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THE EFFECT OF PARTIAL AND CLEARCUTTING ON STREAMFLOW AT DEADHORSE CREEK, COLORADO

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ABSTRACT

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Two subalpine forest subdrainages of Deadhorse Creek, Colarado, USA were used to demonstrate the comparable impact on water yield of two tree-harvesting practices. Of the 40 ha North Fork subdrainage 36% was clearcut commercially using five-tree height circular openings. In contrast, 40% of the basal area on the 41 ha Unit 8 was removed by partial cutting in the first step of a three-step shelterwood cut.

Annual flow and peak flow from the clearcut watershed were increased significantly. The partial cut resulted in a significant increase in total water equivalent in the winter snowpack and an apparent increase in total annual streamflow that was comparable to the clearcut. The timber harvest on the two subdrainages, however, represented only 10% of the total basal area of the larger Deadhorse Creek Watershed in which they are located. Annual flow at the mainstream gage was not significantly increased as a result of harvest.

INTRODUCTION

Much information about the effect of timber harvesting on snowpack accumulation and melt, as well as its effects on streamflow, has been developed from research on the Fool Creek Waterhed on the Fraser Experimental Forest, Colorado, and in nearby subalpine forests (Troendle and King, 1985; Troendle and Meiman, 1984; Troendle, 1983a; Leaf, 1975; Hoover and Leaf, 1967).

The Deadhorse Watersheds, also on the Fraser Experimental Forest, Colorado, USA, are being used as pilot demonstration areas to evaluate watershed management strategies. This paper examines the hydrologic response of two of the three treatments applied to the Deadhorse Watershed complex — a patch clearcut and a partial cut with each treatment removing 35–40% of the stand.

WATERSHED DESCRIPTION AND MEASUREMENTS

Deadhorse Creek is a 270 ha gaged watershed (Fig. 1). It drains to the east, at elevations ranging from 2880 to 3536 m. The two separately gaged subdrainages of Deadhorse Creek are 41 ha North Fork and the 78 ha Upper Basin. The 120° V-notch streamgage on main Deadhorse Creek was built in 1955. The 90°

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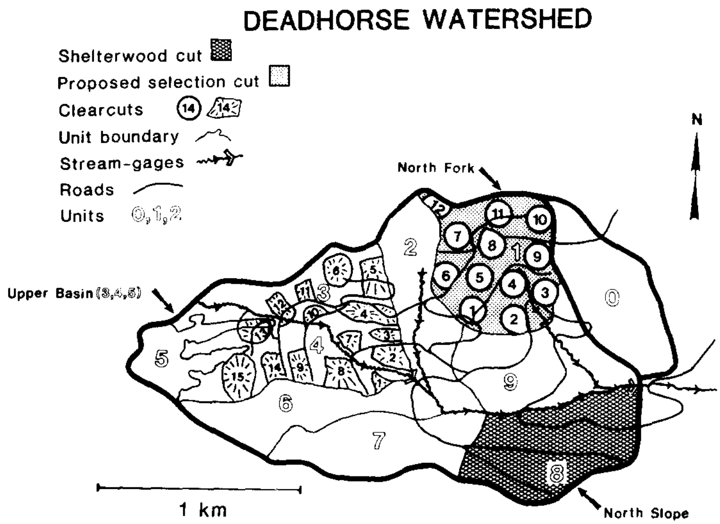

Fig. 1. The Deadhorse Watershed complex showing the harvesting alternatives applied to the North Fork, North Slope, and Upper Basin.

weirs on the North Fork and Upper Basin were built in 1970 and 1975, respectively. The main watershed and two subdrainages are calibrated against a 767 ha control watershed, East St. Louis Creek, which has been gaged since 1943. Unit 8 is an ungaged, north-facing slope, 41 ha in area that lies downstream of both the North Fork and the Upper Basin subdrainages. Unit 8 represents a portion of the 149 ha interbasin area lying below the two-gaged subdrainages and above the main streamgage.

