Options for Harvesting Timber to Control Snowpack Accumulation

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Timber harvest has been demonstrated to have a significant effect on snowpack accumulation and melt. In one of the earliest studies, Wilm and Dunford (1948) reported on the effect of differing harvesting levels on snowpack accumulation in lodgepole pine stands on the Fraser Experimental Forest. They observed a consistent increase in peak water equivalent with increased intensity of harvest and concluded that the increase was a reflection of the interception savings associated with timber harvest; that is, the amount of snow previously intercepted by the canopy and vaporized back to the atmosphere was being reduced. They inferred that clearcutting was the most efficient means to maximize this savings. This thinking persisted well into the late 1950's when a second interpretation was made.

Hoover and Leaf (1967) evaluated the significance of interception in the subalpine forest. In light of previous work by Goodell (1964) and other studies, Hoover and Leaf concluded that differences in snowpack accumulation between forest and clearcuts were a reflection of deposition and redistribution processes rather than interception savings. They concluded that although there was an "interception savings," the savings would be lost through increased evaporative loss from the snowpack. This interpretation was further expanded by Leaf (1975) and Troendle and Leaf (1980) and represents "state of the art".

The problem, however, is that this interpretation puts constraints on the use of other options. A 5-tree-height (5-H) opening may still be the most efficient accumulator of snowpack, but can other sizes be used? By the same token, the assumption that the interception loss savings that occur following clearcutting are lost in increased evaporative loss from the pack may be valid, but can we assume it is also lost under partial cuts?

This paper will report the results of several recent studies on the Fraser Experimental Forest in Colorado that look at what other options may be available to harvest the forest and still optimize the impact on the snowpack, reduce interception loss, and subsequently impact the water resource. Specifically, it will address:

1. Whether or not large openings can be created without causing significant snow scour.

2. Whether or not the differential accumulation known to occur between forest and opening occurs during or between snow events, or both.

3. Whether or not reducing stand density has an effect on snowpack accumulation on a large scale.

Because the data indicate the dominance of differing processes in each case, they will be treated separately.

THE EFFECT OF OPENING SIZE

Church (1912) first envisioned that a forest honeycombed with openings would function as an efficient snowtrap, and the shade from the residual stand would delay melt. Numerous studies since then have demonstrated that moderate-sized openings are quite efficient collectors of snow, and the work by Gary (1974) probably best defines the nature of the balance that exists. Figure 1 represents the pattern of snowpack accumulation in a small 1-H opening and in the surrounding forest. The 2 years of data show the balance that exists between increased accumulation in the opening and the

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Presented at the Western Snow Conference, April 17-19, 1984, Sun Valley, Idaho.

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decrease downwind. Gary (1974) noted similar balances for a range of opening sizes and, at least for that study, the balance clearly indicates no net change in total accumulation. At the watershed scale this balance also has been verified at Wagon Wheel Gap and Fool Creek (Hoover and Leaf, 1967) and Deadhorse Creek (Troendle, 1983) in Colorado, and at the James River (Golding and Swanson, 1978) and Marmot Creek (Swanson and Golding, 1982) watersheds in Alberta.

Studies such as these have aided in the development of snow retention relationships like that depicted in figure 2. Inherent in the snow retention relationship is the assumption of equality of area--that is, for each unit clearcut, an area downwind is necessary to balance the increased accumulation (Troendle and Leaf, 1980). Also implied is the restriction placed on large openings. As the size of an opening increases, its efficiency in trapping snow decreases to the point (approximately 15-17 H) where there is a net loss. This loss is associated with increased scour and sublimation losses and reflects a net reduction in precipitation not offset by an accumulation elsewhere (Tabler, 1975).

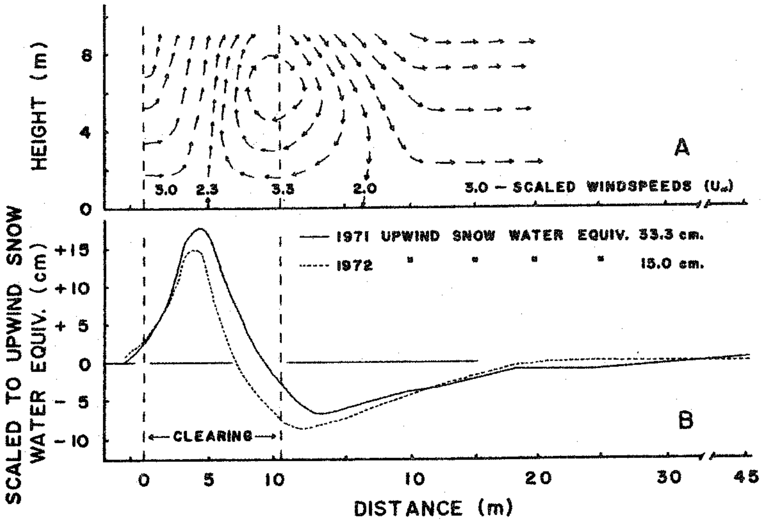

Figure 1.--Peak water equivalent and relative windspeed in the open and the downwind forest (Gary, 1974).

