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A Colorado Episode: Beetle Epidemic, Ghost Forests, More Streamflow²

Abstract

When a small watershed is clearcut, it temporarily yields more water. The implication is that water yield and land use are closely related. This interdependence is illustrated for two large watersheds in Colorado where bark beetles destroyed the living timber trees. Substantially greater water yields are still evident 25 years after the epidemic because significant elements of the watersheds have not yet reverted to their former status—dead trees still occupy the land, and have not yet been replaced by live trees. The variable hydrologic effects of the epidemic in the studied watersheds reflect differences in their exposures.

Introduction

Many experiments have shown that a small, forested watershed will yield more water after it is clearcut. This increase is temporary if a new forest becomes established, or may be permanent if a new land use is instituted. In a larger sense, the experiments demonstrate the principle that water yield is related to land use. Our knowledge of water yield as related to land use is based on experiments generally conducted on small watersheds of a few acres (cf. Hibbert, 1967). But we now have data to show that the principle holds true on areas covering hundreds of square miles.

Great winds have always affected man and his environment. Ages ago winds deposited the loess that covers vast areas in Europe, Asia, and North America (Robinson, 1951). In our own time, violent winds blew down forests in New England (Patric, 1974) and leveled swaths of giant trees in the forests of the Northwest. An intense wind that struck the high plateaus of Colorado in 1939 is of particular interest, not because it was unique, but because of events that followed in its wake: in the uprooted and weakened trees of the White River watershed, bark beetles multiplied to epidemic proportions and by 1946 had attacked and killed forest trees covering hundreds of square miles in both the White and Yampa River watersheds and eastward to the Continental Divide (Wygant and Nelson, 1949). When the epidemic finally ran its course, it covered 30 percent of the gaged watersheds and killed up to 80 percent of the forest trees.

Ecologic effects of the epidemic are visible and clearly evident. Before the epidemic the forests consisted primarily of Engelmann spruce and subalpine fir in a 4:1 ratio,³ with basal area of 34 m²/ha, and volume of 343 m³/ha. Twenty-five years after

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³ Silvicultural data furnished by Messrs. Ski Milanowski, U.S. Forest Service, Steamboat Springs, Colorado, and Donn B. Cahill, U.S. Forest Service, Denver, Colorado.

the epidemic, dead trees are still standing; new, live trees are again spruce and fir but in a 1:4 ratio; and basal area and volume are only 10 m²/ha and 60 m³/ha.

The beetle epidemic also changed the hydrology of the region, as evidenced when the data are subjected to specialized analytical techniques. Love (1955) was the first to suggest that streamflow increased after the beetles destroyed the timber on the White River watershed. He hypothesized a 2-inch (5.08 cm) yearly increase by analyzing limited streamflow and snow course data for both the White and the unaffected Elk River watersheds. Others (Bue *et al.*, 1955) objected to the analysis, contending that without further data it was not possible to prove whether streamflow increased in one watershed or decreased in the other.

This paper verifies Love's conclusions by offering additional data and subjecting them to rigorous analyses. Locations of the four studied watersheds⁴ are shown in Figure 1. Yampa and White watersheds were affected by the epidemic, but Plateau and Elk watersheds were spared.

Analysis of Vertex Angles for Annual Water Yields

The following analysis of streamflow data uses a previously unreported "integrating triangle method" devised by the author to evaluate the response of watersheds to natural disturbances and management practices in the absence of long-term records. Complete documentation and review of the technique is currently underway, hence rigorous evaluation, in a statistical sense, has yet to be accomplished.

Consider a triangle having sides (a, b, c) that represent annual streamflow of the Elk, White, and Yampa watersheds (Fig. 2). The length of each side (L_s) represents a river's annual flow (x_i) expressed in terms of its pre-epidemic average (x_a).⁵ If side a is the triangle's base and represents the Elk River's streamflow, then the opposed vertex angle A is readily calculated,⁶ and may be used to characterize the relationship among the three watersheds. A significant change in their relationship would be reflected in the size of the vertex angle. Thus, if the epidemic induced increased streamflow of the White and Yampa rivers, then angle A should be smaller than its characteristic value prior to the epidemic.

