold (14)). A defined bed armor is more evident in the Idaho streams than in the Wyoming stream depicted on the Leopold-Emmett curve. More bedload data are needed for higher stream powers and for particle sizes larger than sands in mountain streams to further refine these relationships.

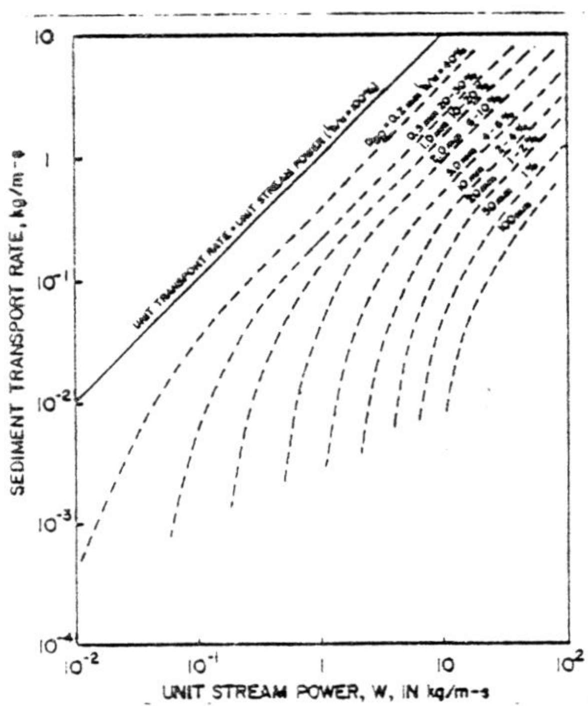


Figure 10.--Sediment transport rate as a function of stream power and particle size for streams not well armored (Lepold and Emmett 1976).

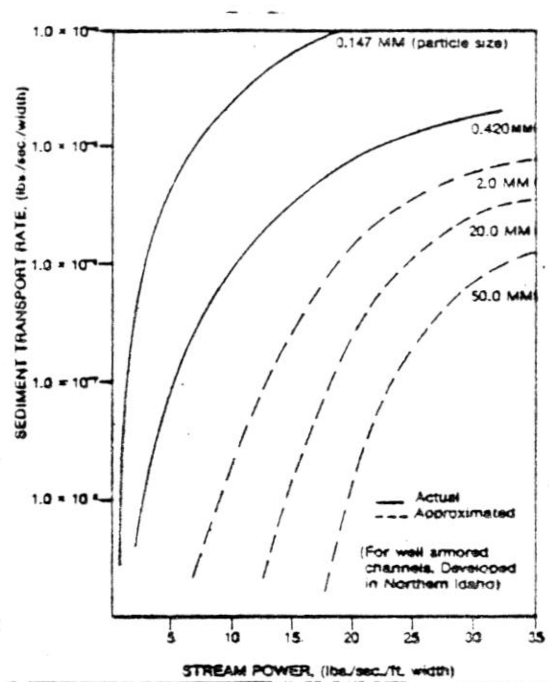


Figure 11.--Bedload transport rates as a function of particle size and stream power for various armored channels in northern Idaho (Rosgen 1975).

Stream channel encroachments from logging debris, road fills, etc., which alter the stream power or sediment supply can be evaluated by the change in stream power-bedload transport using the relationships shown in figures 10 and 11. Potential changes in bedload can be calculated by showing the change in stream power which can result from debris jams, and associated gradient and width changes, channel constrictions, increased flow, change in velocity, and/or change in the size and volume of material contributed for a given flow. For these induced changes, bedload transport increases and/or stream aggradation/degradation can be calculated. This is done by inserting changes in the stream power and bedload transport rate variables for which changes are anticipated. These changes in the variables will indicate the potential for stream aggradation or degradation. If the stream is not energy limited, the stream may have the competence to transport higher sediment concentrations with resultant increases in sediment concentrations. Relative departures from existing transport rates and/or stream power as a result of silvicultural activities can be determined utilizing these relationships. These prediction techniques are not recommended to replace local bedload data and/or transport prediction capability, should they be available. Since little data exists, bedload rating curves and the local development and use of sediment transport-stream power curves provide the basic process relationships involved for bedload prediction and associated channel stability changes.

