WATER RESOURCES RESEARCH, VOL. 22, NO. 13, PAGES 1931–1940, DECEMBER 1986

Snow Distribution Patterns in Clearings and Adjacent Forest

DOUGLAS L. GOLDING

Faculty of Forestry, University of British Columbia, Vancouver

ROBERT H. SWANSON

Northern Forest Research Centre, Canadian Forestry Service, Edmonton, Alberta

Snow accumulation patterns were determined for clearings and adjacent forest at Marmot Creek experimental watershed and James River, Alberta. At maximum accumulation snow water equivalent (SWE) was greater in clearings than in forest whether clearings were large, as in 8- to 13-ha blocks where SWE averaged 20% more than in the forest, or small as in the 1/4 to 6-H (height) diameter circular clearings where SWE was 13–45% greater than in the forest. SWE was 42 to 52% less in north than in south sectors of 2–6 H clearings. These differences increased with clearing size and time since beginning of accumulation period and are caused by snow ablation (melt and evaporation), a function of direct solar radiation reaching the snowpack. In such situations the snow that has accumulated on the ground cannot be considered a measure of the snow that has actually fallen there. For water balances and hydrologic modeling, snow measurements in partially cleared watersheds must be adjusted for temporal and spatial factors specific to the watershed.

INTRODUCTION

Background

The interaction of snow accumulation and ablation with forest and forest clearings is important in any hydrologic system in which snowmelt accounts for a substantial part of streamflow. Water yield increases of less than 20 mm to more than 140 mm have resulted from partial or complete forest cutting in the Rocky Mountain region of the United States and Canada. These increases are due to changes in evapotranspiration and in patterns of snow accumulation and ablation. Only the two snow processes are addressed in the studies reported in this paper.

Many studies have shown that snow accumulation is less under a forest canopy than in small clearings. Maximum accumulation occurs in clearings of 2–5 H width (where H is the height of surrounding trees) whether the forest is coniferous [*Anderson*, 1963; *Church*, 1912; *Troendle and Leaf*, 1980] or leafless deciduous [*Swanson and Stevenson*, 1971]. In an earlier paper [*Golding and Swanson*, 1978] we reported greater snow accumulation in 1/4 to 6 H clearings at James River, Alberta, than in the forest: 14% greater in 1/4 H, rising to 45% greater in 2 H, and dropping to 32% in 6 H.

However, in clearings greater than 20 H in width accumulation may be less than in the forest because wind speed at the snow surface of large clearings is relatively unaffected by the surrounding forest [*Swanson*, 1980]. High wind speeds may increase evaporative loss and may blow accumulated snow into the downwind forest [*Swanson*, 1980; *Troendle and Leaf*, 1980].

The sources of increased snow in forest clearings are (1) snow that would have accumulated on and evaporated from the forest canopy (interception) and (2) snow that is removed from the surrouding canopy (or prevented from reaching there) or from beneath it as a result of perturbations in the wind streamlines at the interface between forest and clearing (redistribution). It is important in understanding the effect of forest treatment on snowmelt runoff to know what part of the increased accumulation is due to interception and what part is due to redistribution. Interception is a loss to the local hydrologic system; redistribution is not a loss to the system although it may change ablation patterns, and therefore runoff patterns. Increased accumulation in forest clearings has been attributed largely to altered distribution patterns by *Hoover and Leaf* [1967] and *Gary* [1974] in Colorado and by *Smith* [1974] in California, but largely to interception by *Haupt* [1979] in Idaho, by *Wilm and Dunford* [1948] in Colorado, and by *Miner and Trappe* [1957] in Oregon.

Snow accumulation in 2-H-wide blocks in Colorado was greater than in the adjacent forest by 30% where the block was clearcut, and by 14 and 13% where trees of one half and three quarters the height of the adjacent forest, respectively, occupied the 2-H blocks [*Gary*, 1979]. Increases were attributed to less snow evaporation from the protected lower-level canopies than from the adjacent stand. This conclusion may be supported by data from *Swanson* [1980] that showed wind speeds at 2 m above ground in 1–6 H circular clearings to be only 5% of those at 10 m above the canopy.

Miller [1961] questioned the accuracy of the snow measurements and the availability of energy for evaporation of such amounts. He suggested that where radiation surpluses are small, advected energy is usually accompanied by vapor pressures sufficient to suppress evaporation. However, there are locations where this is not the case, e.g., during chinooks along the foothills of the Rockies in Alberta high levels of advected energy are accompanied by very low vapor pressures.

Evaporation from snow on the ground has been shown to be a significant part of total snowfall, e.g., up to 1.8 mm/day of snow water equivalent (SWE) in the Colorado Rockies [*Bergen and Swanson*, 1964]; and 16 mm SWE for winter and 55 mm for spring, 1940, in a forest clearing in Colorado [*Wilm and Dunford*, 1948]. Differences in energy and vapor balances may account for even greater losses from intercepted snow than from snow on the ground.

Paper number 6W1930.
0043-1397/86/006W-1930$05.00

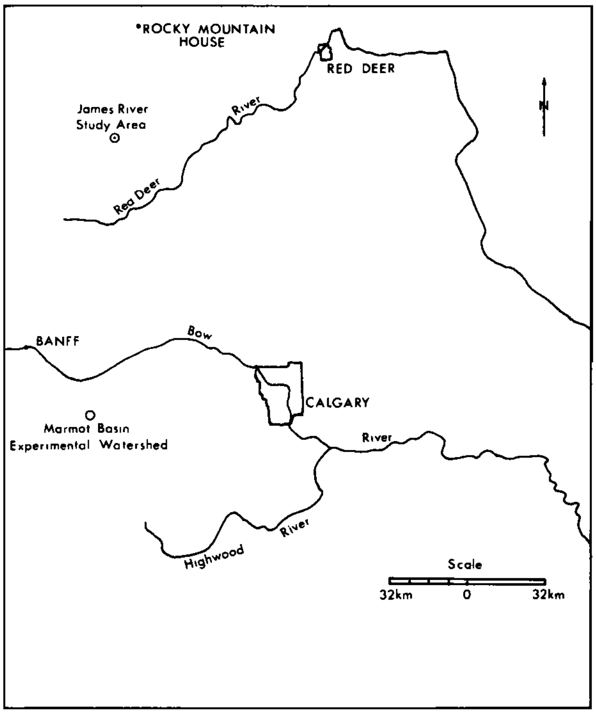

Fig. 1. Location of study sites, Alberta, Canada.

