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A Reevaluation of the Wagon Wheel Gap Forest Watershed Experiment

Bruce P. Van Haveren

ABSTRACT. The original, published streamflow data from the Wagon Wheel Gap watershed deforestation study were analyzed using modern computational and statistical methods. Annual hydrograph parameters were generated for the two paired watersheds for the pre- and postreatment periods and tested using regression and covariance analyses. Average annual water yield, maximum daily discharge, high-flow volumes, recession flows, and baseflow were all increased significantly following complete deforestation of one watershed. With the exception of the first full year after treatment, deforestation had little effect on hydrograph timing. Deforestation increased both the slope and intercept of a linear equation describing the flow duration curve of Watershed B. The results for these major hydrograph parameters agree with the results reported from the original study, conducted between 1910 and 1926 at Wagon Wheel Gap, Colorado. However, some of the original study results for other hydrograph parameters could not be statistically supported. FOR. SCI. 34(1):208–214.

ADDITIONAL KEY WORDS. Deforestation, water yield, forest hydrology.

THE STATED OBJECTIVES of the original watershed experiment beginning in 1910 and ending in 1926 at Wagon Wheel Gap, Colorado, were to quantitatively determine the effects of deforestation on the volume and timing of streamflow, soil erosion, and sediment loading (Bates 1911). Foresters at the turn of the century believed that forests acted to reduce the magnitude of floods, to maintain streamflow (through springs) in dry weather, to prevent erosion, and to reduce the amount of silt carried by streams (Bates and Henry, 1922). Those contentions were countered by many water-supply engineers of that time. The study at Wagon Wheel Gap was the first of its kind in the United States to quantitatively examine the effects of forest denudation on streamflow and sediment yield.

This paper reports on a reevaluation of the original Wagon Wheel Gap streamflow data and conclusions as published by Bates and Henry (1928). Their conclusions were based on mean values of study variables without the benefit of a statistical treatment of year-to-year variability. My objective in this reevaluation was to extract additional information from and apply modern statistical analyses to the original data set.

METHODS OF REANALYSIS

Fortunately, Bates and Henry (1928) included the daily precipitation and streamflow data for Watersheds A and B in the appendix of their final report. All the streamflow data from 1912 to 1926 were keypunched and stored on a mainframe computer. A data screening program was used to search for any significant discrepancies in the data set. The more obvious typographical errors in the data set were found and corrected. The streamflow data were then run through a hydrograph analysis computer program based on a procedure developed by Bethlahmy (1972) and designed to generate 45 parameters from annual hydrographs. This paper concentrates on the annual hydrograph parameters originally analyzed by Bates and Henry (1928) and a few additional parameters of particular interest to present-day forest hydrologists. Covariance and linear regression analyses were employed to de-

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termine whether deforestation had an effect on the annual hydrograph parameters and flow duration curve of Watershed B.

As a treatment for the original watershed experiment, Watershed B was clearcut during the summer of 1919. A 15-m streamside strip along the main channel was left uncut. All slash was windrowed. In the fall of 1920 the leave strip was logged and the slash windrows burned.

RESULTS AND DISCUSSION

Comparison of Watersheds A and B Before Deforestation

During the eight-year calibration period (1912–1919), Watersheds A and B remained in a pristine state. Bates and Henry (1922) provided the results of the pretreatment calibration phase of the experiment. In the present analysis, five physiographic variables, five annual hydrograph parameters, and average annual basin precipitation were all used to compare the pretreatment characteristics of Watersheds A and B. The physiographic characteristics of the two watersheds are shown in Table 1. The hydrograph parameters and basin precipitation were subjected to linear regression analyses. These results are shown in Table 2. All five hydrograph parameters plus basin precipitation were tested for pretreatment differences between the two paired watersheds. Based on t-tests at the 95% level, no significant differences were found to exist between the two watersheds. They were indeed "well-paired" watersheds. Pretreatment flow-duration curves for watersheds A and B are shown in Figure 1.

Effect of Deforestation on Streamflow

Deforestation had a significant effect on average annual water yield, peak flow, baseflow, recession flow, and low flow. These results in some cases disagreed with the conclusions of Bates and Henry (1928); in other cases they supported the original conclusions and also brought to light additional information not reported in the original study. Results of the reevaluation are compared against the conclusions of Bates and Henry (1928) in Table 3.

In all study years, runoff from rain-on-snow and rainfall made an insignificant contribution to the annual hydrograph. Runoff was due almost entirely to snowmelt. In fact, runoff from rainfall was a rare event during the study period.

