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The Effect of Timber Harvest on the Fool Creek Watershed, 30 Years Later

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The Fool Creek watershed at the Fraser Experimental Forest, Colorado was harvested using a pattern of alternating clearcut and forested strips in 1956. Today, with almost 30 years of postharvest record, subtle impacts on the hydrology of the watershed can be detected that were not significant in the past. In addition to the depositional increases in the snowpack in the openings, average peak water equivalent over the entire watershed has been increased (9%). Long-term, postharvest, climatic records now available show a strong correlation between estimated increases in flow and winter and melt period precipitation. Much of the annual variability in increased flow, now explained by precipitation, was formerly attributed to regrowth or time. Peak discharges, advanced 7.5 days following harvest, have also been increased 20%, with the largest effect occurring in the wettest years. Increases in peak water equivalent, annual flow, and date of peak flow occurrence all appear to be returning to preharvest levels at a very slow rate.

Numerous paired watershed experiments have been conducted on the effect of timber harvest on water yield. Regional summaries of these efforts have been well documented by *Douglass* [1983], *Harr* [1983], *Hibbert* [1983], *Kattelmann et al.* [1983], and *Troendle* [1983], while *Bosch and Hewlett* [1982] summarized almost 100 experiments worldwide. One watershed experiment, the Fool Creek study [*Goodell*, 1959; *Hoover and Leaf*, 1967; *Leaf*, 1975; *Troendle and Leaf*, 1981] has become a benchmark for watershed response in the Rocky Mountain Region. The treatment effect reported is unique worldwide because of its longevity in a semiarid region. This paper is intended to build on those of the past because the everlengthening posttreatment record is allowing more subtle inferences to be drawn on the hydrologic impact of the treatment, as well as what appears to be a very slow recovery to preharvest conditions.

Fool Creek Experiment

The study began in the early 1940's at the Fraser Experimental Forest in Colorado. The streamgage on Fool Creek, the 289-ha treatment watershed, was built in 1941; the gage on East St. Louis Creek, the 803-ha control watershed, was built in 1943. The paired watersheds were calibrated from 1943 until 1952, at which time the road system was built on Fool Creek. Approximately 14 ha of the watershed were impacted by roads and log decks. After 2 years of postroading stabilization, the watershed was harvested during the summers of 1954, 1955, and 1956. The objective of the experiment was to determine the effect that harvesting has on snowpack accumulation, sediment production, and the total yield and timing of streamflow. Forty-percent of the watershed was harvested (50% of the timbered area) using alternating cut and leave strips which varied from 1 to 6 tree heights wide (Figure 1).

Snow courses located on both watersheds were monitored about April 1 each year from 1943 to 1954 to calibrate the relationship of peak water equivalent between the control and treated watershed. The snow courses consisted of approximately 100 permanently marked stations on each watershed. The stations were located along a looping pattern that traversed all aspect, elevation, and stand conditions in the watershed. Generally, they were located under canopy, between canopies, or in small openings at fixed distances along the course. The mean value of peak water equivalent (PWE), as estimated from the snow course, represents an index to the net winter accumulation that is comparable between watersheds. It was not intended to represent an absolute estimate of winter precipitation. *Leaf and Kovner* [1972] described the errors associated with using snow course data to index winter precipitation. Postharvest data were collected at the original sampling points in both watersheds in 1959 and from 1966 to 1984 to determine treatment effect. In addition, intensive surveys of peak water equivalent in the individual cut and leave strips on Fool Creek were made in 1964 and 1980 to determine the effect of opening size on the snowpack accumulation pattern. The number of samples taken in each cut and leave strip was determined by the size of the unit. The intent was to estimate the amount in the forest and the amount in the various openings to evaluate how the mean watershed value, estimated from the snow course, was distributed.

As a forerunner to the Fool Creek experiment, *Wilm and Dunford* [1948] noted that peak water equivalent of the snowpack increased more than 30% in small clearcuts in lodgepole pine. This increase was significantly greater than the increases observed under differing levels of partial cutting. Consequently, the Fool Creek watershed was treated using differing size clearcuts to take advantage of what was then believed to be the most efficient way to increase peak snow water equivalent, minimize transpirational draft, and maximize streamflow. Using different cut and leave strip sizes also afforded the opportunity to determine the effect of opening size on snowpack accumulation.