The analysis showed that the average value of angle A decreased from 1.047 radians before the epidemic⁷ to 0.987 radian after the epidemic. The change is significant at the 99 percent level of significance using student's "t" test.

A similar analysis using Plateau Creek as the triangle's base revealed that angle A decreased from a pre-epidemic value of 1.045 radians to 0.923 radian, and again, the change is highly significant at the 99 percent level of significance using student's "t" test.

Average values of vertex angle A for different periods are listed in Table 1.

⁴ Identification numbers and areas of the four watersheds are: Elk at Clark (9.304, 534 km²); Plateau near Colbran (9.965, 208 km²); Yampa at Steamboat Springs (9.2395, 1564 km²); White near Meeker (9.3045, 1974 km²). Analyses are based on data in USGS Water Supply Papers 1313, 1733, 1924, 1925.

⁵ $L_s = \arctan e^{w}$, where $w = (x_i - x_a) / (2x_a)$.

⁶ $A = \arcsin \frac{2\sqrt{s(s-a)(s-b)(s-c)}}{bc}$ and $s = \frac{a+b+c}{2}$.

⁷ The years 1930-1940 comprise the pre-epidemic period; 1946-1965 the postepidemic period. In other analyses the pre-epidemic period is 1911-1940.

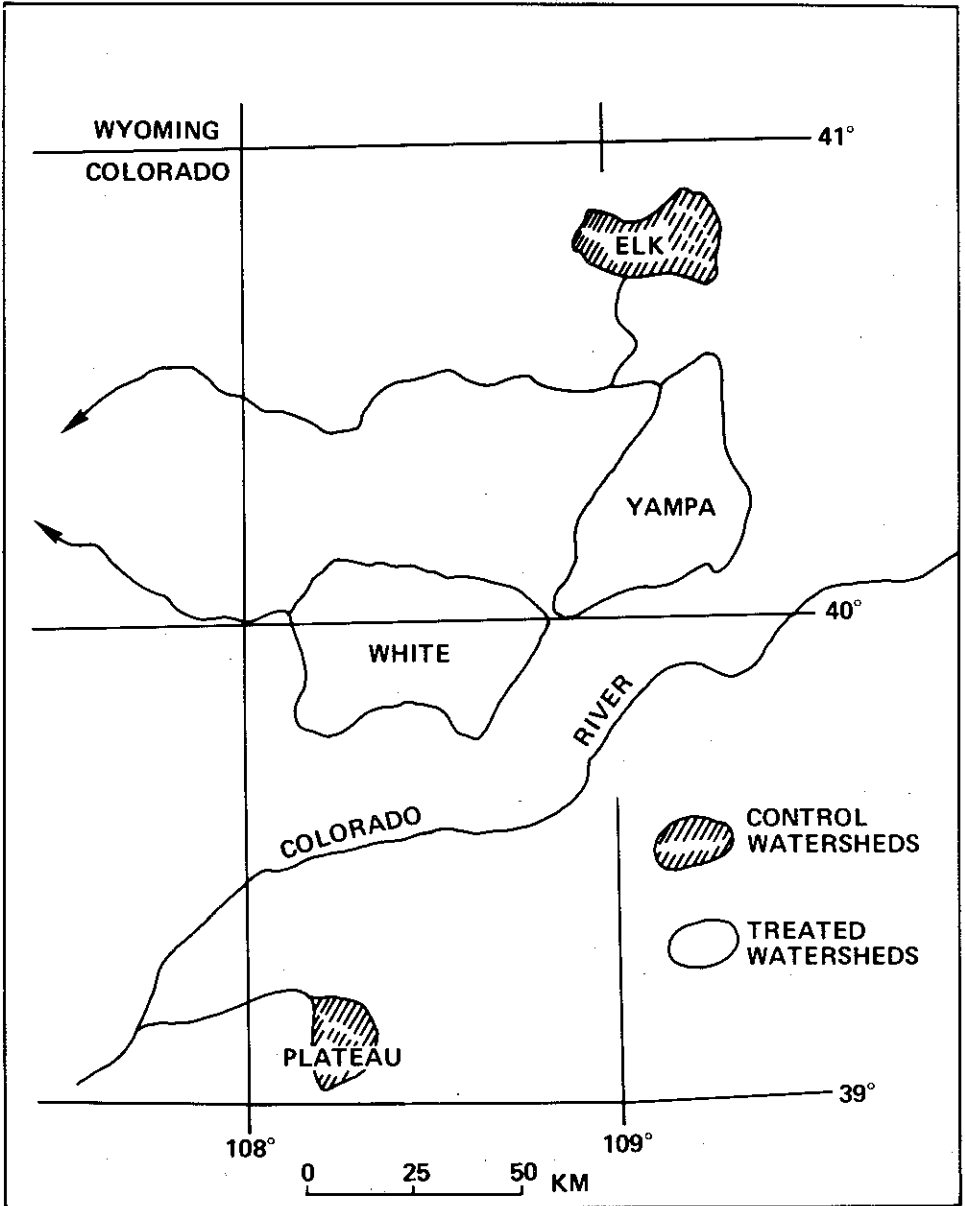


Figure 1. Location of studied watersheds. Only White and Yampa watersheds were affected by the beetle epidemic.