Forest cover on the Experimental Forest consists of spruce–fir stands along the stream channels, on north slopes, and at upper-slope positions. Lodgepole pine grows on all low- and mid-elevation southerly or high-energy exposures. Alpine tundra is above the timberline. There is an average of 210 $m^3 ha^{-1}$ of sawtimber on the forested portion of the Deadhorse Creek Watershed. The North Fork subdrainage, because of its mid-elevation southerly exposure, consists mostly of the lodgepole pine, Unit 8 is largely spruce-fir, and the remainder of Deadhorse Creek has a general mix of spruce and fir.

Earlier publications (Alexander and Watkins, 1977; Troendle 1983a, b), listed Lexen Creek, 124 ha watershed adjoining Deadhorse Creek, as the control for Deadhorse Creek. However, as part of the analyses for this study, an evaluation was made to determine if East St. Louis Creek, the control watershed for Fool Creek, was also adequate to serve as the control for Deadhorse Creek. In terms of total annual flow, peak discharge, time to peak, and peak water equivalent in the snowpack, East St. Louis Creek proved to be as well calibrated a control as Lexen Creek. In no case did a loss in resolution or decrease in the power of a test occur. Therefore, because of the tremendous cost of maintaining two control watersheds, East St. Louis Creek is now used as the single control watershed on the Fraser Experimental Forest.

Streamflow is monitored at each gage from mid-April to mid-October. Year-round measurement has been discontinued, because very little flow occurs during the winter, as streams usually recede to a reasonably constant base flow which approximates $0.02\,l\,s^{-1}\,ha^{-1}$. The measured flow includes all flow occurring from mid-April, when the stream gages are opened, until mid-October, when they are shut down. Winter baseflow is not included in the estimate of yield. Snow courses, to index peak water equivalent; precipitation; temperature and humidity; and annual sediment export also have been continually monitored. Comparative snow course observations between the Deadhorse Creek and East St. Louis Creek began in spring 1967, and are used to estimate the mean water equivalent for each of the watersheds. Samples (118) of snow water equivalent are collected at 40 m intervals on Deadhorse Creek, along transects that cross all major slope aspects and elevations. The estimate of mean water equivalent is used to index winter precipitation. Five rain gages (two recording and three standard) on Deadhorse Creek and one standard gage on East St. Louis Creek are used to index the precipitation. Temperature and humidity are measured on two sites, one north- and one south-facing slope, on Deadhorse Creek.

WATERSHED TREATMENT

The first treatment was imposed on Deadhorse Creek and occurred on the North Fork subdrainage in 1977. Timber was removed on 36% of the land area of the subdrainage (Fig. 1) by commercially clearcutting 12 small units, uniformly spaced through the drainage. The circular openings were about 122 m or 5 H (H = tree heights) in diameter, and occupied about 1.2 ha each. Timber on 11 of the openings was removed in 1977; the twelfth unit was cut early in the summer of 1978. Harvesting consisted of felling all trees 10 cm in diameter and larger and removing all merchantable material from the site. All slash was lopped to a 10 cm top and was scattered. Approximately 2450 m^3 of sawtimber was harvested from the North Fork of Deadhorse; this averages about 168 $m^3\,ha^{-1}$ clearcut, or 36% of the total volume on the subdrainage.

In 1980 and 1981, Unit 8 (Fig. 1) was harvested in the first step of a three-step shelterwood cut. Approximately 40% of the basal area was removed as individually marked trees 17.8 cm d.b.h. and larger. The entire area was harvested uniformly, removing a total of 4080 m^3 of sawtimber. Although the percentage of the total stand volume removed was almost the same on the North Fork subdrainage (36%) as it was on the Unit 8 (40%), a greater volume of timber actually was removed on the more productive Unit 8.

During the summers of 1983 and 1984, approximately 30% of the gaged Upper Basin (Fig. 1) also was harvested in irregular-shaped clearcuts, varying in size from 1 to 6 ha. The effect of treatment on the hydrology of the Upper Basin cannot be addressed yet; but the fact that another subdrainage was impacted creates a breakpoint in downstream response and a good place to summarize response from the other two treatments.