Deforestation had a highly significant (99% level) effect on the average annual water yield of Watershed B. The increase, averaged over the seven-year posttreatment period, was 15.4% or 2.46 cm of water, which closely agrees with Bates and Henry (1928). A linear regression analysis (Figure 2) showed that water yield increased in all posttreatment years based on the 95% confidence limit. The increase peaked in 1922 and then gradually declined. This decline over time was likely due to a rapid invasion of aspen sprouts on Watershed B.

Plotting annual water yield increases against annual precipitation showed no apparent correlation. However, the range of annual water yields in the posttreatment period was rather small. In Figure 3, the ratio of annual water yield increase to annual precipitation is plotted against time.

The maximum daily discharge from Watershed B following deforestation increased an average of 50%, which agrees with the original results. The effect of deforestation was highly significant. However, Bates and Henry (1928) concluded that Watershed

TABLE 1. Pretreatment comparison of the physiography of Watersheds A and B.

Variable	A	B
Drainage area (ha)	90	81
Maximum elevation (m)	3,461	3,338
Minimum elevation (m)	2,857	2,818
Mean aspect	S. 85°E	N. 68°E
Horton form factor	0.18	0.41

TABLE 2. Pretreatment comparison of the hydrology of Watersheds A and B.

Variable	A	B	Regression R^2
Average annual basin precipitation (cm)	53.4	53.6	0.92
Average annual water yield (cm)	15.3	15.8	0.99
Average annual maximum daily flow ($L\ s^{-1}km^{-2}$)	29.9	32.4	0.88
Average annual duration of daily flows 20 $L\ s^{-1}km^{-2}$	9.0	10.0	0.90
Average annual recession period median flow ($L\ s^{-1}km^{-2}$)	3.2	2.8	0.84
Average annual half-flow date	May 15	May 19	0.78

B peaked three days earlier following deforestation. The present analysis indicates the date of the maximum daily discharge was not affected by treatment ($P = 0.95$).

Hydrologists generally agree that it is not necessarily the instantaneous peak but rather the duration of very high flows that can cause serious channel erosion, downstream flooding, and associated damages (Ziemer 1981). With this in mind, two hydrograph parameters related to the volume of high flows above a threshold level (20 $L\ s^{-1}\ km^{-2}$) were computed. This threshold was approximately equal to a 1.5-yr return period flow. The cumulative volume of daily flows greater than the threshold flow increased an average of 90% on Watershed B following deforestation. The effect was significant at the 95% level. For the seven-year posttreatment average, the duration of daily high flows greater than the threshold flow was not significantly affected by deforestation. However, deforestation did significantly increase ($P = 0.95$) the duration of these flows in 1921, the first complete year following treatment.

Many land-use hydrologists have assumed a relationship to exist between water yield increases and peak flow increases following deforestation. This relationship was tested for Wagon Wheel Gap for both the annual maximum daily flow and the

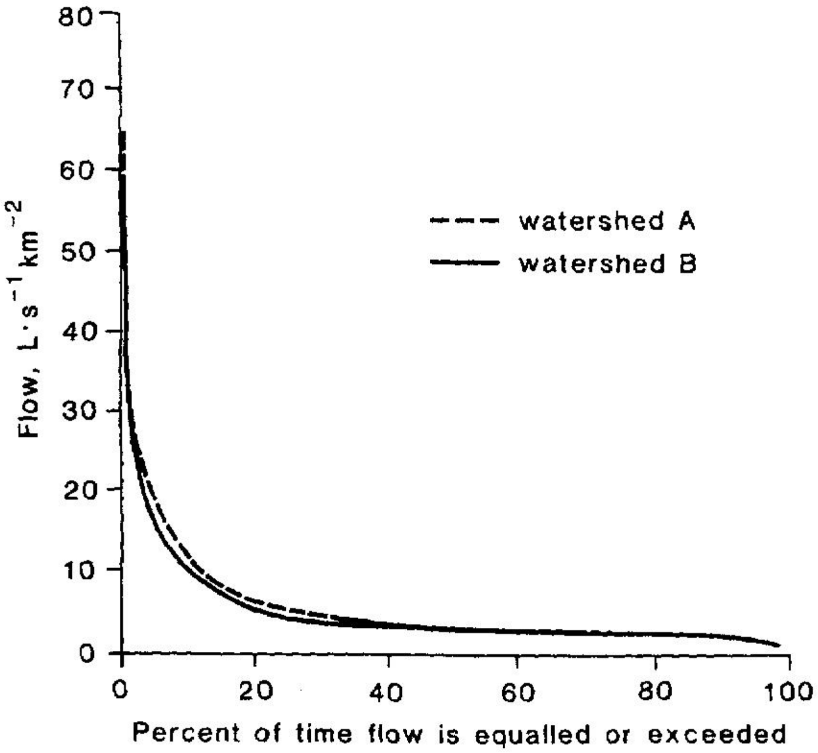

FIGURE 1. Pretreatment (1912–19) flow duration curves for Watersheds A and B.