The purpose of this paper is to evaluate the effect of the treatment over the 30 years since the first trees were harvested. The hydrologic impacts have been well documented [*Leaf*, 1975; *Troendle and Leaf*, 1981; *Troendle*, 1983], but the longevity of both records and treatment effect now allow the detection of more subtle impacts not possible to detect in the earlier analysis. To some extent, the longer record now allows better definition of the process changes which have occurred.

RESULTS

Effect on Flow Volume

Table 1 presents a summary of the estimated increase in April through September flow for the Fool Creek watershed, for the postharvest years 1956–1983. Annual increases were

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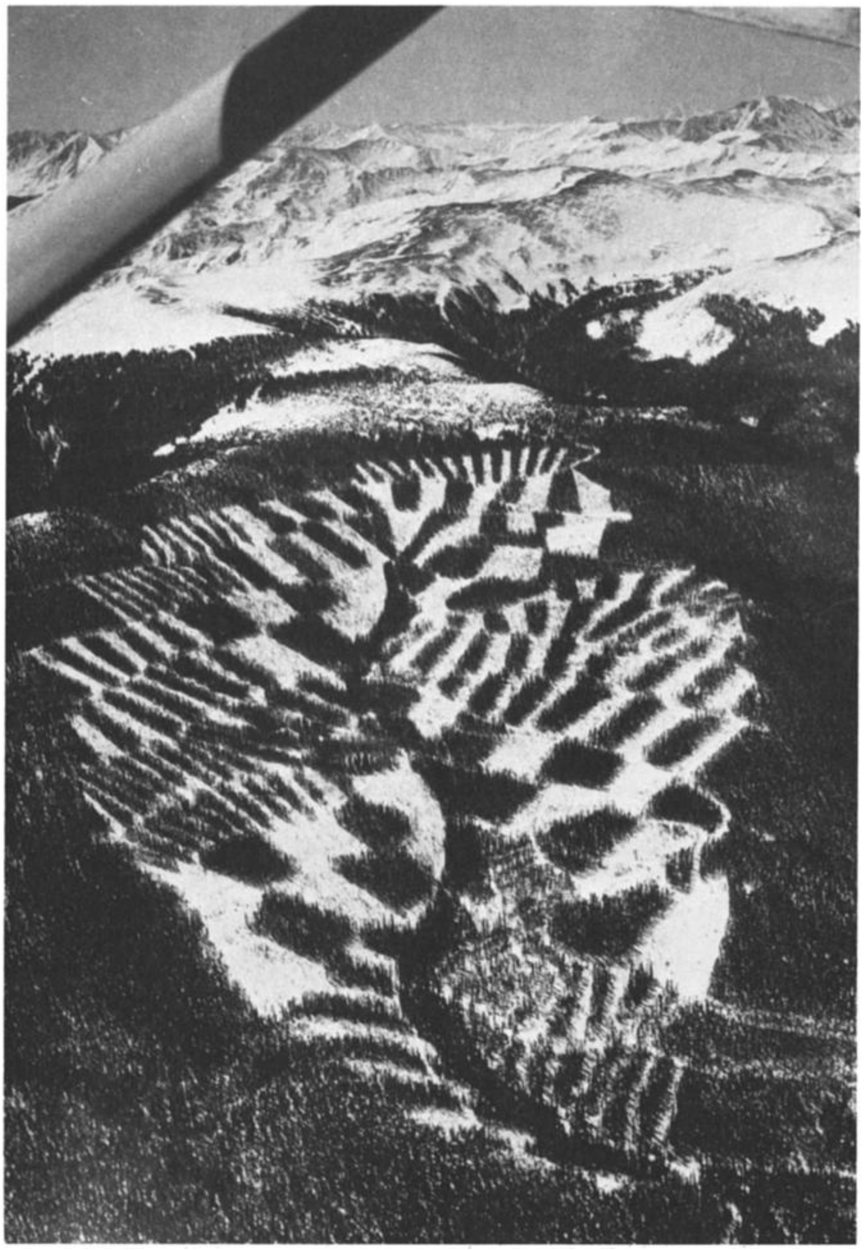

Fig. 1. Fool Creek watershed, Fraser experimental forest. Photo taken in 1958, 2 years after harvest.

estimated as the difference between the observed flow on Fool Creek and that predicted to occur using the calibration equation and the flow from the control watershed. Over the 28-year period, the increases have averaged 8.2 cm, or 40% of the "expected" flow from the watershed. The annual variation in increases has been quite large and usually inferred to be associated with wetness [*Leaf*, 1975; *Troendle*, 1983] or level of flow; in wet years the increase is greater than in dry years. No statistical reliability is implied in the estimate of flow changes presented in Table 1. Covariance analysis of the pre- and posttreatment flow relationships between treated and control watersheds indicate that the posttreatment increase in the mean flow of 8.2 cm is highly significant ($p < 0.001$). The annual estimates are presented to demonstrate the range in variability.