Study Area and Methods

In 1980, it was proposed that an 8-ha area surrounding one of the original 3-ha clearcut plots studied by Wilm and Dunford (1948) be clearcut. Wilm and Dunford had noted that on average more than 30% more peak water equivalent occurred in the 3-ha clearcuts than in the 3-ha control plots, and Gary (1980) noted that this effect was still present in 1976.

The clearcut, including the original study area, was to be 22-H wide parallel to the wind, and because it was on an exposed slope, it would provide an opportunity to verify one point on the snow retention coefficient (fig. 2). In March 1981, water equivalent (W.E.) was measured at the 25 sample points in the original clearcut block and the 25 in the forested control. The original 3-ha clearcut contained not only the few overmature noncommercial spruce, fir, and lodgepole pine left from the original harvest in 1940, but also the stand of 10- to 15-m lodgepole that came in since harvest in 1940, which was almost a doghair stand. Both the 8-ha area surrounding the clearcut and the original 3-ha clearcut were harvested during the summer of 1981. All merchantable trees were removed, the slash lopped and scattered, and most of the larger cull trees felled. About 4 to 6 cavity trees per acre as well as the noncommercial stems less than 15 cm d.b.h. were left standing.

After treatment, the entire area was covered with a mat of slash, in places as much as 60 cm high. A few scattered Engelmann spruce, subalpine fir, and lodgepole pine of various sizes were still standing. Water equivalents at the 25 measurement points on the clearcut plot and the forested control, as well as a transect across the entire

11-ha clearcut area, were monitored monthly from January to April during the winters of 1981-82, 1982-83, and 1983-84.

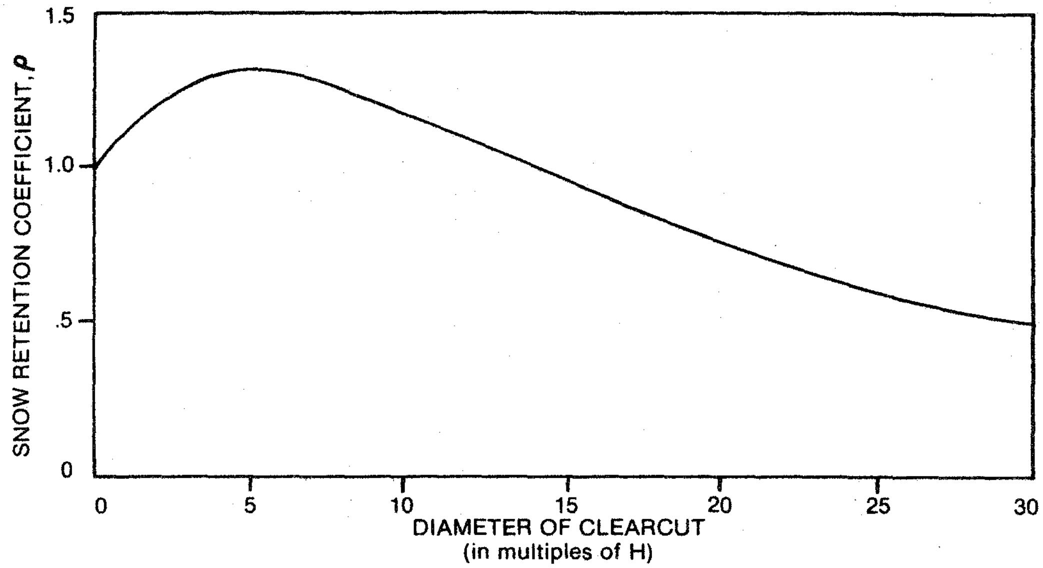

Figure 2.--Snow retention as a function of clearcut size. H is height of surrounding trees (Troendle and Leaf, 1980).

During the summer of 1983, all remaining trees on the site were felled. Only a few broken top stems remained. A layer of slash, up to 60 cm high, still persists but above that there is no significant roughness. The study plots were measured on January 4, 1984 and again in March.