TABLE 3. Results of the reevaluation of posttreatment data compared to the conclusions of Bates and Henry (1928).

Hydrograph parameters	Original study conclusions	Reevaluation results
Average annual water yield	Increased 0.96 in (2.44 cm)	Increased 15.4% or 2.46 cm (sig. at 99% level)
Annual maximum daily flow	Increased about 50%	Increased an average of 50% (sig. at 99% level)
Date of the annual maximum daily flow	Advanced 3 days	Advanced 6 days (NS)
Snowmelt runoff	Increased 22%	Increased 22% (sig. at 95% level)
Duration of snowmelt runoff	Decreased 2 days	NSD
Starting date of snowmelt runoff	Advanced 12 days	Advanced 5 days (NS)
Half-flow date	Advanced 3 days	Advanced 5 days (sig. at 99% level)
Rising limb runoff	Increased 0.68 in (1.73 cm)	NSD
Falling limb runoff	Increased 0.12 in (0.30 cm)	NSD
Snowmelt recession flows	Increased 7%	Increased an average of 12% (sig. at 99% level)
Length of recession period	Steeper recession reported	NSD
Baseflow recession flows	Increased 0.09 in (0.23 cm) 11%	Increased an or average of 17% (sig. at 99% level)
Antecedent flow (over-winter period prior to snowmelt runoff)	Increased 0.07 inches (0.18 cm)	NSD
Cumulative volume of daily flows >20 L $s^{-1}km^{-2}$	Not reported	Increased an average of 90% (sig. at 95% level)
Duration of daily flows >20 L $s^{-1}km^{-2}$	Not reported	No change in the average; an increase of 12 days in 1921 (sig. at 95% level)
Annual 30-day low flow	Not reported	NSD
Flow duration curve	Not reported	Both slope and intercept increased

NS—Regression equation not significant ($P = 0.95$).
NSD—No significant difference attributable to treatment.

annual high-flow volume. Both the peak flow increases and the high-flow volume increases were independent of annual water yield increases. However, the plots did suggest a pattern of large peak flow and high-flow volume increases associated with large annual water yield increases. In addition, the greatest increases in Watershed B high-flow volumes occurred in years when Watershed A experienced lower high-flow volumes.

Flows at the middle of the recession period on the falling limb of the hydrograph were increased an average of 12%. This increase was significant at the 99% level. Farther down the falling limb, at the beginning of the baseflow recession period, flows were increased an average of 17%. Again, this was a highly significant increase over the pretreatment period. In general, these findings are in agreement with the original data. However, Bates and Henry (1928) concluded that Watershed B had a shorter recession period following deforestation, whereas my analysis showed no statistically significant change in the length of the recession period. The present analysis also showed an average increase of 12% in baseflow between snowmelt runoff events. This increase was significant at the 95% level. There was no signifi-