During the spring melt period at James River, ablation rates were lowest in the 1 H clearings with rates increasing with smaller clearings (to 31% greater in the uncut forest than in the 1 H) and with larger clearings (to 35% greater in the 6 H than in the 1 H) [*Golding and Swanson*, 1978].

Objectives

The objective of this paper is to describe and to discuss the areal distribution and temporal ablation patterns of the snowpack within clearings and surrounding forest on two treated subbasins of Marmot Creek experimental watershed (near Banff, Alberta) and at James River (near Sundre, Alberta) (Figure 1). In 1974, Cabin subbasin of Marmot Creek received a conventional commercial harvest. In 1979, Twin subbasin of Marmot Creek was subjected to a treatment to alter snow accumulation, areal distribution, and ablation patterns. The intent was to prolong recession flow from snowmelt and to delay the time of peak runoff. The James River study was designed to determine the relationship of snow accumulation and ablation to size of forest clearing.

METHODS

Snow Measurements

Snow depth and SWE were determined with the U.S. Department of Agriculture Soil Conservation Service standard Mt. Rose snow sampler at times and locations specific to each study area as described below. All measurements have been converted to millimeters of water.

Study Areas, Treatments, and Sampling Programs

James River. The James River study area is 100 km northwest of Calgary, Alberta (Figure 1). Description of the area, the treatment, and the sampling scheme is given by *Golding and Swanson* [1978]. The area is particularly well suited for study of the effect of clearing size on snow accumulation because of its low topographic relief. In 1970–1972, nine circular clearings, ranging from 1/4 to 6 H in diameter, plus the uncut

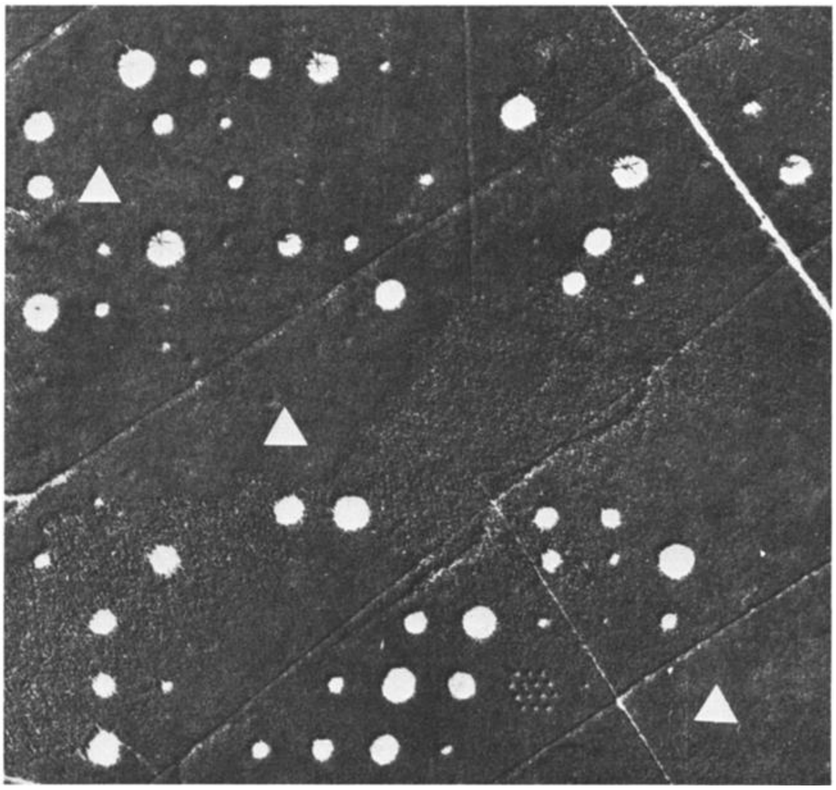

Fig. 2. James River study site showing clearings and location of wind towers (open triangle).

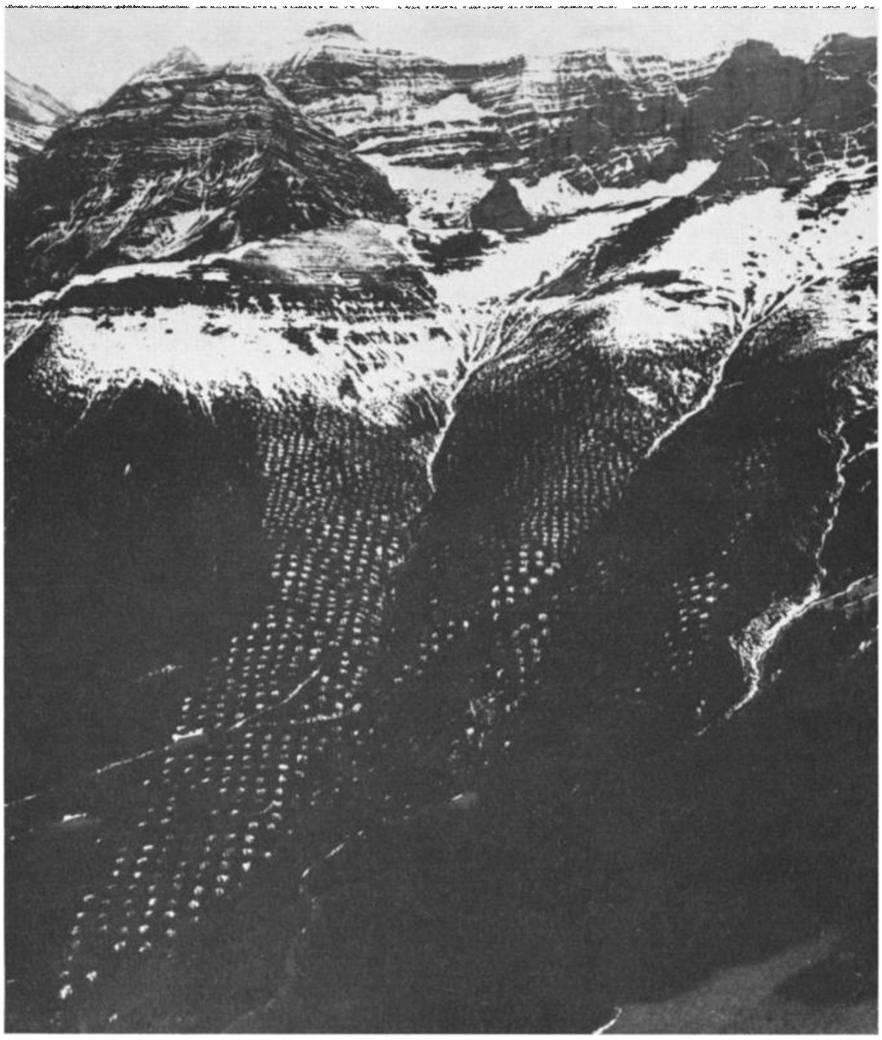

Fig. 3. Twin Creek subbasin of Marmot Creek experimental watershed, showing 3/4 to 1-1/2 H clearings.

control (0 H) were replicated 10 times on a 201 × 201-m grid (Figure 2).