Results and Discussion

Figure 3 represents a plot of peak water equivalents across the entire 11-ha opening on April 7, 1982. The transect was begun near the west edge of the opening, crossed to the east, through the intensively sampled area (original 3-ha clearcut) in the center, and continued into the lee forest to the east. The distribution of water across the plot (fig. 3) is typical of that obtained during all four surveys in 1981-82, 1982-83, and 1983-84. The accumulation pattern across the opening, although variable due to micro relief, slash, wind, etc., indicates no apparent zones of scour or deposition as one might expect in a large windswept opening. The snow surface elevation and erosional features were quite uniform although snow densities varied greatly. In each of the 3 years since the site was clearcut, the slash has filled with snow by mid-December to early January and the average water equivalent was 20-25 cm when the slash was totally covered with snow.

Table 1 lists the average water equivalent on the control plot and the clearcut area for periodic measurements from 1938 to 1983. The treatment and control plots were virtually the same during the two calibration years, 1938 and 1939. Harvesting resulted in an increase in accumulation of almost 50% more snow water equivalent (S.W.E.) in the clearcut for the first few years. Covariance analysis was used to evaluate the data set obtained during the entire 42 years following harvest.

Several things can be concluded from the analysis. First, because the 2 years of record for the period following reharvest in 1981 are not significantly different from the previous record, we must conclude that reharvest of the study area as well as the "commercial clearcutting" of an additional 8 ha around it did not alter the pattern of accumulation. Second, when a linear time index was included in the regression of the clearcut and control data set, time was found to be significant in the relationship.

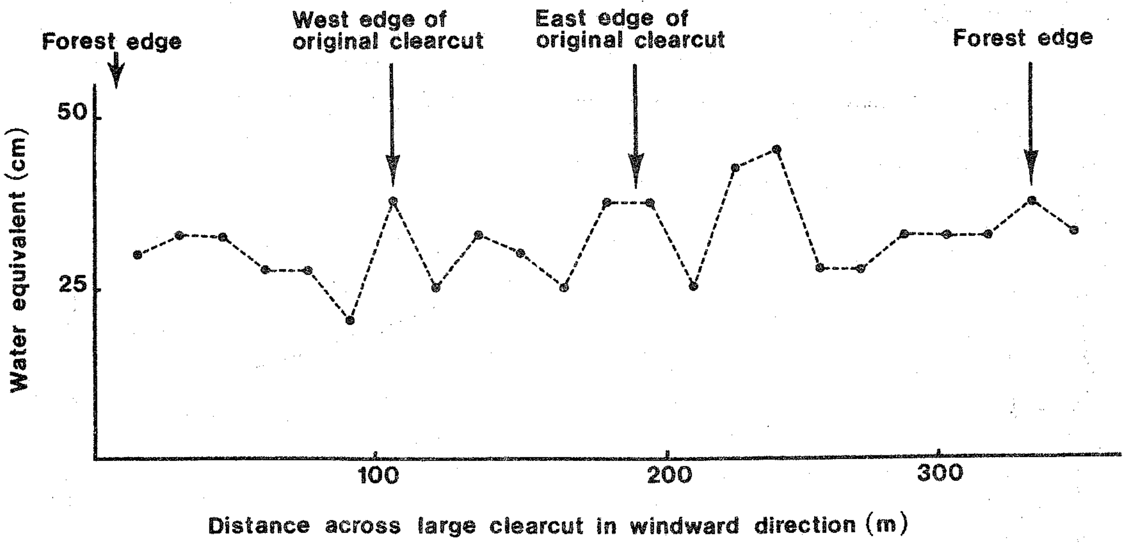

Figure 3.--Peak water equivalent across the 11-ha opening, showing relative position of forest boundaries, and original study area.

The analysis indicated that under the average conditions for the study period (17.7 cm S.W.E. in forest) the increased accumulation in the clearcut was 7.5 cm (42%) and this increase has been diminishing by 0.07 cm per year since 1941. The decrease is presumably due to interception loss by the regrowth. In the 40 years from 1941-1981 the recovery was 2.9 cm. Using the linear fit, total recovery would occur in 103 years. However the linear fit is to the first part of a growth curve that is nonlinear. Total recovery, assuming it follows the growth curve, can be expected to occur in less than 103 years.

The initial question in this experiment was whether the creation of the 11-ha commercial clearcut would cause scour in the original 3-ha study area. This did not happen. The residual stand as well as the deep slash apparently maintained a roughness boundary layer sufficient to retain the annual accumulation of snow on-site.

On January 4, 1984, when the study plots were again measured after all remaining trees had been felled, the slash on the clearcut appeared full, with 25.7 cm of water, and the surface was clean and windswept. There was 21.8 cm of water in the forested control. The clearcut had 3.9 cm (18%) more water equivalent than the forest. This percentage was somewhat less than in previous years but the difference was not significant at the 0.05 probability level. January 1984 was dry but windy, with windspeed (measured at a site 5 k from and 300 m above the study area) frequently in excess of 30 m s^{-1} and predominantly out of the west. On February 2, 1984, accumulation in the forest had increased to 23 cm but it was still 25 cm in the open (only 8% more water than the forest). It had not increased above what the authors consider to be the snow storage capacity of the slash.

