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The effect of aspen harvest and growth on water yield in Minnesota

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ABSTRACT Annual water yield increased following the clearcutting of a mature aspen forest in years 1-9 and year 14 of subsequent aspen regrowth. Maximum increases of 85, 117, and 88 mm year^{-1} occurred during the first 3 years of regrowth. Increases in streamflow volumes from snowmelt and early spring rains were minimal and more variable after harvest and regeneration. Most of the increases occurred during the leaf-on periods, but sporadic increases occurred during the fall-early winter recharge period as long as 15 years after harvest. Increases in water yield were best explained by changes in aboveground biomass, but precipitation, especially during the leaf-on periods, improved the relation. Increases in annual water yields became insignificant when aboveground biomass approached 57 tonnes ha^{-1} (17 percent of mature forest biomass at 14-15 years of age).

L'effet de la récolte et de la croissance du tremble sur les débits au Minnesota
RESUME Les débits annuels ont augmenté après la coupe à blanc d'une forêt mature de peuplier faux-tremble (tremble) au cours des années 1-9 et 14 de repousse du tremble. L'augmentation a été faible et irrégulier en temps de fonte et de pluies printannières. La plus grande partie de l'augmentation des débits s'est produite durant la période foliée, bien que des augmentations en automne-début d'hiver aient été observées sporadiquement jusqu'à 15 ans après la coupe. Le changement dans la biomasse aérienne explique le mieux l'augmentation des débits, bien que la précipitation améliore la relation, spécialement en période foliée. L'augmentation des débits fut réduite à rien quand la biomasse aérienne a atteint 57 tonnes ha^{-1} (17% de la biomasse de la forêt mature à l'âge de 15-17 ans).

INTRODUCTION

Cutting forests from well-drained mineral soils usually results in annual water yield increases (Hibbert, 1967; Bosch & Hewlett, 1982). This was also reported for the first year following an aspen clear cut in northern Minnesota (Verry, 1972). Subsequent declines in annual water yield were reported for another eight years (Paul & Verry, 1980) and were related to increases in woody biomass (Bernath *et al.*, 1982). This paper documents 15 years of aspen regrowth, the effect of more data years on relations between annual water yield and biomass, and considers changes in seasonal water yield. These extended data provide relationships suitable for regional hydrologic models. In addition, a modification of paired watershed calibration procedures is made for the case where one watershed exhibits greater retention/detention storage and deep seepage than the other.

This experiment is located at the Marcell Experimental Forest in north-central Minnesota (ca. 47°32'N, 93°28'W) in an area of relatively flat topography, strong continental climate, and extensive glaciation. Basin no. 4 was clearcut of a mature aspen-birch forest after 9 years of hydrological calibration against control basin no. 5. Detailed descriptions of the climate, soils, and vegetation are given in Verry (1972) and Verry & Timmons (1982). In general, the area receives 762 mm of precipitation annually, with 210 mm of water equivalent as snow. Average January and July temperatures are -14 and 19°C. The highest elevation is 438 m above sea level and ranges 9 and 16 m on basins 4 and 5, respectively.

FIG.1 The clearcut basin (4) is in the foreground with a black spruce bog in the middle. The boomerang-shaped opening in the middle of the spruce is a natural opening. The control basin (5) is immediately above (east).

The upland portion of basin no. 4 (26 ha) was harvested from December 1970 through August 1971. A centrally located bog (8 ha) that drains to 2 basin outlets was left undisturbed. Basin no. 4 has a north outlet stream and a south outlet stream. This basin lies on a continental divide (going through the bog) between the Hudson Bay and Mississippi River drainages (Fig.1).

The aspen-birch upland and the black spruce peatland form an upland-peatland unit typical of primary watersheds in lands surrounding the western Great Lakes in the United States and Canada. In the Lake States alone, the aspen-birch type covers 6.3 million ha, and organic soils an additional 6.9 million ha. The aspen-birch forest prior to harvest was 52 years old, had an aspen site index of 23 m at 50 years, and a basal area of 24 m^2ha^{-1}. The upland soil has a sandy loam surface texture in a glacial till that grades to clay loam from 0.3 to 3.5 meters. Subsurface flow through the A horizon is common, and some deep seepage through the C horizon and through 3-4 meters of sand underlying the till cap. Saturated sands may extend another 23 meters to igneous bedrock (Ely greenstone).