Analysis Procedures

The following assumptions are made for the proposed analytical procedure:

1) No distinction will be made between material detached from channel banks versus that which has been previously deposited on the streambed and on channel bars and made available for redistribution under varying flow regimes.

2) Suspended sediment and bedload increase exponentially with stream discharge and can be determined through measurements. Differences in sediment supply with various flows, such as rising versus falling limbs of the hydrograph, snowmelt versus stormflow runoff, and early versus late season stormflow should be analyzed separately to determine these various relationships.

3) Sediment rating curves represent equilibrium conditions or the existing relationship between sediment supply and stream energy for the particular stream reach and watershed. Changes in the temporal and spatial distribution of sediment will only be evaluated as indicated by a change in the sediment rating curve and/or channel stability.

4) Average bedload size available for transport at bankfull stage can be determined from the median surface particle size at depositional sites in the channel excluding pool areas. These sites involve surface materials of the lower bank portions of point bars and on the downstream side of central bars.

5) The size of material delivered to streams from surface erosion is assumed to be silt and clay (wash load) or smaller than .062 mm.

6) One hundred per cent of the introduced wash load sediment is transported through individual stream reaches, i.e., no storage is calculated and the stream has sufficient energy to transport this size sediment.

Generalized Analysis Procedure

The following paragraphs provide an analysis framework for evaluating potential changes in sediment discharge and channel stability associated with silvicultural activities. The quantitative evaluation of suspended sediment and bedload are based on locally-derived regression equations (sediment rating curves); while qualitative evaluations of impacts of introduced sediment and channel impacts are based on the stream power-sediment transport rate curve. This procedure is designed for third order streams or smaller.

The flowchart (figure 12) indicates the interrelation between the sediment derived from the surface erosion processes and mass wasting contributions, and those derived from stream channels in response to streamflow changes. The flow chart is a graphical display of the following step-wise procedure:

Analysis Step

Step	Description
1.	Delineation of watershed and stream reach characterization.
	Suspended Sediment Calculation
2.	Pre and post-condition hydrographs obtained (from technique described by Troendle (27), or other comparable analysis).
3.	Establish sediment rating curves and obtain channel stability.
4.	Calculate potential pre-condition suspended sediment discharge (tons/yr).

$$S_{pre} = (C)\ (Q_{pre})\ (K)\ (T)$$

Where: S_{pre} = pre-condition sediment discharge

C = suspended sediment concentration in mg/l from sediment rating curve

Q_{pre} = pre-condition stream flow in cfs

K = a constant to convert to tons/day (.0027).

T = duration of streamflow in days.

