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Streamflow Changes After Clear-Cut Logging of a Pine Beetle-Infested Watershed in Southern British Columbia, Canada

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The paired watershed technique was used to assess the streamflow changes of Camp Creek in interior British Columbia after clear-cut logging occurred over 30% of its 33.9 km^2 watershed. Existing hydrometric data for Camp Creek and those of an adjacent control, Greata Creek, were analyzed for both the 1971–1976 prelogging and 1978–1983 postlogging periods. Postlogging Camp Creek streamflow changes are characterized by increases in annual and monthly water yields and annual peak flows, as well as earlier annual peak flow and half flow volume occurrence dates. The direction and magnitude of these postlogging streamflow increases are clear and consistent. The results are in good agreement with the findings of most previous studies conducted on watersheds which generally have been smaller than 2.5 km^2. This study provides strong evidence that changes in streamflow from a large forested watershed can be significant if a sizeable portion of its drainage area is clear-cut. Possible causes for the streamflow changes are discussed.

INTRODUCTION

In the southern interior region of British Columbia, streamflow originates mainly from snowpacks in high-elevation headwater areas with a substantial cover of lodgepole pine (*Pinus contorta* Dougl.). Recently, clear-cut logging of stands infested by mountain pine beetle (*Dendroctonus ponderosae* Hopkins) with cut blocks sometimes exceeding 500 ha has accounted for a significant portion of the annual allowable cut in the region. These headwater areas are important to downstream water users who are extremely concerned about the potentially detrimental effects of this type of large-scale clear-cut logging on streamflow quantity and regime (timing).

Our present knowledge of streamflow changes resulting from watershed logging is based mainly on experiments usually conducted on small watersheds less than 2.5 km^2 in size [*Hibbert*, 1967; *Bosch and Hewlett*, 1982]. As pointed out by *Hewlett* [1971], watersheds on the order of 10 km^2 or larger are avoided for experimental purposes simply because it is impractical or unacceptable due to other considerations to apply a uniform treatment such as clear-cut logging over such watersheds. Concern has often been expressed about the validity of extrapolating experimental results from small to large watersheds because hydrologic processes and relationships of these two types of watersheds may be different. Therefore studies to provide evidence of streamflow changes resulting from forest removal on a watershed large enough (e.g., 10 km^2) to serve as a primary water supply source are of both scientific and practical importance.

There are few published observations of forest removal effects on the discharge of streams draining larger watersheds (e.g., greater than 10 km^2) [*Love*, 1955; *Patric*, 1974; *Bethlamy*, 1974; *Helvey and Tiedemann*, 1978; *Cheng*, 1980; *Potts*, 1984]. These studies deal with streamflow changes resulting from deforestation by fire, insect, or wind with or without subsequent clear-cut logging. Due to limitations imposed by the availability of streamflow data used in these referenced studies, the method of analysis and the number of streamflow variables analyzed varies from one study to another. Except for *Cheng* [1980] and *Potts* [1984], none of these studies on watersheds larger than 10 km^2 deals with the impact of forest removal on monthly water yields.

This paper reports the results of a study that applied the control watershed method to existing hydrometric and climatic data in assessing the changes in annual and monthly water yields and flow regimes after clear-cut logging in the 33.9 km^2 Camp Creek watershed located in the interior of British Columbia (Figure 1). This information compliments the results of an earlier study on the effects on streamflow of large-scale watershed deforestation by fire in another interior watershed [*Cheng*, 1980].

STUDY WATERSHEDS

Camp Creek and its control, Greata Creek, are located approximately 25 km northwest of Penticton, in the Okanagan Highlands of British Columbia. Greata Creek drains an unlogged watershed of 40.7 km^2 located immediately northeast of Camp Creek (Figure 1). The terrain is mountainous, with gentle to moderate slopes and generally medium to coarse-textured soils. Some physiographic characteristics of these two watersheds are presented in Table 1.

Lodgepole pine covers much of both watersheds with some ponderosa pine (*Pinus ponderosa*) and Douglas fir (*Pseudotsuga menziesii*) occurring in single or mixed types of lower elevations. Engelmann spruce (*Picea engelmannii*) and balsam fir (*Abies lasiocarpa*) are found in high-elevation areas, but in small amounts.