When the study area was again sampled in March 1984, the forest had 26.2 cm of water while the opening had 28 cm or 7% more. In the period from January to March 1984, the large clearcut accumulated 2.4 cm (28.0 - 25.6) while the forest accumulated 4.4 cm. Unfortunately, January and February 1984 were fairly dry months and the increased accumulation is not very large, but it does appear that the efficiency of the opening in trapping snow was greatly reduced once the slash was filled. During this 2-month period, the opening accumulated only 45 percent as much water as the forested control.

The study will be continued; however, it is not unreasonable to conclude that large clearcuts can be created without significant loss of on-site moisture as long as scattered slash and residual trees or other forms of roughness have the capacity to store the winter season water equivalent. What cannot be addressed at this point is how long the slash will remain effective or the mechanics of how the slash can be managed.

Table 1.--Average peak water equivalent from 25 stations in a 3 ha clearcut and 3-ha forested control in lodgepole pine. Regrowth was allowed to occur in the clearcut until reharvest in 1981

Year	Peak water equivalent (cm) Clearcut	Forest	(Clearcut - Forest) ÷ Forest
1938	18.0	18.0	0.00
1939	16.8	17.3	-.03
Harvest			
1941	21.1	14.7	.44
1942	23.1	15.7	.47
1943	33.3	23.9	.39
1956	31.5	24.9	.26
1964	19.3	13.2	.46
1968	20.1	16.3	.23
1972	25.4	20.1	.26
1976	19.3	15.7	.23
1981	9.4	6.8	.38
Reharvest			
1982	25.4	19.8	.28
1983	29.5	23.4	.26

THE EFFECT OF DEPOSITION AND REDISTRIBUTION PROCESSES

The previous section described the effect of opening size on snowpack accumulation. No attempt was made to describe how or when the increased accumulation occurred. This section will present the results of a small study at the Fraser Experimental Forest that addresses the problem.

Leaf (1975) suggested that removal and transport of intercepted snow from surrounding trees into the opening was more important than interception savings on-site in accounting for the increased accumulation in clearcuts. The statement was an extension of the work of Hoover and Leaf (1967), who felt that the increased accumulation in the opening was largely the result of the redistribution of snow intercepted by the surrounding canopy and redeposited in the opening. They also felt that since most intercepted snow was removed from the canopy within a few days of the snowfall event, there was little opportunity for vaporization loss from the canopy. Hoover and Leaf (1967) speculated that increased ablation losses in the opening probably offset the interception savings that occurred following harvest. This inference was drawn because water snowpack water balances between forest and open do not show a net change but only depositional differences before and after cut.

Methods

To investigate this question, three 1.5-H circular openings were cleared in a 16-m-tall lodgepole pine stand on the Fraser Experimental Forest. Six 30 x 60 cm white snowboards were placed in each of the openings. Six were also placed in the upwind (west side) and six in the downwind (east side) forest. On the average, the transect from downwind forest to open to forest, had an azimuth of 245°. The average wind direction during and between snowfall events, based on wind measurements, was 270°.

Snow depths were read and the boards cleared after each snowfall event and as frequently as possible between events, especially if there was a significant amount of wind. For expedience in visiting all sites as quickly as possible, only snow depth was measured on the boards. It was felt that if readings were taken immediately after (or during) a snowfall event, the depth could be used as a comparable index to show what proportion of the increased accumulation occurred during the event and how much occurred between events. During March 1984, peak water equivalent was measured in the upwind and lee forest as well as the opening at all three study sites.

Results and Discussion

Table 2 presents the average accumulation for 18 measurement periods for each opening as well as the forest or either side. The data in table 2 represent observations taken from 1 day to 1 week apart. Some sample periods include multiple storms; others represent between-storm periods with high wind and little or no new snow. As can be seen, the mean value for the open approaches 16 cm (range of 0-40 cm for individual observations). Of the 16 cm, no more than 2 cm was ever observed to accumulate between events. Most of the time there was no accumulation on those boards in the open between events. In the forest, accumulation occurred on the boards between events but the majority of this snow appeared to be bulk snow falling from the canopy. In general, it appeared as though the increased deposition that occurred on the boards during the individual events was at least an order of magnitude greater than any redistribution or movement that occurred between events. On average, 31% more snow was deposited in the opening than the upwind forest.