Figure 2 represents the average observed flow for Fool Creek for the period 1941–1955 and for 1956–1971. The two 15-year periods represent the pretreatment period and that portion of the posttreatment period least affected by hydrologic recovery. As can be noted on Figure 2, the increases in flow, presented in Table 1, occur early in the year with no detectable effect on the recession hydrograph. Part of the increase occurs in April and a very little in June, most of the increase occurs in May. Flow for the months of July, August, and September (and presumably the winter baseflow period) have not been influenced by the treatment. Figure 3, an aerial photo of Fool Creek taken in 1982, indexes the revegetation, especially in lodgepole pine at the lower elevations, that has occurred during the 28-year postharvest period.

Troendle and Leaf [1981] presented the following scenario to describe why the increases occur when and where they do. During the growing season, the evapotranspirational draft,

TABLE 1. April to September Streamflow From East St. Louis Creek and Fool Creek and an Estimate of the Increase From Fool Creek Due to Timber Harvest

Year	Observed Runoff East St. Louis Creek	Observed Runoff Fool Creek	Estimated Increase Fool Creek*
1956	39.6	35.4	9.4
1957	54.3	52.7	16.2
1958	33.4	30.4	8.9
1959	30.2	30.3	11.0
1960	35.4	34.8	11.9
1961	25.7	24.4	8.3
1962	47.6	43.8	12.1
1963	13.2	11.0	4.0
1964	25.6	22.8	6.9
1965	44.5	39.5	10.0
1966	19.8	17.4	5.5
1967	32.0	28.0	7.5
1968	29.8	23.2	4.2
1969	37.2	30.8	6.5
1970	46.8	37.6	6.4
1971	45.3	40.1	10.0
1972	31.3	29.6	9.6
1973	38.7	31.1	5.7
1974	40.7	35.1	8.3
1975	32.4	26.4	5.6
1976	24.2	19.6	4.6
1977	20.4	15.8	3.6
1978	37.0	32.7	8.6
1979	26.8	26.9	10.1
1980	34.0	29.7	7.7
1981	21.1	17.0	4.3
1982	23.6	25.9	11.4
1983	34.8	32.8	10.2
$\bar{x}$			8.2

Values are in centimeters.

*Estimated as $\Delta Q = Q_{\text{F.C.}} + 2.39 - 0.717Q_{\text{E.S.L.C.}}$, $R^2 = 0.84$, standard error = 2.8 cm; where ΔQ is the increase in flow on Fool Creek (cm); $Q_{\text{F.C.}}$ is the runoff on Fool Creek (cm); and $Q_{\text{E.S.L.C.}}$ is the runoff in East St. Louis Creek (cm).

and the accompanying depletion of stored soil moisture, is reduced when trees are removed. As a result, harvested areas have a higher soil moisture content at the beginning of the dormant season. From mid-October until April or May, precipitation is stored on the ground as winter snowpack. The following spring, snow melts, soil moisture storage requirements are satisfied, and "excess" water becomes streamflow. Because less snowmelt water is required to recharge the clearcut areas, a greater proportion of the snowmelt becomes excess. A portion of the flow increase also was attributed to the efficiency associated with placing more snow in the openings where less recharge is required and losses are smaller. At the same time, less snow is presumably deposited in the forest where recharge requirements and subsequent evapotranspirational demand is greater. The complex nature of the impact is evident in the range of estimated increases shown in Table 1. In 1957, the highest flow year of record, the increase was 16.2 cm; the smallest increase (3.6 cm) occurred in 1977, a very dry year.

To further evaluate the factors that might influence the annual variability in flow changes, seasonal precipitation variables, as well as "time", were regressed on the estimate of increase in flow. This was not possible in the past, because continuous precipitation records (either recording raingages or storage gages read monthly) were not begun on the Experimental Forest until 1956, and then only monitored during summer months. To evaluate the effect of precipitation and time (as an index to regrowth or hydrologic recovery) on the estimated increases in flow, the following data set was constructed for the water years 1956–1983.