The Greata Creek watershed has a larger portion of its area covered by Douglas fir than Camp Creek watershed. Furthermore, the lodgepole pine in the Greata Creek watershed is mostly between 40 and 60 years old and thus not susceptible to beetle infestation. Even the mature lodgepole pine stands occupying a small area in the southeast corner of the Greata Creek watershed has so far been spared by the pine beetle. On the other hand, the mountain pine beetle had significantly affected mature lodgepole pine stands in the Camp Creek watershed. Clear-cutting was used to salvage the infested trees

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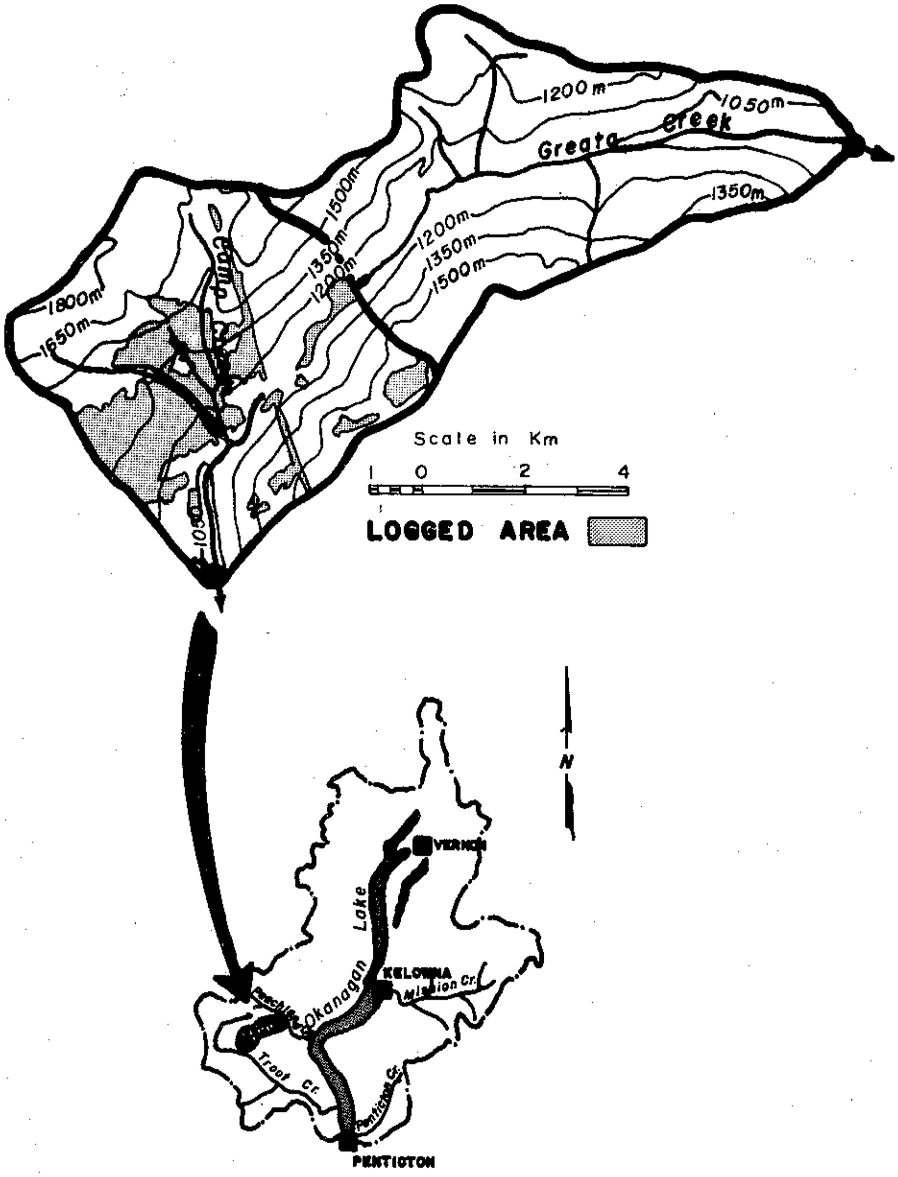

Fig. 1. Location map showing the Okanagan basin within which the study watersheds are located.

and, as a preventive measure, to bring the pine beetle epidemic under control by removing potentially susceptible mature stands. The logging resulted in 30% of the total watershed area being denuded of forest cover. The extent of clear-cut logging on the Camp Creek watershed is shown in Figure 1.