Elk and Plateau: the Unaffected Watersheds

Although the preceding analyses may be interpreted to mean that a change occurred in the water yields of the beetle-infested White and Yampa watersheds, one could also argue that identical results would be obtained if the control drainages (Elk and Plateau) yielded less water. These two drainages are approximately 190 km apart, and it is not reasonable to believe that a change would occur in the most widely separated water-

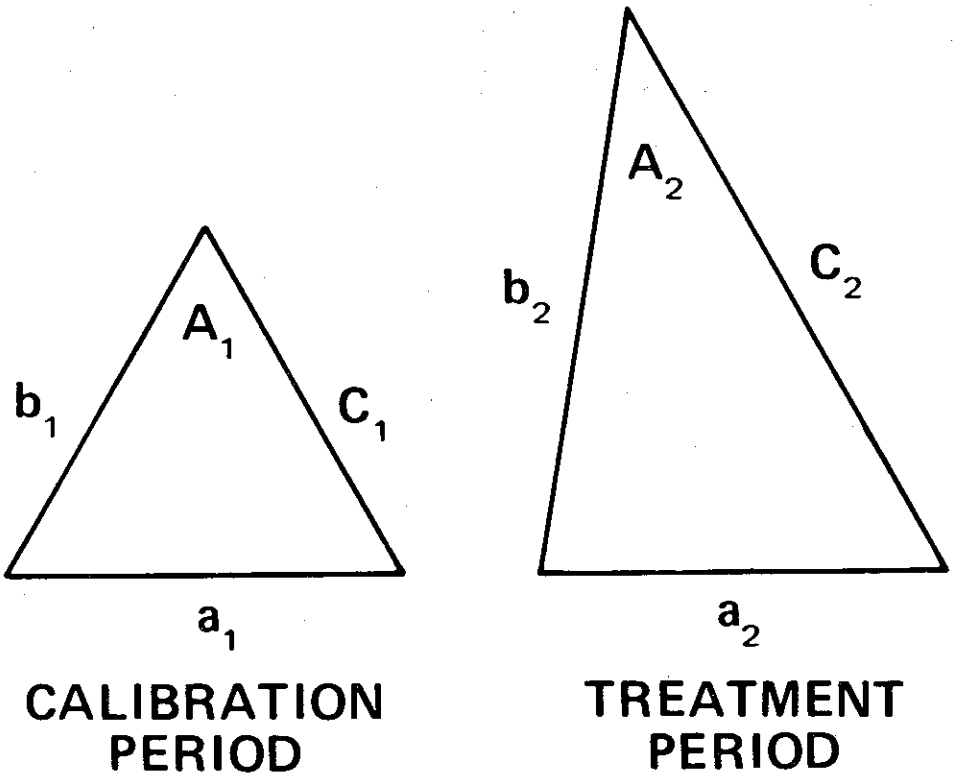


Figure 2. The integrating triangle method used to analyze and illustrate changes in relations among three watersheds. Base a represents the control watershed; sides b and c represent treated watersheds. Length of each side represents a river's measured variable expressed in terms of its average during the control period. Angle A_1 approximates 60° during control period, but will change significantly (A_2) if relations are altered among the watersheds.

sheds without also occurring in the two intervening watersheds. Accordingly, the hypothesis of increased water yields from the White and Yampa watersheds may be accepted if we show that the relation between Elk and Plateau remained constant during the pre- and postepidemic periods.

