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Predicted increased water yield after clear-cutting verified in west-central Alberta

R.H. Swanson and G.R. Hillman

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PREDICTED INCREASED WATER YIELD AFTER CLEAR-CUTTING VERIFIED IN WEST-CENTRAL ALBERTA

BY

R.H. SWANSON and G.R. HILLMAN

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ABSTRACT

The effects of clear-cutting on the North Western Pulp and Power Company Ltd. lease near Hinton, Alberta on water yield were predicted to be (1) an increase in streamflow during the snowmelt freshet, (2) an annual yield increase of 20-30%, (3) an increase in storm flow peak magnitude of four to five times, and (4) a longevity of more than 30 years before these effects begin to diminish. These predictions were made using an informal model that states that the change in water yield resulting from forest harvest may be inferred from the alterations in stand structure, density, and arrangement that occur during harvesting which produce predictable changes in the interception, transpiration, snow accumulation, and snowmelt processes that in turn affect generated runoff. Validity of the predictions was tested by statistically comparing water yield from nine logged and nine unlogged catchments on the lease. Results were (1) 59% more streamflow during the snowmelt freshet, (2) 27% greater yield over the gauged season (April 25-September 15), and (3) an increase in storm peaks of 1-1/2 to two times. Since the first two effects confirmed the predictions, and the average harvest age is 10 years, longevity will likely be as predicted also.

RESUME

On a prédit que les effects d'une coupe à blanc sur le rendement en eau dans la concession de la North Western Pulp and Power Company près de Hinton, en Alberta, seraient comme suit: (1) une augmentation du courant dans les ruisseaux durant la période de fonte des neiges, (2) une augmentation du rendement annuel de 20 à 30%, (3) une augmentation du point culminant des crues (après orages) par quatre ou cinq fois, (4) une longévité de plus de 30 ans avant que ces effets ne commencent à diminuer. Ces

prédictions furent faites avec un modèle spécial qui énonce que le changement du rendement en eau résultant de la récolte forestière pourrait être déduit (observé) selon les modifications de structure des peuplements, de leur densité et de leur position, qui ont lieu pendant l'exploitation et produisent des changements prévisibles de l'interception, la transpiration, l'accumulation de neige, et le processus de fonte des neiges qui, à leur tour affectent l'écoulement généré. La validité des prédictions fut vérifée en comparant statistiquement le rendement en eau dans neuf bassins-versants exploités et neuf autres non exploités de la concession. Voici les résultats obtenus: (1) le courant des ruisseaux augmenta de 59% durant la période de fonte des neiges, (2) le rendement en eau augmenta de 27% au cours de la saison étudiée (du 25 avril au 15 septembre) et (3) le point culminant des crues d'orages augmenta de 1½ à deux fois. Etant donné que les deux premiers effets confirmèrent les prédictions, et que l'âge moyen de l'exploitation est de 10 ans, la longévité sera vraisemblablement telle qu'elle avait été prévue.

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INTRODUCTION

Clear-cut harvesting of forests is an established silvicultural practice throughout much of Canada. Several forested experimental watersheds in the United States and elsewhere have been harvested in various clear-cutting configurations to determine the effect of this practice on water yield. It is our contention that the physical reasons for the water yield response from clear-cutting are well enough established from these studies that one can predict in relative quantitative terms the general effect that will obtain wherever forests of similar type are harvested in this manner.

The informal model that we tested in this paper may be stated thus: The change in water yield resulting from forest harvest may be inferred from the alteration in the effectiveness of a process determining generated runoff[1]. The changes resulting from these processes are predictable from a knowledge of their interaction with stand structure, density, and arrangement before and after harvest.

Changes in generated runoff are predictable because the physical parameters of the forest that cause such change operate the same everywhere. Stand structure, which refers primarily to the vertical space occupied by tree crowns, and stand density, which refers to the number of individuals per unit area, operate to alter the wind, moisture, and radiant energy regimes in the crown volume and at the soil surface, and the moisture regime within the soil. Stand arrangement, which refers primarily to the areal pattern of cut and uncut areas existing at any given time, operates to concentrate energy and/or mass inputs into clear-cut areas. These stand descriptors interact to alter runoff-determining processes of interception, snow or rain microdistribution, evapotranspiration, and snowmelt rate. The kind of alteration that forest harvest makes in these processes is relatively independent of general climate or topography; however, the magnitude of the effect that these alterations will have on

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[1] Generated runoff is that increment of water added during a given time interval, usually one day, that will eventually leave a catchment. All on-site losses have been deducted but the water has not passed through the stream-gauging point. This definition is in agreement with that proposed by the U.S. Army Corps of Engineers (1956), which states that generated runoff is in transitory storage in the soil, groundwater, or stream channel.

local runoff is highly dependent upon current weather and existing topography. The qualitative predictability of their effect on generated runoff is reasonably good for each process in isolation and for their interaction in a limited number of experimental situations. (By "qualitative", we mean that the alteration must be expressed relative to that which existed prior to or without harvest rather than as an absolute quantity.) Also, we are unable with forest harvest data alone to route the generated runoff to streamflow, which means that predictions apply to the water yield from areas in general and not to any specific catchment.

We have two purposes in this paper: (1) to predict (using our informal model) the effect that the presently clear-cut areas on the 7783 km^2 North Western Pulp and Power Company's (NWPP) lease near Hinton, Alberta (Fig. 1) have on water yield and (2) to establish the validity of these predicted effects through a statistical comparison of the water yield from clear-cut and uncut sample catchments on the lease (Fig. 2).

Although the predicted effects will be based on alterations in the effectiveness of runoff-generating processes that are affected by the interaction among surface vegetation, precipitation, and evapotranspiration, our verification must necessarily be based on observed streamflow. The streamflow from any given catchment does not necessarily arise solely from precipitation on that catchment's surface. There may be transfer into or out of any catchment from its neighbor.

Our knowledge of the subsurface hydrology on any specific catchment on this lease area is very limited. Therefore, we have established a large areal-size criterion for any sample catchment so that both surface and subsurface drainage will coincide. Failing that, we trust that the number of catchments is sufficiently large so that the loss from one or more is balanced by an equivalent gain elsewhere in our sample.

The characteristics of the lease area and forest-management operations relevant to predicting generated runoff change are timber age and type (for estimating stand structure and density), silvicultural system used (for describing postharvest stand arrangement), and the time distribution of runoff (for determining the type(s) of precipitation that

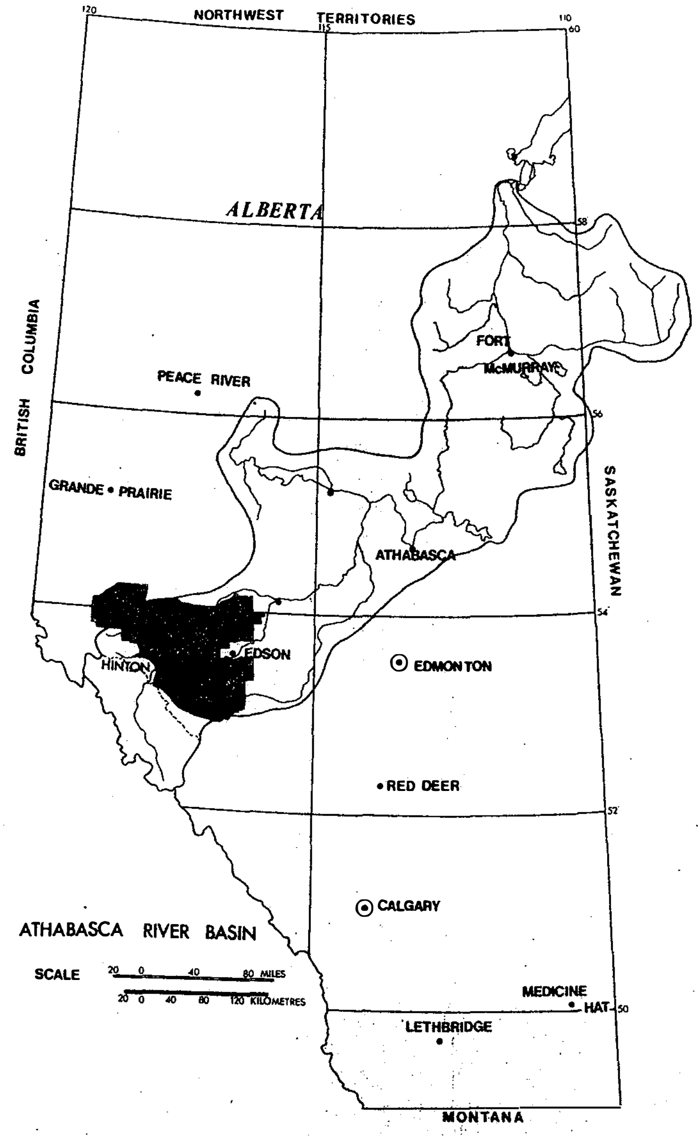

Fig. 1. Location of the North Western Pulp and Power Company Ltd. lease in the Athabasca River Basin. The shaded area includes both the current management portion (7773 km^2) and an additional 7800 km^2 provisionally allocated to the company.