The road system used to access the streamgages and harvest the timber was constructed over a 26 yr period. Although not in the Deadhorse Watershed, access to the main streamgage was afforded in 1955 when 1.61 km of road was built. In 1970–1971, an additional 4 km of road built to the North Fork and Upper Basin weir sites. An addition 1.61 km of main access road and 1.2 km of spur road were constructed in 1976 to harvest the North Fork Watershed. During the summers of 1977 and 1978, 1.6 km of main access and 0.8 km of spur road were constructed to harvest the North Slope. Three kilometers of road were also built in 1981 to harvest the Upper Basin. In total, 11.3 km of main access road and 2 km of spur road were constructed to either access the gaging stations or to harvest timber. This represents a surface disturbance (cut slope, road bed, fill slope) of about 9.3 ha.

Generally, the road system is located on contour, is flat or outsloped, and is drained by rolling dips at 30–70 m spacing. The roadbed is about 4 m, wide with a minimal cut and fill slope.

The 5 H circular clearcuts imposed on the North Fork were intended to maximize snowpack accumulation in the clearcuts and to optimize flow increases for the basal area removed (Troendle and Leaf, 1980).

In contrast, it was reasoned that partial cutting would have little effect on streamflow because: (1) in a semi-arid environment, such as the subalpine (Leaf, 1975), the residual stand would have access to and use any transpirational savings during the growing season; and (2) without clearcutting and the attendant aerodynamic changes, there would be no redistribution of snow, no net change in the deposition pattern of the winter snowpack, and, therefore, the efficiency in delivering water to the stream would not be enhanced. The hypothesis in this assumption was that partial cutting (harvesting by individually marking trees for removal or thinning) would be far less efficient in increasing streamflow than would be the removal of the same percentage of the forest in small (5–8 H) clearcuts.

To evalutate this hypothesis, an area equal in size to the North Fork (41 ha), was partially cut, removing approximately the same percentage of the forest by individually marking trees. However, unfortunately and unlike the North Fork subdrainage, the partially cut Unit 8 is not independently or directly gaged. The annual flow of the Upper Basin and the North Fork must be subtracted from the total flow from the watershed to partition out the flow from the interbasin area, which includes the contribution from Unit 8. Partitioning the flow increases the opportunity for error and decreases the reliability of the experiment, but must be done for two reasons:

(1) Unit 8 is only 41 ha, while the entire Deadhorse drainage is 270 ha. Any impact restricted to Unit 8 would be less likely to influence total flow than it would be to influence the partitioned interbasin flow.

(2) The North Fork subdrainage had been harvested 3 yrs before harvesting Unit 8. Partitioning allows removal of the effect of that treatment on flow at the main weir.

Partitioning was done for total annual flow only, with no attempt made to isolate peak flow rates or timing of peak, etc., for the interbasin area. The

TABLE 1

Watershed size, dominant timber type, treatment, and length of record available for evaluating the effect of treatment on subdrainages in Deadhorse Creek as compared to the Control, East St. Louis Creek

Watershed	Area (ha)	Timber type	Timber volume (m^3 ha^{-1})	Type of harvest	% area/ volume cut	% area in roads	Length of record (yr)	
							preharvest	postharvest
Main Deadhorse Creek	270	Spruce, fir, lodgepole pine	210[b]	Clearcut, partial cut	10	3.4	21	6
North Fork	41	Lodgepole pine[a]	168	Small clearcuts	36	3.1	6	6
Upper Basin	78	Spruce, fir, lodgepole pine	210	Partial cut	30	3.2	7	0
Unit 8	41	Spruce, fir[a]	252	Small clearcuts	40	4.9	5	3
East St. Louis Creek	767	Spruce, fir, lodgepole pine	210	Control	NA		42	NA

[a] Denotes predominant species.
[b] Volume converted using assumption 5 board feet = 1 ft^3.

characteristics of each watershed and the treatment applied are summarized in Table 1.