The relationship between water yields of Elk and Plateau is best studied by applying an analysis of covariance (Snedecor, 1948) to evaluate the significance of changes in either the regression coefficients or the adjusted means that characterize the regression lines of the pre- and postepidemic periods. The analysis revealed no change in the values of either the regression coefficients or the adjusted means ($F_{\text{regression}} = 0.70$; $F_{\text{mean}} = 0.91$). Therefore, one may safely conclude that runoff relationships between the two control watersheds remained constant during the period of study.

TABLE 1. Average vertex angle (radians) of runoff triangles¹ before and after the Colorado bark-beetle epidemic. Comparisons are for annual, high-month, October, and January runoff.

Period	Annual	High month ²	October	January
Triangle Base: Elk River Flows				
Pre-epidemic	1.047	1.047	1.039	1.045
Postepidemic	0.987	1.009	0.951	0.973
1946-50	1.004	1.028	0.976	1.036
1950-55	0.978	0.981	0.925	0.940
1956-60	0.966	1.000	0.938	0.962
1961-65	0.999	1.026	0.966	0.954
Triangle Base: Plateau Creek Flows				
Pre-epidemic	1.045	1.049	1.035	1.045
Postepidemic	0.923	0.971	0.871	0.950
1946-50	0.986	0.990	0.891	1.006
1951-55	0.955	0.951	0.850	0.963
1956-60	0.922	0.974	0.853	0.946
1961-65	0.828	—	0.890	0.887

¹Two sets of triangles: Elk-White-Yampa and Plateau-White-Yampa. Elk and Plateau watersheds escaped the epidemic, and their runoff constitutes a triangle's base. The length of each side represents the investigated runoff expressed in terms of its pre-epidemic average.

²High-month runoff is generally May or June.

Analysis of Annual Water Yields

The preceding analyses of two sets of data indicated that the relationship among three watersheds changed over time, and that the change was not caused by changes in the control watersheds—Elk and Plateau. The inference was that the change resulted from an increase in flow of either the White River or the Yampa River or of both. The question was readily resolved by individual analyses of covariance (Table 2). Results indicated that highly significant changes occurred in the yields of both the White and Yampa watersheds.

How much more water did the watersheds yield after the epidemic? The answer may be obtained by comparing annual flows measured during the postepidemic years to flows calculated on the basis of the pre-epidemic regression equations. Two estimates are available for each watershed because both the Elk and the Plateau watersheds served as controls in calculating the individual regression equations. Averages of the two independent estimates are shown in Table 3. Average annual increases appear to be substantial. Twenty-five years after the epidemic, annual water yields of the gaged watersheds are still approximately 10 percent greater than the expected yields.

Figure 3 illustrates the marked contrast between annual water yields of the control and epidemic-affected ("treated") watersheds. Three features are noteworthy: (1) the control watersheds exhibit reduced streamflow from 1947 to 1955, but the treated watersheds show gains during most of that period; (2) gains are curtailed sharply when yield of the control rivers is far below the long-term average; (3) the treated watersheds again show distinct gains when more moisture is available, as indicated by gains in the control rivers.

Seasonal Changes in Streamflow

(a) Flows during October

The hydrologic year starts in October, at which time streamflow is derived primarily from groundwater flows. Streamflow should increase if transpiration decreased during the preceding months. An analysis of October flows shows that streamflow did indeed

TABLE 2. Values of variance ratio F from analyses of covariance of annual, October, and high-month yields (in cm) for periods before and after the Colorado bark-beetle epidemic, and values of a and b in regression equation $Y = a + bX_i$.