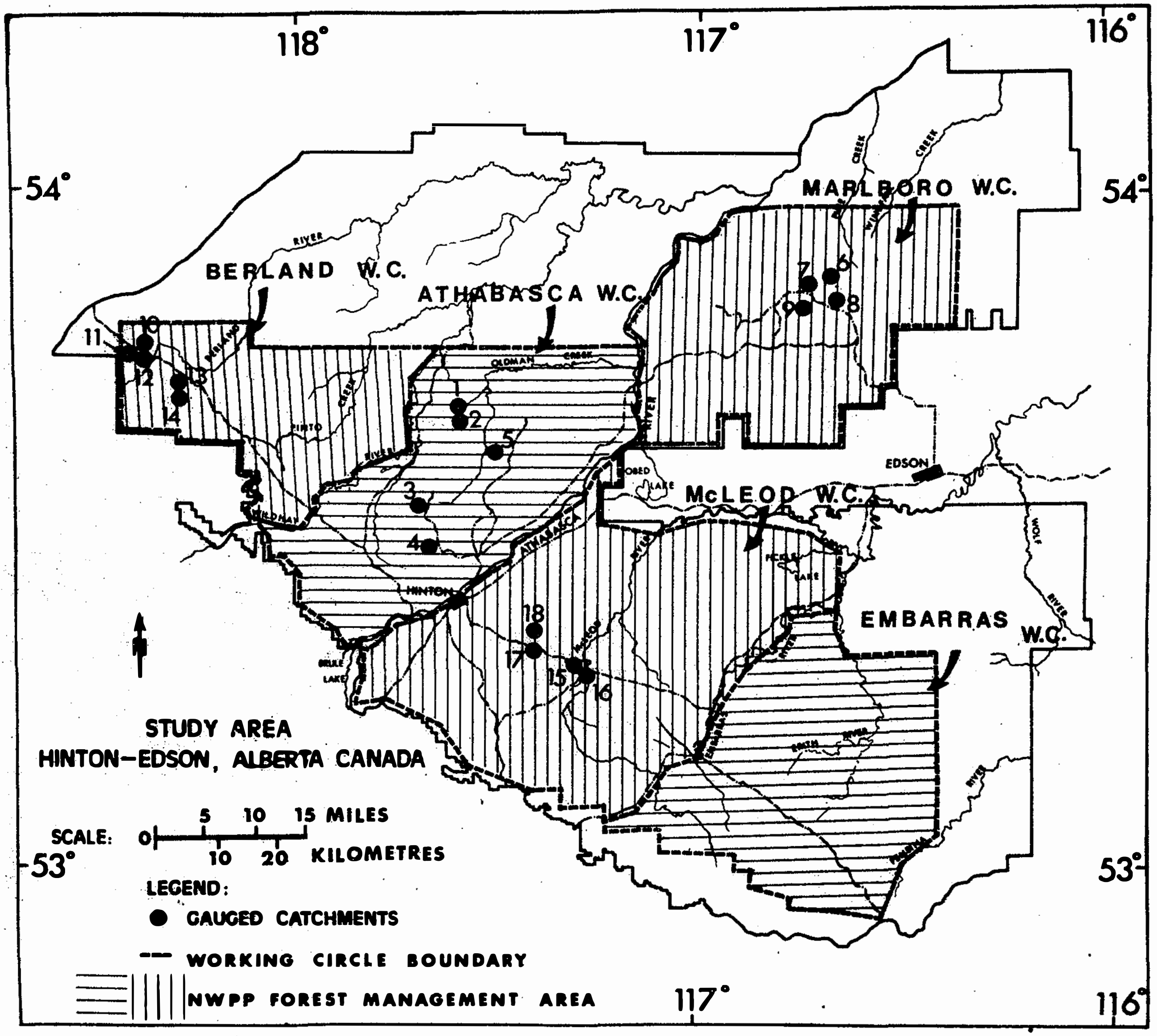

Fig. 2. Working circle boundaries and gauged catchment locations, NWPP lease area. The crosshatched portion is currently under lease agreement with the Province of Alberta; the remainder is subject to negotiation.

causes streamflow). Those characteristics relevant to the statistical verification are principally the division of harvesting operations among geographic units (working circles), the concentration of clear-cut areas within each working circle to the first of four 20-year cutting cycles (which tends to concentrate the effect within each working circle), and the uniformity in time of occurrence of runoff from snowmelt or frontal activity to reduce sampling variation.

GENERAL DESCRIPTION OF THE FOREST MANAGEMENT AREA

PULP LEASE AND OPERATION

The NWPP lease area is located east of the Rocky Mountains near Jasper National Park between latitudes 53 and 54°N and longitudes 116 and 118°W. It supports spruce-lodgepole pine forest typical of the Lower Foothills (B.19a) and Upper Foothills (B.19c) sections of the Boreal Forest Region (Rowe 1972). Growing stock over the lease by areal percentage is 53% lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.), 19% white spruce (*Picea glauca* (Moench) Voss.), 8% black spruce (*P. mariana* (Mill.) B.S.P.), 5% alpine fir (*Abies lasiocarpa* (Hook.) Nutt.), 9% *Populus* spp., and 6% standing dead trees (MacArthur 1968).

The lease is divided into five working circles for management purposes (Fig. 2). The boundaries of each working circle are generally major rivers, which also lend their names to the area bounded. Each working circle is further divided into a number of compartments, each containing an estimated timber volume at harvest time of 1 250 000 m^3. The company extracts a total of 900 000 m^3 from one or more compartments each year (the timber on approximately 4500 ha) (Crossley 1972; MacArthur 1968). The boundaries of these compartments generally coincide with historical fires that created a large number of even-aged stands. At maturity these stands appear remarkably uniform in height and density; the trees are from 17 to 20 m tall, with 1000-1500 stems/ha.

The intial harvest cut in each compartment removed the trees from roughly 50% of the area in alternate 16- to 25-ha clear-cut strips or blocks (Fig. 3). The leave strips or blocks are being removed in a

Fig. 3. A sample of the cutting pattern on the Athabasca working circle that exists midway through and at the end of a cutting cycle. The strip in the foreground was clear-cut in the first half of the cutting cycle; the leave area between strips is to be clear-cut in the second half of the cycle. The end result at the conclusion of all harvest during a cutting cycle is shown in the left background. All but a few isolated patches of trees have been removed. In terms of hydrologic alteration, the end result is a complete clear-cut, even though new trees are well established on the initial clear-cut areas. (Photo taken 11 March 1976.)

second cut. In 1974, near the end of the first 20-year cutting cycle, large clear-cut blocks up to 1400 ha exist, but not all timber has been removed from most areas. The company must leave a buffer strip adjacent to both sides of designated streams and other designated water bodies. Also, some of the timber, mainly the *Populus* species, is undesirable under current milling practices and is not harvested. Nor is timber removed from slopes too steep for extraction without severe damage to the soil. Therefore, even where clear-cutting is completed, timber may remain on about 5-40% of the surface area.

CLIMATE

The climate is continental with long, cold winters and short, cool summers. Annual precipitation averages between 500 and 550 mm, of which about 30% occurs as snow between October and April (Alberta Environment 1974). Mean annual and mean summer temperatures are 2-3 and 8-12°C respectively.

HYDROLOGY

Summer precipitation and hydrographs for 1974 from three different-sized watersheds covering the major elevation zones of the lease are given in Fig. 4. (These rivers and streams are not gauged from freeze-up through breakup, roughly November through April.) The Wampus Creek and McLeod River hydrographs show that approximately one-half of the total seasonal streamflow arises from snowmelt (snow on the ground at the end of April 1974 was 158 mm, water equivalent) and from mixed rain and snow during May. All three hydrographs are from watersheds relatively free of harvest influence, as none has occurred in the 27.7-km^2 Wampus catchment nor in the 966-km^2 Wildhay watershed, and less than 10% of the 2610 km^2 McLeod watershed has been harvested.

The hydrograph from the Wildhay River (gauged at the western boundary of the lease) has been included to illustrate the differing runoff pattern that this predominantly alpine watershed produces compared to those patterns of the lower elevation forested areas represented by Wampus

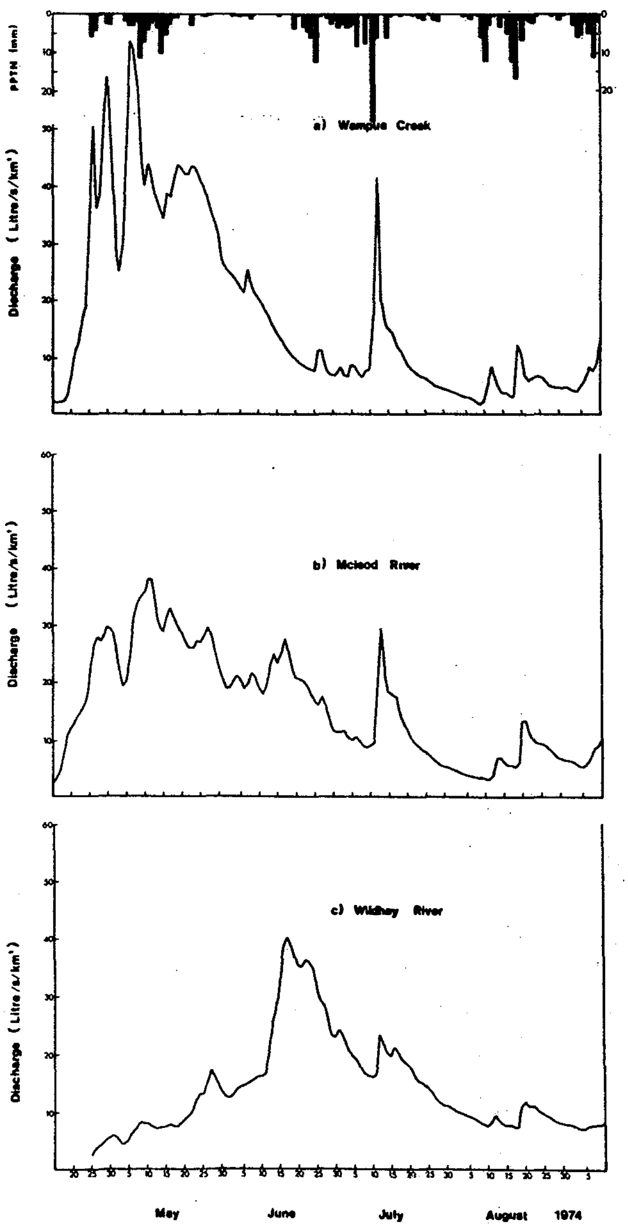

Fig. 4. Summer precipitation over the lease--hydrographs from Wampus Creek and the McLeod River, which originate within the forested portion of the lease. The Wildhay River hydrograph has been included to illustrate the flow distribution in time from an alpine watershed versus that of the two mid- to low-elevation watersheds. (Streamflow data courtesy Water Survey of Canada.)

Creek (which is part of the McLeod basin), and the McLeod River itself. The water yield from a small alpine portion in the McLeod watershed tends to keep this watershed's runoff at a higher level during the summer than the totally forested Wampus catchment.

The only precipitation other than that occurring during snowmelt that causes appreciable response in the large river hydrographs is that associated with cold low or frontal storms. The marked peak occurring in July and the smaller one in August (Fig. 4) are from such storms. Isolated convective storms are common throughout the lease. These do cause local runoff but their effect is generally masked when it is combined in the major river hydrographs.