EFFECT OF TIMBER HARVEST ON SNOWPACK ACCUMULATION

The pretreatment calibration of average peak water equivalent (estimated by those snow course stations on the subdrainage) on North Fork with that for the control is shown by eqn. (1).

$$\text{NFPWE} = 1.10\ \text{ESLCPWE} - 0.09 \tag{1}$$

where:

NFPWE = North Fork peak water equivalent (cm)

ESLCPWE = East St. Louis Creek peak water equivalent (cm)

$r = 0.978$, $n = 11$, std. error $= 2.0$ cm

The pretreatment mean peak water equivalent, usually estimated about April 1, was 30.1 cm on the North Fork. Covariance analysis of the pre- and posttreatment relationships indicated there was no change in the adjusted mean water equivalent on the North Fork Watershed ($p = 0.24$) following timber harvest. Unlike the Fool Creek Watershed, where a 9% increase was found (Troendle and King, 1985), analysis failed to show a statistically significant change in net water equivalent on the North Fork subdrainage as a result of clearcutting. Figure 2 represents a double mass plot of the data, and no shift is evident following harvest in 1977.

In addition to the snow course observations, several of the openings and the forest around them have been sampled intensively in 1981 (Troendle, 1983a). The mean water content for the samples taken in the forest was 40 cm, while it averaged 52 cm for those taken in the openings. Because the overall watershed mean, as indexed by the snow course data, did not change, it can be assumed that differential deposition occurred, and that the increase in snowpack in the openings primarily reflects the change in depositional patterns caused by the harvest. The average of 52 cm of water observed in the openings reflects an 18% increase relative to the adjusted mean for all subsamples. The greater amount of water equivalent in the openings is generally consistent with other observations made by Gary (1980), Golding (1981), Troendle and Leaf (1980), and others.

Other research (Gary and Troendle, 1982; Troendle and Meiman, 1984; Troendle and King, 1985; Gary and Watkins, 1985; Troendle and Meiman, 1986) demonstrates that, along with any redistribution effect, there is also a reduction in interception loss following harvest and that the combined effect can cause a net increase in peak winter equivalent on the watershed, as well as in the opening. Canopy removal on the south-facing slopes apparently caused an offsetting increase in early ablation loss, because a net change in peak water equivalent was not evidence at the watershed level only small increases in the open portion.

The second portion of the Deadhorse Creek Watershed to be harvested was

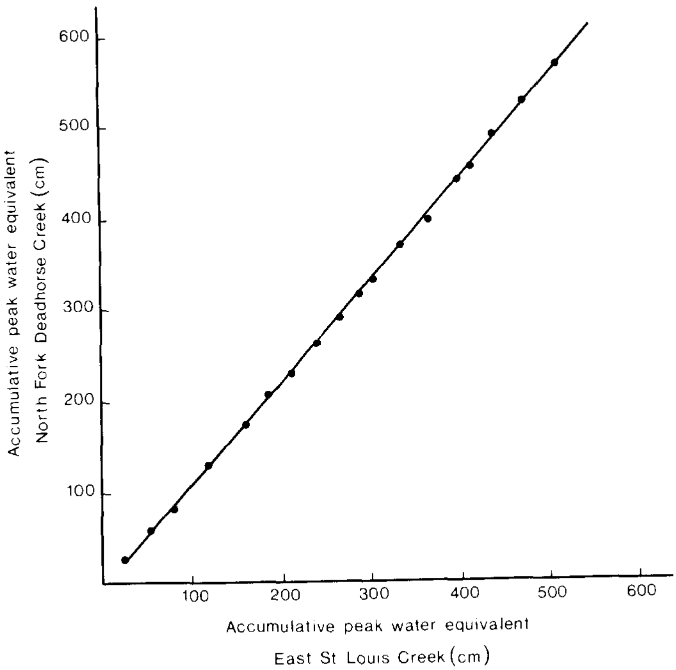

Fig. 2. Double mass plotting of peak water equivalent on the North Fork subdrainage over that for the control, East St. Louis Creek.

Unit 8. Except where groups of two or three trees were cut and in road right-of-ways, no true clearcuts were created on this steep, north-facing slope. Because Unit 8 was not harvested until 1980, there are 14 yrs of pretreatment and 4 yrs of posttreatment snow course record available. The pretreatment calibration of Unit 8 with East St. Louis Creek, as shown in eqn. (2), is quite good:

$$\mathrm{NSPWE} = 1.08\ \mathrm{ESLCPWE} + 0.09 \tag{2}$$

where:

NSPWE = Unit 8 peak water equivalent (cm)

ESLCPWE = East St. Louis Creek peak water equivalent (cm)

$r = 0.98$, $n = 14$, std. error = 0.6 cm

Unlike the North Fork, however, covariance analysis of the pre- and posttreatment regressions indicated a significant increase ($p = 0.002$) in the adjusted mean water equivalent on Unit 8 after timber harvest. Peak water equivalent, when compared to the control, increased 4.8 cm or 16% over the entire unit. The increase is well demonstrated by the double mass plot of Fig. 3.

