50TH EASTERN SNOW CONFERENCE
61ST WESTERN SNOW CONFERENCE
Quebec City 1993

Partitioning the Deposition of Winter Snowfall as a Function of Aspect on Forested Slopes

C.A. TROENDLE, R.A. SCHMIDT AND M.H. MARTINEZ
Rocky Mountain Forest and Range Experiment Station
240 West Prospect Road
Fort Collins, Colorado 80526-2098 U.S.A.

ABSTRACT

Snowpack accumulation, expressed as Peak Water Equivalent (PWE) is usually least and peaks earliest on south facing slopes. This study, conducted as part of an ongoing effort to define snow deposition and ablation processes, attempted to partition the components in the deposition process that could result in the differences in PWE. Total flux into the canopy on opposing north and south facing slopes was found to be similar, although some difference in particle size at interior canopy positions occurred. Ventilation, or windspeed within the canopy, was greater on the south slope. Throughfall (storm basis) was equal on both slopes but accumulation on the south slope lagged behind that on the north slope. The initial lag was attributed to evaporative differences. In March, melt on the south slope was more significant. The south slope had 7.7cm less water equivalent than the north slope on April 1. One-third of the difference was attributed to melt, two thirds to greater vaporization.

INTRODUCTION

The significant role of the winter snowpack as the source for the water supply of the Western United States has long been appreciated. Paired watershed experiments dating to the early 1900's have defined the role snowpack deposition processes have in the water balance and the subsequent changes in those processes that occur following forest disturbance (Troendle and King 1985, 1987). Because snow plays such a significant role in the water balance and subsequent water supply, there has been and continues to be considerable research into snowpack accumulation and ablation processes in order to explain the responses seen at the watershed level. Church (1912) was one of the earliest modern observers to note the increase in snowpack accumulation that occurs in small glades or openings in the forest. Wilm and Dunford (1948) demonstrated the strong relationship between forest-stand density and peak water equivalent in the snowpack. Troendle and King (1987), Wheeler (1987), Schmidt and Troendle (1989), and others have concluded increased accumulation reflects a reduction in what would have been interception loss or vaporization. However, much variation occurs in the magnitude of change following forest disturbance, especially as a function of aspect.

Packer (1962), Gary and Coltharp (1967), Gary (1979), and others have noted snowpack accumulation varies with aspect. Gary (1979) noted snowpack accumulation was 18-40 percent less under lodgepole pine on south slopes than under similar stands on northern exposures. In earlier efforts, Gary and Coltharp (1967) noted snowpack accumulation peaked earlier (March 3 versus April 1) on south slopes, under spruce-fir cover, and had lower peak water content. Similar responses were observed under aspen stands and in grassland plots. In an extensive study under white pine on the Benton Creek watershed in northern Idaho, Packer (1962) found snowpack accumulation increased strongly with elevation, and at all elevations snowpack was significantly less on southerly aspects. His analysis demonstrated a significant interaction between aspect, elevation, and amount. Aspect differences were greatest at high elevations and during wet years. More recently, Toews and Gluns (1986) looked at snowpack accumulation patterns in paired plots in both forest and clearcuts on North, South, East, and West aspects. In general, they noted an increased accumulation on north slopes relative to the south slope while the east and west slopes fell in between the two extremes. The observation held for both forest and openings and over several years with different precipitation amounts.

The influence of aspect is also reflected in the influence on both snowpack accumulation and streamflow after timber harvest. At the Fraser Experimental Forest near Fraser, Colorado, small openings created on north facing slopes have resulted in as much as a 50 percent increase in snowpack accumulation relative to the undisturbed forest (Troendle and Meiman, 1986). On east-west or neutral slopes, the increase approaches 30 percent (Wilm and Dunford, 1948, Troendle, 1987); on south slopes the increase in the opening averages only 20 percent more than the undisturbed forest (Troendle and King, 1987). In the same paper, Troendle and King noted the increase in flow following removal of 40 percent of the vegetation on the north slope was far greater than the increase in flow following a similar basal area reduction on a southerly aspect. A large part of the difference in response was assumed to have come from the greater increase in snowpack on the north slope.

Southerly exposures consistently exhibit the tendency to accumulate less snowpack than their northerly counterparts. They reflect this same tendency in responding to timber harvest or forest disturbance.