Mean annual precipitation is about 600 mm and 550 mm for Camp Creek and Greata Creek watersheds, respectively, with more than half occurring as snow during the November–April period. The discharges of both watersheds are measured with recorders to provide continuous data. These hydrometric stations were established for general water resource inventory rather than specifically for the present study. Water Survey of Canada consider the records to be good (the accuracy being approximately 10%). Streamflow in the study area has a significant snowmelt contribution and generally starts to rise in March or April and peaks in May or early June. The mean annual water yields for the prelogging period are 140 mm and 101 mm and approximately 23% to 18% of the mean annual

TABLE 1. Physiographic Characteristics of Camp Creek and Greata Creek Watersheds

Watershed	Area, km^2	Elevation, m		Aspect	Bedrock Geology
		Median	Range		
Camp Creek	33.9	1450	1070–1920	S	granite, granodiorite, and other intrusive igneous rocks
Greata Creek	40.7	1280	880–1620	E	granite, granodiorite, and other intrusive igneous rocks, plus andesite and basalt

TABLE 2. Regression Equations for Monthly and Annual Water Yields and Annual Peak Flow During the Calibration Period

Flow Variable and Equation	Correlation Coefficient r	No. of Observations
Annual water yield		
$\hat{Y} = 0.0403 + 1.1452X$	0.942	6
Annual peak flow		
$\hat{Y} = 0.381 + 1.2192X$	0.947	6
January		
$\hat{Y} = 0.248 + 0.6654X$	0.953	6
February		
$\hat{Y} = 0.0156 + 0.9656X$	0.918	6
March		
$\hat{Y} = 0.0084 + 1.3585X$	0.817	6
April		
$\hat{Y} = 0.0491 + 0.7553X$	0.862	6
May		
$\hat{Y} = 0.3117 + 0.8252X$	0.846	6
June		
$\hat{Y} = -0.0078 + 1.9777X$	0.967	6
July		
$\hat{Y} = 0.0294 + 1.1926X$	0.976	6
August		
$\hat{Y} = 0.0257 + 1.0333X$	0.988	6
September		
$\hat{Y} = 0.0323 + 0.8903X$	0.858	6
October		
$\hat{Y} = 0.0123 + 1.2950X$	0.962	7
November		
$\hat{Y} = 0.0185 + 0.8992X$	0.963	7
December		
$\hat{Y} = 0.0129 + 1.0312X$	0.933	7

X is flow from the control watershed in cubic meters per second.

precipitation values for Camp Creek and Greata Creek watersheds, respectively. For comparison, the mean annual water yield for the control (Greata Creek) in the postlogging period is 51 mm, indicating considerable drier years than the prelogging period. More than 80% of the annual yield occurs in the April–August period for both watersheds.

METHODS

The analyses are based on the control or paired watershed method, which is normally considered the most satisfactory approach for detecting streamflow changes following watershed cover modification [*Hewlett*, 1971; *Bosch and Hewlett*, 1982]. Streamflow variables considered include annual and monthly flows, annual maximum daily peak flows plus occurrence dates of annual peak flows, and annual half flow volumes. The annual half flow volume occurrence date is defined as the date on which half of the annual total streamflow volume has passed [*Court*, 1962].

A regression equation and its 95% confidence limits for the prelogging calibration period were developed for each selected streamflow variable using data from Camp Creek as the dependent variable and its control, Greata Creek as the independent variable. The calibration regression was developed using six observations (1971–1976) for every streamflow variable except the monthly flows of October, November, and December which have 1 year's additional data of 1970. These prelogging regressions provide an experimental control over climatic variations within and between years. Because the majority of the Camp Creek drainage clear-cut logging occurred in 1977, data for this year were not used in the analyses.

Streamflow changes in Camp Creek for the postlogging period (1978–1983) were evaluated for individual years. For a given streamflow variable, the calibration regression equation and observed postlogging values of the control Greata Creek were used to compute what the corresponding predicted values for Camp Creek would have been had its watershed not been clear-cut logged. Observed and predicted streamflow values were then compared. Differences between the measured and predicted values for Camp Creek were attributed to logging and levels of statistical significance of these changes were assessed.

Because logging was expected to increase streamflows, a one-tailed t test was used to evaluate the overall logging effect on a given streamflow variable by determining whether its mean of percentage streamflow increases is statistically different from zero or whether the mean ratio of the observed values over respective predicted values for six postlogging years is statistically different from 1. Mean differences in annual peak flow and half flow volume dates between Camp Creek and Greata Creek for the 1978–1986 postlogging period as compared to the 1971–1976 prelogging period were evaluated by an unpaired t test using the pool mean square estimate of variance [*Dixon and Massey*, 1969] to see whether there is significant change in streamflow timing.

RESULTS AND DISCUSSION

Regression equations and their correlation coefficients developed from the calibration period data for annual and monthly water yields as well as for annual peak flows are presented in Table 2. Differences between the observed and the predicted streamflow values of Camp Creek for the postlogging period in cubic meters per second were converted where appropriate to depth (in millimeters) over the watershed area.