Table 2 also shows that there was variability between study sites. All openings showed the 31% increase in accumulation relative to the upwind forest, but only unit 1 consistently had a significant decrease downwind, like that observed by Gary (1974) and implied in the discussion presented earlier.

Once the analysis indicated the increased accumulation was occurring during the event, a possible association with wind occurrence and direction was investigated. Recording rain gage information from a central location was used to tabulate the timing and amount of precipitation associated with each measurement. After it was determined when the storm occurred, windspeed and wind direction were estimated from a site 4 km away and at an elevation 300 m higher than the study sites. Wind during each event was arbitrarily classed as low (0-16 km hr^{-1}), moderate (16-48 km hr^{-1}), and high (48-112+ km hr^{-1}). There was no apparent correlation between windspeed and resulting accumulation pattern. The presence or absence of wind did not appear to alter the efficiency of catch in the opening or the relationship between upwind/downwind accumulation.

Table 2.--Average accumulation of snow in forest and open for 18 selected observations

Unit	West forest	Open	East forest
		cm	
1	14.5	18.9*	12.2*
2	11.4	15.0*	10.4**
3	11.4	15.0*	10.8

*Significantly different from west forest at P = 0.05.
**Significantly different from west forest at P = 0.10.

The data indicate that the differential accumulation on these sites occurs during the storms. Hoover and Leaf (1967) concluded that the snow intercepted in the canopy was not being vaporized in part because it was being redistributed to the openings. We cannot evaluate the disposition of the snow except to say it doesn't appear to be blown into the openings during the periods between storms.

Although table 2 indicates that, based on the individual events, 31% more snow was accumulated in the openings through March 1984, the estimates of peak water equivalent in the snowpack (based on two federal snow tube samples near each snowboard) indicated there was less water actually on-site in the openings.

Peak water equivalent in the open ranged from 116% to 126% of that in the windward forest. Peak water equivalent in the lee forest ranged from 93% to 99% of that in the upwind forest. Although not conclusive, the data do support Hoover and Leaf's (1967) inference that increased ablation of the exposed pack in the open tends to offset the interception savings as the combined snowboard and peak water equivalent data indicate more was desposited than can be found in the snowpack in the spring.

The snowboard discussion helps set the stage for the comments on interception that will follow, but several cautionary statements need to be made concerning the study. First, snow depth was measured and this may be misleading. Second, the sites used were moderately wind protected and, therefore, may not be representative of exposed sites. Last, the sample was not large; however, the results both between events and sites were very consistent.

THE EFFECT OF PARTIAL CUTTING

Since 1967, most of the research on snowpack accumulation in the subalpine has dealt with clearcuts. Very little has dealt with the effect of thinning on snowpack accumulation. A recent paper (Gary and Troendle 1982) showed that in thinned plots in Wyoming and Colorado, the areas with the lowest stand density appeared to have the greatest accumulation of snow water equivalent. The increase was similar to that reported by Wilm and Dunford (1948). Gary and Troendle (1982) attributed the increases, at least in part, to an interception savings but were unable to address the "mass balance" associated with the increase. The small plots they used did not allow for a mass balance to determine if the observed increase was truly an interception savings (and reflected a true increase) or was a depositional difference that would be balanced elsewhere. This is an important distinction because any actual increase in net precipitation could affect the water balance whereas a depositional difference would be specific to these small study areas and not transferable on an operational scale.

Study Areas and Methods

Peak snow water equivalents occurring under 4 different stand densities in lodgepole pine at the Fraser Experimental Forest were determined for the 6 years from 1978 to 1983. Each thinning level is applied to a 0.2-ha area and has been replicated 5 times. This is one of the study sites used by Gary and Troendle (1982) with 3 years of additional data. On a large scale, an ongoing experiment is being conducted on the Deadhorse watershed, also located at the Fraser Experimental Forest. Deadhorse Creek is a 250-ha gaged watershed that contains two gaged subwatersheds--a 40-ha North Fork and an 80-ha upper basin (see fig. 4). All three watersheds are well calibrated to a control watershed (Lexen Creek) and with respect to streamflow and peak water equivalent in the snowpack, as indexed by snow courses.