THE STUDY

The objective of this study was to identify those factors responsible for the differential accumulation of snow on north and south slopes. The approach to the experiment was: (1) to define the relative flux of winter precipitation (snow) into the forest canopy on opposing north and south facing slopes, (2) determine the throughfall under each canopy on an event basis, (3) monitor snowpack accumulation (water equivalence) on the ground through the accumulation period and, (4) monitor the soil-water recharge under each stand during the winter. In this manner we attempted to partition and track the disposition of snow input to both sites and identify where differences occur.

The study sites are located on the West St. Louis drainage, Fraser Experimental Forest, on opposing hillslopes with 20^{o} and 200^{o} aspect and 35 to 40 percent slopes. On the north slope, the stand is primarily spruce-fir with some lodgepole pine. Stand density is approximately 36ma^{2}ha with an average canopy height of 21m (Schmidt and Troendle, 1989). The stand on the south slope is typical lodgepole pine with some spruce and fir and has a density of 34m^{2}ha. Kaufmann et al. (1982) found the projected leaf area (index to intercepting surface) of either Engelman spruce or subalpine fir was more than two times that of lodgepole pine per unit of basal area. The canopy is more open on the south slope, canopy structure is different, and total intercepting surface is less. Canopy height on the south slope is 1-2m less than the north slope. Towers (30cm triangular towers) were erected on both slopes to gain access to the canopy and above. A 34m tower was erected on the north slope and a 30m tower erected on the south slope. Instrument pairs consisting of a Snow Particle Counter (SPC) and a cup anemometer were positioned at 15m and 21m on both towers and also at 34m on the north tower. In addition, a directional wind vane was placed at 21m on both towers. All instrument signals were hardwired back to a PC data collection system in a nearby instrument trailer (Schmidt and Jairell, 1987).

Thirty-six snowboards were located on each slope and measured at the end of each snowfall event from December 12, 1992, until April 1, 1993, to index throughfall to the forest floor. Nine snowboards were located at 3m intervals on each of four transects or lines located perpendicular to the slope and 17m apart. Two transects were placed upslope of the tower and two below such that the instrument tower was in the center of the snowboard grid system (Figure 1). After each storm, the boards were measured, cleared, and then moved one board width (0.67m) to the right in preparation for the next storm. The procedure was reversed when the snowboards were moved far enough to overlap the initial starting point for the next board on the transect. Three equidistant sites were established on each of the four transect lines to periodically monitor the accumulation of water equivalent in the snowpack. A federal sample was used. Four neutron-probe, soil-moisture access tubes were also randomly located about each tower to periodically index soil-moisture content in the upper 60cm of soil during the winter period. Neutron-probe, soil-moisture measurements and water equivalent estimates were made at approximately 2 week intervals from mid-December until April 1.

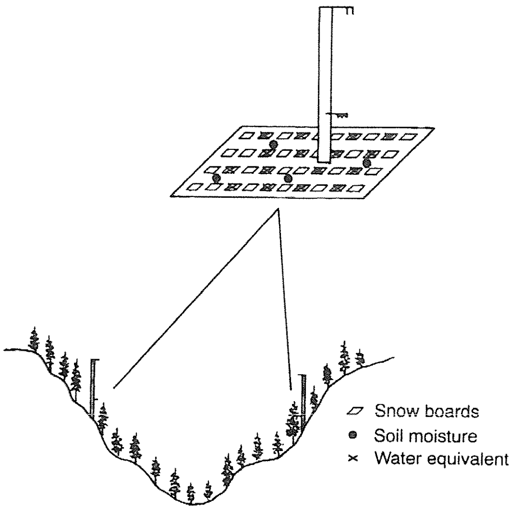

Figure 1: Schematic of the study area showing the relative location of instrument towers and sampling area.

METHODS

Nineteen storms, ranging from approximately 0.35 to 2.0cm of water were monitored from mid-December 1992 to April 1, 1993. A storm, loosely defined, consisted of a precipitation event that was preceded by a period of no snowfall, allowing the clearing of the snowboards, and followed by a period of no snow that was adequate in length to allow measurement and clearing of the boards. Not all the storms that actually occurred were measured because of overlap, partial data loss, etc.

Snow Particle Flux

Measurement of particle flux into the canopy was sampled in 5 minute intervals using SPC's. The rational was reported on earlier (Troendle, et al, 1988, Schmidt and Troendle, 1989). The SPC located at the top of the north facing tower (34m) was used as a reference or standard count for the other measurements (21 and 15m) taken on both slopes. The measurements were evaluated in terms of absolute numbers (actual particle counts per sampling interval) and as the ratio of count at either 21m or 15m to the standard or reference count. In addition to the number of snowflakes counted, the magnitude of the individual signals (counts) was also recorded. The magnitude of the signal is an index to particle size and this allowed partitioning the flux or number of particles into 10 relative size classes for further evaluation (Schmidt 1977).