The Upper Basin subdrainage of Deadhorse Creek was not harvested until 1983. An analysis, similar to those for the North Fork subdrainage and Unit 8, also was conducted on the Upper Basin snow course data to verify that the

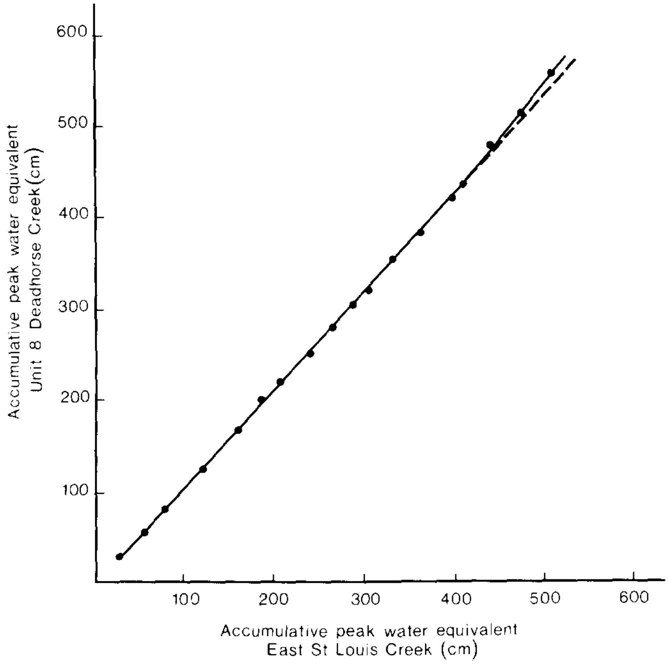

Fig. 3. Double mass plotting of peak water equivalent on the North Slope Unit of Deadhorse Creek over that for the control, East St. Louis Creek.

increase observed on Unit 8, since 1980, was not the result of or the cause of a shift in the accumulation in the Upper Basin. Analysis of covariance indicated no change in the peak water equivalent occurred on the Upper Basin relative to the control watershed prior to 1983.

The partial cut on Unit 8 increased the peak water equivalent an average of 4.8 cm following harvest. A significant increase was not detected after patch cutting the North Fork. Covariance analysis of the pretreatment (1967–1977) and posttreatment (1978–1984) regressions for the entire Deadhorse Watershed (combined data) do not indicate a significant increase ($p = 0.75$) in the total peak water equivalent. We assume the net increase in accumulation on Unit 8 (North Slope) reflects an interception savings, since the increase cannot be correlated to a decrease elsewhere.

EFFECT OF TIMBER HARVEST ON STREAMFLOW

North Fork subdrainage

Total water yield

Troendle (1983a,b) summarized the preliminary effect of patch clearcutting on streamflow from the North Fork. Table 2 lists the observed flow and estimate of change in flow for the 7 yrs (1978–1984) since harvest. Covariance analysis

TABLE 2

Observed flow and estimate of increase due to timber harvest on the North Fork of Deadhorse Creek

Year	Observed flow (cm)	Increase in flow[a] (cm)
1978	27.0	8.1
1979	21.1	10.6
1980	23.1	6.7
1981	9.4	3.5
1982	28.4	8.4
1983	37.3	2.0
1984	39.6	3.1
$\bar{x}$	26.5	6.0

[a] Increase is estimated as: ΔQ = QDH − (0.81 QESL − 11.2), where: ΔQ = change in flow, North Fork (cm); QDH = observed annual flow, North Fork (cm); QESL = observed annual flow, St. Louis Creek; $r^2 = 0.98$; and std. error of est. = 1.10.

of the pre- and posttreatment means indicate that a 6.0 cm increase ($p = 0.004$) in the adjusted mean flow has occurred since 1978.