1. Winter precipitation (October1 to March 30) was estimated as the April 1 peak water equivalent on the Soil Conservation Service snow course near the headquarters of the Experimental Forest.
2. Melt period precipitation (April 1 to June 30) was estimated from the raingage at the headquarters of the Experimental Forest.
3. Growing season precipitation (July 1 to September 30) was also estimated from the raingage at the headquarters.
4. Vegetative regrowth was represented as a variable t, where t = years since harvest.

Use of the precipitation variables from the headquarters gage in the above seasonal format was necessary to accommodate missing data (winter), periodic measurements (storage gages), and sampling problems (winter snowfall). The logic for the seasonal format selected was documented by *Troendle and Leaf* [1980]. Regression techniques then were used to correlate the estimated increase in flow (ΔQ) with the precipitation variables and the time factor.

In addition, precipitation for the previous growing season also was included in the analysis to establish or verify the presence of an antecedent moisture effect (i.e., to determine if the previous summer precipitation influenced the fall soil moisture recharge requirements and therefore the subsequent annual increase).

The posttreatment increase in flow was most significantly correlated with peak water equivalent on April 1 ($R^2 = 0.37$, $P = 0.001$). Precipitation during the melt period was next with an R^2 of 0.30 ($P = 0.003$). The time variable (in a linear form) also was correlated with the increase ($R^2 = 0.10$, $P = 0.099$), indicating that the initial increase was diminishing at a rate of 0.1 cm/year since harvest. This would imply that the "first year" increase (assuming conditions of average peak water equivalent and average spring precipitation) of 10 cm has been reduced to 7.2 cm as a result of regrowth during the past 28 years. Neither current nor previous growing season precipitation correlated ($P > 0.30$) with the observed increase. The fitted equation is

$$\Delta Q = 0.69 + 0.17\text{PWE} + 0.28\text{SPRPRC} - 0.10t \quad (1)$$

where

ΔQ estimated increase in flow (cm);
PWE peak water equivalent on April 1 (cm);
SPRPRC melt period precipitation (cm);
t time (in years) since harvest;
Adj. $R^2 = 0.62$;
Std. Error = 1.83 cm.

Conceptually, we would expect a nonlinear log or exponential expression of the time variable to best fit the hydrologic recovery of Fool Creek. However, since that recovery is long term, the linear fit is best at this point. Based on the linear coefficient derived in (1), we estimate an 80-year period is required for hydrologic recovery. In a complimentary effort, *Kaufmann* [1985] reported that basal area in the uncut leave strips currently averages 39.1 $m^2\ ha^{-1}$, while it averages only 7.5 $m^2\ ha^{-1}$ in the cut strips (Figure 3). Much of the regrowth occurs in the lower one third of the watershed and consists of

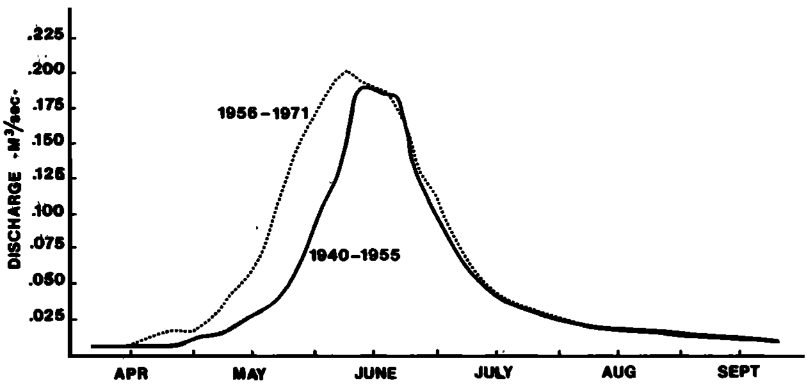

Fig. 2. Average hydrographs for Fool Creek watershed. Solid curve is average hydrography for 1940–1955, before the timber harvest; dotted curve is average hydrograph for 1956–1971, following timber harvest.

lodgepole pine naturally regenerated since harvest. The leaf area index of the cut strips is 2.9, and Kaufmann projected it would take 75 years for the stand to grow back to 39 m^2 ha^{-1} basal area. He noted that since a higher percentage of the new stand will be spruce, a species that uses more water than lodgepole pine, he estimated that the watershed will hydrologically recover in 70 or so years.