RESULTS

The flux rate or precipitation entering the sites was similar on both sites at the 21m elevation. Flux rates were quite variable on both slopes and positively related to increasing windspeed (Figures 2). Note that windspeed at 21m was often greater on the south slope (Figure 2). This is further emphasized in a large reduction in flux (and wind) between the 21m and 15m positions on the north slope versus the minimal reduction on the south slope (Figure 3). The greater windspeed in the canopy on the south slope implies more turbulence, perhaps more mixing of snow particles, and a slower fall velocity at 15m than occurs on the north slope. Particles on the south slope are likely breaking up as more mid-size particles appear to be present at 15m than 21m while less large particles are present (Figure 3).

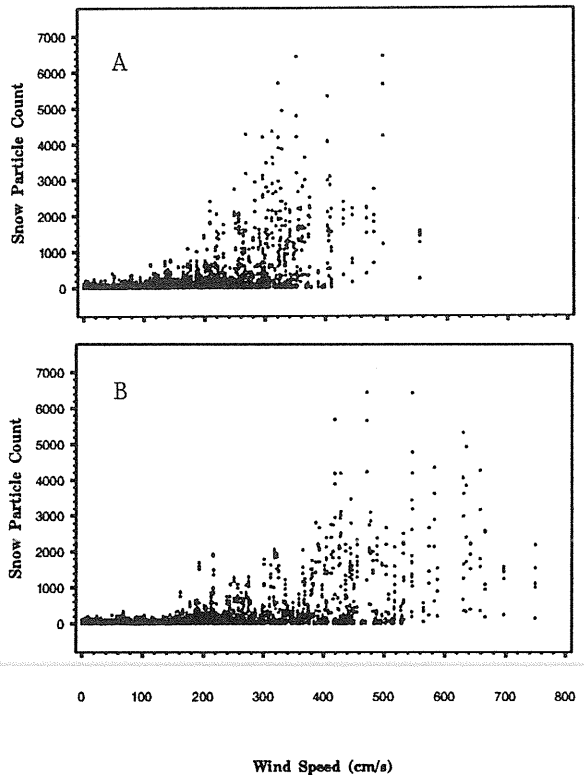

Figure 2: Particle count at 21m height for each five minute sampling interval plotted over average windspeed for the interval. Data is from all storms monitored. "A" represents north slope and "B" represents south slope.

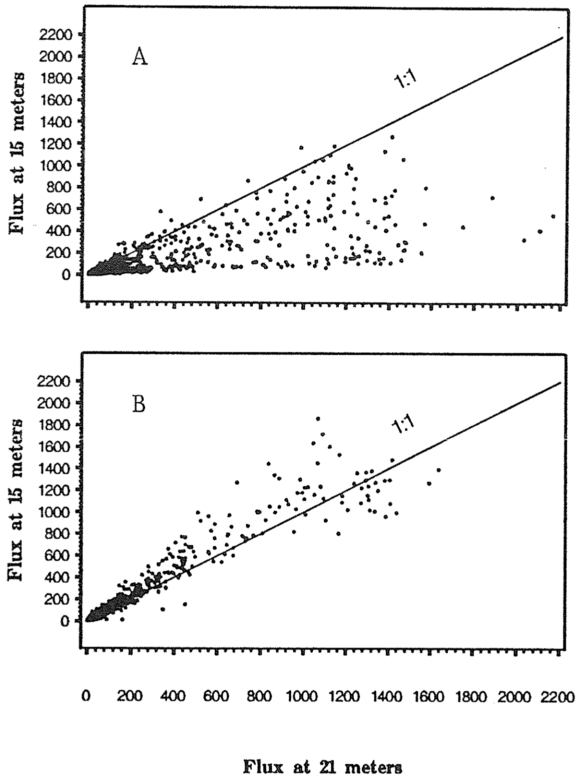

Figure 3: Relationship of particle counts, weighted for frequency of occurrence, at 15m elevation plotted over counts at 21m.

