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First-Year Water Yield Increase After Forest Cutting:

An Alternative Model

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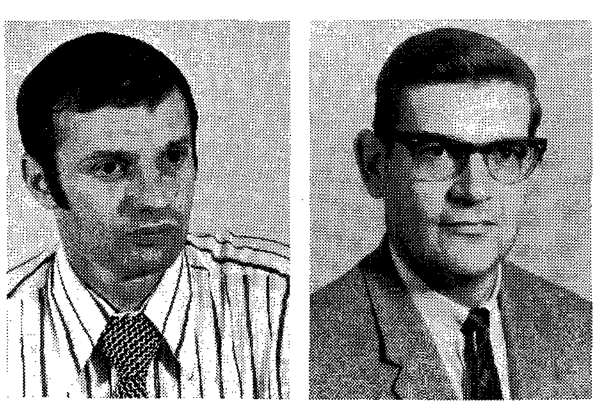
ABSTRACT—Analysis of the biologic and hydrologic processes suggests a more logical and general nonlinear model than the simple linear one previously used. Predictions of water yield increase based on the alternative model agree with those of the earlier model for heavy reductions in stand density, but are also forced to be non-negative for light reductions in stand density.

In 1966, Hibbert (*3*) reported on a worldwide survey which included first-year water yield measurements for 30 experimental catchments after forest cover changes. The relationship of first-year increases to percent reduction from full forest cover proved quite variable. With reference to temperate climates, he noted that ". . .most of the points lie below a line extending from the origin to a yield increase of 450 mm at 100 percent reduction in cover." This work offered some idea about expected maximum yield changes following various levels of forest cutting. Douglass and Swank (*1*) subsequently computed a linear regression combining the results of 22 experiments in the Appalachian highlands. Their prediction equation is $Y = -1.39 + 0.13X$, where Y is the first-year streamflow increase after treatment (inches) and X is percent basal area reduction of fully stocked hardwood stands. The data include wide differences in slope, aspect, climate, and vegetative conditions.



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Although this linear model is useful within the usual range of heavy reductions in stand density (greater than 25 percent), we felt the need to develop a more general rule-of-thumb model that would be logically consistent over the full range of possible forest-cover removal. The ideal model would describe a curve similar to Douglass and Swank's within the domain of the data presented by them, but would also force first-year increase to be non-negative for small values of the independent variable.

A more generalized model would also be in keeping with existing knowledge of forest evapotranspiration processes. Changes in vegetal cover influence the annual water yield of drainage basins through changes in rates of land evaporation; that is, through changes in rates of transpiration through stems and leaves, changes in crown and forest floor interception losses, and bare soil evaporation. Response of total evapotranspiration rates to forest cover changes is such that all of these (except minor changes in soil evaporation) are bound to be reduced by even limited cutting of trees and shrubs. Removal of one tree, thus eliminating most of its crown interception loss and severing its transpiration stream completely, causes a net reduction in effectiveness as an evaporative heat sink. Even though nearby trees may assume some of the evaporative loss because water in the root zone is slightly more available, it is highly unlikely that net loss per unit area would remain the same, and even more unlikely that evaporative losses would increase. However small the reduction in net evapotranspiration, the change can result only in an increase in net water yield by the basin. When the basal area removed is less than 10 percent of the total stand, increases are usually impossible to detect by available hydrological methods. Although changes in stream discharge may be only a few percent and well within the measurement error of most gaging stations, results from watershed experiments involving various levels of forest clearing and planting indicate that response in water yield to small reductions in cover is not linear. No experiments indicate that the response to cutting will be negative, nor