Apparently, growing season precipitation (approximately 18 cm) for either the current or preceding year is not well correlated with increase in streamflow. The precipitation estimates used in this analysis represent conditions at the Experimental Forest Headquarters because comparable data are not available on the Fool Creek Watershed, as raingages were not installed until the mid-1960's. Based on recent records, the average annual precipitation (combination of peak water equivalent, spring and summer rainfall) for Fool Creek is estimated as 76 cm, while the comparable index at Headquarters is only 63 cm. However, precipitation is positively correlated with elevation on the Experimental Forest, [*Leaf*, 1975]. The SCS (Lapland) snow course is well correlated with the more extensive snow course on East St. Louis Creek, the control for Fool Creek, and was used because the estimate of winter precipitation from the SCS course is more compatible with the estimates of spring and summer precipitation from the Headquarters site, which is about 1 km from SCS site and at the same elevation. Substitution of peak water equivalent estimated at either a second SCS snow course above Winter Park, Colorado, from the undisturbed Lexen Creek watershed (also on the Experimental Forest) or from East St. Louis Creek into the analysis in place of SCS course used, all yield the same result. The precipitation parameters chosen appear to represent a reasonable index to the seasonal and annual variability of precipitation on Fool Creek, and it is the variability that correlates well with change in flow.

Effect on Peak Discharge

Covariance analysis using the 12 years of pretreatment and 28 years of posttreatment record currently available indicate that the peak mean daily discharge from Fool Creek has been increased an average of 23%, or about 55 L^3 s^{-1} (Table 2). Subsequent regression analysis of the yearly estimates indicated a significant positive correlation existed during the posttreatment years between the increase in peak mean daily discharge and peak water equivalent on April 1. The higher the peak water equivalent, the greater was the increase in peak discharge. The highest flow in the 40 years of record on Fool Creek occurred in 1983, with a peak discharge of 518 L^3 s^{-1}.

As with earlier analysis, the covariance analysis of date of peak flow indicates that on average, peak mean daily discharge occurs about 7.5 days earlier in the year, because timber harvest advanced snowmelt and resulted in a quicker satisfaction of recharge requirements. The time variable, also used in the analysis, was significant at $P = 0.10$, indicating that the date of peak flow occurrence is returning toward the pretreatment level. A similar analysis did not indicate a reduction in the peak flow rate was occurring with time, however. This may have been masked by the large increase in peak in 1983. The years prior to that did appear to show a reduced peak flow rate.

Effect on Peak Water Equivalent

Goodell [1959], *Hoover and Leaf* [1967], *Hoover* [1969], and *Leaf* [1975] all addressed the processes involved in the differential accumulation of snow water equivalent in the cut and leave strips on Fool Creek. Figure 4 represents the average differential accumulation observed in two different size openings, as well as their uncut leave strips. The data was collected as part of intensive surveys made in almost all openings in 1964 [*Leaf*, 1975]. Another intensive survey, made in April 1980, indicated the same accumulation patterns evident in Figure 4 still existed, and that regrowth appears to have had little effect on the accumulation pattern. Earlier analysis of snow course data for the entire Fool Creek Watershed [*Hoover and Leaf*, 1967; *Leaf*, 1975] indicated that timber harvest did not alter the net or average water equivalent on the watershed; but, instead, a change in aerodynamics and differential deposition resulted, with more snow being deposited in the openings and less deposited in the downwind forest. In a subsequent analysis, *Troendle and Leaf* [1981] noted that 13 years (1956–1978) of posttreatment record indicated that the average peak water equivalent on the entire watershed had been increased an average of 11 percent ($P = 0.15$). Currently, there are 19 years of posttreatment observations, and covariance analysis indicates that the peak water equivalent on Fool Creek has significantly increased since harvest ($P < 0.01$). The adjusted group mean peak water equivalent was 30.5 cm before treatment, and it is 33.3 cm for the posttreatment period. This represents an average 2.8-cm, or 9% increase in peak water equivalent over the entire watershed. Table 3 presents the observed posttreatment water

Fig. 3. Fool Creek watershed, Fraser experimental forest. Photo taken in 1982, 26 years after harvest.

equivalent for the period of record, along with the estimate of the increase; there is considerable yearly variability.