One of the fundamental hypothesis of this study is that the input to both slopes, at the canopy level, is the same. The 21m elevation appears to be the best level to evaluate this hypothesis. An estimate of weighted flux for each storm from mid-February to April was made by weighting the snow particles, by size class, and by their frequency of occurrence in order to obtain an estimate of mass flux (Schmidt 1977). We found no difference in the weighted input to each site (Figure 4). There was very little difference in the frequency of occurrence of particles in the 10 differing size classes but calculating the weighted flux adjusts for even those minor discrepancies.

Based on the observations made on individual storms occurring from early February until late March, the flux into both stands seems similar. Any differences appear to be related to turbulence and windspeed within the canopy. For the most part, the storms monitored were generated out of the near west or 260^{O} azimuth (Figure 5). This meant the dominant wind direction was perpendicular to both slopes. Neither slope was the recipient nor the donor of wind-blown snow from the opposing slope.

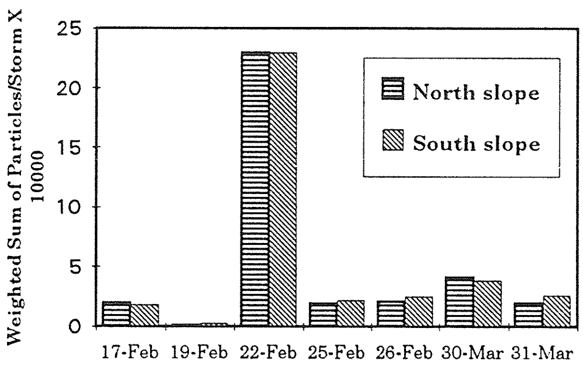

Figure 4: Histogram of the mass flux into the canopy of both sites for storms in February and March 1993.

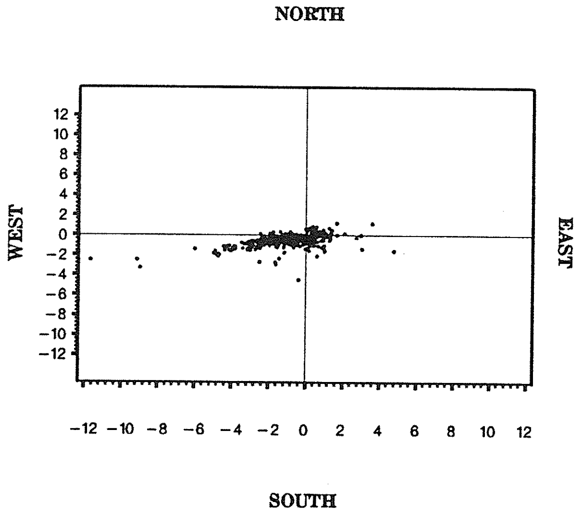

Figure 5: Schematic plot of relative particle counts over the average wind direction for the sampling interval. The lower left quadrant implies wind dominantly out of the south to west or 180^{O} to 270^{O} azimuth.

Snowboard Observations

Nineteen separate storms were monitored and they varied from 0.35-2cm in water content. Snowfall reaching the ground, or throughfall, was the same on north and south slopes (Figure 6). If anything, the fitted regression indicated slightly more (5 percent) on the south slope although the difference was non-significant. In earlier studies it had been documented, and confirmed in this study, that little snow falls to the boards, from the canopy between events (Wheeler, 1987).

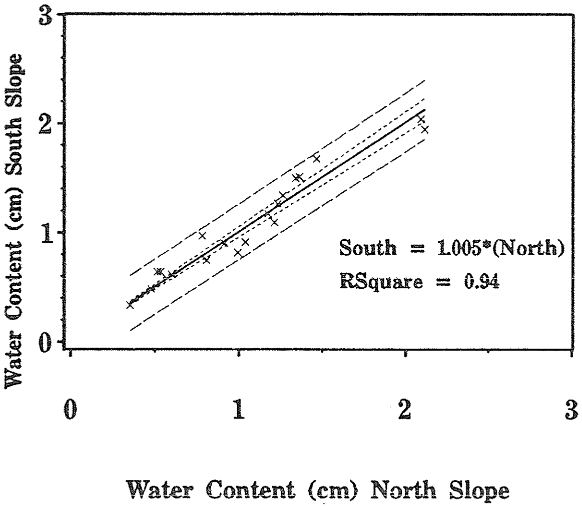

Figure 6: Relationship between snowboard accumulation on the south slope over that on the north slope for individual storm events.