EXPECTED EFFECTS OF HARVEST ON STREAMFLOW

To use our informal model, we have taken into account general similarities in forest cover, climate, and hydrologic response that exist between several experimental watershed tests (mainly those from Wagon Wheel Gap and Fool Creek in Colorado) and the lease area to predict the change in water yield attributable to forest harvest. Our prediction is not annual or seasonal runoff, which is highly dependent upon how much snow or rain falls in a particular year, but the difference that forest clear-cut harvesting will cause in the normal runoff pattern from uncut watersheds subject to the same climatic conditions.

The hydrographs and some raw data from the Fool Creek experiment were made available to us in 1971 prior to their publication by Leaf (1975). The inferences we have drawn from them are our own.

TIMING

The hydrographs from two experimental watersheds in Colorado (Fig. 5) show the same dominant snowmelt characteristics as those from the lease area (Fig. 4). The postharvest hydrograph (dotted lines) from both Colorado catchments illustrates that timber clear-harvest causes greater instantaneous streamflow magnitude during the rising limb of the hydrograph. The effect on Wagon Wheel Gap from clear-cutting 81 ha in one

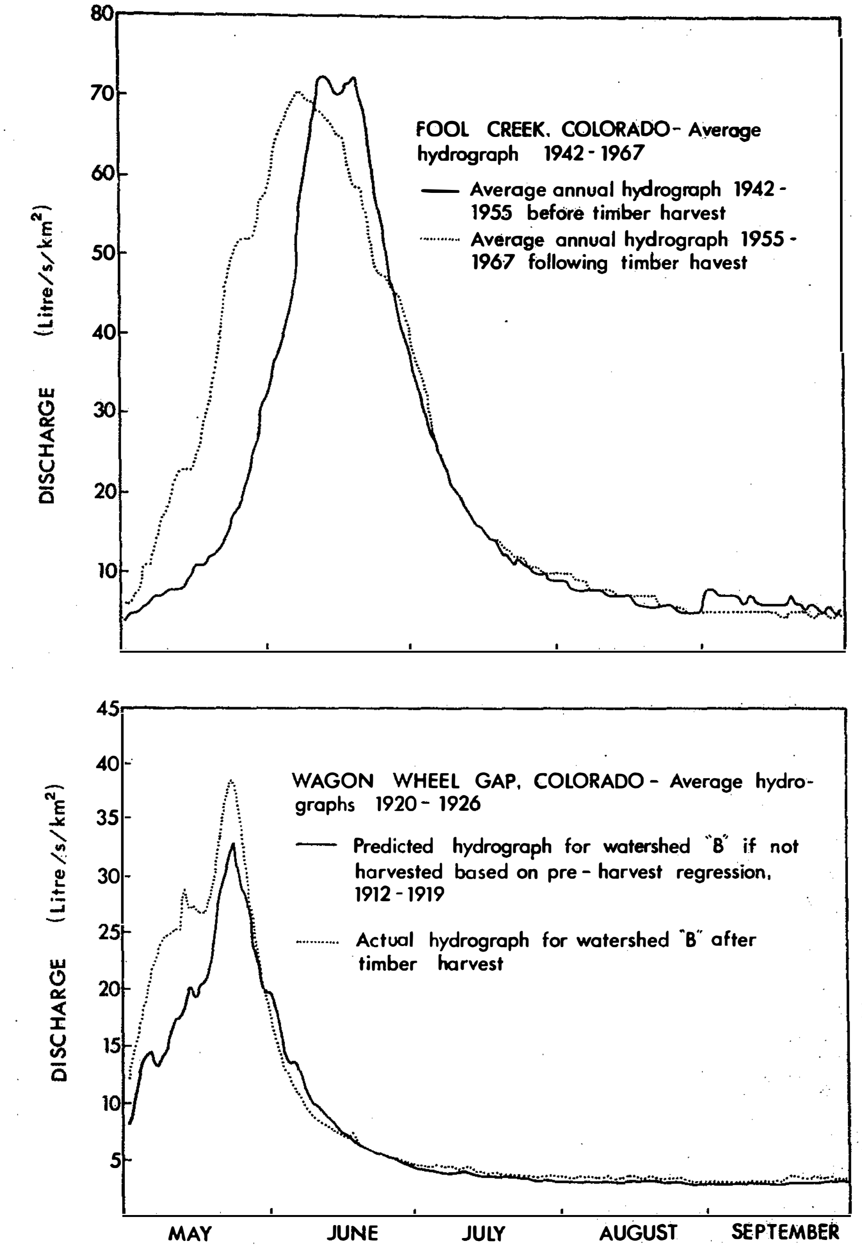

Fig. 5. Hydrographs from experimental watershed harvests in forested areas of the Rocky Mountains, Colorado. Fool Creek watershed, Fraser, Colorado (Leaf 1975). Area 289 ha, elev. 3200 m, 40% of area harvested in small patches in 1954-57. Wagon Wheel Gap watershed, Colorado (Bates and Henry 1928). Area 81 ha, elev. 3100 m, 100% of area harvested in 1919.

block is not as pronounced as that on Fool Creek from harvesting 96 blocks 0.25-1.5 ha. This greater early volume is in effect a change in regime because a larger volume of flow occurs prior to the peak time than before harvest. Earlier runoff is attributed to higher runoff efficiencies after clear-cutting caused by: (1) reduced evapotranspiration and subsequent higher soil moisture carry-over in the cleared blocks, (2) earlier snowmelt caused in part by direct solar radiation at the snow surface, and on Fool Creek, reradiation from the surrounding canopy, and (3) a greater volume of snow in the cleared blocks due to nil interception. On Fool Creek with its many small clear-cuts, the amount of snow in these blocks is further augmented by redistribution of snow into them from the adjoining and intervening unharvested leave strips (Hoover and Leaf 1967).

The cleared areas on the NWPP lease are mostly large, 20-1400 ha, compared to those on Fool Creek. The ratio of forest edge to opening area on the lease, 70 m/ha, is small compared to 494 m/ha at Fool Creek. The clear-cut area and edge/area ratio, 50 m/ha, at Wagon Wheel Gap are fairly typical of those on the lease. Because of the largeness of the clear-cut blocks on the pulp lease, we do not expect reradiation nor redistribution of snow from the surrounding uncut areas to be major determinants of snowmelt rate nor accumulation amount. Therefore, we expect snowmelt from the pulp lease clear-cut areas to produce a hydrograph change more similar to that of Wagon Wheel Gap than of Fool Creek.

ANNUAL YIELD

The results from harvesting a large number of experimental catchments were summarized by Hibbert (1967). Table 1, prepared from his summary, shows the changes in annual yield as a percentage of precipitation that have occurred following varying amounts of harvest. The Fool Creek and Wagon Wheel Gap hydrographs (Fig. 5) indicate that where snow is a significant precipitation component this increase occurs primarily during snowmelt and is in the order of 25-30% of annual yield. Since the hydrographs from the lease (Fig. 4) also are dominated by the snowmelt process, we expect the effect on the pulp lease to be of this same magnitude; that is, a 20-30% increase in annual (ice-free season) yield.

Table 1. Percentage area harvested and annual streamflow as percentage of annual precipitation for 10 experimental watersheds (adapted from Hibbert 1967)

Watershed	Area (ha)	Location	Area Clear-cut %	% Precipitation as Streamflow		
				Uncut	Clear-cut	Ratio
Coweeta 13	16.1	N. Carolina USA	100	43	64	1.49
Coweeta 3	9.2	N. Carolina USA	100	33	40	1.21
Coweeta 22	34.4	N. Carolina USA	50	62	71	1.15
Fernow 1	29.9	W. Virginia USA	85	38	47	1.24
Fernow 2	15.4	W. Virginia USA	36	44	48	1.09
Fernow 7	24.2	W. Virginia USA	50	54	60	1.11
Wagon Wheel Gap	81.1	Colorado USA	100	29	36	1.24
Fool Creek	289.0	Colorado USA	40	37	48	1.30
Kamakia	35.2	East Africa	100	28	51	1.82
Kenya	688.0	East Africa	34	22	27	1.23
Mean	122.25		69.50	39.00	49.20	1.29

STORM YIELD

The volume of streamflow that occurs as a result of summer rain on the lease is small compared to the snowmelt contribution. Nevertheless, the peak instantaneous magnitude of streamflow during summer storms, even from fully forested catchments, may be as high as that occurring during snowmelt (Fig. 4).

If we assume with Hewlett and Hibbert (1967) that all flow from forested land is subsurface until proven otherwise, then there are only three ways that storm flow peaks can be increased:

1. By forcing some ordinarily subsurface flow to a surface path
2. By increasing the efficiency of precipitation delivery to the subsurface system
3. By increasing the area of the wetted-stream perimeter

There is evidence on the NWPP lease that some subsurface flow has been forced to the surface. One can find instances along road cuts where subsurface flow has been intercepted and diverted along a roadside ditch to streams. There is also evidence that the wetted perimeter of some streams has been increased: boggy areas now extend beyond the normal wet site indicators (black spruce, willow, etc.) into clear-cut areas. There is little or no undergrowth in these forests, so the clear-cuts will experience markedly reduced transpiration following harvest. The result of this lower transpiration will be higher soil moisture and increased efficiency in delivering precipitation to the subsurface flow system.

We therefore expect this operation to have an effect similar to that experienced by others following clear-cutting. The hydrographs of Fig. 6 from the Fernow experimental watershed in West Virginia, which indicate a four- to fivefold increase in peak magnitude, are probably at the upper extreme. We expect an effect within this upper bound to occur on the lease.