Data editing for this analysis resulted in a slight alteration in the values, as used in previous analysis. Correction of a tabulation error found in the 1954 control watershed snow survey data reduced the error term for the calibration regression. As a result, the 11% increase reported by *Troendle and Leaf* [1981] was, in fact, significant ($P < 0.01$). As was noted earlier, snow course observations were made in 1959 and from 1966 to 1984. In 1966, a variety of snow tube types were used in the survey, partly to compare the different types of samplers with the Federal snow tube that had been used previously. After the survey, all values were adjusted to the Federal sampler equivalents. This should not have introduced an error, but if the 1966 data were included in the analysis, the estimated increase in peak water equivalent for 1966 would be 16 cm of water and the overall mean increase for the posttreatment period would be raised to 3.3 cm rather than the 2.8 cm we are reporting. The data for 1966 was deleted because it is a mathematical outlier and the more conservative estimate of a 2.8-cm increase retained.

The increase in peak water equivalent, noted in Table 3, was estimated by entering the mean peak water equivalent for the control watershed for each posttreatment year into the pretreatment calibration equation and solving for an expected value for the treatment watershed. The later value is what would be expected to occur on the treated watershed if it were not affected by treatment. The difference between the observed

TABLE 2. Estimated Increase in Mean Daily Peak Discharge From Fool Creek Watershed

Year	Observed Peak East St. Louis Creek (1)	Expected Peak Fool Creek (2)	Observed Peak Fool Creek (3)	Increase in Peak* (2–3)
1956	863	276	389	113
1957	1585	547	512	−35
1958	776	243	384	141
1959	626	186	307	121
1960	747	232	337	105
1961	451	121	185	64
1962	877	281	302	21
1963	260	49	102	53
1964	389	97	207	110
1965	1080	357	424	67
1966	291	61	117	56
1967	564	163	218	55
1968	755	235	236	01
1969	706	216	235	19
1970	883	283	312	29
1971	1159	384	364	−20
1972	774	242	317	75
1973	907	292	339	47
1974	843	268	305	37
1975	632	189	338	149
1976	468	127	153	26
1977	533	152	124	−28
1978	882	282	374	92
1979	836	190	248	58
1980	726	224	331	107
1981	744	231	196	−35
1982	897	288	282	−06
1983	1204	404	518	114
$\bar{x}$				55

Values are in L s^{-1}.

*Estimated as $\Delta Pk = Pk_{FC} - (.38Pk_{ESL} - 48.7)$, $R^2 = 0.90$, standard error = 9.9; where ΔPk is the change in mean daily peak discharge on Fool Creek; $Pk_{F.C.}$ is the mean daily peak discharge on Fool Creek; and $Pk_{E.S.L.}$ is the mean daily peak discharge on E. St. Louis Creek.

value and the expected value represents an estimate of the change due to harvest. As with estimates of changes in annual flow, no statistical significance is implied in the individual values, although covariance analysis indicates the mean has significantly increased. As noted earlier, the increases in peak water equivalent, as shown in Table 3, are significantly correlated ($R^2 = 0.37$), with increases in flow shown in Table 1. However, direct tabular comparison is not as conclusive because of the equally significant role of both spring precipitation ($R^2 = 0.30$) and years since harvest ($R^2 = 0.10$), which also explain part of the variation in flow increases.

Hoover and Leaf [1967] noted that if the average 30% increase in accumulation, expected to occur in the openings on Fool Creek, reflected an interception savings rather than a distribution effect, then there would be a net 12% increase in water equivalent over the entire drainage. This estimate on their part approximates what is now observed. They also noted that if an increase occurred and it were due to an interception savings, then one should be able to detect a recovery trend as the clearcuts are revegetated. To this end, time in years since harvest as an index of regrowth was included in the analysis of peak water equivalent data. A negative correlation ($P = 0.10$) between time, in years since harvest, and increased peak water equivalent exists, implying that regrowth may soon seriously affect the accumulation pattern. *Troendle and Meiman* [1984], working with a nearby lodgepole pine stand first cut in 1940, noted that after 40 years of regrowth, snowpack accumulation in a clearcut opening was decreasing at a rate of 0.07 cm/year.