Relation tested	Parameter tested		Period characterized			
	Regression coefficient	Adjusted mean	Before		After	
	F	F	a	b	a	b
Annual Yields						
Y (White) versus						
X_1 (Elk)	3.24	14.32**	6.81	0.34	3.91	0.46
X_2 (Plateau)	12.08**	13.12**	15.94	0.25	11.43	0.52
Y (Yampa) versus						
X_1 (Elk)	5.31*	9.36**	2.59	0.39	-3.31	0.56
X_2 (Plateau)	10.05**	6.52**	15.70	0.18	7.76	0.56
October Yields						
Y (White) versus						
X_1 (Elk)	1.95	2.77	0.79	0.57	1.25	0.23
X_2 (Plateau)	0.00	4.71*	1.06	0.46	1.20	0.47
Y (Yampa) versus						
X_1 (Elk)	2.34	10.44**	0.14	0.37	0.10	0.55
X_2 (Plateau)	7.63*	5.74*	0.32	0.28	0.17	0.82
High-Month Yields						
Ln Y (White) versus						
Ln X_1 (Elk)	0.46	6.97*	-1.10	0.99	-1.49	1.18
Ln X_2 (Plateau)	0.01	5.62*	0.07	0.65	0.21	0.67
Ln Y (Yampa) versus						
Ln X_1 (Elk)	0.59	2.62	-0.18	0.77	-0.81	1.02
Ln X_2 (Plateau)	0.48	2.29	0.86	0.45	0.54	0.63

*95 percent level of significance.

**99 percent level of significance.

TABLE 3. Average¹ change in annual, October, and high-month water yields of White and Yampa watersheds during the postepidemic period.

Period	Annual increase		October increase		High-month ² increase	
	cm	% ³	cm	%	cm	%
White River						
1946-50	3.46	13.5	0.04	3.1	1.44	20.7
1951-55	3.86	16.8	0.20	15.9	1.73	28.2
1956-60	5.17	21.0	0.20	14.8	1.29	18.0
1961-65	2.68	11.5	0.06	4.5	—	—
Yampa River						
1946-50	2.89	12.4	0.22	39.1	0.26	2.9
1951-55	2.37	11.4	0.13	29.2	1.07	13.0
1956-60	6.30	27.8	0.14	29.4	2.26	24.8
1961-65	2.52	11.7	0.15	28.1	—	—

¹ Average of the two independent estimates based on Elk River and Plateau Creek regression equations.

² High-month flow is generally May or June.

³ Percent of expected values based on pre-epidemic regression equations.

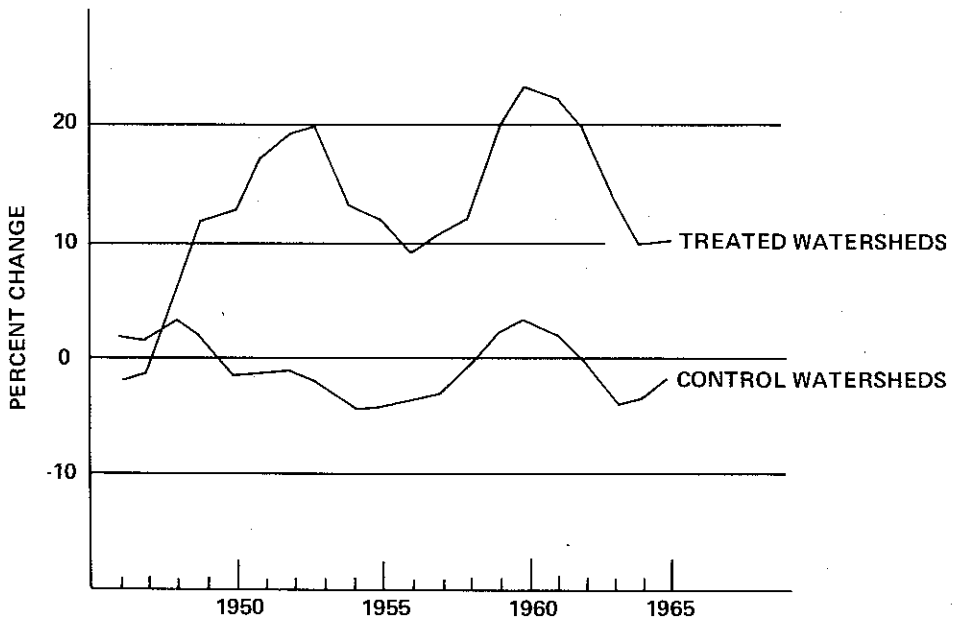


Figure 3. Five-year moving averages of change in expected yields of two groups of watersheds (each comprised of two watersheds) after a bark-beetle epidemic destroyed forests in the Treated Group but bypassed the Control Group.

increase after the epidemic. Integrating-triangle analyses (Table 1) showed that vertex angles decreased significantly (99 percent level of significance) and that more detailed analyses were warranted. Analyses of covariance (Table 2) revealed that after the epidemic, Yampa River yielded larger amounts of water (Table 3) but that White River flows changed significantly with respect to one control watershed (Plateau) but not with respect to the other (Elk).