LONGEVITY OF EFFECTS

There are four physical factors that determine how long a particular harvest will affect generated runoff and water yield: (1) the rate

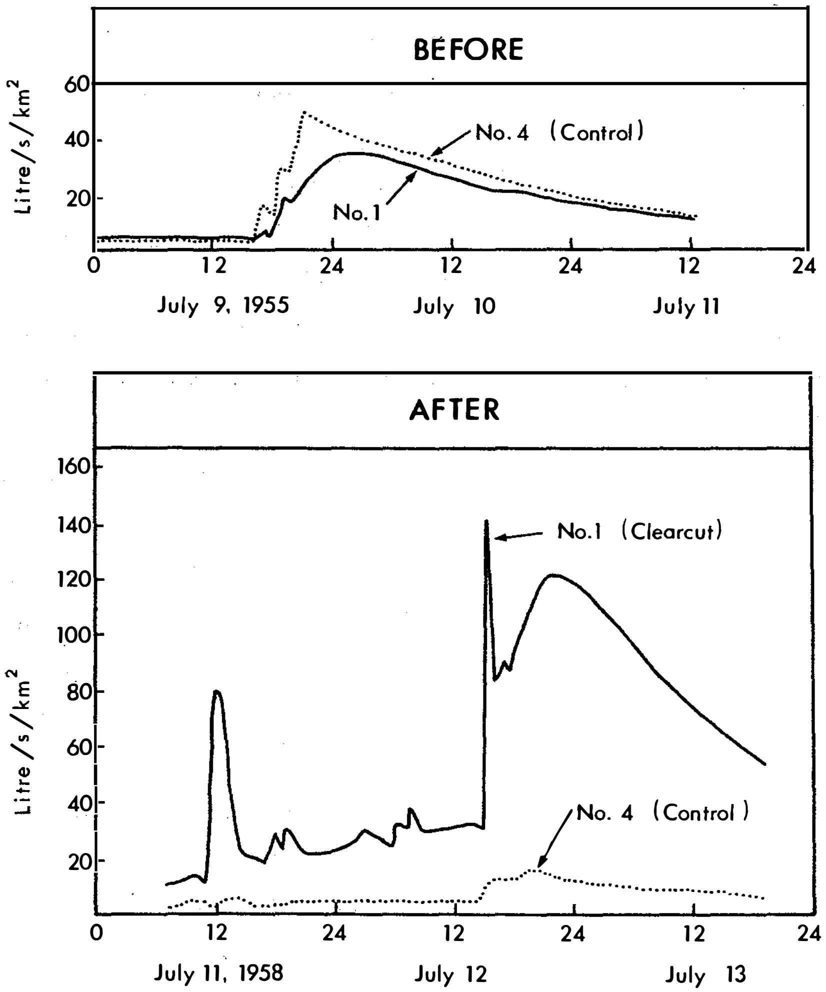

Fig. 6. Sample storm hydrographs before and after clear-cutting, Fernow, West Virginia (Reinhart and Eschner 1962).

of evapotranspiration, (2) the time that transpiration occurs, (3) the amount of precipitation reaching the ground surface, and (4) the speed of snowmelt. All must return to preharvest levels before the harvest effect will vanish.

In the fully forested state, evapotranspiration is primarily transpiration, which is dramatically reduced by clear-cut harvesting. Transpiration from mature lodgepole pine in Alberta ranges from 170 to 240 mm for the June to September period (Swanson 1975). Similarly, Engelmann spruce in Colorado transpired 300 mm from May through October (Swanson 1975). Either of these amounts makes up a large percentage of the 500-550 mm annual precipitation on the lease.

The length of time required for transpiration volume to return to preharvest levels depends upon the rate of growth and density of the regeneration. Where evapotranspiration is the dominant process affected by harvest (as in areas of the world where snow doesn't occur or is not stored for release in the spring freshet), first-year yield increases after clear-cutting are spectacular but relatively short-lived. Hibbert (1967) states that the general pattern of decline in increased yield is a linear function of the logarithm of time since harvest. That is, there is a rapid initial decline in increased yield followed by slight reductions each year until the effect is no longer measurable, which for his South Carolina example is a period about 35 years.

When vegetation presents the same surface area as did the crowns of the mature trees before clear-cutting, then transpiration should reach preharvest levels. According to Tajchman (1971), the difference in evapotranspiration between a 70-year old Norway spruce forest and an adjacent 2-year old alfalfa field (presumably with full areal occupancy) was only 4%. Quick revegetation by coniferous trees to the "alfalfa field" condition may only occur following wildfire, which results in tree densities of 35 000-600 000 stems/ha (Crossley 1976). The revegetation goal for managed forests at NWPP (D.I. Crossley, personal communication) is from 1000 to 1500 stems/ha, which if equally spaced at approximately 3 x 3 m, would result in full crown occupancy when near maturity, projected to be 80 years.

Transpiration from mature trees occurs while there is still some snow on the ground under them (Swanson 1967). However, seedlings covered by snow do not transpire. Thus, the length of time it takes for new trees to grow to a crown position above a 50- to 100-cm deep annual snowpack must be considered in evaluating longevity effects. Some of the new growth on older clear-cuts on the lease was 1-3 m tall in 1974, but there are few trees visible on either the strip clear-cuts in the foreground of Fig. 3 (snow depth approximately 60 cm deep) which were 12 years old, or in the larger cleared area in the left background which has undergone the second cycle cut, portions of which are 3 to 14 years old.

Snow and rain are intercepted by tree foliage, where some evaporates. Clear-cutting initally reduces interception of both rain and snow to zero. Some snow, and possibly rain too, is redistributed into clear-cut areas from the canopy of the residual forest edge. Both lowered interception and redistribution act to augment the amount of snow on the ground in a clear-cut compared to adjacent forest. Berndt (1965) reports 25-50% more snow in clear-cuts in lodgepole pine in Wyoming than under the surrounding forest. Swanson and Stevenson (1971) also reported augmented accumulations of this same order of magnitude in clearings in aspen forest in Alberta.

The relative effectiveness of interception reduction and distribution in augmenting snow accumulation in clear-cuts probably cannot be separately appreciated except at the extremes--complete clear-cut or total forest. However, the longevity of such augmentation is apparently considerable, as indicated by the time trend of snow accumulation in clear-cuts and various density selection cuts in lodgepole pine in Colorado. According to Hoover and Leaf (1967), citing results from a study started in 1940, "...relative snow storage amounts [compared to uncut stand] have changed little [in 1964], if any, with time since cutting in spite of considerable regrowth of young trees and increased canopy density on the heavily cutover plots." On the lease, we expect snow caught in the crowns of isolated trees or isolated patches of trees to be more vulnerable to redistribution to the surfaces under them than snow caught in the canopy of a closed forest where wind cannot freely penetrate. Therefore, we expect augmentation of snow volumes by about 20-30% in the clear-cuts due to reduced interception and some minor redistribution to continue until crown closure occurs.

The speed with which snow melts is also altered by clear-cutting. Results from a study of snow accumulation and melt in mature lodgepole pine forest near Sundre, Alberta, show snow melting 1.16 times faster in 5-tree height wide openings than under closed-canopy forest (D.L. Golding, personal communication). Berndt (1965) also reported that snow persisted in the uncut stand 12 to 14 days longer than in 2- to 8-ha clear-cut blocks. The earlier melting that occurs in clear-cuts increases the efficiency of catchments in yielding streamflow from snow because it occurs at a time and place where soils are wettest and transpiration demand is at its lowest.

According to Gartska *et al.* (1958), pratically all of the heat utilized in the melting of snow can be ascribed ultimately to solar radiation. A description of the total radiation regime of an area in transition from clear-cut to closed canopy is beyond the scope of this paper, but according to Reifsnyder and Lull (1965) the most influential parameters determining the regime are crown closure and crown depth. Regrowth cannot affect crown closure at all during snowmelt until the canopy shows above the snow. However, crown depth will affect snowmelt from the time the canopy is visible until it is well above the snowpack because the canopy is the warmest portion of a forest (Baumgartner 1973).

The longevity of any effect of regrowth on snow accumulation and melt is most difficult to anticipate on the lease because we don't know how dense new regeneration is or how fast crown closure will occur. As well, the edge influence is continually changing as residual blocks left after the first cutting cycle are clear-cut. Very likely there will be no significant edge effect at the end of the second cutting cycle in any given compartment because new trees on the first cycle blocks are not large enough to form a definite physical boundary between old and newly clear-cut blocks.

The regeneration and regrowth problem cannot be so easily addressed. Regeneration surveys to determine the degree of restocking by new trees are made 7 years after harvest (MacArthur 1968) where the number of milacre plots with one or more trees is counted. This survey does not indicate the total number of trees present or their areal distribution. These latter two figures would help in estimating the time until crown closure and thus the longevity of this harvest's hydrologic alteration. It is perhaps sufficient to say that the time to crown closure and maximum canopy depth could be highly variable on this lease, where casual observations of stem densities range from less than 200 to more than 30 000/ha. The most commonly observed density is 1200-3000 stems/ha, which would probably result in crown closure and maximum crown depth at 40-60 years after clear-cutting.

Reduced transpiration and interception as well as any precipitation redistribution will affect soil moisture during snowmelt and throughout the growing season. The length of time this effect will persist is somehwat speculative and difficult to generalize for the entire lease because of the inconsistency of regeneration time, stocking density, and growth rate on spruce and lodgepole pine areas. Leaf and Brink (1975) provide a table of time trends for use in their simulation model that shows no decline in available soil water after clear-cutting for 15 years in lodgepole pine and 30 years in spruce-fir. They also indicate that precipitation redistribution effects, which are inseparable from interception reduction effects, do not begin to decline for 40 years in lodgepole pine and 80 years in spruce-fir. We have no reason to doubt these estimated time trends. Our casual observations of regeneration on these clear-cuts in Alberta indicate that it is similar to regeneration we have observed in Colorado and Wyoming. Therefore, we expect any hydrologic alteration due to clear-cutting at NWPP in Alberta to last at least 30 years before it begins to diminish.

SUMMARY OF EXPECTED EFFECTS

The harvest on the NWPP lease near Hinton, Alberta, is expected to have the following effects on local streamflow compared to uncut areas in the same vicinity: (1) Earlier and greater runoff from snowmelt; that is, a larger volume of runoff in the spring freshet, (2) 20-30% greater annual streamflow, (3) storm-flow peaks four to five times higher, and (4) a longevity in excess of 30 years before the effects on snow accumulation, melt, evapotranspiration, and subsequent streamflow begin to diminish.