The length of posttreatment record on the North Fork subdrainage is too short to expect a time or recovery trend; but a least-squares analysis was conducted between change in annual flow (ΔQ) and: (1) winter precipitation (October 15–March 30); (2) spring or melt period precipitation (April 1–June 30); and (3) growing season precipitation (July 1–October 15). Peak water equivalent entered the equation first with an r of 0.74 ($p = 0.03$), and spring precipitation entered second ($p = 0.06$). Unlike the Fool Creek analysis (Troendle and King, 1985), current growing season precipitation was correlated ($p = 0.11$) with observed change or increase in flow. The adjusted R^2 for the multiple fit was 0.76. Winter precipitation was correlated as strongly with change in flow on the North Fork as it was with the change in flow on Fool Creek (Troendle and King, 1985).

Peak discharges

Two hypotheses concerning peak discharges were tested on the North Fork data. First, covariance analysis of the pre- and posttreatment relationships indicated that the adjustment mean peak discharge increased from 26.6 to 39.6 $l\,s^{-1}$ ($p = 0.07$). The 50% increase in peak flow rate is in the same order of magnitude as that for nearby Fool Creek (20%) (Troendle and King, 1985) and equal to that for Wagon Wheel Gap (Van Haveren, 1981).

A second analysis was conducted on the date of peak flow occurrence (the number of days from May 1 until the peak occurs) before and after harvest. Prior to harvest, the mean date of peak flow occurrence was May 31; after harvest it was June 3. The change is not significant ($p = 0.58$); although the duration of melt appears to be extended, since the hydrograph responds earlier in the year yet peaks at the same time.

Unit 8

The calibration of flow from the interbasin area, which includes Unit 8, (Q_8) to flow from the control, East St. Louis (QESL) was:

$$Q_8 = 0.242 \text{ QESL} - 16.7 \qquad (3)$$

$r = 0.90$, std. error $= 1.5$ cm, $n = 6$

Covariance analyses of the adjusted group means for the 6 pre- and 3 post-treatment yrs indicated that flow from the entire interbasin area may have increased 2.5 cm ($p = 0.34$) after partial cutting. This represents a unit area increase of about 9.1 cm from the 41 ha area actually harvested. However, the posttreatment record years were well above average in precipitation, and as such, we would expect the increases to be larger than what might be expected under drier conditions. The hypothesis in establishing the treatment, however, was that partial cutting would have no effect on water yield under any conditions. The statistical analysis did not indicate a significant increase in flow from the partially cut portion of the interbasin area. However, since only 40% of the basal area on less than 30% of the interbasin area was cut (10–12% of total basal area on interbasin area), we really cannot expect a detectable response to occur, as the error term is too great for the area impacted.

Main Deadhorse Creek

Total water yield

The calibration of main Deadhorse Creek on its East St. Louis Creek control has an r^2 of 0.95 and a std. error of 0.75 cm based on a 21 yr calibration. After 4 yrs of postharvest record on the North Fork, Troendle (1983a) noted that the significant increase in flow detected at the North Fork gage could not be detected downstream at the main gage. Covariance analysis at that time indicated that mean flow on Deadhorse Creek increased an average of 1.8 cm for the period 1978–1981; but it was not significant ($p = 0.37$).

Currently, covariance analysis still indicates the 1978–1983 adjusted mean has not increased significantly, although the net effect of both treatments increased the flow 1.5 cm ($p = 0.31$). The estimated change in flow at the main stream gage of 1.54 cm is not significant; it is very reasonable, considering the measured change on the North Fork represents a mean change of 0.84 cm over the entire Deadhorse Watershed, while the harvest on the North Slope contributed 0.89 cm. The total (0.84 + 0.89) of 1.73 cm compares well with the estimate of 1.5 cm at the main gage. Note that only 30% of the area of the entire watershed has been impacted, and only 36–40% of the basal area has been removed on the impacted area or 10% of the total watershed basal area.

Effect on peak discharge

Covariance analysis of pre- and posttreatment means did not indicate any change in either the magnitude or the date of occurrence of the peak discharge at the main Deadhorse gage.