Marmot Creek Experimental Watershed. Marmot basin, 40 km SE of Banff, Alberta, was established as an experimental watershed in 1962 to determine the effect of forest clearing practices on streamflow. The forest is Engelmann spruce (*Picea engelmanni* Parry), subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), and lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) of 20- to 25-m height, 35–85% crown closure. Elevation ranges from 1525 to 2750 m above sea level with tree line at 2285 m. Annual precipitation is 900 mm, 75% of which falls as snow. Average water yield is 450 mm.

Cabin subbasin is 212 ha, of which 50% is forested, the remainder being above treeline. In 1974, 20% of the basin (i.e., 40% of the forested part of the basin) was clearcut in five blocks of 8–13 ha (150–275 m (7–14 H) wide by 200–400 m long). Treatment of the 264-ha Twin subbasin was completed in 1979 and consisted of 2103 circular clearings of 15 m and 20 m diameter (i.e., three quarters to one and one half H diameter), resembling a giant honeycomb (Figure 3). The layout was mechanical over most of the watershed, the clearings centered on alternate intersections of a square grid 15 or 20 m apart. Slash and nonmerchantable trees were flattened. Merchantable trees were removed in tree lengths with rubber-tired skidders from the accessible parts of the subbasin. Half of Twin subbasin is below treeline, 40% of which is now in small clearings. In Cabin and Twin subbasins only that part of the basins below tree line is included in the studies reported here. In this paper, the whole subbasin includes the clearings and remaining forest below tree line. Middle subbasin (285 ha) has been retained as an uncut control for both Cabin and Twin treatments.

An intensive snow survey of the forested part of Marmot basin began in 1969, with measurements taken the third week of March each year on a 20 (east-west) × 200-m (north-south) grid. In anticipation of the treatment of Cabin subbasin, sampling intensity was doubled in 1972 in and adjacent to those areas designated for harvest. SWE was calibrated for each sampling point on Marmot basin and for particular groupings of these points (e.g., individual cut blocks, all cut blocks combined, north or south edges of cut blocks) using Middle subbasin mean SWE as control. After treatment the calibration equation was used to predict SWE as if the pretreatment relation still held. The difference between predicted and observed values was tested with the "t" test at $P < 0.10$. Before the studies were carried out, the 10% probability level was chosen to indicate significant differences in mean SWE. Sampling locations for the forest surrounding the clearings at James River were selected arbitrarily. Therefore means were not tested statistically.

TABLE 1. Mean SWE at Maximum Snow Pack (1973–1976) by Sector in Clearings and Surrounding Forest at James River, Alberta

Clearing Size, H	Snow Accumulation (SWE, mm) N	NE	E	SE	S	SW	W	NW	Overall Mean
0	k	···	k	···	k	···	k	···	···
	(86) a	···	(78) a	···	(86) a	···	(78) a	···	(82)
1/4	k	···	k	···	k	···	k	···	···
	92 ab	···	94 b	···	91 ab	···	92 b	···	93 c
	(81)	···	(80)	···	(77)	···	(86)	···	(81)
1/2	k	···	k	···	k	···	k	···	···
	90 ab	···	99 bc	···	103 b	···	95 b	···	99 c
	(82)	···	(74)	···	(92)	···	(75)	···	(81)
3/4	k	···	kn	···	n	···	kn	···	···
	103 b	108	111 cde	116	116 c	112	107 c	108	110 b
	(80)	···	(85)	···	(82)	···	(79)	···	(82)
1	k	···	n	···	m	···	kn	···	···
	102 b	109	114 def	117	123 c	114	110 c	108	112 ab
	(72)	···	(86)	···	(91)	···	(86)	···	(84)
2	k	···	n	···	m	···	n	···	···
	95 ab	106	122 f	130	135 d	133	124 e	100	119 a
	(61)	···	(83)	···	(92)	···	(82)	···	(79)
3	k	···	n	···	m	···	n	···	···
	91 ab	100	119 ef	126	137 d	136	122 de	103	117 a
	(54)	···	(78)	···	(88)	···	(78)	···	(75)
4	k	···	n	···	m	···	n	···	···
	82 a	94	109 cd	122	124 c	128	114 cd	91	110 b
	(51)	···	(70)	···	(86)	···	(79)	···	(72)
5	k	···	n	···	m	···	nm	···	···
	84 a	100	107 cd	119	121 c	125	114 cde	94	109 b
	(42)	···	(63)	···	(83)	···	(69)	···	(64)
6	k	···	n	···	m	···	nm	···	···
	82 a	92	105 bcd	120	124 c	119	114 cde	99	108 b
	(38)	···	(64)	···	(78)	···	(71)	···	(63)

Figures in parentheses are for surrounding forest; others are for clearings. Values without the same letter are significantly different at the 10% level of probability by Duncan's Multiple Range Test. Letters k, m, and n compare quadrants within a clearing size (i.e., horizontal comparisons). Letters a to f compare opening sizes within a quadrant (i.e., vertical comparisons).

RESULTS

James River

At James River, the 1973–1976 mean SWE at maximum snowpack was consistently greatest for the south quadrant and least for the north quadrant (at the 10% level of probability) for clearings greater than 3/4 H (Table 1) Below 3/4 there was no significant difference between north, south, east, and west quadrants. Data from the forest surrounding the clearings could not be treated statistically because sample points were not selected randomly but were established at selected distances from the clearing edge. However, the same trend existed in the quadrants in the surrounding forest as in the clearings. Mean SWE in each sector for all clearing sizes expressed as a percentage of that in the south was north, 75; northeast and northwest, 80; east and west, 91 and 92, respectively; and southeast and southwest, 96 and 98, respectively. SWE in the north sector as a percentage of that in the south sector decreased with increasing clearing size from 89% in 1/2 H to 66% in 6 H clearings. This trend was also evident for northeast and northwest sectors. Accumulation patterns in the east half of clearings was almost identical to patterns in the west half (i.e., accumulation was symmetrical about the north-south axis).