Annual Water Yield

For all six postlogging years the measured streamflow values for Camp Creek are consistently higher than the values predicted from the calibration equations using Greata Creek Data. The increases range from 10 mm in 1978 to 59 mm in 1982, with a mean value of 29 mm (or about 100 mm on an area cut basis) which is 21% more than the average predicted value (Figure 2). Because the variances for the pre- and postlogging periods are not homogeneous, the analysis of covariance cannot be used to test the significance of overall statistical differences. Based on the t test, the mean (29 mm) of six postlogging percentage streamflow increases is significant at the 95% confidence level (Table 3). For the six postlogging years the 1982 increase (59 mm) is the highest and is statistically significant at the 95% confidence level. For comparison, the mean annual water yield increase calculated by summing up the increases of individual months is 30 mm (Table 3).

Monthly Water Yield

The March–November water yields during the 1978–1983 postlogging years increased in nearly all of the months, some of the individual month increases being statistically significant at the 95% confidence level (Figure 3). Streamflow changes in the winter months (December–February) were small, erratic, and not significant until the start of snowmelt in March (Table 3). The most significant and consistent increases appear to be in the early snowmelt season months of March and April. The means and individual monthly water yield changes for the

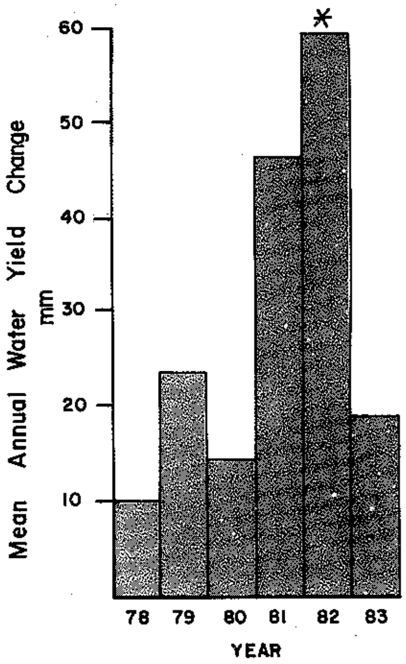

Fig. 2. Annual water yield changes in Camp Creek after clear-cut logging in the watershed.

1978–1983 period are presented in Figure 4 and Table 3, respectively. The *t* test results indicate that the average streamflow increases for individual streamflow variables calculated from six postlogging years are all significant at the 95% confidence level except for the monthly flows of December, January, and September (Table 3).

Annual Peak Flows and Streamflow Timing

Annual peak flows in Camp Creek increased in all but one (1978) of the six postlogging years (Figure 5). The changes range from 0.12 m^3/s (9%) decrease in 1978 to 0.41 m^3/s (34.5%) increase in 1981 with an average increase of 0.25 m^3/s (21%). Peak flow increases in 1982 and 1983 are statistically significant at the 90% confidence level. Based on *t* test results the mean percentage increase (21%) in peak flow magnitude calculated from six postlogging values is significantly increased at the 95% level.

Peak flow occurrence dates of Camp Creek have also been affected by clear-cut logging. On the average, the Camp Creek annual peak flows during the 1971–1976 prelogging period occurred 11.3 days later than those of Greata Creek. However, during the 1978–1983 postlogging period, the annual peak flows of Camp Creek occurred an average of 1.7 days earlier than those of Greata Creek, indicating an advancement of 13 days (Figure 6). During the 1971–1976 prelogging period, the annual half flow volume dates in Camp Creek occurred on average 5 days later than those in the control, Greata Creek. However, during the 1978–1983 postlogging period, the average half flow volume date in Camp Creek was 3.3 days earlier than that in Greata Creek, a timing advance of 8.83 days (Figure 7). The unpaired *t* test results indicate that the differences of pre- and postlogging annual peak and half flow volume occurrence dates between the logged and control watersheds are significantly changed at the 95% confidence level.

The overall magnitude of increase and timing advance of Camp Creek streamflow following clear-cut logging in the watershed can also be illustrated by comparing its average annual hydrographs with those of Greata Creek for the 1971–1976 prelogging period and the 1978–1983 postlogging period

TABLE 3. Monthly and Annual Water Yield Changes for Camp Creek During the 1978–1983 Postlogging Period