The control basin (no. 5) is 53 ha in total area, with a centrally located bog (6 ha) that drains the basin through a single stream. Five other wetlands are located at elevations above the central bog. These small wetlands and their sub-basins account for 35-40 percent of the total basin, and provide both retention and detention storage. They contribute to total basin streamflow during wet periods, but retain water for evapotranspiration at potential rates and deep seepage during average to dry periods.

METHODS

The annual water flow year was defined as 1 March - 29 February because streamflow from these primary basins ceases in January or early February due to freezing in the channel, and because snow is usually stored until late March melt. The precipitation water year was defined as 1 November - 31 October because snowpacks begin accumulation in early November and stay until late March. Seasonal precipitation and streamflow periods are defined in Table 1.

TABLE 1 Precipitation and streamflow periods analyzed

Season and Comment	*Precipitation period*	*Streamflow period*
Annual	*1 November-31 October*	*1 March-29 February*
Spring (near saturation)	*1 November-15 May*	*1 March-15 May*
Summer (leaf-on period)	*15 May-30 September*	*15 May-30 September*
Fall-winter (after leaf fall)	*1 October-31 October*	*1 October-29 Feb.*

Changes in streamflow were assessed by regressing basin 4 (clearcut) flow against basin 5 (control) flow for annual and seasonal periods. A calibration period of 9 years (1962-1970) was used prior to clearcutting basin 4. Subsequent changes in flow from basin 4 were estimated by subtracting predicted flow from measured. During the entire experiment (1962-1985), all three stream gages were replaced once (basin 4 north - October 1984, basin 4 south - October 1980, basin 5 - September 1982). Double mass curves (annual and seasonal) between precipitation and flow and between north and south gages on basin 4 were used to estimate possible leakage prior to streamgauge replacement (120° V-notch weirs with concrete cutoff walls). Leakage at basin gage 4 north, during the summer period prior to replacement, was estimated at 37 percent.

The retention/detention storage areas in basin 5 (35-40 percent) cause a smaller area-water-yield than from basin 4. These areas, however, do contribute after full retention conditions are met in wet spring and fall periods. This behaviour suggests that calibration equations to predict basin 4 flow from basin 5 are curvilinear rather than the linear equations normally found. Adding a squared term for basin 5 flow (a parabola) reduced the mean squared error of seasonal prediction equations as much as three-quarters, and residuals from actual values by one-half. The calibration equation for annual flows was not improved, but for consistency, the parabolic form was used throughout (Table 2).

TABLE 2 Coefficients of determination (r^2) and mean squared errors (MSE) for linear and parabolic prediction equations

	Linear		Parabolic	
Season	r^2	*MSE*	r^2	*MSE*
Spring	.99	27	.99	20
Summer	.97	31	.98	14
Fall & Winter	.93	32	.99	8
Annual	.96	97	.96	102

Woody biomass on the upland of basin 4 was measured on 4 m^2 plots spaced on centre every 61 m. Measurements were taken in 1968, 1971, 1972, 1974, 1976, 1978, 1980, 1982, and 1984. Intervening or adjacent years were interpolated or extrapolated. Wood, bark, and branch weights were estimated using equations of Perala (1973), Buckman (1966), and on-site equations (1980 onward). Tree and shrub foliage, herbaceous, and low shrub weights were estimated from representative stand type and size tables developed for northeastern Minnesota (Ohmann & Grigal, 1985).

Post-clearcutting changes in streamflow from basin 4 were explained with a multiple regression equation incorporating precipitation and the natural logarithm of aboveground biomass (dependent variables shown in Fig.2). Changes in flow that exceeded the 95 percent confidence band around calibration period predictions are shown.