Why did the two treated watersheds respond differently to the epidemic? The variable response was not caused by a change in the relationship of the two control watersheds; analysis of covariance showed that neither the regression coefficients nor the adjusted means that characterize their relationship changed during the period of study ($F_{\text{regression}} = 0.9$; $F_{\text{mean}} = 0.3$).

The variable response of the two treated watersheds may be understood if we consider the effect of exposure. This study is complicated by the fact that each of the considered rivers flows in a different primary direction (Fig. 1). The rivers that flow through the treated watersheds flow at almost right angles to each other and drain watersheds that differ greatly in their receipt of solar energy: Yampa River flows northward and drains a low-energy (LE) watershed that receives less heat than the high-energy (HE) White watershed that is drained by a westward-flowing river. Bethlahmy (1973) discussed the important characteristics that differentiate HE and LE watersheds; with these characteristics in mind, the variable response of the two treated watersheds is readily comprehended.

After the epidemic, October streamflow increases were greater on north-facing (LE) watersheds than on west-facing (HE) watersheds. During the 20-year period 1946-

1965, October flows on the LE watershed increased 0.16 cm (31.4 percent) in contrast to 0.12 cm (9.6 percent) on the HE watershed. We conjecture that the variable response of the two treated watersheds reflects smaller transpiration losses on the LE watershed and greater evaporation losses on the HE watershed.

(b) High-flow month

On the Colorado plateaus, winter precipitation occurs primarily as snow, and rivers flood in May and June when the accumulated winter snows melt. Annual runoff is closely related to spring runoff, as evidenced by the following highly significant correlation coefficients between annual runoff and flow during the month of highest runoff: Elk—0.94; Yampa—0.93; White—0.95; Plateau—0.90.

Logic dictates that if annual flows changed as a result of the beetle epidemic, then a concomitant change should have occurred in the high-month flows. Analysis of vertex angles (Table 1) showed that such was actually the case; the vertex angles diminished significantly (99 percent level of significance) when flows of Elk River and Plateau Creek were used successively as the triangle's base.

The importance of exposure again becomes evident in the individual analyses of covariance that showed an especially significant change in the west-flowing White River in contrast to the north-flowing Yampa. Average increases in yield during the 15-year period 1946-1960 were 1.49 cm (22 percent) for the HE White watershed and 1.20 cm (14 percent) for the LE Yampa watershed (Table 3).

(c) Flows during January

In the area studied, minimum flows generally occur in January. Analysis of vertex angles by the integrating-triangle method showed decreases significant at the 99 percent level of significance (Table 1). On the other hand, analyses of covariance showed that the change was limited to the White River.

White watershed is an HE watershed. In winter, only on such watersheds (in contrast to LE watersheds) would an opening in the forest canopy lend any advantage to radiation to increase snowmelt.

The ratio of January yields of White watershed to average yields of the control watersheds increased from 1.84 before the epidemic to 2.01 after the epidemic. Compare these figures to those at Wagon Wheel Gap, Colorado (Bates and Henry, 1928), where a 0.812 km² LE watershed (mean exposure N 68°E) was denuded of its forest cover and burned. Corresponding figures there (where minimum flows occur in February) were 1.207 and 1.216.

(d) Momentary peak flow

Rate and time of occurrence are two elements that characterize annual momentary peak flow—the maximum annual recorded instantaneous rate of flow.

White River's rates increased 27 percent (20.2 m³/s), an increase significant at the 99 percent level of significance. In contrast, no such change occurred in the rate of north-flowing Yampa River; analysis of covariance showed that the apparent 4 percent increase was not significant.