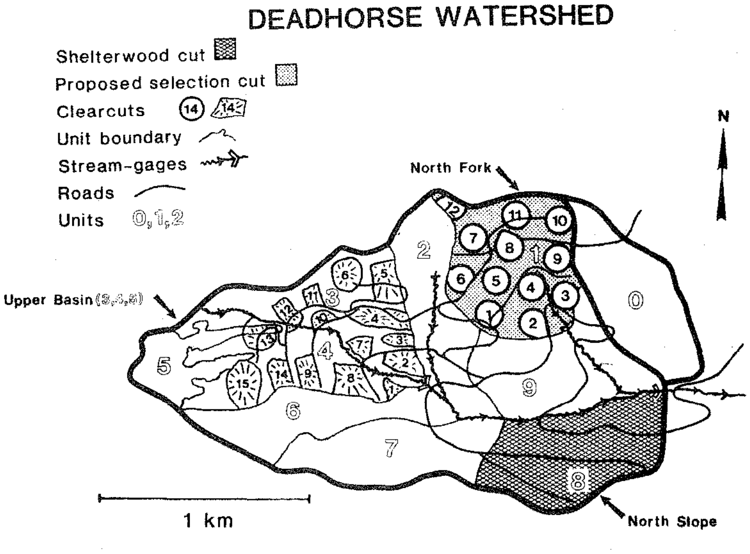

Figure 4.--The Deadhorse Watershed complex showing management alternatives for the North Fork, Upper Basin, and North Slope units. The North Fork and North Slope harvests have been completed (Troendle, 1983).

In this experiment a number of harvesting practices are to be applied to the different watershed subunits. The 40-ha North Fork watershed was harvested in 1977 using a uniform pattern of 5-H circular clearcuts; in all, 36% of that watershed was harvested. Approximately 30% of the Upper Basin will be clearcut using irregularly sized and shaped clearcuts.

In 1980 the 40-ha north slope unit was partially cut when the first entry of a 3-cut shelterwood treatment was applied. Approximately 36% of the basal area of the stand was removed on an individual tree basis. The treatment was comparable, on a large scale, to the thinnings.

Results and Discussion

Table 3 shows that, as noted by Gary and Troendle (1982), the apparent increase in accumulation associated with reduction in stand density has been maintained. Figure 5 plots the ablation of the accumulated pack for 1 year. Note that although each treatment initializes at a different level, all thinned plots melt at a faster rate and snow disappearance occurs 10-12 days sooner than on the control plot.

As noted earlier, the weakness with data such as this is that it is difficult to do a mass balance on the snowpack. Questions arise concerning whether the response is a "plot" effect and whether the observations can be extrapolated to extensive areas.

Figure 6 represents a double mass plotting of peak water equivalent on the north slope unit (8) and the control, Lexen Creek. In this instance a shift in accumulation appears to have occurred following harvest in 1979. On average there appears to be a 3.8 cm increase in peak water equivalent per year, and this represents a 13% increase over the pretreatment average for the site. Covariance analysis of the individual observations for the pretreatment and posttreatment years, through 1984, indicated the treatment effect apparent in figure 6 is significant at P = .01. This supports the observation that interception savings following reducing the basal area on an individual tree basis results in greater net snow water accumulation.

Table 3.--Maximum snowpack water equivalents as affected by thinning lodgepole pine in Colorado. Measurements made about April 1 each year

	Basal area (m^2 ha^{-1})			
Year	32[1]	27.5	18.4	9.2
	---------- cm water ----------			
1978	25.1	23.1	24.4	25.9
1979	22.2	22.6	24.8	26.3
1980	26.7	28.4	29.4	30.7
1981[2]	--	8.4	8.8	9.9
1982	21.0	21.0	22.3	22.7
1983	23.0	24.2	24.2	25.7
$\bar{x}$	23.6	23.9	25.0	26.3
Density effect (cm)[3]		0.3	1.4	2.7
Density effect (%)[3]		1.3	5.9	11.4

Source: In part from Gary and Troendle, 1982.
[1] Unthinned stand.
[2] 1981 not included in average.
[3] Based on unthinned stand.

In the North Fork watershed where 36% of the area was harvested using 5-H circular clearcuts, Troendle (1983) noted that although 22% more water was observed in the openings following harvest, the balance for the watershed remained unchanged. Figure 7 represents a double mass plotting of the peak water equivalent on the North Fork over that for the control, Lexen Creek. The plotting is comparable in nature to figure 6, but in this case there is no apparent shift due to harvest.

Although very limited in amount, available data indicate that partial cutting by marking individual trees for removal may result in a net increase in snowpack accumulation. Presumably the increase is a reflection of interception savings rather than differential deposition phenomenon, such as occurs in openings.

Leaf (1975) concluded that the transpiration reduction associated with individual tree harvest practices would not result in flow increases unless more than one-half the stand was harvested because the residual stand would use the "savings." This is currently being investigated. However, any increase in accumulation in snow water equivalent may reach the stream if the expected accumulation exceeds the storage requirements on-site. Only in dry years would that increase be subject to losses on-site.

Leaf (1975) simulated that a 15% increase in snowpack (following cloud seeding) would increase streamflow. We would expect the increase in accumulation following a partial harvest to do the same, and preliminary evaluations of streamflow from the Deadhorse watershed indicate the increase in peak water equivalent observed on the north slope must be finding its way to the channel.