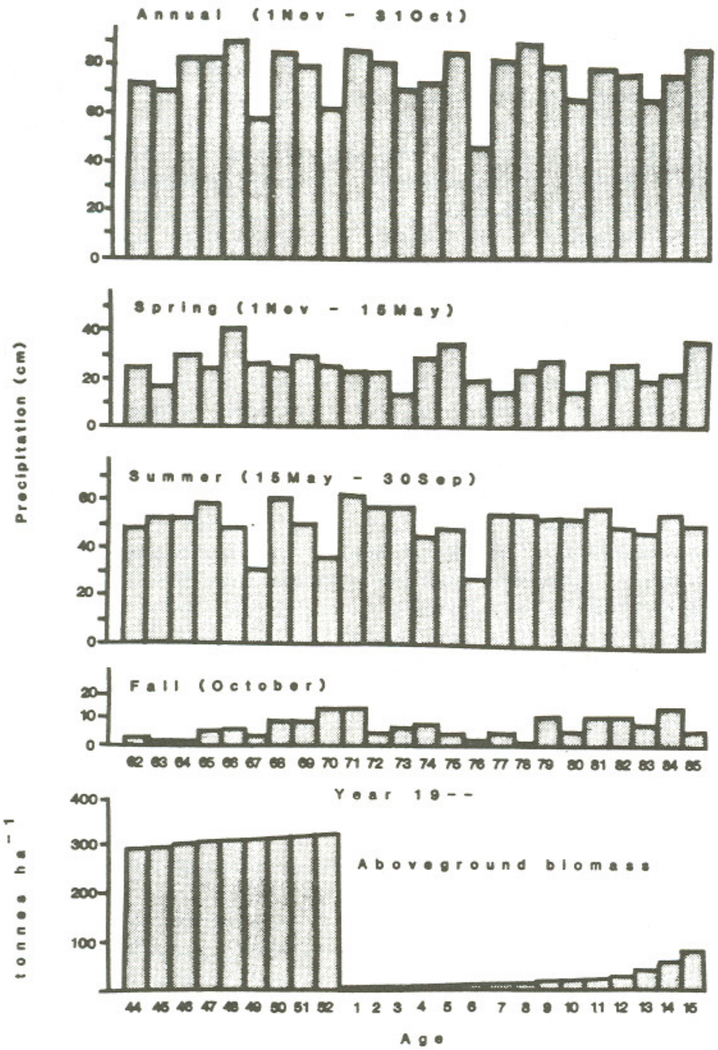

FIG. 2 Fifteen years of annual and seasonal precipitation, and aboveground biomass on the treated basin no. 4.

RESULTS AND DISCUSSION

Changes in streamflow

Parabolic calibration equations that predict basin 4 flow from basin 5 account for 96 to 99 percent of the variation and, on average, predict values within 4 to 10 mm for seasonal and annual streamflow. Clearcutting the upland of basin 4 caused changes in seasonal and annual flow different from predicted values. Changes in streamflow from basin 4 are shown in Fig.3 where deviations less than the 95 percent confidence interval about the calibration years are shaded. Annual flows increased as much as 117 mm and persisted for 9 years, but a significant increase 14 years after clearcutting also occurred. Most of the increased flow occurred during the leaf-on, high evapotranspiration summer period, but contributions from the fall-winter and spring periods combined to give a more consistent pattern of initial increase and subsequent decline for annual streamflow. Negative changes in seasonal streamflow were larger after clearcutting and during juvenile growth than under the mature aspen-birch canopies. It should be noted that seasonal and annual changes in streamflow are based on individual regressions; thus, seasonal changes do not necessarily add to the annual changes.

The small increases in flow during summers of 1974-1976 are associated with the three lowest years of summer precipitation following clearcutting. Large increases in the spring period for 1974 and 1975 are associated with 2 of the largest snowpacks following clearcutting. The decrease in spring period flow some seven years after harvest and regrowth was not expected. Possible leakage at the north gage of basin 4 might be the cause; however, double mass curve analyses of the north gage against precipitation indicate only minor amounts of leakage during the spring periods (less than 3 mm per year). An alternative explanation for the cyclical nature of spring period flow response lies in the large amount of logging slash left on-site, its subsequent decay, and additional water storage. Approximately 30 percent of the biomass in the mature aspen stand was cut and left in place. This included large cull trees (>60 cm diameter) and small unmerchantable trees (<10 cm diameter). Slightly over 100 tonnes ha^{-1} of nonmerchantable trees and branches from merchantable trees were left in place. This logging slash was initially elevated above the ground surface in an open, but tangled superstructure. "Climbing" through the area after logging was a more accurate descriptor than walking. Snow easily fell through the slash to the ground.

The open structure continued for about five years, when most of the limbs and stems had settled onto the ground surface. In 1977, an additional treatment was superimposed on the clearcut and regenerating basin no. 4. During the summer, the entire watershed was fertilized with 336 kg ha^{-1} of ammonium nitrate. Herbaceous (as well as shrub and tree) response was immediate and lush, adding additional litter to the ground surface. During the most recent biomass survey (August 1986), walking through the 15-year-old stand was unimpeded; stumps and limbs were incorporated into the forest floor by decay and scattering by bears.