The symmetry about the north-south axis was as strong in the surrounding forest as in the clearings. The north sector accumulated 69% of that in the south sector, with east and west sectors averaging 89 and 92% respectively, approximately the same percentages as in the clearings (Table 1). The point of minimum SWE at maximum accumulation was in the forest north of the clearing for sizes 1–6 H (Figures 4–6). There was no consistent point of minimum accumulation for 1/4 to 3/4 H clearings. The minimum point was 2 m north of the edge throughout the season for 4–6 H clearings, but moved south in 1–3 H clearings as the season progressed. For example, minimum SWE in the 2 H was 15 m north of the forest

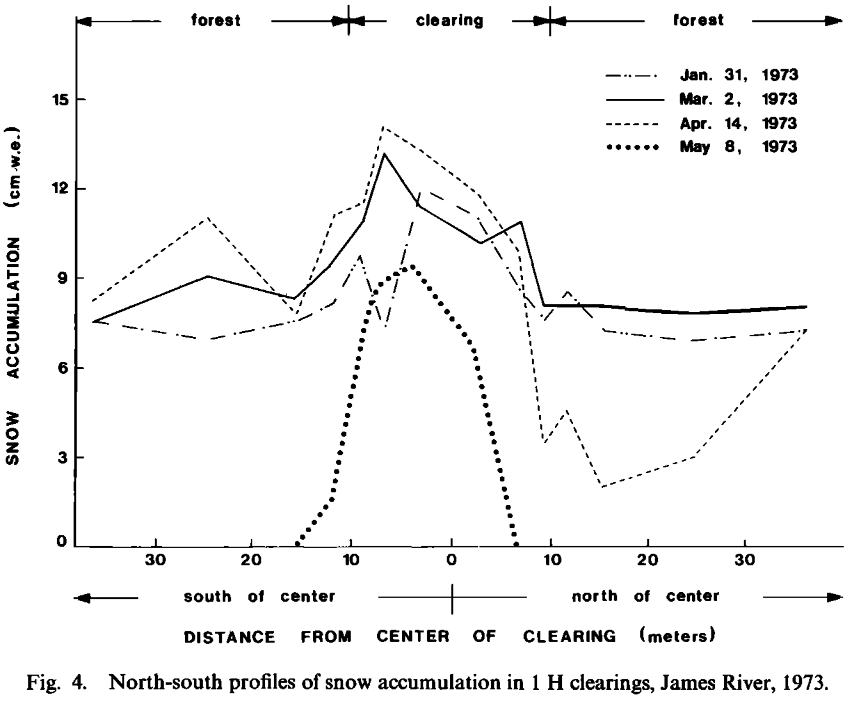

Fig. 4. North-south profiles of snow accumulation in 1 H clearings, James River, 1973.

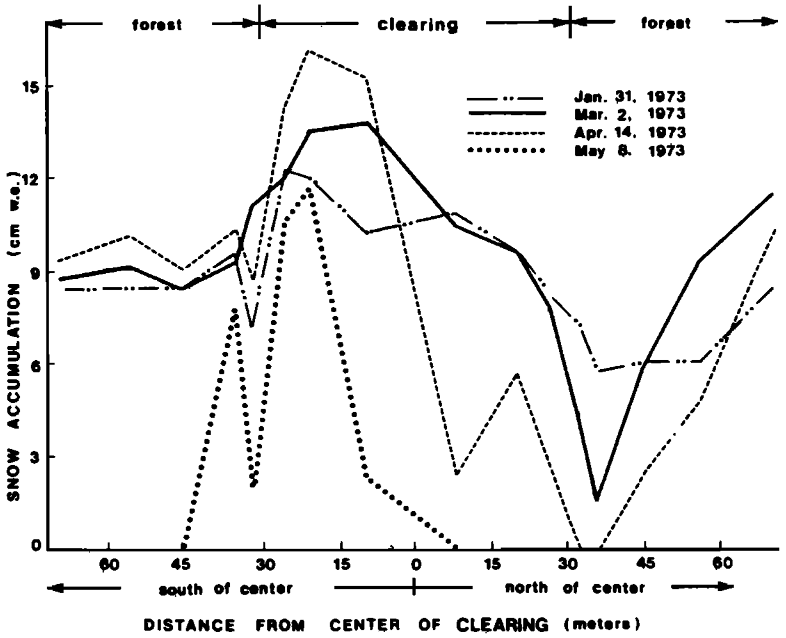

Fig. 5. North-south profiles of snow accumulation in 3 H clearings, James River, 1973.

edge on February 1, 6 m north on March 1, and 2 m north on April 12. Significantly greater SWE accumulated in 1, 2, and 3 H clearings than in any other clearings, and significantly less SWE accumulated in 1/4 and 1/2 H clearings than in larger ones (Table 1).

Marmot Creek Experimental Watershed

Cabin Subbasin. In the five cut blocks of Cabin subbasin there was an increase in observed SWE over predicted of 22% for the 3-year postlogging period 1975–1977. In the areas adjacent to each cut block (i.e., within 60 m of the cut block) and in all of the uncut forest on Cabin subbasin, there was no reduction in snow cover after logging. In fact, while not statistically significant, there was more snow in each of the areas adjacent to the cut blocks in 1975, in two of the five in 1976, and in three of the five in 1977. For the 3 years the adjacent areas averaged exactly the same SWE as predicted from the calibration (Table 2). The area below timberline had 11 mm SWE (7%) greater than predicted. There is no evidence here to support redistribution as the factor responsible for increased snow in the Cabin cut blocks.

Snowfall on Marmot Creek generally occurs with south-east winds [*Storr*, 1973]. There was no consistent trend of greater or lesser accumulation in the adjacent forest to the east or to the west of the cut blocks. Points that accumulated more snow than predicted in one year might accumulate less the following year, indicating that neither the windward nor leeward forest is typically a depletion or an accumulation zone. If the excess SWE in the cut blocks is not due to redistribution from adjacent forest, then most or all of it must be due to elimination of interception. Interception, calculated as the difference between measured and predicted SWE expressed as a percentage of measured SWE, was 22%, 13%, and 22% for the 3 years 1975–1977, respectively, averaging 18%.