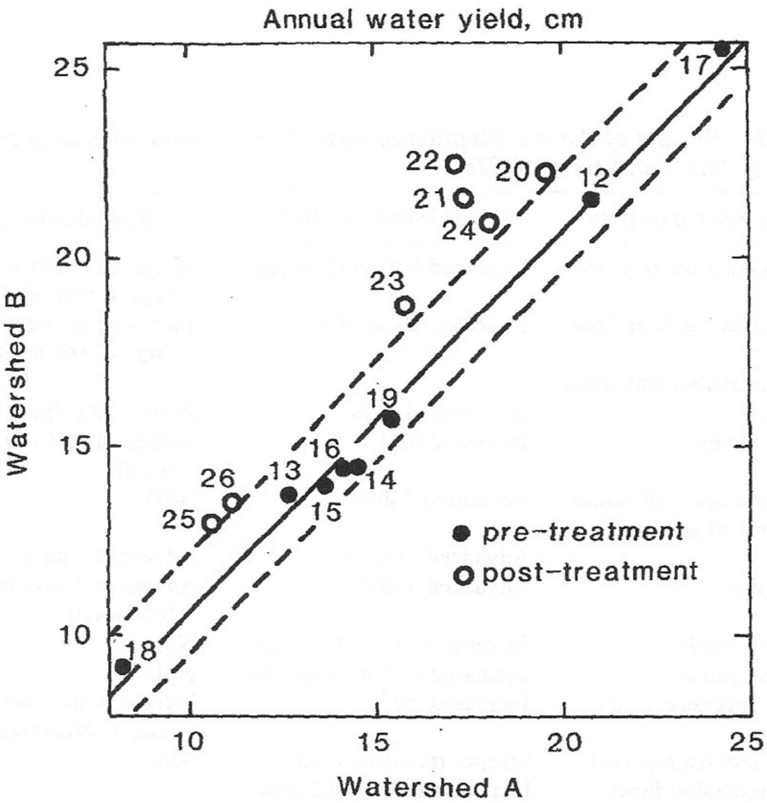

FIGURE 2. Linear regression of annual water yield, Watershed A vs. Watershed B. The numbers refer to years. Pretreatment period was 1912–1919; posttreatment period was 1920–1926. The R^2 is 0.99 and the standard error of estimate is 0.5 cm of water. The plot shows that all seven posttreatment years experienced a significant increase in water yield (P = 0.95). Dashed lines represent the confidence limits at P = 0.95.

cant change in the early spring antecedent flow (discharge at beginning of snowmelt runoff event).

Bates and Henry (1928) concluded that snowmelt runoff on Watershed B following deforestation started an average of 12 days earlier than the pretreatment period. My analysis showed no significant effect of deforestation on the starting date of snowmelt runoff. However, I defined the start of runoff somewhat differently from the original study, which probably explains most of the discrepancy in the two results. In the present study the start of runoff was defined as 5 days in a row of consecutively higher flows.

For each year of their study Bates and Henry (1928) computed a half-flow date, or the date at which half the snowmelt runoff volume has passed the gage, and concluded that deforestation advanced the half-flow date an average of 3 days. My analysis showed that deforestation advanced the half-flow date an average of 5 days. The change was significant at the 99% level. During the first full year following treatment, the half-flow date on Watershed B was advanced 8 days. The slight advance in the snowmelt hydrograph was due to the increased exposure of the snowpack on Watershed B to solar radiation, causing earlier snowmelt and thus earlier runoff.

In the original study, Bates and Henry (1928) concluded that deforestation had no effect on the duration of the average annual snowmelt runoff event. The reanalysis supports this conclusion: no significant difference was found between the two periods.

Flow duration curves for Watersheds A and B were constructed for both pre- and posttreatment periods. The relationships were linearized by taking the natural logs of flow (the ordinate) and "percent time equalled or exceeded" (the abscissa). A least-

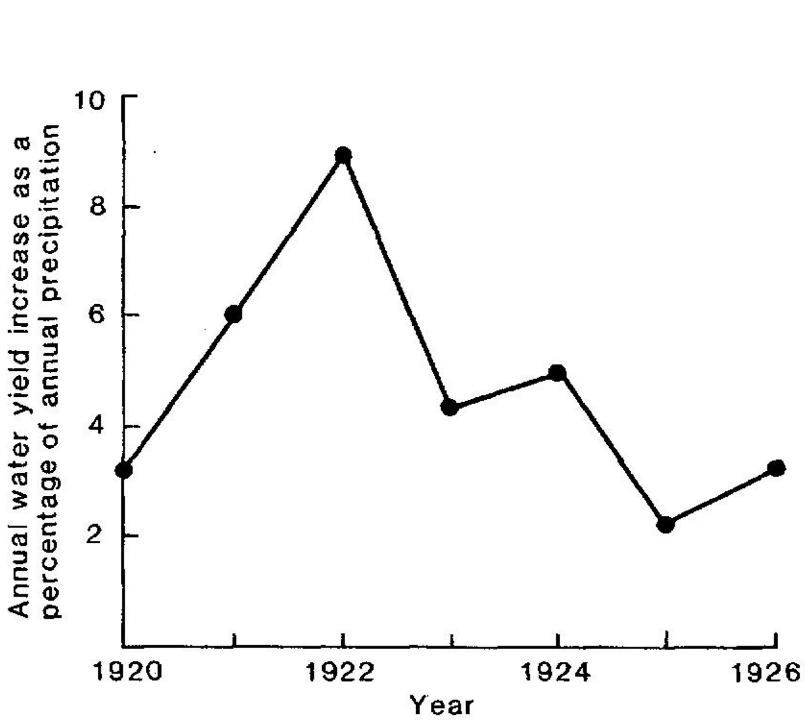

FIGURE 3. Annual water yield increase as a percentage of annual precipitation plotted against time for the posttreatment period.

squares linear regression was then performed on each of the four transformed data sets, resulting in best-fit linear equations of the form:

$$\log (Q) = \text{Intercept} - \text{Slope} * \log (\text{Time})$$

All four equations had R^2 values greater than 0.96.

