DETECTING THE EFFECTS OF FOREST HARVESTING ON STREAMFLOW USING HYDROLOGIC MODEL CHANGE DETECTION

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Abstract.—Knowledge of the effects of forest management on hydrology primarily comes from paired-catchment study experiments. This approach has contributed fundamental knowledge of the effects of forest management on hydrology, but results from these studies lack insight into catchment processes. Outlined in this study is an alternative method of change detection that uses a simple rainfall-runoff model to generate hypotheses about the impact of forest harvesting on streamflow processes. We develop and apply our approach in a managed headwater catchment in the Fernow Experimental Forest in West Virginia. Monte-Carlo simulations are used to generate hydrologic model parameter distributions prior to and following clearcut harvesting. Differences in the distributions of pre- and post-harvest models are proxy for changes in the catchment processes involved in streamflow generation. Changes in model parameters show that harvesting increased the volume of water contributed to catchment storage, thereby increasing baseflow volume, decreasing the time for the catchment to drain, and increasing stormflow response. The change detection approach presented in this study is a useful way to advance our understanding of catchment processes and the effects of disturbance on hydrology.

INTRODUCTION

The effect of forest management on catchment-scale hydrology remains a central research interest in water resources management worldwide (Bosch and Hewlett 1982). There is little doubt of the relationship between forests and hydrology, but the sustainability of water resources depends on both the ability to detect changes that occur following forest harvesting and understanding process-level changes in runoff generation, storage, and movement of water through forested catchments.

Traditional approaches for discerning the effects of forest management on hydrology have focused on the paired-catchment approach, where statistical models relate streamflow in a harvested catchment to streamflow in an undisturbed catchment. Results from a plethora of these studies conducted across the globe generally show streamflow increases following harvesting (e.g., Bosch and Hewlett 1982, Campbell and Doeg 1989, Moore and Wondzell 2005, Eisenbies and others 2007). Changes to process-level hydrology, however, are inferred rather than measured as the paired-catchment method relates streamflow measured at the outlets of two watersheds. Although this approach has greatly increased understanding of the effects of forest management on hydrology, it has not illuminated catchment processes.

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Studies evaluating the effects of forest harvesting on streamflow generation mechanisms are limited due in part to the difficulties associated with observing and measuring catchment processes. Though advances using stable isotope hydrology (e.g., Sklash and Farvolden 1979) have been useful in identifying water sources, partitioning stormflow, and determining water residence time, comprehensive understanding of process-level changes are limited in space and time.

In this study we use a simple rainfall-runoff model to simulate the effects of forest harvesting on daily streamflow to generate hypotheses regarding process-level changes in catchment hydrology resulting from disturbance. Pre- and post-harvest models are compared to shed light onto how forest harvesting affects catchment processes and streamflow generation.

METHODS

STUDY SITE AND HYDROMETRIC DATA

Long-term research conducted at the Fernow Experimental Forest offers a unique opportunity to develop and test the efficacy of detecting change using hydrologic models. The Fernow (Fig. 1) is located in West Virginia and was established in 1934 by the U.S. Department of Agriculture Forest Service, to study the effects of forest and watershed management in the northern and central Appalachian Mountains. Results from forest harvesting studies conducted at the Fernow show that forest harvesting can increase annual streamflow and is related to both the intensity of harvest and basal area (ba) removed (Adams and others 2004).

The Fernow annually receives on average 1,480 mm of precipitation that is evenly distributed throughout the year. Slopes are steep and average elevation for the basin is 762 meters. Vegetation in the Fernow is characterized as mixed mesophytic, currently dominated by oaks (*Quercus* spp.), yellow-poplar (*Liriodendron tulipifera*), and sugar maple (*Acer saccharum*).