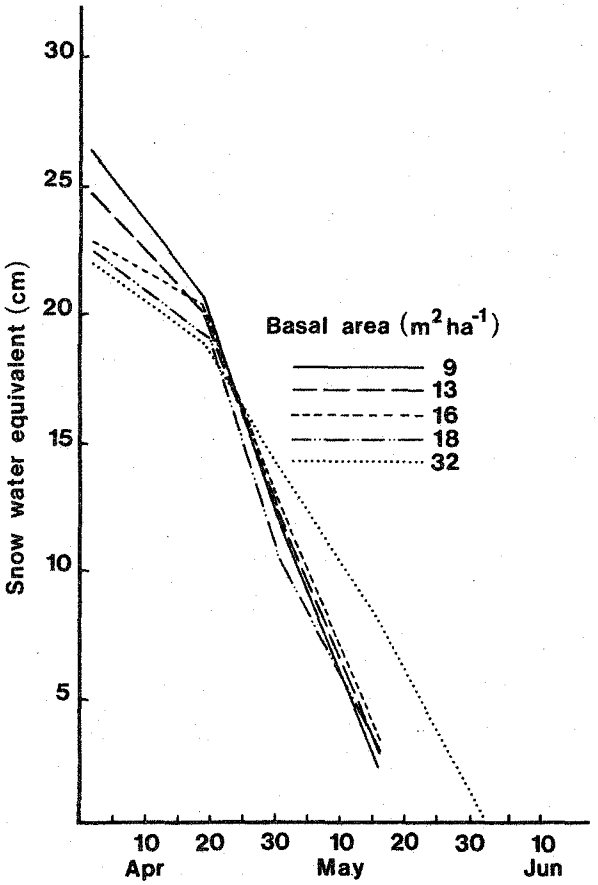

Figure 5.--Snowpack depletion under 5 cover conditions during spring 1979 in Colorado.

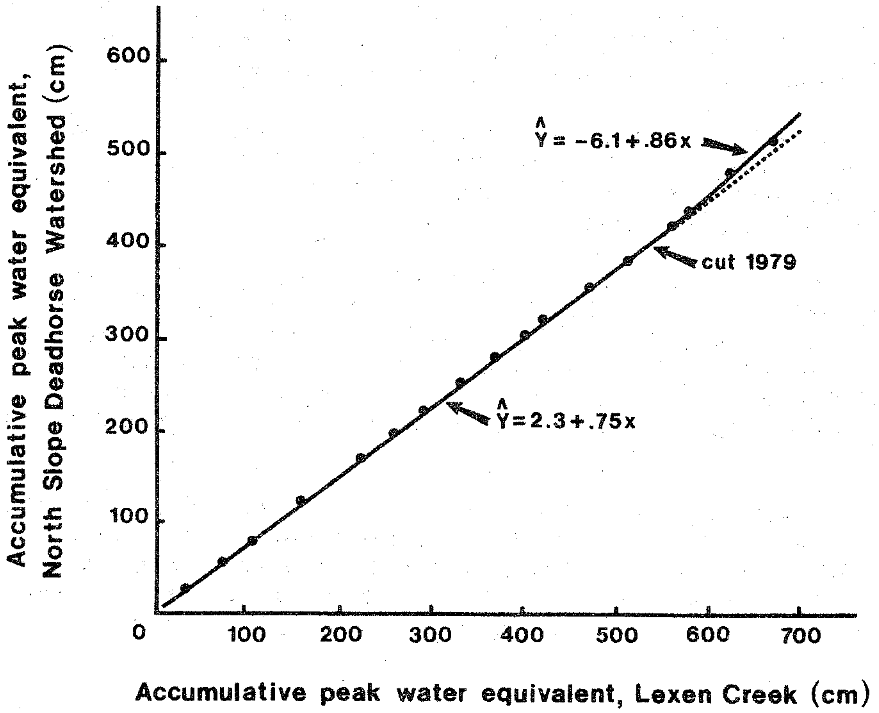

Figure 6.--Double mass plot of accumulative peak water equivalent on the North Slope unit of the Deadhorse watershed over that for Lexen Creek, the control.