The variable response of the two watersheds to the effects of the beetle epidemic is not surprising when exposure is considered as an additional element. During the

spring thaw, rate and time of occurrence of peak flows are controlled by regional and local weather conditions, and, in each watershed, exposure exerts a profound influence on incoming radiation.

Potential solar-beam irradiation (May 18, 50 percent slope) is approximately 825 langleys for Yampa watershed and 929 langleys for White watershed (cf. tables in Frank and Lee, 1966). Clearly, White watershed has an advantage of 12.6 percent with respect to incoming radiation that controls the rate of snowmelt. But two additional elements render this advantage particularly significant: more snow is available for melting because trees denuded of their branches and limbs intercept less snow, and additional storage space for snow is created when whole trees topple; and, if spring thaw is delayed (an occurrence that characterized the postepidemic period), the additional radiation on White watershed is particularly effective in melting the snow.

The following tabulation shows that during the postepidemic period all four watersheds peaked several days later than expected:

Watershed	Day of momentary peak flow	
	Before epidemic	After epidemic
Yampa	149	151
Plateau	142	147
White	145	156
Elk	143	153

The difference is particularly large for White and Elk, the two HE watersheds.

Results of the integrating-triangle method showed that values of the vertex angles did not change from one period to the other. On the other hand, results of individual analyses of covariance showed differences that are best interpreted in the light of contrasting exposures.

The following tabulation may explain the variable response of Yampa and White watersheds to the ravages of the beetle epidemic:

	Delay in peak flow days	Level of significance percent
<u>HE versus HE watersheds</u>		
White vs. Elk	+1	50
<u>HE versus LE watersheds</u>		
White vs. Plateau	+6	90
vs. Yampa	+9	95
Elk vs. Plateau	+5	75
vs. Yampa	+8	90
<u>LE versus LE watersheds</u>		
Yampa vs. Plateau	-3	50

Apparently peak-flow delays that approach an acceptable level of significance occur only between watersheds that have distinctly contrasting exposures.

Past research shows and logic suggests that opening a forest canopy will hasten, not delay, peak flow (Bates and Henry, 1928; Bethlahmy, 1973). But in this instance, general climatic conditions during the postepidemic period induced late peak flows in both HE and LE watersheds. Was the delay less prominent in the treated watersheds than in the control watersheds? The answer is "no" if we compare data from similarly exposed watersheds; neither the treated White nor the treated Yampa differ from their corresponding controls. We also infer that the general climatic conditions that induced universal late peak flows overshadowed the treatment effects and were more effective

on HE than on LE watersheds. We therefore conclude that exposure is a primary variable that should not be neglected in hydrologic analyses.

Discussion and Conclusions

This paper has dealt with the relationships between two groups of watersheds before and after a bark-beetle epidemic killed standing timber over vast areas in Colorado. The analyses indicate that a quarter of a century after the epidemic, the two affected watersheds still yield considerably more water than expected.

The explanation for the increased flows is not a change in climate. The four watersheds are in one climatic zone, and as indicated in one of the analyses, the relationship between the two most widely separated (and epidemic-spared) watersheds did not change during the two periods. A change in irrigation demands could explain the phenomenon, but public records do not support this conjecture.

The most logical explanation relates to vegetative cover. Before the epidemic, the forest consisted of mature and overmature trees that used water and functioned as a forest. After the epidemic, the dead trees no longer used water nor functioned in concert as a living forest with respect to the use of water.

Annual streamflow reflects the interaction of a watershed with its environment. The hydrology of the epidemic-affected watersheds changed because the component elements of the watersheds changed: "ghost" forests permit a greater accumulation of snow that in the spring melts to produce more water; water that dead trees do not pull from the earth seeps downward and appears as streamflow in summer and fall; the open canopy of the ghost forests permits the sun's heat to melt more snow in the winter.

The data presented are unique because of the large areas involved. They may also be unique in another way. We should not necessarily infer that similar results will follow all epidemics, whether insect or disease. Where forests consist of a large variety of species it is not likely that all trees will suddenly succumb to the same virulent agent. Also, natural regeneration may be prompt. Close to timber markets it is likely that the dead trees will be removed promptly; that young, vigorous seedlings will be established quickly; and that streamflow will revert to its pre-epidemic level in a modicum of time.

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