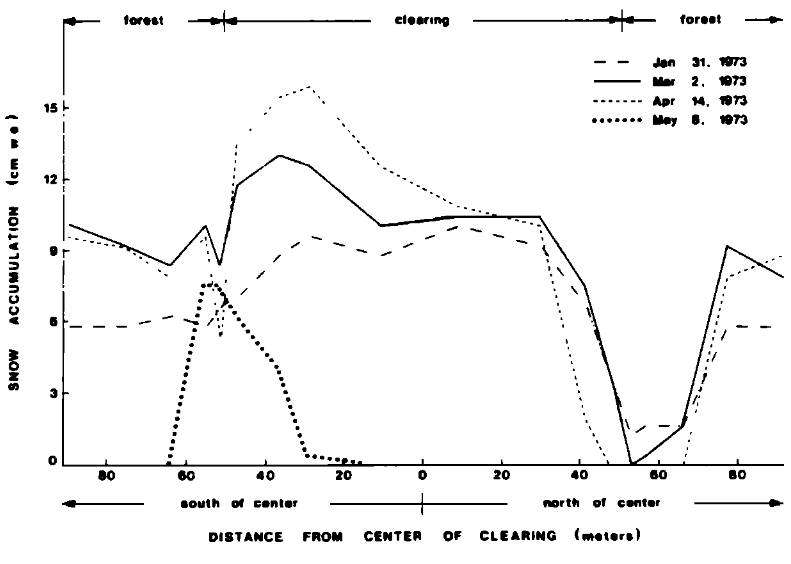

Fig. 6. North-south profiles of snow accumulation in 5 H clearings, James River, 1973.

TABLE 2. Observed and Predicted SWE on Cabin Subbasin Below Treeline at Maximum Snowpack, 1975–1977

Area	Mean Snow Accumulation 1975–1977 (SWE, mm) Observed	Predicted	Difference
Block 1			
cut	190	147	43*
adjacent	155	147	8
Block 2			
cut	188	152	36*
adjacent	152	157	−5
Block 3			
cut	211	163	48*
adjacent	201	183	18
Block 5			
cut	165	152	13
adjacent	150	152	−2
Block 6			
cut	152	130	22*
adjacent	130	140	−10
All cut blocks	180	147	33*
All adjacent areas	157	157	0
Cabin basin uncut	150	155	−5
All Cabin basin below treeline	163	152	11*

*Significant at the 90% level of probability based on 3-year post-treatment record.

Wind speed is usually low during snowfall both at James River and Marmot Creek. At Marmot Creek, 80% of snowfall occurs at wind speeds ≤2.2 m/s, and 50% at ≤1.2 m/s [*Storr*, 1973]. Interception storage should be high, thus providing the source for high interception losses.

In the James River clearings there was less snow accumulation near the north (sunlit) than near the south (shaded) edges of the large clearings. "Edge" data for block 1 (north aspect) and block 6 (south aspect) were examined to see if the same effect is present on Cabin subbasin. These were the only two blocks that had a predominantly north or south exposure. SWE on the south edges of both the northfacing and southfacing blocks averaged 33% greater than predicted for the 3 years 1975–1977 (Table 3). In contrast, the north edge accumulated 21% more than predicted for block 1 (north aspect) but only 8% (statistically nonsignificant) for block 6 (south aspect).

Twin Subbasin. Actual SWE for the March snow survey of 1980, 1981, and 1982 ranged from 23–34% greater in the circular clearings on Twin subbasin than in the intervening forest (Table 4). SWE in the clearings was significantly greater and in the intervening forest significantly less than predicted. SWE on the whole Twin subbasin below tree line (i.e., the clearings and the intervening forest below tree line) was slightly greater than predicted in each of the 3 years, although the increase was not statistically significant.

TABLE 3. Snow Accumulation on North and South Edges of North- and South-Facing Clearings in Cabin Subbasin at Maximum Snowpack, 1975–1977

	Snow Accumulation (SWE, mm)					
	South Edge			North Edge		
Block and Aspect	Actual	Predicted	Difference, %	Actual	Predicted	Difference, %
1 north	197	148	33*	190	157	21*
6 south	118	89	33*	131	121	8

*Significant at the 90% level of probability based on 3-year post-treatment record.

TABLE 4. Snow Accumulation on Twin Subbasin Below Treeline at Maximum Snowpack, March 1980–1982 (410 Measurement Points)

	Snow Accumulation (SWE, mm)					
	Subbasin					
Year	Actual	Predicted	Clearings	Intervening Forest	Difference, %	
1980	261	253	281*	218*	+63	29
1981	169	163	195*	146*	+49	34
1982	190	189	208*	169*	+39	23
All years	207	202	228*	178*	+50	28

*Significantly greater in clearings and less in intervening forest than predicted at the 90% level of probability.

Of the 410 snow measurement points on Twin subbasin, a subset of 362 were selected whose aspects were clearly identifiable as north (northwest through northeast), east (northeast through southeast), and south (southeast through southwest). The two year (1980–1981) mean actual and predicted SWE for this subset were 215 and 206 mm, respectively (Table 5), almost identical to that for the whole basin (215 and 208 mm, respectively) (Table 4). Within the small 3/4 to 1-1/4 H clearings of Twin subbasin, where the snowpack never receives direct sunlight, clearings on both the low-energy north aspect and the high-energy south aspect accumulated 12% greater SWE than predicted (Table 5). The south edges of the clearings had no greater SWE than did the north edges, regardless of aspect, indicating that there was no greater ablation on the north edges of these small openings than on the south edge. These results are attributed to snowpack modification in a manner similar to that in the James River clearings (as illustrated in Figures 4–6).

DISCUSSION

James River

The different SWE in the directional sectors of the clearings and surrounding forest suggest two possible phenomena: (1) a spatial bias at one edge in most clearing sizes because of edge orientation or a predominant wind vector that consistently causes preferential accumulation and (2) a spatially preferential loss from the snowpack, either melt or evaporation, after it accumulates.