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan. to Dec. Total	Annual
1978														
mm	−0.48	0.14	3.66*	8.26*	−7.33	7.88	1.19	0.71	0.69	0.34	0.69	−0.08	15.67	10.3
%	−17.1	6.7	106	100	−11.9	23.2	13	14.8	13.4	7	1.43	−2		6.9
1979														
mm	−0.40	−0.25	0.01	6.68*	13.98	3.36	0.55	0.06	−0.61	0.32	−0.23	−0.90	22.57	23.7
%	−10.9	−7.7	2	103	41.5	36.3	10	2	−18	12.6	−10	−40		30.2
1980														
mm	−1.58	−0.73	−0.91	8.26*	3.16	2.60	2.77	0.70	−0.54	0.16	0.30	0.44	14.63	14.9
%	−57	−31.2	−32.9	116	8.6	17.3	41	20.5	−15	5.8	12.2	19		17
1981														
mm	0.55	0.64	0.90	4.14	12.89	9.33*	8.85*	3.80*	0.	0.08	0.99*	0.92	43.09	46.5
%	19.4	27.3	28.8	72.4	37.1	56.5	106	94.2	0	2.2	40.2	38.2		18.3
1982														
mm	0.87	1.64	0.13	2.15	18.60	11.50*	11.30*	3.95*	1.15	1.19*	0.99*	0.86	54.33	58.6*
%	32.4	74.2	42.9	39.1	43	39.7	98.6	83.3	26.8	32.6	31.3	26.2		52.5
1983														
mm	0.95	1.01	2.24*	12.62*	5.20	−2.68	1.26	0.87	0.92	0.95	1.80*	1.99	27.13	18.6
%	29.3	36.6	52	106	8.2	−10.6	10.9	14.3	17.9	27.2	43.4	60		12.1
Average	−0.15	0.41	1.00*	7.02*	7.75*	5.33*	4.32*	1.68*	0.27	0.50*	0.76*	0.54	29.57	28.8
Percent of change over predicted value	−0.8	16.5	30	93.6	17	24.8	48.9	38.4	8	14	23.7	18.5		25.9

*Significant at 95% confidence level.

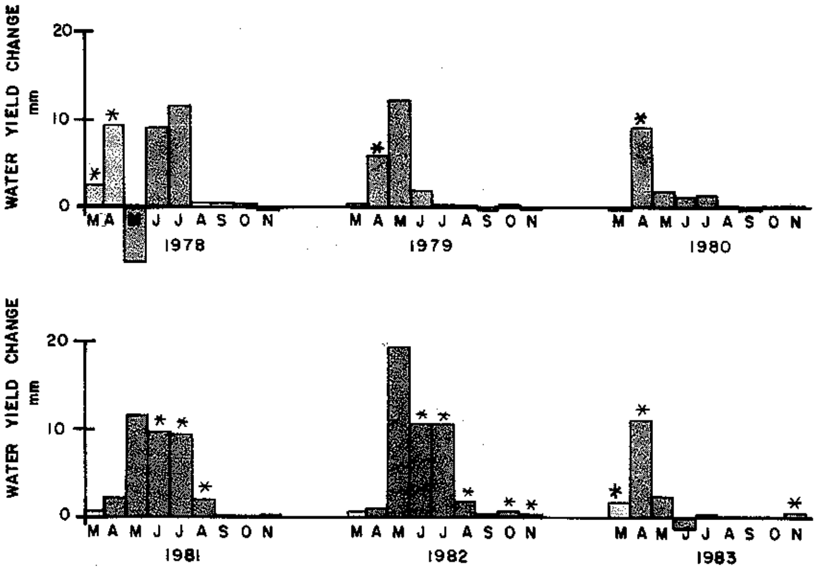

Fig. 3. Water yield changes in Camp Creek for nonwinter months after clear-cut logging in the watershed.

(Figure 8). It is apparent from the concurrent Camp Creek and Greata Creek hydrographs that the differences in streamflows between the two creeks are consistently larger during the 1978–1983 postlogging period compared to the 1971–1976 prelogging period.

Discussion

The paired watershed method has provided consistent results that clearly indicate the direction and magnitude of streamflow changes and the contrast in streamflow timing between the logged watershed and the unlogged control watershed before and after logging periods. Some of the postlogging streamflow changes, e.g., monthly flow increases in May, although large in absolute magnitude, are not statistically significant at the commonly used 95% confidence level due to the wide confidence intervals associated with the prelogging calibration equations. The wide confidence intervals of some regression lines may be in part related to the influences of predominantly different elevation and aspects of the two study watersheds on snow-dominated hydrologic regimes. However, as *Hewlett* [1971] has noted, the treatment effect sometimes is so clear from simple graphical presentation that statistical verification is not necesarily required. This is indeed true when results of the present study are assessed and discussed in the context of their consistency with results from other watershed experiments.