DISCUSSION

The increases in flow estimated in this analysis are similar to those presented earlier [i.e., *Troendle and Leaf*, 1981]. The data in Table 1 indicate that wet years even at the end of a long string of posttreatment record still result in large increases. As was noted earlier, covariance analysis indicated the first year increase for conditions representing average climatic conditions was 10 cm; but in 1982, 27 years after harvest, the observed increase was still 11.4 cm during a wet year. The estimated rate of hydrologic recovery is somewhat less than found in earlier analysis (0.10 cm versus 0.18 cm) [*Troendle*, 1983], but this can be explained by the fact that the posttreatment precipitation record now included in the analysis is stronger in accounting for some of the annual variation that was formerly attributed to time or hydrologic recovery. The new estimate of recovery rate is more consistent with other independent projections of recovery [*Troendle and Meiman*, 1984; *Kaufmann*, 1985].

Timber harvest also significantly increased peak discharge by an average of 23%. Past analyses did not define this effect; but again, its detection at this time may be a reflection of the longer record now available. Given that the last few years of record were wet, with the largest peak of record actually occurring in 1983, sensitivity of the analysis may have been enhanced. The increase was not really very large and therefore difficult to detect, given the normal yearly variability prior to 1983 as indicated in Table 2. The observed increase in peak

TABLE 3. Observed Peak Water Equivalent on the East St. Louis Creek and Fool Creek Watersheds and the Estimate of Increase on Fool Creek Due to Timber Harvest

Year	Peak Water Equivalent East St. Louis Creek	Peak Water Equivalent Fool Creek	Estimated Increase Fool Creek*
1959	30.7	40.1	4.0
1967	24.4	31.0	2.1
1968	28.7	32.3	−1.6
1969	25.4	30.5	0.4
1970	20.4	48.3	1.0
1971	41.4	51.0	2.7
1972	26.9	38.9	7.1
1973	19.8	29.0	5.3
1974	32.3	39.6	1.7
1975	24.9	31.8	2.3
1976	23.4	32.8	2.2
1977	14.7	20.6	2.7
1978	32.5	40.4	2.2
1979	29.0	39.6	5.5
1980	35.3	46.7	5.3
1981	13.7	19.8	3.2
1982	...	...	...
1983	32.0	39.6	2.0
1984	38.4	43.7	−1.2
$\bar{x}$			2.8

Values are in centimeters.

*Estimated as $\Delta PWE = PWE_{F.C.} - (.95 + 1.146PWE_{E.S.L.})$, $R^2 = 0.93$, standard error = 2.8 cm; where $PWE_{F.C.}$ is the peak water equivalent, Fool Creek; and $PWE_{E.S.L.}$ is the peak water equivalent, East St. Louis Creek.

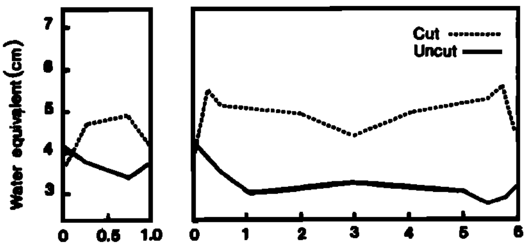

Fig. 4. Comparison of average snow accumulation in one and six tree height strips on Fool Creek, Fraser experimental forest [*Leaf*, 1975].

discharge is consistent with observations at Wagon Wheel Gap [*Van Haveren*, 1981] and Deadhorse Creek [*Troendle*, 1983].

An important finding of this analysis deals with the interpretation of the effect timber harvest had on snowpack accumulation on Fool Creek. As was noted earlier, estimates of average water equivalent were obtained from snow courses on each watershed from 1943 to 1954. Postharvest observations were made in 1959 and continuously from 1966 to present. Because observations were not made immediately following harvest (1956–1958 and 1960–1965), only now does the postharvest record appear long enough to reliably evaluate the impact. Currently, covariance analysis indicates that the average peak water equivalent on the entire watershed has been increased 9%, or 2.8 cm. In average or wetter years, it can be expected that this 2.8-cm increase in water equivalent will translate almost entirely to streamflow, because recharge requirements usually are met with a less than average snowpack. In this situation, the increase in peak water equivalent could account for about one third of the observed average increase in flow. Previously, the increase in flow observed at the streamage was attributed to the combined impact of redistributing snow, with no net increase in water equivalent over the entire watershed, and reducing evapotranspirational draft. First, it was believed that snow intercepted in the surrounding canopy was redistributed to the openings between storms. Because the intercepted snow was redistributed by wind, little evaporative loss could occur. Second, any reduction in interception loss, following harvest, that might have occurred was offset by increased evaporation from the snowpack.