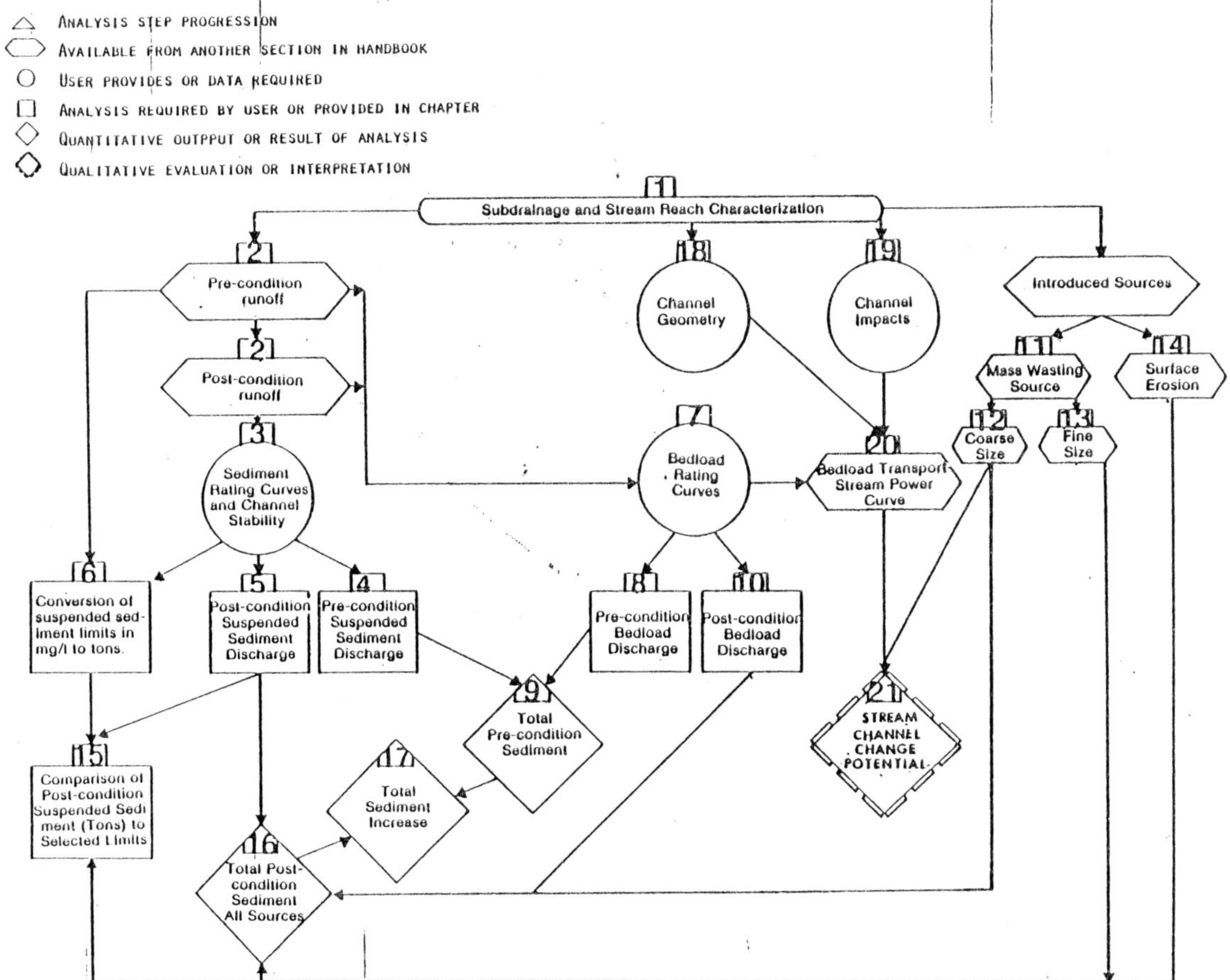


Figure 12.--Generalized flow chart of analysis procedure for determining potential sediment discharge due to silvicultural activities.

5. Calculate potential post-condition suspended sediment discharge.

(due to increase in flow)

$S_{post} = (C)(Q_{post})(K)(T)$

Where: S_{post} = potential post-condition sediment discharge (tons/yr)

Q_{post} = Post-condition stream discharge in cfs

6. Convert allowable limits of suspended sediment increased in mg/l to tons for comparison. (Allowable limits are from a selected water quality objective.)

$S_a = (C_{mx})(Q_{pre})(K)(T)$

Where: S_a = Sediment Discharge Allowable (tons)

C_{mx} = maximum concentration allowable from state standards, channel stability exceedance levels or other selected goal.