In comparison to results from other studies on streamflow increases after watershed forest removal [*Hibbert*, 1967; *Helvey and Tiedemann*, 1978; *Helvey*, 1980; *Bosch and Hewlett*, 1982], the mean annual water yield increase of 29 mm in Camp Creek is not large. This probably reflects both the relatively small porportion of the watershed logged (30%) and its dry climate, as indicated by a mean annual precipitation of about 600 mm and a prelogging water yield of 140 mm. This relatively small increase might also be related to the fact that the postlogging period was drier than the prelogging period. However, the percentage increase (26%) in mean annual water yield falls in the middle of the range of increases reported by most studies in the literature [*Hibbert*, 1967; *Bosch and Hewlett*, 1982]. The study results are also comparable to those from studies conducted on watersheds with similar forest types and climate (Table 4).

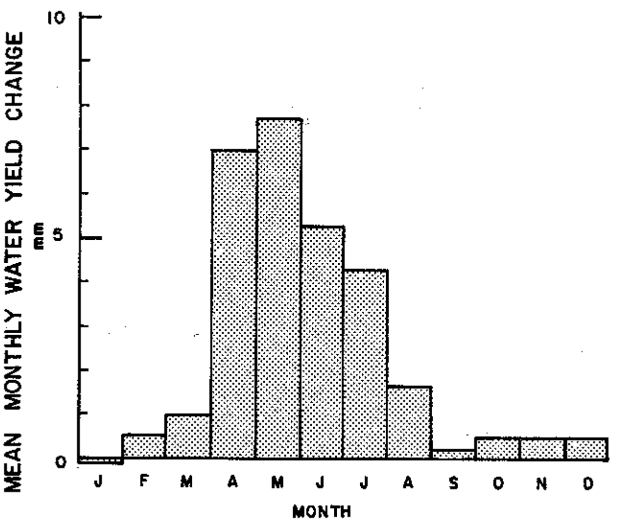

Fig. 4. Mean monthly flow changes in Camp Creek after clear-cut logging in the watershed.

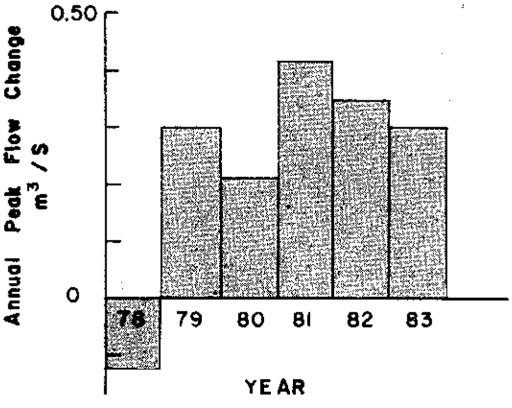

Fig. 5. Annual peak flow changes in Camp Creek after clear-cut logging in the watershed.

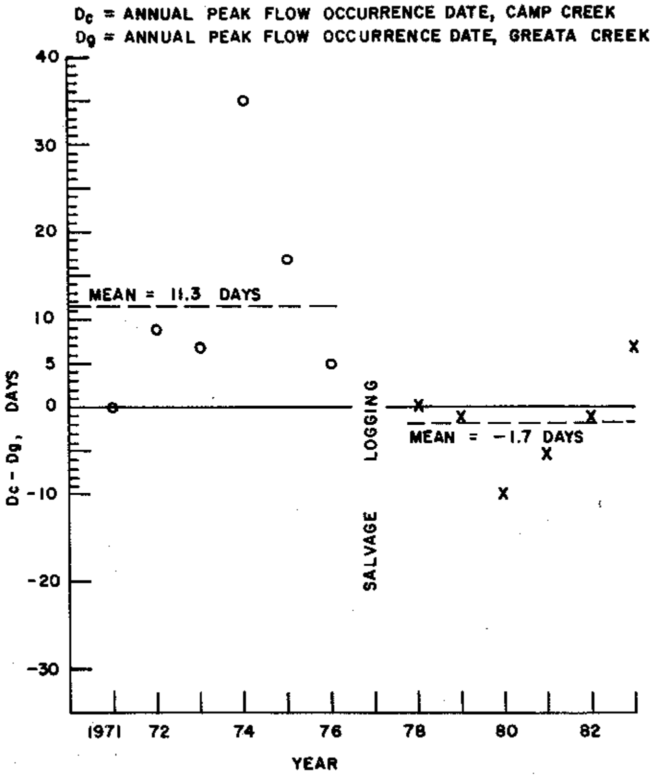

Fig. 6. The differences in annual peak flow occurrence dates, between Camp Creek and Greata Creek before (1971–1976) and after (1978–1983) the clear-cut logging in Camp Creek watershed.