The slash left after logging was approximately three times the weight of the forest floor (estimated from Alban *et al.*, 1978). I speculate that the elevated structure of the slash did not interfere with the infiltration of snowmelt during the first five years, but that water storage was increased when the partially decayed slash settled on the ground and fertilizer-induced herbaceous growth was added to it. This may have reduced streamflow volumes during the snowmelt and early spring rain period, and may have acted as a mulch during the high evapotranspiration summer period. With the passage of 15 years after cutting, the added organic matter was incorporated by mineralization (and red worm mixing), and the storage properties of the forest floor approached mature forest conditions. Unfortunately, a direct measure of the forest floor condition was not made throughout this time. However, a casual survey of soil conditions in October 1986, at 36 sites each on the treated and control watersheds revealed an O horizon of 4 cm on the control watershed and an A_1 horizon of 7.5 cm on the treated watershed.

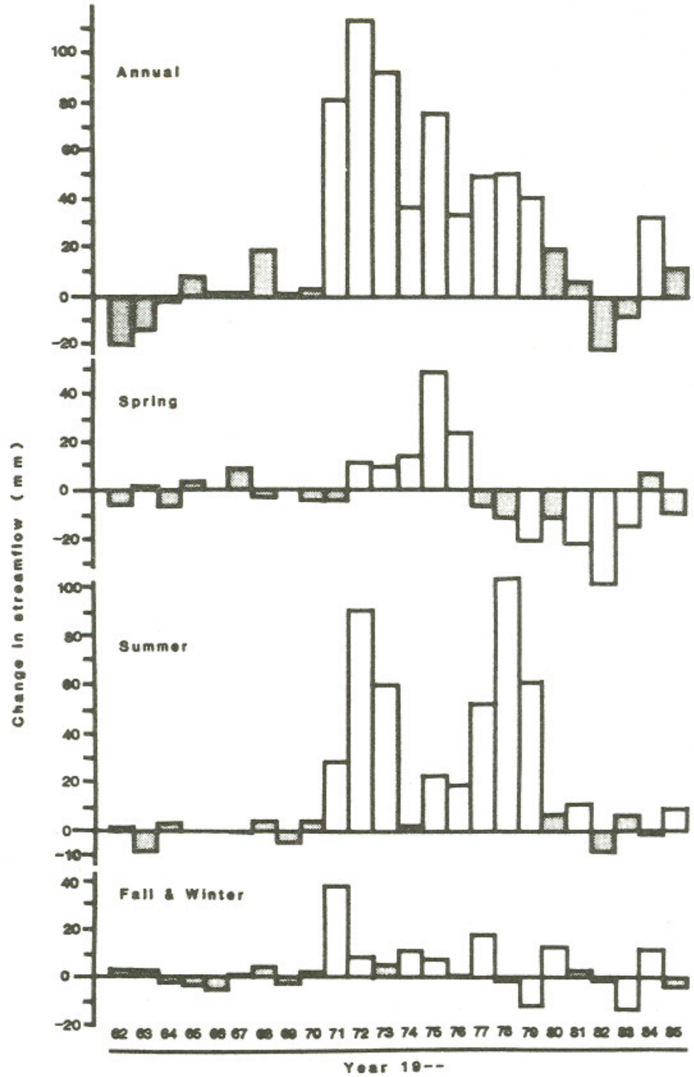

FIG. 3 Annual and seasonal changes in streamflow on treated basin no. 4 in relation to the calibration control (basin no. 5). Shaded bars are within the 95% confidence interval for the calibration period (1962-70), and thus clear bars are significantly different. Clearcutting was completed on basin no. 4 during the growing season in 1971.

Causes of streamflow change

The causes of streamflow can be described by multiple regressions with precipitation and the natural logarithm of aboveground biomass. Equations of this form are significant at the 1 percent level of probability for the annual, summer, and fall-winter periods, and they explain 54, 52, and 39 percent of the variation. During the spring period, changes in flow are not well explained by precipitation and biomass alone (19 percent probability level) where only 11 percent of the variance is explained. Perhaps measures of changes in the forest floor, as discussed above, would improve this prediction. Most of the annual streamflow change occurs during the summer. During this period, the precipitation and Log_e biomass terms are significant at the 10 and 0.5 percent levels. All equations to predict streamflow change and their significance are shown in Table 3.