VERIFICATION OF EXPECTED EFFECTS

METHOD

The method we chose to verify the expected results was to determine the water yield from existing clear-cut and nonharvested areas on the NWPP lease. This was done by gauging a number of harvested and nonharvested (control) catchments and comparing the difference in water yield for the major runoff season, mid-April through mid-September. One or two years' data was thought sufficient, as our goal was to evaluate the change in water yield due to this harvest and not to document long-term hydrologic characteristics.

Our sampling criterion was to determine a 25% change in water yield at the 80% confidence level. We felt that a one-in-five chance of error was acceptable for this evaluation test and for later use in making land-management decisions affecting water.

The entire NWPP lease was considered a single population from which we could select a number of catchments for gauging, although poor access and a lack of harvested catchments precluded samples in the Embarras working circle. Also, we could not be certain that the clear-cut catchments chosen were free of hydrologic bias because the decision as to which areas to harvest first was made quite apart from this study and based on oldest tree age. Obviously, the oldest trees are found in areas that have been free from fires for the longest time, which might mean that these sites were (and may still be) wetter than those surrounding. This is a source of bias that we could not remove. However, wherever possible we selected control catchments as near physically to their harvested counterparts so that present climatic conditions were similar. In general, this precaution ensures that the timber age on a control catchment is within 20 years of its clear-cut counterpart.

There have not been any similar statistical evaluations reported that could guide us in our sampling intensities. Therefore, we estimated the number of catchments necessary to detect a 25% increase in water yield with 80% confidence as nine logged and nine controls from equation (1) (Freese 1967).

$$n = (2t^2s^2)/D^2 \qquad (1)$$

where: n = number of samples (catchments) of each type
D = difference in streamflow we wished detect
s^2= estimate of population variance
t - Students "t" value at desired probability

(An estimate of the variance during the high runoff months of May and June was obtained using streamflow data from the three contiguous basins on the 57-km^2 Tri Creeks experimental watershed located in the southern portion of the McLeod working circle. We assumed that the variance in these data would be less than that over the entire lease, and doubled the value obtained to estimate the number of sample catchments needed as nine.)

Selection criteria were: (1) control catchments could not have more than 10% of their timber removed, (2) logged catchments must be clear-cut over 30% or more of the total area, (3) the area of either type had to be between 7 and 26 km^2, and (4) there had to be reasonable access and a stable stream section for gauging.

ESTABLISHMENT

Sixteen catchments, seven unlogged and nine logged controls, were selected in 1972. Two additional unlogged catchments were chosen in 1973. These catchments are described in Table 2. Except for catchments 4 and 11, the logged and control catchments within each working circle are physically close to each other with similar topography and climate.

A staff gauge was established in a stable reach or at some pre-existing control on the stream draining each catchment. Streamflow was measured manually with a cup-type current meter (three to five times a week

Table 2. Gauged catchments on NWPP lease, Hinton, Alberta

Catchment		Location					Harvest History			
No.	Drainage	Latitude (N)	Longitude (W)	Dominant Forest Cover[1]	Drainage Area (km^2)	Category[2]	Average Age Years[3]	Percent Cut (1974)	Edge/Area Ratio (m/ha)	Elevation (m above msl)
Athabasca Working Circle										
1	Oldman Ck.	53°41'53"	117°33'48"	PL, SW	17.0	C	-	Nil	-	1190-1400
2	Oldman Ck.	53°41'03"	117°33'48"	PL	14.9	C	-	Nil	-	1220-1400
3	Oldman Ck.	53°31'31"	117°40'51"	SW	16.4	L	7.9	84	58	1450-1520
4	Fish Ck.	53°28'50"	117°38'54"	SW	11.6	L	10.6	76	31	1210-1520
5	Oldman Ck.	53°37'18"	117°31'25"	SW, PL	19.7	L	10.2	35	38	1280-1580
Marlboro Working Circle										
6	Pine Ck.	53°54'55"	116°43'20"	PL	23.9	C	-	8	-	1190-1450
7	Pine Ck.	53°54'22"	116°45'44"	PL	22.1	L	6.7	38	148	1190-1370
8	Edson R.	53°50'00"	116°40'54"	PL, SW	7.0	L	7.7	37	88	1140-1450
9	Edson R.	53°48'43"	116°44'52"	PL, SW	23.1	C	-	9	-	1110-1400
Berland Working Circle										
10	Hendrickson Ck.	53°46'37"	118°22'03"	PL	22.0	C	-	Nil	-	1420-1620
11	Vogel Ck.	53°46'58"	118°27'07"	PL, SW	11.1	C	-	Nil	-	1480-1650
12	Cabin Ck.	53°45'51"	118°21'55"	PL, SW	12.6	C	-	Nil	-	1400-1770
13	Fox Ck.	53°43'07'	118°16'11"	PL	18.2	L	8.9	57	39	1370-1520
14	Fox Ck.	53°42'15"	118°16'47"	PL, SW	12.3	L	9.0	60	20	1370-1740
McLeod Working Circle										
15	Anderson Ck.	53°18'19"	117°18'04"	PL, SW	19.7	C	-	6	-	1190-1680
16	Ck. (not named)	53°18'32"	117°17'04"	PL, SW	8.8	C	-	21[4]	-	1190-1460
17	Anderson Ck.	53°19'16"	117°22'43"	PL, SW	10.7	L	11.5	56	90	1280-1620
18	Quigley Ck.	53°20'30"	117°23'17"	PL, SW	16.8	L	11.3	46	114	1280-1430

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[1] PL = lodgepole pine SW = white spruce

[2] C = control catchment L = logged catchment

[3] Average age = Σ[(Area cut in year) x (1974-year cut)]/ΣArea

[4] Catchment 16 is logged in excess of our criterion for a control. Eleven percent was logged prior to 1973, but the extra 1% above our criterion was not considered sufficient to exclude this otherwise desirable catchment. However, an additional 10% of the timber was logged during July-August 1973, bringing the total to 21% at the start of the 1974 runoff season and greatly exceeding our control catchment criteria.

We still used catchment 16 as a control during 1974 because: (1) all of the harvest is near or on the catchment divide, and harvest in this area is generally considered to have the least effect on streamflow, and (2) the cutting was done relatively late in the growing season so that the effect of full forest transpiration during 1973 on carry-over soil moisture to 1974 would already be present. We could not have used this catchment as a control in 1975, if the study had been continued, because (2) above would only be true the first year following late summer harvest.

in 1973; less frequently in 1974) to establish a stage height-discharge relationship for each control section. During 1973, a stilling well and a stage height recorder were installed in each control section. Some data obtained during 1973 are from streams without a stage height recorder and are discontinuous in time. All data obtained during 1974 are from stage height recordings and continuous from ice breakup in April through mid-September.

An Atmospheric Environment Service of Canada MSC type "A" precipitation gauge was installed near each control section and serviced at least once each week. Six U.S. Weather Bureau type Belfort and three Fischer-Porter weighing rain and snow gauges were located at strategic positions throughout the lease. Two snow courses in each working circle were measured in April to ascertain snow on the ground when snowmelt commenced. In addition to these, snow course and precipitation data from an intensive climatic study being conducted in the same area were made available to us (J.M. Powell, personal communication). A compilation of all streamflow and precipitation data collected during 1973 to 1975 will be available upon request after 1977.

DATA PRESENTATION AND ANALYSIS

Daily streamflow was calculated in litres per second and compiled for each catchment. All analyses were conducted on data converted to the unit-area forms of litres per second per square kilometre or millimetre to allow for differences in area between catchments. Precipitation fron non-recording gauges was generally read daily, but if not, weighted over the days-of-occurrence interval indicated by the traces from the recording precipitation gauges. These water yield and precipitation values, both for individual catchments and an areal average for the lease, were displayed graphically to select time intervals for further analyses.

The "t" statistic was used to test the significance of water yield differences noted. Sixteen degrees of freedom (df) were availalbe for the unpaired mean difference comparisons and 7 df for the paired differences. In the results and discussion below, "significant" means at the 80% level except where a higher confidence value is noted.

RESULTS OF THE VERIFICATION STUDY

The results for 1973 are shown in Fig. 7. These composite hydrographs were derived by averaging each day's data from the two catchment types. The shaded portion indicates time periods when the water yield from those logged exceeded that from the control catchments. As anticipated, greater yields from the harvested catchments occurred during snowmelt runoff, May 11-24, and the three rainstorms of May 24-June 1, June 23-27, and August 3-20.

Our data in 1973 were discontinuous and insufficient to satisfy statistical analysis requirements. Some of the flow data for both the logged and control hydrograph on Fig. 7 have been estimated by regression of manually obtained flow against that recorded at one or more control sections. These hydrograph segments are indicated by the dotted lines. Results from selected events in 1973 are summarized in Table 3. Because both actual and estimated data were used to obtain these values, no statistical significance should be attached to them.

The composite hydrograph for 1974 is shown in Fig. 8. Shaded portions indicate time periods when water yield from the logged exceeded that from the control catchments. Table 4 is a summary of the water yield and statistical tests for 1974. During the spring freshet (April 25-May 23), the logged catchments yielded 36.6 mm or 59% more runoff than the controls. For the entire gauged season (April 25-September 15) the percentage was less, 27%, but the absolute increase was still 39.2 mm. Both increases are statistically significant at the design probability level of 80% or higher.

Individual hydrographs for each catchment of the eight pairs are shown in Figs. 9-12. These data have been grouped by working circle and tested for the significance of April to September water yield differences with 1 df (Table 5). This grouping and test are outside the design criteria for the study. Nonetheless, the water yield differences are significant in two of the four working circles.