This study was conducted using daily streamflow and climate records for Fernow watershed 7 (WS7). WS7 is a small (0.24 km^2) east-facing headwater catchment that has continual streamflow monitoring since

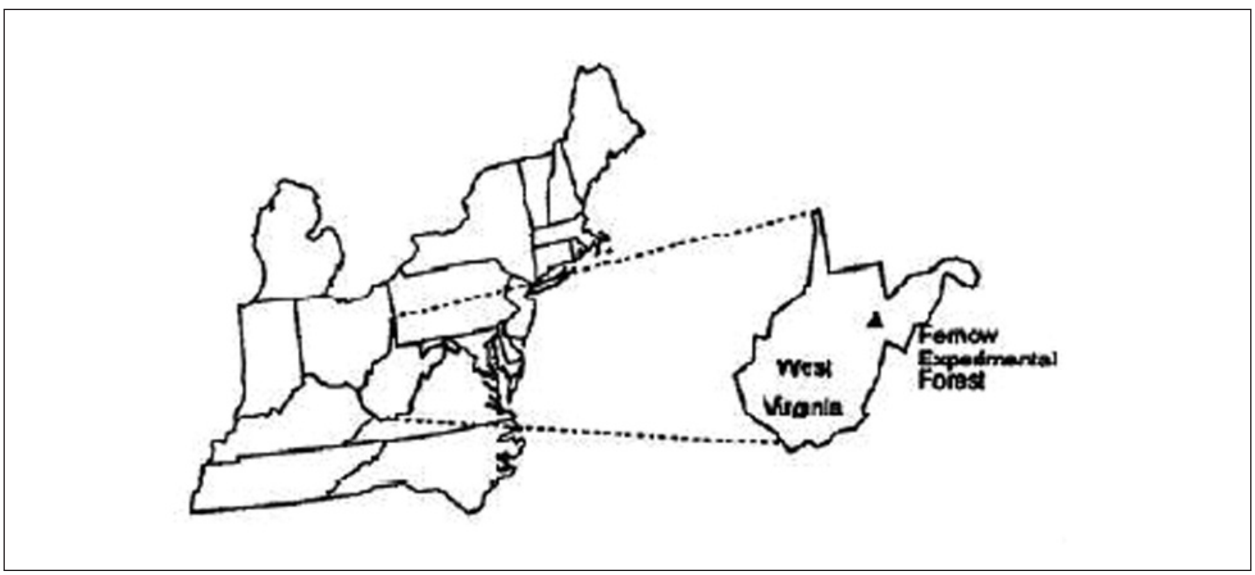

Figure 1.—Location of the Fernow Experimental Forest, West Virginia.

November 1956. The upper half of WS7 was clear-cut harvested from November 1963 to March 1964, removing approximately 49 percent of the watershed basal area. WS7 was maintained barren with herbicides from May 1964 through October 1969. The remaining 51 percent basal area was removed from the lower half of the catchment during a second harvesting treatment applied between October 1966 and March 1967. The entire catchment was maintained barren with herbicides until October 1969, when the catchment was allowed to recover naturally. The extent of the current study, however, is limited to the pre-harvest period (November 1956-October 1963) and the period following the first harvest treatment (November 1963-October 1966).

HYDROLOGIC MODELING AND IDENTIFICATION

The Identification of unit Hydrographs And Component flows from Rainfall, Evaporation, and Streamflow data (IHACRES) (Jakeman and others 1990) model was used to simulate daily streamflow prior to and following forest harvesting in a headwater catchment. IHACRES simulates streamflow using daily inputs of areal precipitation and air temperature. The model consists of two modules, a nonlinear rainfall loss module that converts rainfall to effective rainfall, the proportion of rainfall that eventually becomes streamflow, and a linear unit hydrograph module that represents the transformation of effective rainfall to streamflow (Fig. 2). The model is defined by six parameters; three (t_w, f, and c) are used in the nonlinear module and the remaining three (t_q, t_s, v_s) relate to the linear module (Post and Jakeman 1999). The parameter "t_w" (days) is the time constant governing rate of water loss from the catchment at 20 °C, f varies the rate of catchment water loss due to a unit change in temperature, and c (mm) is a scale parameter that minimizes bias so that the volume of effective rainfall is equal to the total streamflow. The parameter "t_q" (days) is the time constant governing the rate of quickflow recession of streamflow, t_s (days) is the time constant governing the rate of slowflow or baseflow recession of streamflow, and v_s is the ratio of slowflow to total flow. The parameter set, tau = {t_w, f, t_q, t_s, and v_s}, is determined directly from the observed rainfall, streamflow, and temperature while c is optimized such that total volume of modeled effective precipitation is equal to total volume of observed streamflow. Detailed descriptions of the IHACRES model can be found in Post and Jakeman 1996 and 1999.