DISCUSSION

It was assumed (Leaf, 1975; Troendle and Leaf, 1980) that partial cutting would have minimal effect on flow for two reasons. First, the subalpine is an arid environment, and any savings in summer transpiration caused by selective or individual removal of trees probably would be used on site by the residual stand. Second, because winter interception loss was not considered to be a significant factor, it was believed there would be little opportunity to influence the winter snowpack, and thereby, affect flow by increasing net precipitation to the ground. In contrast, the harvesting pattern applied to the North Fork was considered optimal (not maximal) for increasing water yield because: (1) commercial clearcutting (excess of 90% of transpiring surface removed) was the only way to reduce transpiration and not lose the savings to surrounding vegetation; and (2) circular openings, 5 H in diameter, maximized the accumulation of redistributed snow.

The response on Deadhorse Creek has not been entirely as expected, at least with respect to the partial cut. Recent plot studies (Gary and Troendle, 1982; Troendle and Meiman, 1984; Gary and Watkins, 1985) found that interception loss from the input of winter preciptiation can be quite large, and cutting, either partial or clearcutting, can reduce that loss significantly and result in more water equivalent in the snowpack.

The partial cut on Unit 8 resulted in such an increased peak water equivalent in the pack; it can be speculated that the increase is restricted to that unit, and it reflects a reduction in interception loss. The 40–60% north-facing slope of Unit 8 is well shaded from winter shortwave radiation, and increased evaporation from the snowpack did not eradicate the savings. Troendle and Meiman (1986) noted an average 15 cm increase (44%) in peak water equivalent in a nearby clearcut on a similar north-facing slope.

Troendle and King (1985) also found there was a 9% increase in peak water equivalent after clearcutting on the Fool Creek Watershed. In contrast, the surface plane of the North Fork subdrainage is south-facing, and the energy load on the clearcuts on those 30% slopes may be such that any interception savings, if they occurred, were ablated (either to evaporation and/or melt), because no net change in peak water equivalent is evident. If the ablation reflects an evaporative loss, then it would imply no net change in winter precipitation. Melt, however, would not be measured but could add to the increase in flow.

The observation that partial cutting in the subalpine forest may increase snowpack and subsequent streamflow is significant. Although based on only three above-average years, it appears that partial cutting on the north-facing slope of Unit 8 caused an increase in flow comparable to or greater than patch clearcutting the south-facing North Fork subdrainage under similar conditions. Much of the increase can be explained by the increase in the snowpack on Unit 8 that would account for over 50% of the increase. A second factor is that two-thirds more volume (and presumably transpiring/intercepting canopy surface) was removed from Unit 8 than the North Fork subdrainage. Kaufmann (1981, 1985), working on sites within 2 km of Unit 8, did not find any stress-induced reduction in transpiration under the range of conditions that have occurred during the past few years. There is no reason to believe that evapotranspiration savings resulting from partial cutting would have been used on site by the residual stand and, therefore, also should have contributed to flow.

Partial cutting, where trees are individually marked for removal or thinning in younger stands, consistently has resulted in a net increase in water equivalent in the snowpack (Gary and Troendle, 1982). Gary and Watkins (1985), working with both an up- downwind control, found that snowpack accumulation under two stands of lodgepole pine in Wyoming increased 30% after thinning.

Enough information on the effect of timber harvesting on snowpack accumulation has been collected to demonstrate that the impact is significant and is a result of the combined effect of interception loss and alteration of the depositional pattern. The combined effect of both processes during wet years causes efficient increases that are highly correlated with precipitation input.

Research worldwide has shown that eliminating vegetation reduces growing season evapotranspiration and increases streamflow. This is true in the subalpine environment, also. In addition, other process responses also must contribute to the apparent in creased treatment efficiency. Much of this added effect must be associated with the effect that timber harvesting has on net winter precipitation. The potential difference between gross precipitation entering the system during the winter at the canopy level and net precipitation, as indexed by snowcourses on the ground, could be quite great. A significant part of the response from the partial cut on Unit 8 may be a reflection of these savings. Although not "statistically significant", the increase in flow following the partial cut does have a 7 in 10 chance of being real. This plus the demonstrated increase in peak water equivalent under the partial cut forces us to reevaluate the influence of this treatment on streamflow from the subalpine forest. This study definitely points out the need for at least one thorough watershed experiment on the effect of partial cutting on water yield.

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