7. Establish a bedload rating curve and measure particle size in transport (D-50).

8. Calculate pre-condition potential bedload discharge.

$B_{pre} = (i_{bpre})(T)(K)$

Where: B_{pre} = bedload sediment discharge (tons/yr.)

i_{bpre} = bedload transport rate in lbs/sec. or kg/sec. under various stream discharges (from bedload rating curve)

T = duration in days

K = constant converting lbs/sec. or kg/sec. to tons/day

9. Calculate pre-condition total potential sediment discharge. (S_{pt})

$S_{pt} = (S_{pre}) + (B_{pre})$

(step 4) (step 8)

10. Calculate post-condition potental bedload sediment discharge (due to flow increase only).

$B_{post} = (i_{bpost})(T)(K)$

Where: B_{post} = post-condition potential bedload sediment discharge in tons/yr.

i_{bpost} = post-condition bedload transport rate in lbs/sec. or kg/sec. based on post-condition flow.

(T) = duration in days

(K) = constant converting lbs/sec. or kg/sec. to tons/day

11. Obtain total introduced sediment from soil mass movement in tons/yr. Use procedures developed by USFS (30) or similar method that delivers eroded material to the stream.

12. Obtain volume in tons of coarse size soil from mass wasting sources (sands or larger).

13. Obtain volume in tons of fine size soil from mass wasting sources (silts and clays).

14. Obtain total introduced sediment from surface erosion in tons/yr. Use procedures developed by USFS (30) or similar method that delivers eroded material to the streams.

15. Compare total post-condition potential suspended sediment discharge to selected limits.

    $S_a = \Sigma[(S_{post}) + (\text{surface erosion}) + (\text{fine size soil mass movement})]$

    If increases exceed selected goal limits, proceed to evaluate various management controls affecting processes or mitigative measures.

16. Calculate total post-condition potential sediment discharge - all sources.

    $S_{tot\ post} = \Sigma[(S_{post}) + (B_{post}) + (\text{soil mass wasting}) + (\text{surface erosion})]$

17. Calculate total potential increases in sediment discharge.

    $S_I = (S_{tot\ post}) - (S_{pt})$

    Where: S_I = total potential sediment increase

    $S_{tot\ post}$ = total potential sediment - post-condition (step 16)

    S_{pt} = total potential sediment - pre-condition (step 9)

18. Measure channel geometry, bankfull width, water surface slope, and particle size.

19. Evaluate direct stream channel impacts on the variables affecting sediment transport including changes in stream width, depth, water surface slope, and discharge.

20. Establish bedload transport-stream power relationships. From channel geometry, bedload and stream flow data collected in steps 2, 7, and 18 calculate stream power using stream width, discharge and surface water slope for each value of bedload transport.

$$\text{Log } i_b = a + b \log \omega$$

Where: $\text{Log } i_b$ = logarithm of measured bedload transport rate (lbs/sec./ft.)

a = intercept of the regression line

b = slope of the regression line

$\text{Log } \omega$ = logarithm of stream power (lbs/sec./ft.)

Plot by various particle sizes (D-50) as seived during collection of bedload data. This is developed in order to calculate changes in bedload transport and channel change potential due to changes in the stream power variables and volume and particle size of introduced material.

Total Potential Sediment Discharge

21. Evaluate potential post-condition stream channel change due to increased sediment supply by comparing introduced sources to transport rates under available stream power qualitative interpretations of aggradation-degradation due to streampower changes.

Summary

Although the complexities involved in sediment discharge and stream channel morphology often limit the applications of prediction techniques, there has been an expanse of process research data made available to wildland hydrologists. The procedure discussed in this report makes an effort to utilize existing "state of the art" information into consistent comparative analyses. The analyses are not designed to obtain absolute answers but to predict relative potential changes in sediment discharge and/or stream channel morphology in a more concise manner.

While preliminary, these techniques have been utilized in one form or another by practicing wildland hydrologists for several years. As additional information becomes available it may be directly incorporated into these procedures. This is an attempt to consolidate analysis techniques in a framework with which to provide consistency of application and more widespread validation.

The overall goal is to incorporate these analyses into site specific planning as a basis for instituting "best management practices" to prevent adverse water quality change and stream channel adjustments prior to initiating a wide range of silvicultural activities.

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