The individual hydrograph pairs are included largely to indicate storm response and the sources of variation in the composite data. The

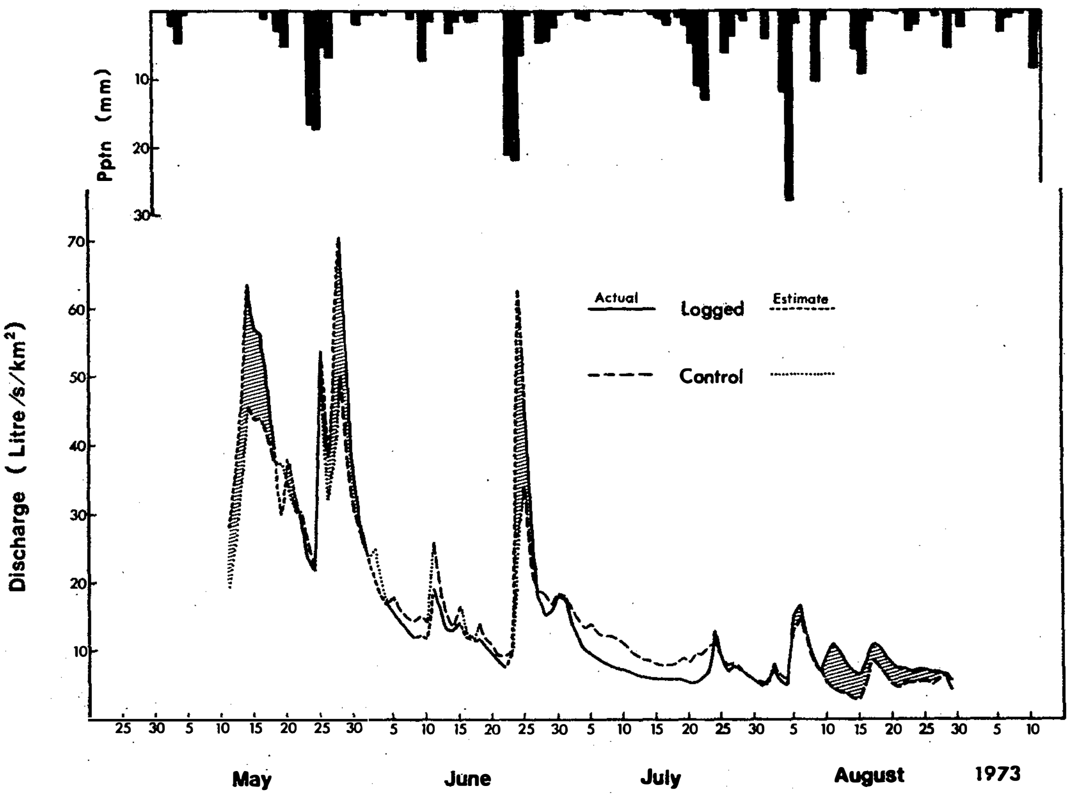

Fig. 7. Composite hydrographs and precipitation for 1973 from nine logged and seven control catchments on the study area. Shaded portions indicate times when logged water yield exceeded control.

Table 3. Comparison of runoff from logged and control catchments for selected events, 1973

Runoff Period	Event	Precipitation (mm)	Runoff (mm)	
			Logged	Control
May 11-24	Snowmelt	130[1]	47.0	40.1
May 24- June 1	Snow and rainstorm	46	29.9	24.4
June 23-27	Rainstorm	50	14.0	9.4
August 4-9	Rainstorm	42	5.5	5.0

[1] Snow on ground at beginning of snowmelt

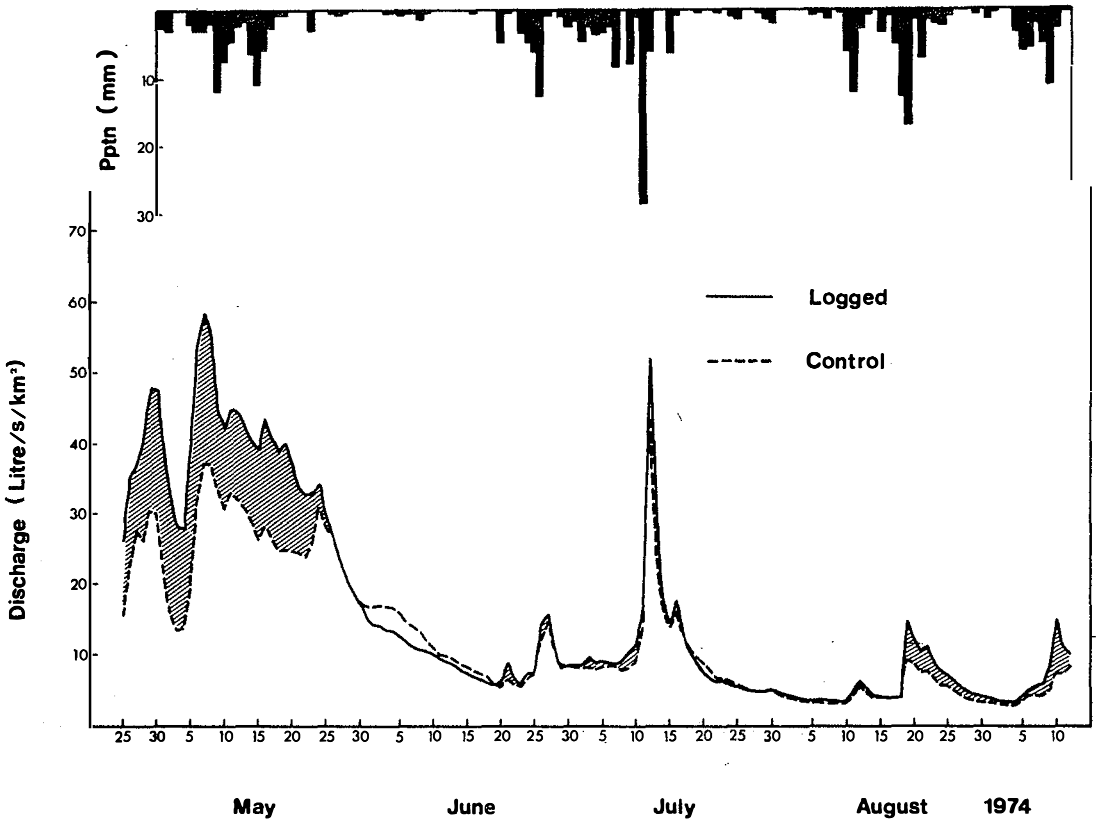

Fig. 8. Composite hydrographs for 1974 from nine logged and nine control catchments on the study area. Shaded portions indicate times when logged yield exceeded control.

Table 4. Comparative statistics of composite runoff from logged and control catchments for 1974

			Runoff (mm)						
			Unpaired Comparison df = 16[1]				Paired Comparison df = 7[1]		
Runoff Period	Event	Precipitation (mm)	Logged	Control	"t"	Confidence Level (%)	Difference	"t"	Confidence Level (%)
April 25-May 23	Snowmelt and rain	278[2]	98.9	62.3	1.907	90	34.2	2.958	95
June 1-8	Recession	4	8.8	10.9	-0.954	n.s.[3]	-0.4	-0.372	n.s.
July 9-14	Recession	43	11.9	10.0	0.749	n.s.	2.2	2.519	95
August 19-28	Rainstorm	43	7.8	5.8	1.630	80	2.1	2.424	95
Sept. 7-10	Rainstorm	34	3.0	1.9	3.027	99	1.2	3.070	98
April 25-Sept. 15	Mixed	513	186.6	147.4	1.416	80	42.4	2.455	95

[1] df = degrees of freedom.

[2] Snowpack April 11, 1974 and rain and snow to May 23.

[3] n.s. = not significant at 80% confidence level.