TABLE 3 Equations to predict changes in streamflow following aspen clearcutting and regrowth as a function of precipitation and biomass for annual, spring, summer, and fall periods (probability level %)

Change in streamflow (mm)	*Constant*	*Precipitation (mm)*	*Log_e Biomass ($t\ ha^{-1}$)*
Annual (.2)	*+74.35 (21)*	*+.0882 (20)*	*-35.800 (.2)*
Spring (19)	*+14.66 (58)*	*+.0858 (33)*	*-12.980 (10)*
Summer (.2)	*-37.25 (41)*	*+.0709 (10)*	*-14.450 (.5)*
Fall-Winter (1.3)	*+28.20 (2.2)*	*+.0949 (15)*	*-10.600 (1)*

It should be noted that snowmelt peak rates of flow can double in size. We speculate that this occurs because long wave radiation out of the aspen sucker stand melts the snowpack more quickly than from mature stands. This effect may last as long as 15 years (Verry *et al.*, 1983). It was also reported in that reference that March and April snowmelt volumes did not change for 9 years after clearcutting. On the average they did not, but the linear regression analysis used then did not recognize the cyclic pattern shown in this analysis (Fig.2).

Annual changes in streamflow are useful for modeling the impacts of timber harvesting on water yield. TIMWAT is such a model where annual water yield is predicted over a series of years (Bernath *et al.*, 1982). It used data from basin 4 to develop a water yield increase/decrease response following clearcutting and aspen regrowth. The original equation was based on precipitation (P in mm) and aboveground biomass (B in tonnes ha^{-1}), using 9 years of data:

$$Q = 99.05 + 0.11\ (P) - 58.72\ (\log_e B) \qquad (1)$$

A 15-year data base produced a different equation:

$$Q = 74.35 + 0.09\ (P) - 35.80\ (\text{Log}_e\ B) \qquad (2)$$

The additional six years of data extended the response in streamflow to higher biomass values at zero change (Fig.4), and lengthened the years of positive response by 3-4. The normalized impact of aspen clearcutting and regrowth reaches zero change after 14 years of growth assuming an annual precipitation of 800 mm.

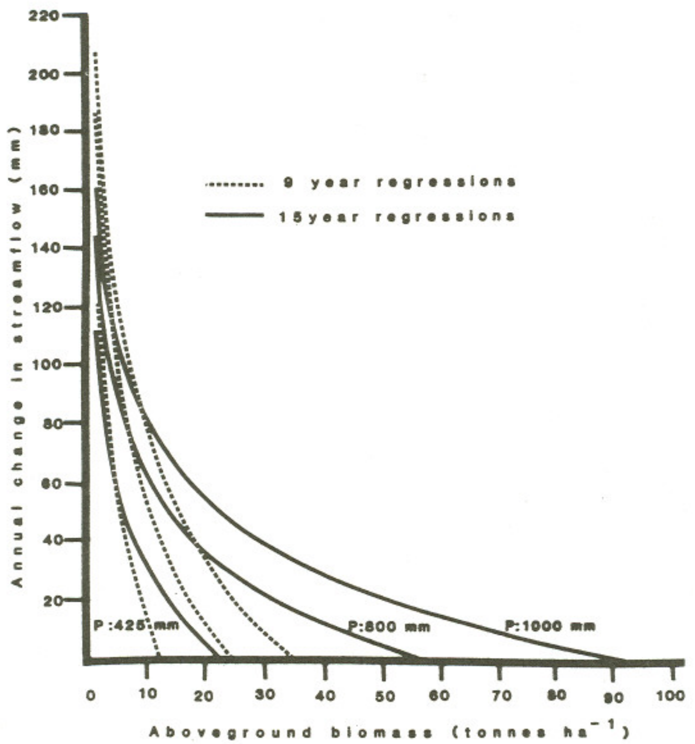

FIG.4 The relation between changes in annual streamflow, aboveground biomass, and annual precipitation (P) for 9- and 15-year data sets. Levels of annual precipitation increase from left to right for both the 9-year and 15-year regressions.

These analyses have demonstrated that: (a) watersheds with unequal detention storage can be calibrated with curvilinear regressions, (b) most of the streamflow response occurs during the summer period, (c) logging slash accumulation and decay may cause cyclic responses over 15 years during the saturated spring period, and (d) longer data sets can modify flow response relations.

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