Edge orientation can be discarded as a possible reason because clearings were made circular to eliminate effect of edge orientation, *Gary* [1974] and *Leaf* [1975] have reported a zone of deficit accumulation at the down wind edge of a forest clearing. Because the deficit at James River is consistently at the north edge of the clearings, and because the snow accumulation pattern is symmetrical about the north-south axis, the obvious assumption is that south winds are responsible for either differential accumulation or differential redistribution. Weekly wind run data at 10 m above the forest canopy (Figure 2) obtained during the study indicate that wind is not predominantly from the north or south. A few records of wind velocity and direction from natural gas extraction plants within 35 km of the study area indicate that winds during snowfall were predominantly northwest followed by north but

TABLE 5. Snow Accumulation in Clearings and Intervening Forest on Three Aspects of Twin Subbasin at Maximum Snowpack, March 1980 and 1981 (362-Point Subset)

	Snow Accumulation (SWE, mm)								
	Clearings			Forest			Clearings and Intervening Forest Combined		
Aspect	Actual	Predicted	Difference, %	Actual	Predicted	Difference, %	Actual	Predicted	Difference, %
N	226	202	+11.9*	203	213	−4.7	212	209	+1.4
S	241	216	+11.6*	215	213	+0.9	225	214	+5.1
E	247	193	+28.0*	189	199	−5.0	212	197	+7.6
All	235	202	+16.3*	202	209	−3.3	215	206	+4.4

*Significant at the 90% level of probability.

include all directions except east and southeast. High velocity winds that might be important in redistribution of snow on the ground are not north or south but generally from southwest through northwest, associated with chinooks. However, most snow movement occurs at wind speeds greater than those within the James River clearings [*Tabler and Schmidt*, 1972; *Swanson*, 1980]. Therefore neither differential accumulation during snowfall nor redistribution after initial accumulation are responsible for the patterns noted in this study.

Nonuniform depletion of the snowpack after accumulation, either by melt or evaporation, is the more likely cause of the effect noted here. The amount and extent of the reduction in SWE on the north sides increased with clearing size and as the season progressed (Figures 4–6). In the 5 H clearings, for example, the reduction was evident in late January, the first measurement of the season (Figure 6). It was also evident in clearings as small as 3 H (Figure 4) at that time but the smaller the clearing the smaller the effect. By the first of March a reduced snowpack was found in the north edge of the 2 H clearings and by mid-April, in all openings greater than 1/2 H. The depth into the forest at which there was a reduction in snowpack increased as the season progressed.

A plot of the angle of the sun above the horizon (solar attitude) at 52°N latitude at solar zenith on different dates [*List*, 1958] illustrates the relationship between time of snowpack depletion and opening size (Figure 7). At the lowest solar altitude, 15° on December 21, the north edges of the 4 to 6 H clearings are in sunlight. The north edge of a 3 H clearing does not receive sunlight until mid-January, a 2 H until mid-February, a 1 H until mid-April. Direct sunlight would not be expected to reach the floor of a 1/4 H clearing at any date.

For each clearing size the area that would receive direct solar radiation at noon if the day were clear was plotted over date. The area under the curve, i.e., the integral of area receiving sun over time, was obtained for the periods between December 21 (the day having the lowest solar altitude and assumed to be the beginning of the snow accumulation period) and the date of each of the four snow surveys in 1973. These integral values were expressed as a percentage of the total possible if the entire clearing received direct solar radiation for the duration of the snowpack (Table 6). These illustrate trends over time within one clearing size, and also the trend by clearing size for a particular date. Mean SWE at maximum snowpack in the north sector of both the 1 to 6 H clearings and the adjacent forest is highly correlated with the integral values of Table 6, with correlation coefficients of −0.96 and −0.99, respectively ($P < 0.01$).

If no direct sunlight reaches the floor of a clearing, e.g, the 1 H clearing (Figure 4), the snowpack is reasonably uniform within the clearing and in the forest surrounding it. As clearing size increases, or as the season progresses, the area that receives direct sunlight also increases (Table 6). For example, in a 4 H clearing, some of the snowpack receives direct solar radiation at all times of the year and SWE is less in the sunlit northern sector than in the shaded southern sector, being almost identical in the southern sector to that in all sectors of the 1 H clearing (Table 1). Once the clearing is large enough or the season sufficiently advanced so that both direct sunlight, and that reflected from the snow in the clearing, is incident on the tree trunks and snowpack at the north edge of the clearing, then the SWE at any given date decreases markedly from south to north (Figure 5).

Granted, the fact that area of clearing receiving direct solar radiation is highly correlated with SWE at maximum snowpack in the north sector of the clearings does not impart a cause and effect relationship. However, this relationship does seem to explain the depletion of the snowpack during the accumulation period, whereas the other probable explanation, effect of wind, has been shown not to explain the relationship.

What is the disposition of the snow "lost" from the north sectors of the clearings? The dry and relatively warm air that occurs during chinook winds (generally 10° to 20°C warmer than snow surface temperatures) would favor evaporation [*Satterlund*, 1972, Figure 8.1]. On the other hand, evaporation is low at low wind speeds, regardless of the vapor pressure deficit or air temperature [*Satterlund*, 1972, Table 8.5]. *Smith* [1974] attributed the lower snow accumulation on the north side of east-west strips at the Central Sierra Snow Laboratory to back radiation from the trees on the north side. In the warm snowpacks of the California area, the effect was to melt the snow, not evaporate the pack. *Meiman et al.* [1971] showed high correlation between snow distribution and solar radiation in the Swiss pre-Alps where the effect was also to increase the melt rate.

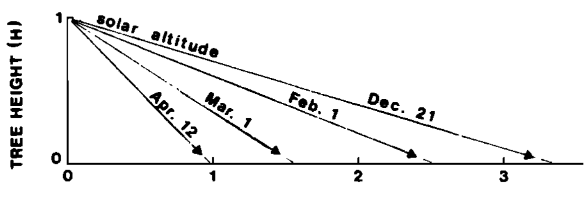

Fig. 7. Shadow length at solar zenith as a function of date of year, by clearing size, at 52°N latitude.

TABLE 6. Area of Clearing at James River (52°N Latitude) Receiving Direct Sun at Noon Weighted by Days From December 21 to Measurement Date Expressed as Percentage of the Total Area of Clearing Weighted by Days

Clearing Size, H	Time-Weighted Clearing Area in Sun as Percentage of Time-Weighted Clearing Area From December 21 to Measurement Date, %			
	January 31	March 2	April 14	May 8
1				3.2
2		0.3	9.3	16.5
3		6.6	21.2	29.9
4	4.1	16.5	31.7	38.8
5	22.3	30.9	41.9	48.3
6	32.2	41.5	49.4	55.5

At James River, the difference in SWE between the north edge and the south edge is a measure of snowpack ablation over the accumulation season. Many of the measurement points in the forest on the north edge have no snow left at the time of maximum accumulation. For the 6 H clearing, for example, SWE in the forest on the south side of the clearing averaged 78 mm at maximum snowpack (Table 1). Therefore all else being equal, 78 mm SWE is a measure of ablation at those points in the forest on the north edge of the 6 H clearings where no snow remains at maximum accumulation. This ablation is probably due to a combination of melt and evaporation. Casual observation at James River suggested that snowmelt seldom occurs during the winter. If, indeed, this is the case, then the 78 mm SWE ablation is largely due to evaporation. This amount seems high, especially in view of (1) *Storr*'s [1968] conclusion that snowpack evaporation would be negligible during the winter at Marmot Creek, 100 km to the south, except during chinooks when as much as 13 mm per day was possible, and two Tables 8.1 and 8.5 in the work by *Satterlund* [1972].