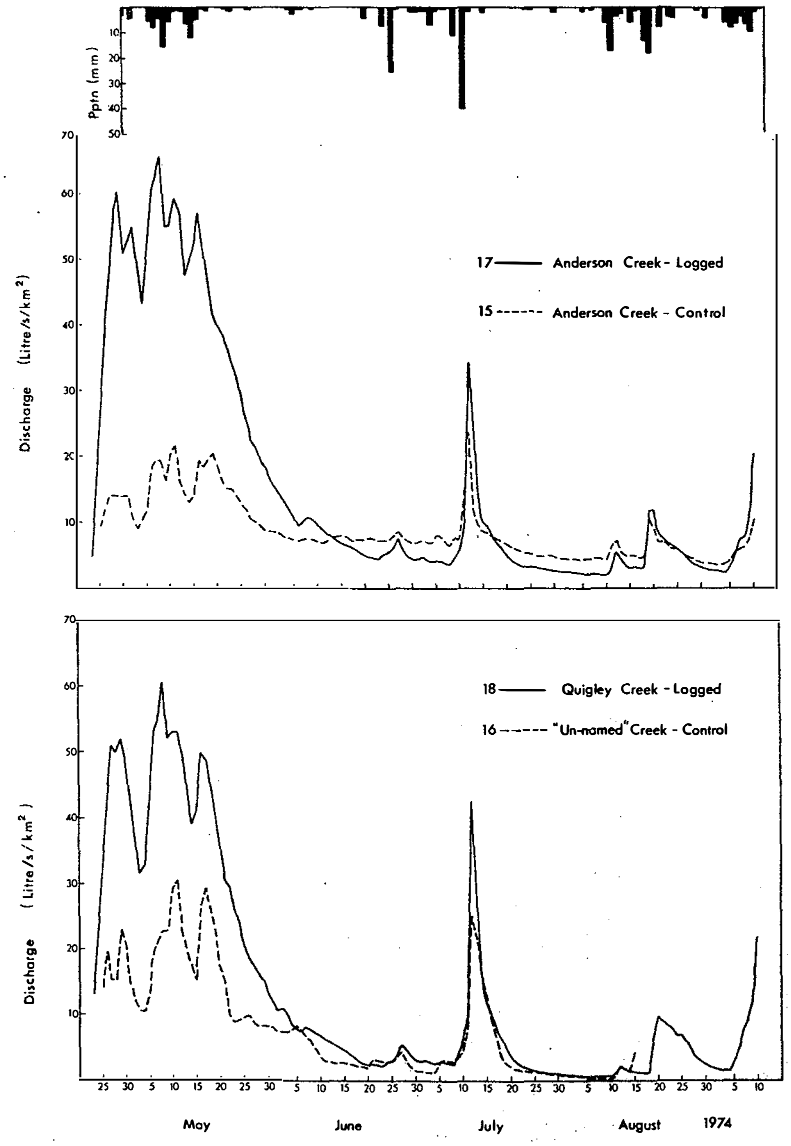

Fig. 9. Hydrographs from catchment pairs, McLeod working circle

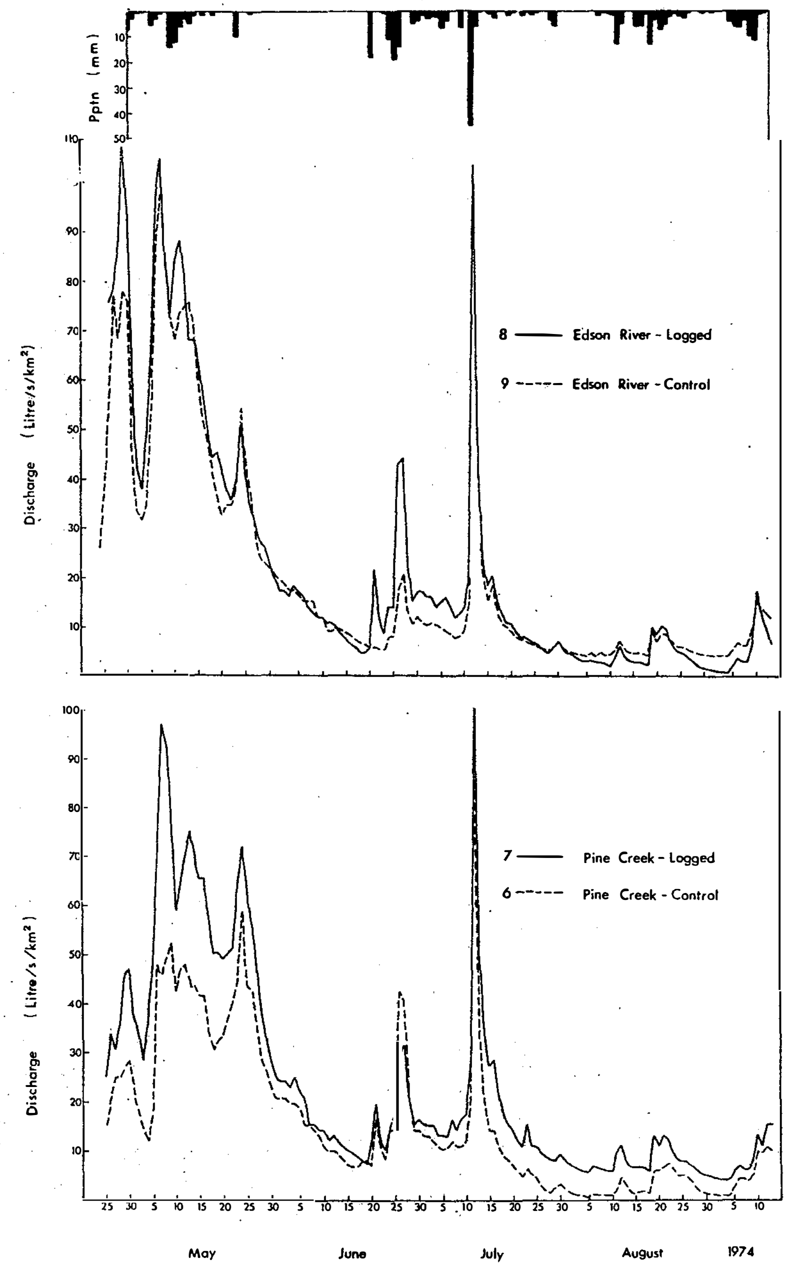

Fig. 10. Hydrographs from catchment pairs, Marlboro working circle

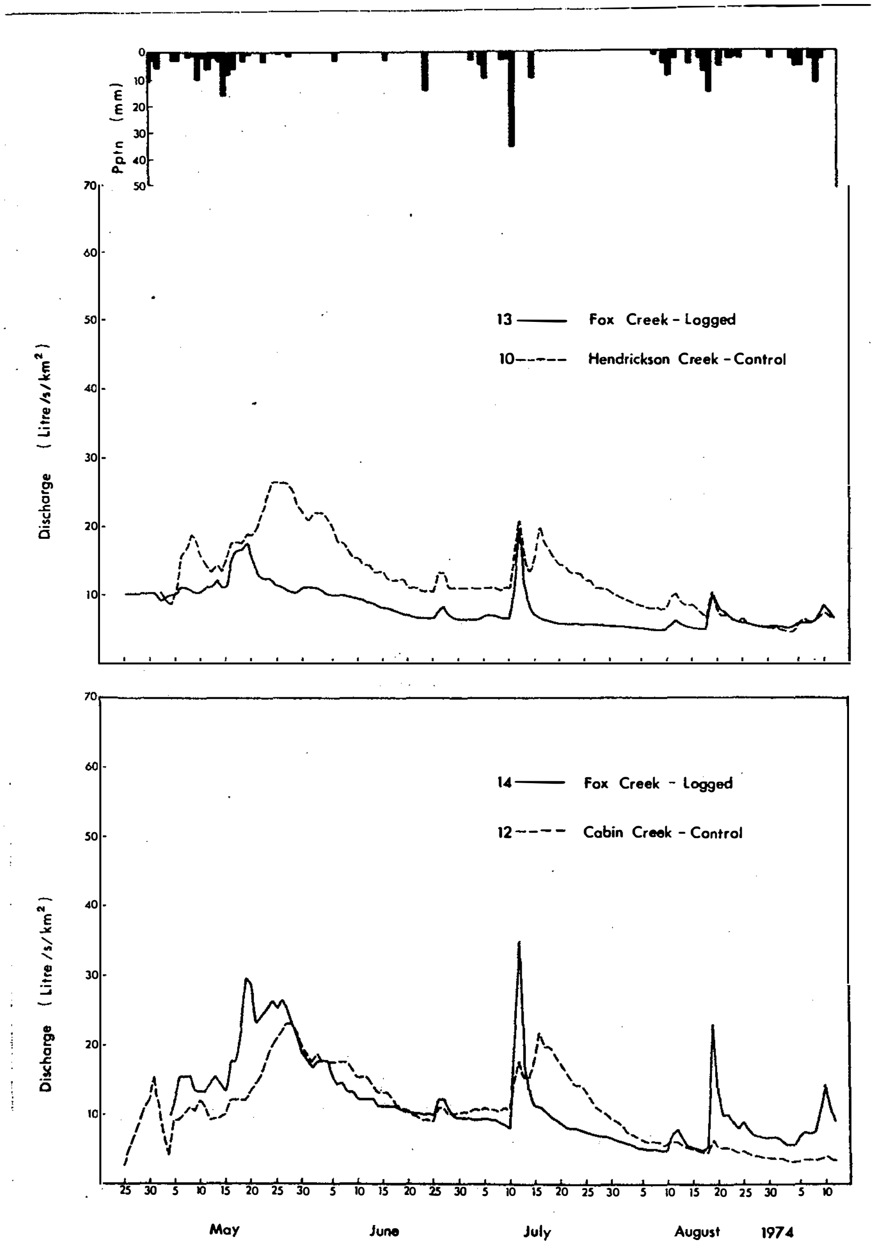

Fig. 11. Hydrographs from catchment pairs, Berland working circle

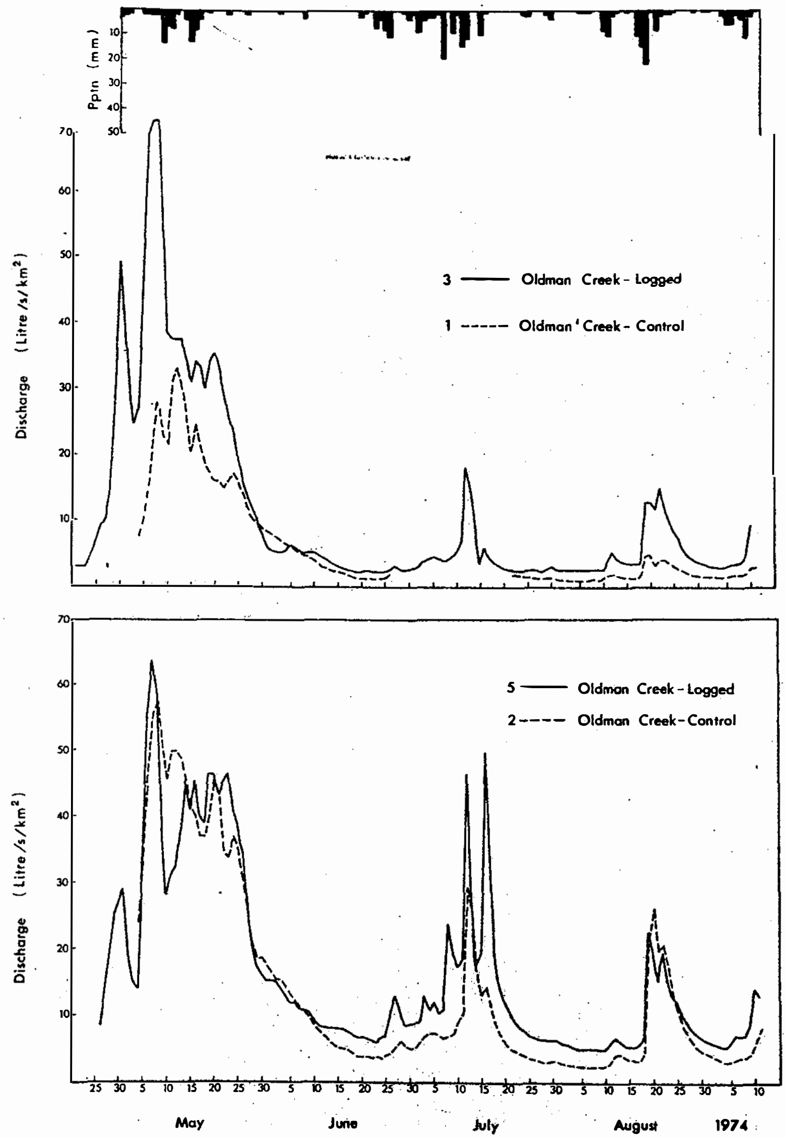

Fig. 12. Hydrographs from catchment pairs, Athabasca working circle

Table 5. Comparative statistics of runoff from catchment pairs in each working circle for period April 25-September 15, 1974

Working Circle	Runoff, mm		Statistics, 1 df	
	Logged	Control	"t"	Confidence Level
McLeod	179.2	96.9	13.333	95%
Marlboro	281.6	217.3	2.146	n.s.
Berland	116.9	138.8	-.664	n.s.
Athabasca	169.2	124.2	4.620	80

data from these pairs do not have the same meaning as those found in the literature from paired experimental watershed studies. In our case, the water yield from a logged catchment minus that from a nearby unlogged one has been used as a sample from a local topographic-climatic situation. The water yield from both catchment types is assumed equal if neither were logged, but no measurements were taken prior to logging to verify this equality.