Flow duration curves for Watershed B before and after treatment are shown in Figure 4. The slope of the linearized form of the flow duration curve for Watershed B increased 5% following treatment (highly significant at $P > 0.999$). Likewise, the intercept value of flow [where log (time) = 0 or % time equalled or exceeded = 1] increased 4% following treatment (highly significant at $P > 0.999$). The slope and intercept values for the linearized form of the Watershed A flow duration curves actually decreased slightly following the treatment of Watershed B. Thus, deforestation had a significant effect on the flow duration curve of Watershed B. Figure 4 suggests that the flow increases occurred primarily at the higher flows, an observation that was substantiated earlier in this paper.

CONCLUSIONS

Bates and Henry (1928) concluded that the increase in streamflow following deforestation was due to: (1) a decrease in interception of snow by tree crowns and (2) a slightly earlier snowmelt in the spring, reducing the evaporative losses. Hoover and Leaf (1967) questioned this conclusion and, using the original snow measurements of Bates and Henry (1928), showed that there was no change in snow storage on Watershed B following deforestation. I verified the results of Hoover and Leaf with a covariance analysis and found identical results. It is likely that the increase in snow evaporation, resulting from the increased exposure of the snowpack on Watershed B to solar radiation, nearly compensated for the decreased interception loss. Consequently, the cause of the increased streamflow on Watershed B was primarily decreased evapotranspiration, resulting in lower soil water recharge requirements (Bethlahmy, 1976). The excess water then became snowmelt runoff and finally streamflow. More rapid snowmelt and more efficient conversion of snowmelt to runoff also caused the increased streamflow.

The present study showed that many of the original conclusions stated by Bates

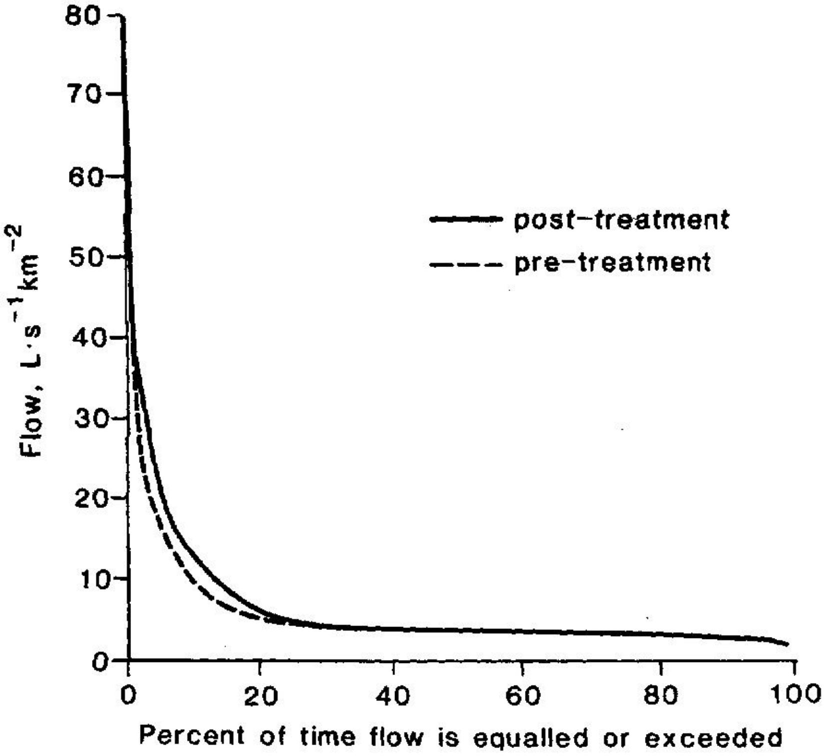

FIGURE 4. Flow duration curves for Watershed B before (1912–19) and after (1920–26) treatment.

and Henry (1928) are statistically supportable. However, a few of their conclusions could not be supported statistically. Of particular interest are the new findings that deforestation increased both the cumulative volume and duration of flows above a threshold of 20 L s^{-1} km^{-2} and significantly altered the flow duration curve of Watershed B.

It is hoped that these new findings will be useful for land-use hydrologists and watershed managers by contributing to their understanding of forest cover-hydrologic relationships. The results should also be of interest to individuals involved with forecasting streamflow in forested regions.

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