However, for 18 sites along the eastern slopes of the Rockies in Alberta, potential snowpack evaporation was as high as 88 mm above tree line and 53 mm in large forest openings for 22 chinook days in January–March 1976 [*Golding*, 1978]. Daily rates were as high as 10 mm above tree line and 5 mm in the forest openings. These losses were due mainly to advected energy and not to conversion of short-wave to long-wave radiation by tree trunks and foliage. Also, in the Rocky Mountains of Colorado, a region somewhat similar in climate to the eastern slopes of the Rockies in Alberta, evaporation from snow in the canopy and on the ground was 33 mm for north and 58 mm for south aspects for the snow season [*Troendle and Leaf*, 1980]. The solar radiation absorbed by tree trunks and canopy on the north edge of the clearings at James River would be emitted as long-wave radiation, almost all of which would be absorbed by the snowpack. Thus there would likely be sufficient energy to evaporate the 78 mm of snow ablation on the north edges. But because of low wind speeds within and adjacent to the clearings, the vapor-pressure gradient near the snow surface is unlikely to be sufficient to permit all available energy to be converted to latent heat of vaporization. Confirmation of which process dominates and the SWE loss attributable to each over any given time span must await the results of a study currently underway. If the predominant process is snowmelt then the ablation resulting from forest-harvesting patterns is not a loss to the system. If evaporation predominates then the ablation is a loss to the local hydrologic system.

These data indicate that there are situations in which the snow accumulated on the ground cannot be considered a measure of the amount of snow that has actually fallen there. In this study, wind direction has had, presumably, minor influence on snow accumulation in a clearing or in the forest immediately surrounding it. This study has demonstrated that intensified solar energy input into the southfacing sectors has modified the accumulated snowpack by evaporation or melt to such an extent that precipitation that falls as snow is not truly represented by measurements of the current accumulation. A valid estimate of precipitation for use in water balance calculations or hydrologic modeling of partially cleared forested watersheds can be obtained only by modifying the on-ground measurements by functions of time and space specific to the local situation.

Marmot Cabin and Twin Subbasins. The effect of such modification of an existing snowpack is illustrated by accumulation data for cutblocks of north and south aspect on Cabin subbasin. The south edge of both blocks was shaded all winter by the uncut forest to the south with the result that SWE was 33% greater than predicted in both cases (Table 3). On the north edge of the north aspect block, where sun reached the snowpack by early spring, SWE was 21% greater than predicted, but on the south aspect block, where the pack was always in sunlight, only 8% greater. In contrast, in the small 3/4 to 1-1/4 H clearings on Twin subbasin, where the snowpack does not receive direct sunlight, clearings on both the low-energy north aspect and the high-energy south aspect accumulated 12% greater SWE than predicted. There was no greater ablation on the north edges than on the south edges of these small openings.

Snow Interception or Redistribution

Unfortunately, the data from James River and Marmot Creek do not provide definite answers concerning the source of increased SWE in forest clearings. At James River the 1/4 H clearings had the least SWE (93 mm) of all clearing sizes, and the forest surrounding the 1/4 H had almost the same SWE (81 mm) as did the 0 H (82 mm). A not unreasonable assumption then is that the excess in the 1/4 H is due to lack of interception, not to redistribution. This assumption is less valid the stronger the wind during snowfall. However, *Storr* [1973] reported that winds during snowfall at Marmot Creek are quite light, with 80% of snowfall occurring with winds less than 4.5 m/s. If that be the case, interception averaged 11 mm or 12% of 1/4 H SWE, with annual values of 24, 8, 3, and 12% for each of the years 1973–1976. In large clearings, increases greater than this must be attributed to redistribution, and the forest surrounding such clearings should show a deficit. In the north sectors, and even in the east and west sectors of the larger clearings, there is significant ablation during the accumulation period. Therefore we cannot use those sectors in a discussion of interception but must use only the south sector. In the south sector of the forest surrounding the clearings, only the 6 H shows a deficit (Table 1). That is, there is no evidence of redistribution in clearings 5 H and smaller. If the increases in the clearings are due to interception only, then the increases should be the same for all clearing sizes, namely, the 11 mm suggested in our discussion of the 1/4 H, but they range from 11 mm for the 1/4 H to 37 mm for the 2 H. That is, there is no evidence of redistribution in clearings 5 H and smaller, yet the data don't support interception as the sole factor responsible.

For the five cut blocks of Cabin subbasin the increased SWE was not at the expense of adjacent areas, i.e., redistribution does not appear to have caused the increase (Table 2). The increase of 33 mm in the cut blocks represents 13 mm over the whole basin, just slightly greater than the 11-mm increase recorded for the whole basin. The increase, averaging 18%, must be attributed then to elimination of interception.

On Twin subbasin, however, the increase in SWE in the clearings seems to be attributable largely to redistribution from the adjacent forest. The increase in the clearings and the decrease in the intervening forest represents 13 and 12 mm, respectively, when applied to the whole basin (Table 4). Thus the increase in the clearings just balances the decrease in the intervening forest, arguing against interception. Or, comparing actual (207 mm) to predicted SWE (202 mm) for the whole basin (Table 4), the statistically nonsignificant difference of 5 mm is only 2% greater than predicted. That is, only 2% of the increase in the clearings might be attributed to interception.

SUMMARY AND CONCLUSIONS

Snow accumulation was greater in clearings than in the forest, whether the clearings were large as in the 8- to 13-ha blocks on Cabin subbasin where SWE averaged 20% greater than in the forest, or small as in the 3/4 to 1-1/4 H circular clearings on Twin subbasin where SWE was 28% greater than in the intervening forest, or at the James River study site where SWE in 1/4 to 6 H circular clearings ranged from 13 to 45% greater than in the forest. In the small clearings of James River the increase probably resulted from a combination of interception and redistribution, but the relative proportion attributable to each cannot be stated. There was no evidence of redistribution of snow from the surrounding forest into the large cut blocks on Cabin subbasin so the increase must be attributed to elimination of interception. On Twin subbasin the increased SWE in clearings seems to be attributable almost completely to redistribution.