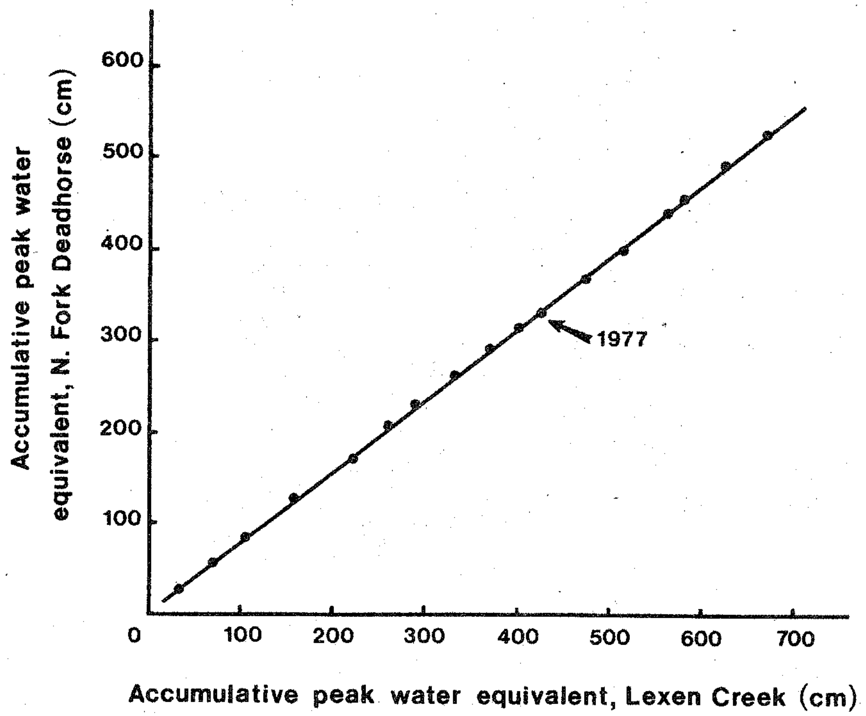

Figure 7.--Double mass plot of accumulative peak water equivalent on the North Fork of Deadhorse Creek over that for Lexen Creek, the control.

SUMMARY

In summarizing the observations made in this study, two inferences can be drawn concerning the effect of forest harvest on snowpack accumulation. A technology or model has been developed that describes, for the central Rocky Mountains, the relative efficiency of differing opening sizes on snowpack accumulation (see fig. 2). Although not evaluated over a wide range of opening sizes, the data indicate large openings can be created, if needed to meet other objectives, and control or mitigative measures can be applied to retain the snowpack on-site. However, the site-specific problems of slash orientation and longevity, effect of wind exposure and terrain, or the stability of the residual trees have not yet been addressed.

At the other extreme, the data indicate that the increased accumulation under partially harvested stands may be real and not offset by a decrease in accumulation elsewhere. This may translate to an increase in water available for streamflow.

When manipulating forest to increase water yield from snowpack in the Rocky Mountains, many processes are obviously impacted. From a practical management perspective, the effect of timber harvest on snowpack accumulation can be addressed in terms of two dominant components--the interception/vaporization losses and aerodymanic/depositional processes.

In a given stand, timber harvest may consist of removal of from one to all the trees (from a very light individual tree selection cut to a clearcut). When an occasional tree is removed, one can envision that the snow normally intercepted by that tree and vaporized would be saved and be added to the snowpack. The other extreme is the clearcut where the reduction in interception "loss" would be maximum. In the latter case, however, the sublimation losses in the exposed pack are also maximum. This conclusion, which was reached by Hoover and Leaf (1967), has been well supported by watershed snowpack balances such as the one on the North Fork of Deadhorse Creek. It appears, however, that in partial cuts with 10% to 40% of the basal area removed on an individual tree basis, the residual stand is not subject to this increased sublimation loss and there appears to be a net reduction in vaporization of the snowpack of 12% to 15%.

Also associated with timber harvesting, is the potential for a change in aerodynamics of the canopy and the attendant change in the depositional pattern. This effect is of course minimized, if affected at all, with light partial cutting and maximized with clearcutting. Changing the aerodynamics causes the increased deposition in the openings. However, there is no net change in total accumulation if the associated uncut forest is considered. Larger openings can be created but care must be taken to avoid scour and provisions (roughness) must be made to allow storage and retention of the snowpack. To maximize the trapping efficiency of a large opening, something less than a complete clearcut may be best, as it would reduce the scour or loss implied in figure 2. Since "protection" is a key, any additional protection afforded by small openings or openings designed to take advantage of the protection afforded by slope position and aspect may not only delay melt (as projected by Swanson and Golding (1982)) but may also reduce sublimation losses and further increase the efficiency of the opening.

At this point it is difficult to weigh the relative efficiency of clearcutting versus partial cutting on streamflow increases. Clearcutting can influence the placement of the snowpack but not the total volume on an areal basis. Partial cuts cannot control the placement but can increase the net amount on an areal basis. More research is needed to translate the effect that each of these impacts has on streamflow.

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