In a paired experimental watershed study, this assumption of equal yield is not made; the flow or water yield from the two catchments is not directly compared. The two catchments are simultaneously gauged for a number of years prior to any logging to establish an equation from which the streamflow from the catchment to be treated can be predicted from that of the control. Water yield differences are treated streamflow minus that predicted if treatment had not occurred.

This difference in definition of pairing and experimental method is an important point to remember in interpreting the data from this study. We, as well as some readers, may be tempted to compare the difference between hydrographs from individual catchments of a pair. (For example, the yield of control catchment 10 is higher than that of its treated counterpart, 13.) Such comparisons are not valid. However, these comparisons may be useful starting points for future more detailed research to see why and if the apparent difference really exists.

The variance among the logged and control sample catchments was subjected to Bartlett's test of homogeneity (Freese 1967) to see if the samples came from populations having equal variance. The calculated chi-square of 0.2373 does not refute the hypothesis that the population variances are equal (1 df, P = .01).

The 1973 and 1974 composite hydrographs and five of eight of the individual pair hydrographs indicate a trend during late recession (May 25 to mid-June) that is also present on the experimental catchment hydrographs of Fig. 5: The flow from the control catchments exceeds that from the logged for a brief period during recession. This small flow difference is not statistically significant. It probably does not have any consequence for water users, either. What is important is that a response to clear-cutting this small is present even in our rather crude test.

COMPARISON OF EXPECTED AND ACTUAL EFFECTS

All comparisons below are based on 1974 data, although in general, 1973 data corroborate the findings.

Timing

Almost all of the increase occurred during the spring freshet. The April-May portion of the hydrograph of Fig. 8 is very similar in appearance to that from Wagon Wheel Gap (Fig. 5). Both higher instantaneous flows early in the snowmelt season and greater overall volumes in the freshet occurred as anticipated.

Annual Yield

The expected effect was 20-30% more yield from the harvested catchments. The actual increase of 27% is almost exactly the same as that from the mean of the 10 experimental watershed studies of Table 1.

Runoff from Storms

We anticipated four to five times higher peak flows from the harvested catchments. An increase of this magnitude is not evident in the composite hydrograph (Fig. 8).

On individual hydrographs, the pattern of storm discharge is clearer but still highly variable. The maximum difference in peak discharge between logged and control of 3.3 times occurred on catchment pair 12-14 (Fig. 11) during August 17-20, when peak discharge from the logged catchment was 23 L/s/km^2 compared to 7 L/s/km^2 on the control. Several others indicate discharge differences in the two- or threefold range (Fig. 10, pair 8-9, June 25-30; Fig. 11, pair 12-14, July 10-15; and Fig. 12, pair 1-3, August 17-25). Apparently the storm causing the peak at 50 L/s/km^2 on catchment 5 (Fig. 12, July 17-20) did not occur on its control. Both catchment pairs of Fig. 10 showed the same response to the storm of July 10-15; that is, the peak discharge from both logged and controls was the same.

The response of logged catchment 13 (Fig. 11) is somewhat interesting in that the peak discharge during rain equalled that from the control even though the overall discharge from the logged appears substantially less than the control at other times. The storm response time of both of these logged catchments (13 and 14) in the Berland is markedly quicker than their control counterparts.

In summary, the difference in storm response is not as great as that at Fernow, West Virginia (Fig. 6), although the general pattern is similar. The magnitude of discharge difference from logged versus uncut catchments varies from none (or even slightly less) to more than three times. The average response difference is about 1-1/2 to two times. The duration of discharge is shortened on some but not all logged catchments.

Longevity of Effect

There does not appear to be any strong relationship between the age of the clear-harvest areas and the magnitude of the streamflow response. The overall increases at this time are similar to those of Table 1, which are for the most part for the initial 5 years following harvest. Since the time of response and annual increase are as expected from the experimental watershed results, we believe that the longevity will be too.

The clear-cutting on the areas we have evaluated ranges from 1 to 19 years old. The effect we have noted from an average 10-year old harvest is similar to that recorded for the early years elsewhere. Judging from the Colorado experience and the slowness of regrowth on the lease, we conclude that a conservative estimate for the duration of the effect obtained here will be at least 30 years.

DISCUSSION

We have demonstrated with a reasonable degree of confidence that the general effects of clear-cut harvesting on generated runoff and subsequent streamflow can be estimated from an understanding of the physical processes involved. The estimate was not too difficult to make in this case because (1) fairly large clear-cuts were dispersed over a large area which has a reasonably uniform climate, and (2) the clear-cut locations on any particular catchment did not favor any topographic position. The clear-cut harvesting program on the NWPP lease encompasses most of the possible clear-cutting configurations and thus produced an average effect.

It is important to realize that an operation that concentrates clear-cutting activities in a particular topographic position within catchments may not produce average effects. For instance, the North Fork Workman Creek experimental harvest in Arizona produced a 55% increase in streamflow (Rich 1965). This clear-cut was confined to the moist zone adjacent to the stream channel and occupied only 32% of the catchment area. In sharp contrast, the South Fork Workman Creek produced slightly less than 4% more water yield after 45% of its timber was removed. The South Fork cutting was dispersed over the whole catchment as an individual-tree selection harvest, a 24-ha burn (20% of the catchment area) on an upper slope position, and assorted roads and skid trails (Rich 1965).

The specific effect that a clear-cut harvest will have on the streamflow from a particular catchment is difficult to predict because clear-cutting is not a single practice even with respect to runoff generation. Harvested areas can take on an infinite variety of shapes and/or sizes. Watersheds aren't uniform either. Our widely differing samples from the Berland (Fig. 11) and the McLeod (Fig. 9) are ample evidence of this! The size, shape, slope, drainage pattern, drainage density, geology, soils, and surface-subsurface curvature of a catchment define routing. In no two catchments are these completely the same. The hydrologic response to a clear-cut, which can be located anywhere on a catchment where timber exists, depends upon these parameters.

Simulation modeling may be useful to tie runoff-generating and flow-routing parameters together, but no model currently available combines the realism needed to adequately describe the operation of the physical system and the simplicity necessary to enable its use. The land use model proposed by Leaf and Brink (1975) describes the effect of clear-cutting on generated runoff. It is useful for simulating the effects intermediate to large-sized cleared blocks (4-6 H and larger, where H = height of surrounding trees) will have. Freeze (1972a and b) has put forth a most realistic description of what happens to generated runoff in its process of becoming streamflow. Stephenson and Freeze (1974) successfully applied this description to Reynolds Creek in Idaho to simulate the snowmelt contribution to streamflow. However, they conclude that a massive data gathering program of soil and formation parameters would be necessary before a model of this complexity could be applied on a routine basis.

General statements of harvest effects are probably sufficient unless a forested watershed is being specifically managed or forestry operations are being restricted to enhance some aspect of water usability or to minimize damage. Water resource planners responsible for the area of the Athabasca River downstream from the NWPP lease should at least be aware that a higher annual runoff level will be attained and maintained permanently as long as the forestry operation continues. Likewise, those responsible for designing culverts and/or bridges to accommodate streams flowing from areas of clear-cut or those to be clear-cut should be aware that peak flows may be two to three times those from unharvested areas.

If forest harvest operations are to be modified to produce some specified water yield increase or to limit increases to some specified value, then a simulation model coupling runoff generation effects of the harvest and a routing of that runoff through the particular topographic situation is needed. If, however, only the general effects of forest clear-cutting are required, then an informal model of the type used here should suffice.

SUMMARY AND CONCLUSIONS

1. The change in water yield resulting from forest clear-cutting may be inferred from the degree of alteration during harvest. Altered stand parameters produce predictable changes in interception, transpiration, snow accumulation, and snowmelt processes that in turn affect generated runoff.
2. Using this informal model, we predicted that the effects of clear-cutting on the NWPP lease on streamflow, compared to uncut areas in the same vicinity, would be earlier and greater runoff during the snowmelt freshet, 20-30% greater annual streamflow from the logged catchments, storm-flow peaks four to five times higher from harvested catchments, and a longevity of greater than 30 years before the effects on interception, snow accumulation, transpiration, snowmelt, and subsequent streamflow begin to diminish.
3. The streamflow measured during 1974 from 9 logged and 9 uncut control catchments from 7-26 km^2 in area was compared using the "t" statistic to ascertain significance. Higher instantaneous flows early in the snowmelt season and greater overall volumes in the freshet occurred as expected. Logged catchments yielded 27% more water (187 compared to 147 mm, significant at 80% level unpaired comparison using data from all catchments; 42 mm difference, significant at 95% level using stratified data from eight catchment pairs). Increases in storm flows ranged from none to 3.3 times greater, averaging about 1-1/2 to two times greater. The effective age of the harvest on the logged catchments was 10 years (range 1-20 years), and regrowth is sparse and not visible above the snowpack during much of the snowmelt period on most

clear-cuts. Therefore, the influence of clear-cutting on any given catchment is expected to affect streamflow in excess of 30 years.

4. The general water yield increase caused by the current forest management activities of the North Western Pulp and Power Co. Ltd. in western Alberta is 27% which is in agreement with the average for world-wide experimental watershed results. This increase was predictable because of the similarity of this clear-cutting operation to those in similar timber-climate type in Colorado, and a sufficiently large sample on diverse topography so that subsurface flow between catchments "averaged out". However, one should exercise caution in applying this generalization to a specific catchment, as our results ranged from a slightly negative effect on one of the Berland catchments to a 100% increase on the McLeod catchments. Our informal model incorporates only the interaction among forest vegetation, precipitation, and transpiration. This interaction is reasonably predictable from a knowledge of before-and-after-harvest stand characteristics. However, forest stand parameters contain little or no information on streamflow routing via surface or subsurface pathways, and routing is all-important if one is to define the effect of a particular harvest on a particular catchment. Highly sophisticated simulation models incorporating surface and subsurface physical parameters are required for this last.

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