The snowmelt season (March–June) streamflow changes in Camp Creek can be attributed partly to a more efficient and speedier conversion of watershed snowpack to streamflow as a result of higher snowmelt rates over a shorter period after the removal of shade-providing trees. In addition, reduction in evapotranspiration losses in logged areas also resulted in reduced soil water deficits and lower soil moisture recharge requirements. Consequently, more water would be available for streamflow.

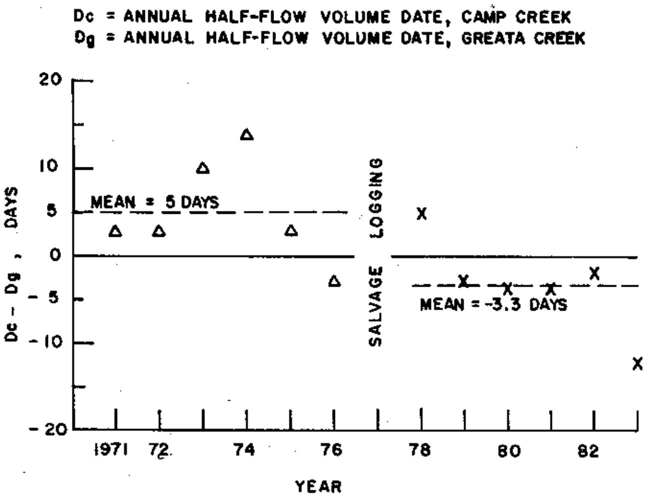

Fig. 7. The differences in annual half flow dates between Camp Creek and Greata Creek before (1971–1976) and after (1978–1983) the clear-cut logging in Camp Creek watershed.

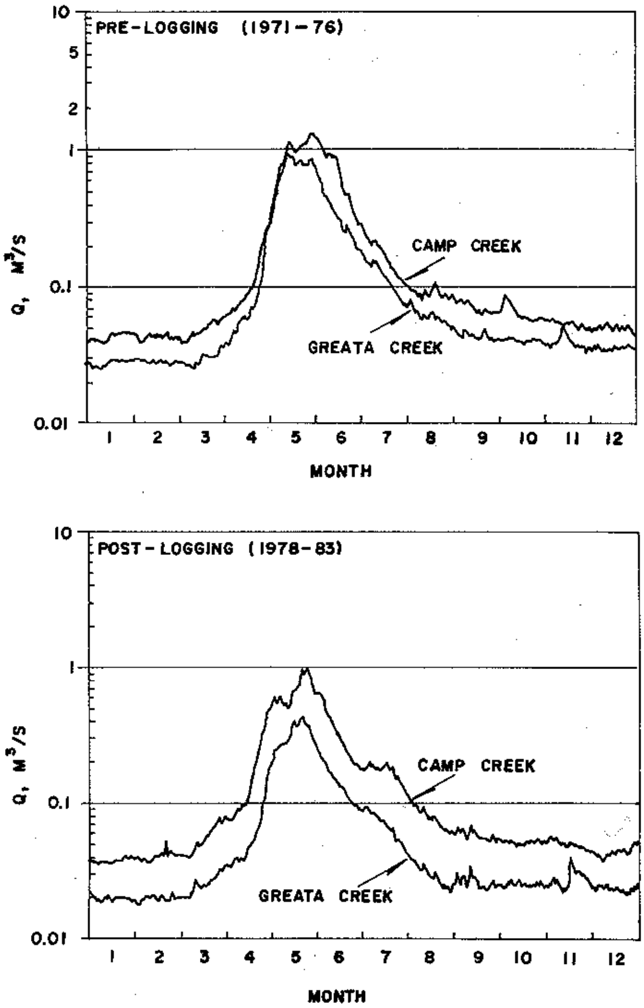

Fig. 8. Average annual hydrographs of mean daily flow for Camp Creek and Greata Creek before (1971–1976) and after (1978–1983) the clear-cut logging on 30% of Camp Creek watershed.

The desynchronization effects of an increased snowmelt rate and the advanced snowmelt timing in the clear-cut portion of the watershed is capable of shifting a large amount of streamflow from one period to another [*Nakano*, 1971; *Hornbeck et al.*, 1970]. These mechanisms could be partially responsible for the reduction in monthly flow of May 1978 as well as the decreased annual peak flow in that year and the advancement of annual peak flow and half flow volume dates observed in this study and the works by *Cheng* [1980] and *Hornbeck and Pierce* [1970].