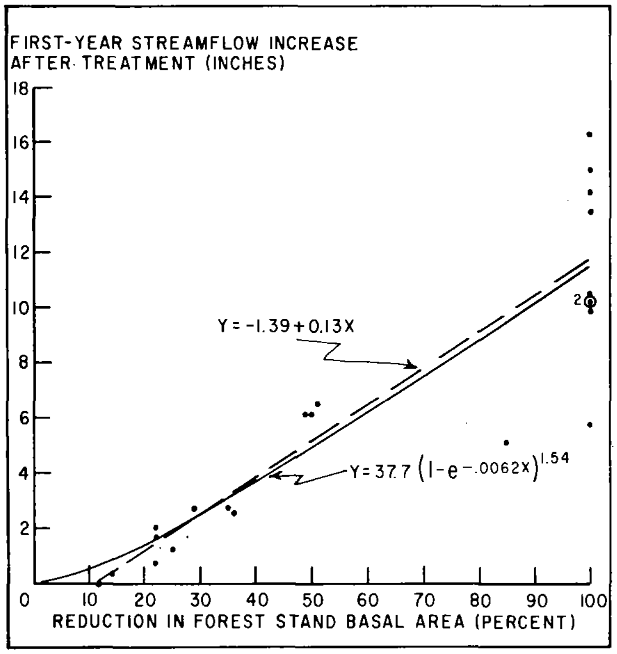

Figure 1. First-year streamflow increase related to reduction in forest stands.

does the limited hydrologic precision possible in such experiments allow a conclusion that changes in yield in this realm would be zero.

Grosenbaugh (*2*) examined several mathematical functions capable of describing a wide array of curve forms. He included one generalized function that "conveniently unified" a number of functions previously used to describe growth phenomena. The function is of the form:

$$Y = H + A(1\text{-exp}[-B(X\text{-}G)])^{M+1}, \text{ where}$$

X = the independent variable,
H = the lower asymptote,
A = the difference between the upper and lower asymptotes,
B and M jointly control both the curvature and inflection point, and
G is the value of X for which Y = H.

We selected this general model because of its flexibility.

With percent basal area as the independent variable and first-year streamflow increase as the response variable, the lower asymptote is zero and G is logically zero. This results in a model of the form:

$$Y = b_0 + b_1(1-\exp[-b_2X])^{b_3}, \text{ where}$$

$b_0 = 0$, and the remaining three parameters are estimated from the data.

We fitted the model to Douglass and Swank's data using an updated version of the nonlinear least-squares computer algorithm discussed by Marquardt (*4*).

The two models produced almost identical predictions except in the lower range of the independent variable (*Figure 1*). The sums of squared deviations ($\Phi = \varepsilon\ (Y_i - \hat{Y}_i)^2$) are 112.6 for the linear, and 113.8 for the nonlinear models. Predicted yield increases are all within 0.2 inch of each other at basal area removals greater than 15 percent; this is well within the experimental error of most catchment experiments. Both models were fitted to untransformed data, giving more weight to observations occurring in the upper range of the independent variable, since the variance of the response variable obviously increases with basal area removed (*Figure 1*).

No attempt was made to attach biological or hydrological significance to coefficients other than the lower asymptote, b_0. In similar situations there may be reason to fix the upper asymptote as well. In our case, however, the estimated upper asymptote, b_2, would be approximated well out of the range of the independent variable (near X = 750). Hence, our derived model is merely a segment of a sigmoidal curve with lower asymptote zero and upper asymptote of 37.7 inches.

The general model is not offered as the ultimate means of describing the effect of forest removal on first-year streamflow. As knowledge accumulates, simpler and more specific algebraic expressions probably can and should be used. The model should be applied with caution in instances of patch clearcutting, strip cutting, or in single tree selection where a substantial basal area is removed. It should serve well enough, however, where a small percentage of the basal area is removed, despite some uncertainty about the exact response to a range of silvicultural and harvesting techniques. Two advantages of the model are:

(1) it provides logical predictions over the entire range of the independent variable; and

(2) it is so flexible that other curve forms (based on additional data) will require only new estimates of the parameter values, rather than new algebraic forms as well.

More precise data will undoubtedly reveal some significant differences in equation parameters accompanying such gross vegetal differences as hardwood-versus-conifer stands and the large differences in total phytomass that characterize a mature cove hardwood type and a mature but scrubby oak-hickory type. The end result should be a family of curves, all passing through zero, but diverging over most of the range from 25 to 100 percent reduction in basal area. ■

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