At James River, SWE was less in the north than in the south edges of clearings, ranging from 42 to 52% less in 2 to 6 H circular clearings. The amount by which south sector SWE exceeded that in the north sector increased with increasing size of clearing and with time since the beginning of the snow accumulation season. Wind had no discernible influence on accumulation in the clearings or adjacent forest. SWE in the north sector of the clearings was highly correlated with the integral of the fraction of the clearing receiving direct sunlight over time since the beginning of the accumulation period. In Cabin subbasin the amount by which actual SWE exceeded predicted on north and south edges of the large clearcuts depended on the aspect of the clearcut. On the north aspect there was an increase over predicted SWE of 21% on the north edge and 33% on the south edge. On the south aspect block the increase was only 8% on the north edge but remained at 33% on the south edge. The difference in north and south sector accumulation in both Cabin subbasin and James River is due to snow ablation in the north sector which is a function of direct solar radiation reaching the snowpack and adjacent tree trunks. Snowpack ablation is likely a combination of melt and evaporation but this study provides no insight into the relative contribution of each.

Finally, measurement of snow on the ground in partially cleared forested watersheds is not a valid measure of snowfall. For water balance or hydrologic modeling of such watersheds ground measurements must be modified by consideration of temporal and spatial factors relative to the particular situation.

Acknowledgments. Part of the work reported herein was supported by Research grant A6957 from the Natural Sciences and Engineering Research Council of Canada. Support by the Northern Forest Research Centre, Canadian Forestry Service, Edmonton, Alberta is also acknowledged.

REFERENCES

Anderson, H. W., Managing California's snow lands for water, *Res. Pap. PSW-6*, 28 pp., U.S. Dept. Agric., For. Serv., Washington, D. C., 1963.

Bergen, J. D., and R. H. Swanson, Evaporation from a winter snow cover in the Rocky Mountain forest zone, paper presented at Proceedings 32nd Annual Western Snow Conference, Nelson, British Columbia, 1964.

Church, J. E., The conservation of snow—Its dependence on forests and mountains, *Sci. Am. Suppl.*, *74*(1914), 152–155, 1912.

Gary, H. L., Snow accumulation and snowmelt as influenced by a small clearing in a lodgepole pine forest, *Water Resour. Res.*, *2*(2), 348–353, 1974.

Gary, H. L., Duration of snow accumulation increases after harvesting in lodgepole pine in Wyoming and Colorado, *Res. Note RM-366*, U.S. Dep. Agric., For. Serv., 7 pp., Washington, D. C., 1979.

Golding, D. L., Calculated snowpack evaporation during chinooks along the eastern slopes of the Rocky Mountains in Alberta, *J. Appl. Meteor.*, *17*, 1647–1651, 1978.

Golding, D. L., and R. H. Swanson, Snow accumulation and melt in small forest openings in Alberta, *Can. J. For. Res.*, *8*(4), 380–388, 1978.

Haupt, H. F., Local climatic and hydrological consequences of creating openings in climax timber in North Idaho, *Res. Pap. INT-223*, U.S. Dep. Agric., For. Serv., 43 pp., Washington, D. C., 1979.

Hoover, M. D., and C. F. Leaf, Process and significance of interception in Colorado subalpine forest, in *Proceedings International Symposium on Forest Hydrology*, pp. 213–223, Pergamon, New York, 1967.

Leaf, C. F., Watershed management in the Rocky Mountain subalpine zone: The status of our knowledge, *Res. Pap. RM-137*, U.S. Dep. Agric., For. Serv., 31 pp., Washington, D. C., 1975.

List, R. J., *Smithsonian Meteorological Tables*, 6th ed., 527 pp., Smithsonian Institution, Washington, D. C., 1958.

Meiman, J. R., E. Remmenga, and H. Keller, Snow distribution in relation to solar radiation on two Swiss pre-Alp watersheds, *Water Resour. Res.*, *7*(6), 1636–1640, 1971.

Miller, D. H., Folklore about snowfall interception, paper presented at 42nd Annual Meeting, 5 pp., AGU, Washington, D. C., 1961.

Miner, N. H., and J. M. Trappe, Snow interception, accumulation, and melt in lodgepole pine forests in the Blue Mountains of eastern Oregon, 4 pp., *Pacific N.W. For. and Range Exp. Sta. Res. Note 153*, U.S. Dep. Agric., For. Serv., Washington, D. C., 1957.

Satterlund, D. R., *Wildland Watershed Management*, 372 pp., Ronald Press, New York, 1972.

Smith, J. L., Hydrology of warm snowpacks and their effects upon water delivery ... Some new concepts, in *Advanced Concepts and Techniques in the Study of Snow and Ice Resources*, pp. 76–89, National Academy of Sciences, Washington, D. C., 1974.

Storr, D., An estimate of snow evaporation potential in Marmot Basin, paper presented at National Workshop Seminar on Snow

Hydrology, Can. Natl. Comm. for the Int. Hydrol. Decade and Univ. of New Brunswick, Fredericton, N.B., 1968.

Storr, D., Wind-snow relations at Marmot Creek, Alberta, *Can. J. Forest Res.*, *3*(4), 479–485, 1973.

Swanson, R. H., Surface wind structure in forest clearings during a chinook, paper presented at Proceedings of the 48th Annual Western Snow Conference, Laramie, Wyo., 1980.

Swanson, R. H., and D. R. Stevenson, Managing snow accumulation and melt under leafless aspen to enhance watershed value, paper presented Proceedings 39th Annual Western Snow Conference, Billings, Mont., 1971.

Tabler, R. D., and R. A. Schmidt, Weather conditions that determine snow transport distances at a site in Wyoming, paper presented at Proceedings The Role of Snow and Ice in Hydrology, UNESCO-WMO-IAHS, Banff, Alberta, Sept. 6–20, 1972.

Troendle, C. A., and C. F. Leaf, Hydrology, in *Water Resource Evaluation Non-Point Sources in Silviculture*, pp. 1–173, U.S. Environmental Protection Agency, Washington, D. C., 1980.

Wilm, H. G., and E. G. Dunford, Effect of timber cutting on water available for streamflow from a lodgepole pine forest, *Tech. Bull. 968*, 43 pp., U.S. Dep. Agric., Washington, D. C., 1948.

D. L. Golding, Faculty of Forestry, University of British Columbia, Vancouver, B. C., V6T 1W5

R. H. Swanson, Northern Forest Research Centre, Canadian Forestry Service, Edmonton, Alberta, T6H 3S5.

(Received March 12, 1984;
revised June 11, 1986;
accepted June 17, 1986.)