Snowpack Accumulation

Water equivalence in the snowpack was periodically monitored from December to April. Accumulation on the south slopes paralleled but was less than that accumulated on the north slope (Figure 7). Accumulation on both slopes was somewhat similar until about March 1, at which time water equivalent peaked on the south slope (the variance was also greatest at this time on the south slope). Water equivalent peaked at or after April 1 (measurement discontinued) on the north slope. There was a 5.5cm increase in water equivalent on the north slope during March and a 2cm decrease on the south slope during the same period resulting in a 7.7cm difference in PWE between the two sites on April 1. At this point, the north slope had 32 percent more water equivalent than the south slope even though flux into the canopy and net storm input to the pack (snowboards) was similar on both sites.

Soil Moisture Content

The neutron-probe, soil-moisture access tubes on the north slope were originally installed as part of a complimentary study (Troendle and Meiman, 1986). Tubes on the south slope were installed specifically for this study.

There was a warming trend in early February which may have caused some melt and caused the slight rise in moisture content on both sites as reflected in the February 15 measurement (Table 1). The north slope did not express any other change in moisture content during the study period. It can be noted that data (not shown) for the 60cm and 90cm depths on the north slope also show no change. There was little if any change on the south slope until March. Then an increase in moisture content of 3 and 4 percent by volume occurred at both the 15m and 30m depths. These measurements represent a 45cm soil profile and the volumetric change represents a 2.0cm increase in soil moisture content. This implies melt occurred on the south slope but did not occur on the north slope during the same period.

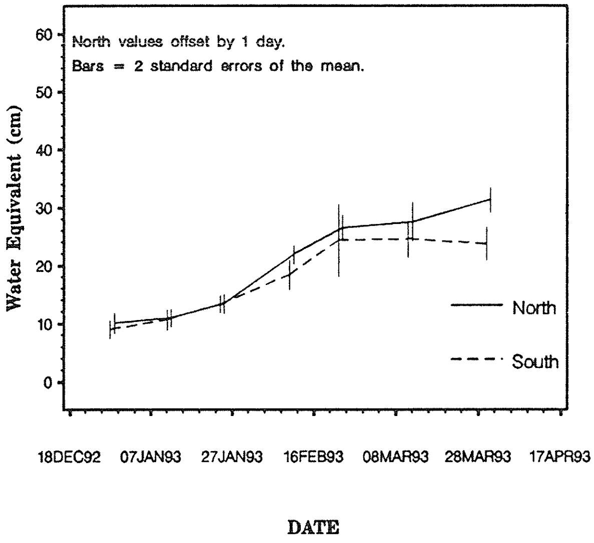

Figure 7: Comparison of water equivalent cumulation on north and south slope. Error bars indicate two standard errors about the point. On April 1, the two sites had significantly different peak water equivalents.

Table 1: Average Soil Moisture Content (cm water/cm depth) at 15cm and 30cm depths on north and south slopes.

Date	Aspect			
	North		South	
	15	30	15	30
	Depth (cm)			
12-29-92	0.17	0.17	0.19	0.16
02-12-93	0.18	0.18	0.19	0.16
02-15-93	0.19	0.18	0.20	0.17
30-09-93	0.18	0.18	0.19	0.16
03-22-93	0.18	0.17	0.19	0.18
04-05-93	0.18	0.17	0.22	0.20

DISCUSSION AND CONCLUSIONS

Based on the observations made in this study, it would appear precipitation input to the north and south slopes is similar and not the cause of any differences seen on the ground. The storm track was primarily from the west, and the windspeed across and through the canopy on the south slope is apparently maintained at levels which exceed those on the north slope. The higher or less dampened windspeed in the canopy could result in a flatter snow particle trajectory (or lower fall velocity) and longer travel time, causing more particle breakup. Given the same input rate above the canopy, one might expect greater throughfall on the south slope because of the more open canopy conditions. Given the potential for a flatter trajectory, once the particles are into the canopy on the south slope, perhaps the intercepting surface is better reflected by what is in front of the particle rather than what is below it. Since the net snowfall reaching the ground was virtually the same on both north and south slopes; the greater windspeed on the south slope may have driven more of the snow into the canopy, and the increased wind ventilation and particle breakup may have created a condition favoring a greater efficiency in vaporization of snow, or the snow may have been transported to a different location. The net effect is that canopy abstraction seems the same on both slopes.