However, at study sites near the Fool Creek watershed, *Troendle and Meiman* [1984] found that the increased accumulations in small clearcut openings occurred primarily during, not between, snowfall events, at least raising the question that the disappearance of snow from the canopy between events could result from evaporation as well as redistribution. They also noted that removal of 36% of the basal area by partial cutting on the 40-ha north slope of nearby Deadhorse Creek resulted in a 14% increase in overall snowpack water equivalent, again raising the question of an interception reduction, since no detectable shift in peak water equivalent could be detected on any of the snow courses surrounding the 40-ha unit. Patch clearcutting 36% of a second 40-ha subdrainage did not alter overall peak water equivalent. *Golding* [1982] noted that about 12 of the approximately 30% increase in peak water equivalent found in small openings in Canada could be attributed to interception savings. *Gary and Watkins* [1985] observed a 30% overall increase in peak water equivalent following thinning of lodgepole pine in southern Wyoming.

Troendle and Meiman [1984] noted that with respect to clearcutting, two process changes may be occurring. First, changing the aerodynamics of the stand alters the depositional pattern of the snowpack, increasing what is deposited in the opening. The degree to which the depositional pattern is altered is a function of opening size, canopy roughness, exposure to wind, etc. Second, timber harvest reduces foliar cover and intercepting surface, resulting in greater throughfall and less opportunity for interception loss. The amount of initial savings probably is a function of canopy removed; but the efficiency associated with keeping the savings from being lost to further ablation while on the ground is a function of aspect and degree of protection provided by residual vegetation.

In the case of Fool Creek, both processes appear to be involved; and there appears to be enough protection afforded by the canopy in the leave strips to reduce evaporation from the pack and, in effect, keep what we speculate to be interception savings from being lost. The result is that not only is there an increase in the openings resulting from depositional difference, but there is also a net gain for the watershed as well, perhaps because of reduced interception loss. In other situations, such as Wagon Wheel Gap [*Hoover and Leaf*, 1967] and the North Fork of Deadhorse Creek [*Troendle and Meiman*, 1984], where the clearcut is either very large (Wagon Wheel Gap) or else more directly exposed to increased energy loading (southfacing Deadhorse Creek), the net increase is not present or at least not detectable.

There still is much to be learned about the interaction of the evapotranspiration processes in the subalpine. Recent findings [*Troendle and Meiman*, 1984] demonstrate that partial cutting or thinning does increase net water equivalent reaching the ground, presumably because of reduced losses in the canopy. A similar response occurred in Fool Creek, following clearcutting 40% of the watershed. This was not the case in the clearcuts on the nearby North Fork of Deadhorse Creek, also partially cut using small circular clearcuts [*Troendle*, 1983]. On Deadhorse Creek, the openings are oriented to the south, occur on slopes greater than 30% and are exposed to direct solar loading during much of the winter. If there are any interception savings on that watershed, the increased ablation from them eliminates or masks them. If the loss from the snowpack is evaporative, it is a loss to the system; but if snow is melting sooner or during the winter, then the interception savings not detectable in the snowpack still would be part of the increase in flow that is observed at the streamgage.

The Fool Creek analysis also indicated that summer precipitation, current or past, was not well correlated with the observed increase in flow, even though summer precipitation averages 20–25 cm. It can be assumed that the summer precipitation is either stored on site or it was consumed on site or nearby through evaporative loss or increased transpiration from the understory.

CONCLUSIONS

Troendle and Leaf [1981] concluded that approximately one third of the expected increase in streamflow resulting from partial clearcutting the subalpine coniferous forest could be attributed to the efficiency of differential snow deposition after clearcutting. Two thirds was attributed to evapotranspiration modification, primarily during the growing season. In the case of Fool Creek, it does not seem likely that depositional differences can play as significant a role as previously thought

[*Troendle and Leaf*, 1981]. Apparently, the net increase in peak water equivalent, now apparent in the posttreatment record, may account for up to one third of the observed change, with depositional differences and growing season evapotranspirational reductions accounting for the remaining two thirds. Because only minor reductions in the increase in peak water equivalent have resulted from regrowth during the past 28 years, and because the distributional pattern of the snowpack (based on the 1980 intensive survey) does not appear to have changed since the survey in 1964, the recovery of streamflow that has been observed to occur so far must dominantly reflect growing and dormant season evapotranspiration increases, a result of vegetative regrowth. This still seems most logical, even though no effect of antecedent growing season precipitation was detected in the analyses.

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