Outside the snowmelt season, the largest percentage increases occurred in the major growing season months from July to August (Table 3). This is mainly due to decreased evapotranspiration, resulting in increased soil moisture in the logged watershed as compared to the control watershed. Several watershed studies [e.g., *Hornbeck et al.*, 1970] have reported similar results. The streamflow increases during the summer growing season, although small in absolute quantity, are important because they occur at a time when the demand for water is at its highest.

Changes in dormant season streamflows not involving snowmelt were seldom statistically significant at 95% or 90% levels, indicating similar soil moisture regimes on both the control and logged watersheds. The erratic and relatively insignificant streamflow changes during the December–February period also probably reflect the difficulty in accurately measuring streamflow during ice cover conditions. However, errors in streamflow measurement, considered

TABLE 4. A Comparison of Streamflow Changes in the Camp Creek Watershed and in Other Watersheds Where Snowmelt Dominates the Hydrograph

Watershed	Area, ha	Forest Types	Annual Precipitation, mm	Annual Streamflow, mm	Forest Removal	Average Annual Water Yield Increase		Annual Peak Flow	
						mm	%	Magnitude Increase, %	Date Advancement, days
Wagon Wheel Gap, Colorado [*Van Haveren*, 1981]	81	Aspen conifers	536	157	100% clear-cut	25			7.5
Cabin Creek, Alberta [*Golding*, 1981]	212	Lodgepole pine, spruce	840	310	21% clear-cut	17		24 (May flow)	14
Fool Creek, Colorado [*Troendle and King*, 1985]	289	Lodgepole pine, spruce	762	283	40% strip-cut	74		23	7.5
Hinton, Alberta [*Golding*, 1981]	1497	Spruce, lodgepole pine	513	147	50% clear-cut	42	27	59	
Palmer Creek, British Columbia [*Cheng*, 1980]	1800	Lodgepole pine, spruce	750	350	50% burned	83.5*	24	50	13
Camp Creek, British Columbia	3390	Lodgepole pine, spruce	600	140	30% clear-cut	29	21	21	13

*April-August seasonal flow only.

random in nature, should not significantly effect on the calculation of annual water yield. This is because only about 5% of annual streamflow occurs in the December–February ice cover period.

The variations in streamflow change also appear to depend on the year to year variations in snowmelt and rainfall amounts. For example, the water yield increases in April were closely related to rainfall and snowmelt for that month (Table 5). On the other hand, in 1981 and 1982, the clear-cut logging caused no significant streamflow changes in April due to low snowmelt runoff and low rainfall in that month. However, higher and above normal rainfall and snowmelt in May and wet weather in subsequent months in these 2 years had resulted in the two largest annual and May to August water yield increases during the 6 years of record (Figures 2 and 4). As with other experimental results in areas where snowmelt is the major source of streamflow [*Hornbeck and Pierce*, 1970; *Nakano*, 1971], most water yield increases in Camp Creek occurred during the April to June period (Figure 4).

The streamflow changes observed in this study reinforce conclusions from similar studies on smaller experimental watersheds elsewhere [*Hibbert*, 1967; *Bosch and Hewlett*, 1982]. The results of the present study and *Cheng* [1980] should have practical application value to similar watersheds in interior British Columbia because they represent the only locally available quantitative information on streamflow changes after large-scale forest cover removal on watersheds large enough to be important water supply sources [*Cheng and Reksten*, 1980]. Both studies, together with similar studies elsewhere, provide strong evidence that changes in streamflow from a large forested watershed greater than 10 km^2 in size, can be significant and detectable if a sufficient portion (e.g., 30%) of its total area is clear-cut.

TABLE 5. Increases in April Monthly Water Yield of Camp Creek During the 1978–1983 Postlogging Period as Related to Snowmelt and Rainfall Amounts Averaged From Measurements at Three Nearby Climate Stations

Year	April Water Yield Increase, mm	Snowmelt, mm	Rainfall, mm
1978	8.3*	66	65.8
1979	6.6*	55	1.8
1980	8.3*	131	0
1981	4.1	21	4.1
1982	2.1	20	2.1
1983	12.6*	92	8.8

*Significant at 95% confidence level.

CONCLUSION

The application of the paired watershed method to assess streamflow changes after clear-cut logging of the Camp Creek watershed provided consistent results which are in good agreement with findings from watershed experiments elsewhere. The streamflow changes in the logged watershed include increases in annual and monthly water yields and annual peak flows, as well as earlier annual peak flow and half flow volume dates. As many of these streamflow changes are significant at the commonly used 95% confidence level, this study has demonstrated that changes in streamflow from a large forested watershed can be significant if a sizeable portion of its drainage area is clear-cut. The present study has also provided some badly needed quantitative information on the hydrologic impact of large-scale clear-cut logging in interior British Columbia.

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