The flux to the ground, based on the snowboards, appears to be the same on both slopes. In aggregate, the summation of individual events on the north slope tracks the accumulation of snow on the ground quite well, implying minimal ablation during the accumulation period. On the south slope the measured accumulation over time falls increasingly short of the aggregate from individual storms. Some of the ablation is melt, especially in March, the remainder may reflect differences in vaporization loss from the snowpack. Windspeed or ventilation appears to be greater in the lower canopy on the south slope, as is the energy loading especially in late winter, and both of these factors increase the evaporative opportunity. Melt appears to account for about one-third the difference in accumulation on the north and south slopes and differences in evaporation opportunity may account for the remaining two-thirds of the difference.

Several questions were addressed in this study and several others were raised as a result of it. A basic assumption has always been that there are no significant differences in the flux into the canopy as a function of aspect. This seems supportable based on our data. However, we would expect greater interception and abstraction as the snow filters through the more closed canopy on the north slope. This was not supportable by our data as the same amount passed through both canopies to the forest floor. This raises a question about the role the greater ventilation and solar loading (unmeasured but assumed) on the south slope has on the efficiency of interception, evaporative loss, and transport processes within the canopy. Does the difference in ventilation offset the difference in canopy structure causing the somewhat different leaf area indices to be equally efficient in trapping and vaporizing snow? Once the snow reached the ground, greater melt and subsequent soil moisture recharge (measured) and greater vapor loss (assumed by difference) occurred on the south slope as expected.

LITERATURE CITED

Church, J. E. 1912. The conservation of snow--its dependence on forest and mountains. Scientific American Supplement 74(1914):152-155.

Gary, Howard L. 1979. Duration of snow accumulation increases after harvesting in lodgepole pine in Wyoming and Colorado. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado, U.S.D.A. Forest Service Research Note RM-366. 7 p.

Gary, Howard L. and George B. Coltharp. 1967. Snow accumulation and disappearance by aspect and vegetation type in the Sante Fe Basin, New Mexico. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado, U.S.D.A. Forest Service Research Note RM-93, 11 p.

Kaufmann, Merrill A., Carleton B. Edminister, and Charles A. Troendle. 1982. Leaf area determinations for subalpine tree species in the central Rocky Mountains. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado, U.S.D.A. Forest Service Research Paper RM-238, 7 p.

Packer, Paul E. 1962. Elevation, aspect, and cover eeffects on maximum snowpack water content in a western white pine forest. Forest Science. 8:3:225-235.Schmidt, R. A. 1977. A system that measures blowing snow. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado, U.S.D.A. Forest Service Research Paper RM-194, 80 p.

Schmidt, R. A. and R. L. Jairell. 1987. A system that monitors blowing snow in forest canopies. In: Management of subalpine Forests: Building on Fifty Years of Research. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado, U.S.D.A. Forest Service General Technical Report RM-149, p 227-230.

Schmidt, R. A. and C. A. Troendle. 1989. Snowfall into a forest and clearing. Journal of Hydrology, 110 (1989): p 335-348.

Toews, D. A. A. and D. R. Gluns. 1986. Snow accumulation and ablation on adjacent forest and clearcut sites in Southeastern British Columbia. In: Proceedings 54th Annual Western Snow Conference. April 15-17, 1986. Phoenix, Az. Fort Collins, CO 101-111.

Troendle, C. A. 1987. Effect of clearcutting on streamflow generating processes from a subalpine forest slope. In: Forest Hydrology and Watershed Management IAHS Publication, 167: p 545-552.

Troendle, C. A. and R. M. King. 1985. The Fool Creek Watershed - thirty years later. Water Resources Research, 21(12): p 1915-1922.

Troendle, C. A. and R. M. King. 1987. The effect of partial cutting and clearcutting on streamflow at Deadhorse Creek, Colorado. Journal of Hydrology, 90 (1987): p 145-157.

Troendle, C.A. and J. R. Meiman. 1986. The effect of patch clearcutting on the water balance of a subalpine forest slope. Proceedings, 54th Annual Western Snow Conference, Fort Collins, Colorado, p 93-100.

Troendle, C. A., R. A. Schmidt, and M. H. Martinez. 1988. Snow deposition processes in a forest stand with a clearing. Proceedings, 56th Western Snow Conference, Fort Collins, Colorado, p 78-86.

Wheeler, K. 1987. Interception and redistribution of snow in a subalpine forest on a storm by storm basis. Proceedings, 55th Western Snow Conference, Fort Collins, Colorado, p 78-87.

Wilm, H. G. and E. G. Dunford. 1948. Effect of timber cutting on water available for streamflow from a lodgepole pine forest. Washington, D.C., U.S.D.A. Forest ServiceTechnical Bulletin 968, 43 p.