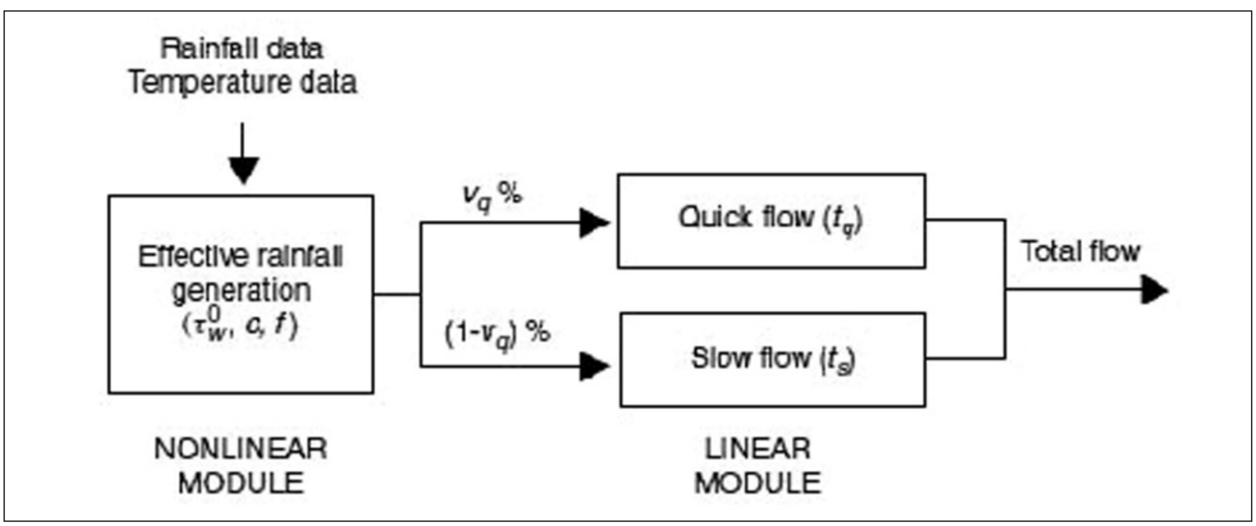

Figure 2.—Schematic of the IHACRES rainfall-runoff model. Parameters are defined as follows: t_w is the time constant (days) governing rate of water loss from the catchment at 20 ºC; f is the rate of catchment water loss due to a unit change in temperature (unitless); c (mm) is a scale parameter used to minimize bias so that the volume of effective rainfall is equal to the total streamflow; t_q is the time constant (days) governing the rate of quickflow recession of streamflow; t_s is the time constant (days) governing the rate of slowflow or baseflow recession of streamflow; and v_s is ratio of slowflow to total flow (from Kokkonen and others 2003).

IHACRES was used to simulate daily streamflow in WS7 using long-term precipitation and air temperature records (3,283 days). The IHACRES model was calibrated using observed daily streamflow measured at the outlet of WS7 for the pre-harvest (2,188 days) and post-harvest (1,095 days) periods.

Many studies have demonstrated the difficulty of identifying, calibrating, and validating hydrologic models. Uncertainties in model structure, parameterization, and observed data make the search for an optimal parameter set identified from manual calibration not practical and model validation impossible (Oreskes and others 1994). Therefore, we used the generalized likelihood uncertainty estimation (GLUE) (Beven and Binley 1992) method to identify populations of appropriate models used for this analysis. GLUE is a Bayesian-like parameter estimation method that allows the conditional assessment of model uncertainty using prior knowledge of model performance to construct probability distributions for each set of model parameters. GLUE requires Monte-Carlo simulations using a large number of parameter sets to assess the performance of each model for simulating streamflow relative to observed streamflow. We used Monte-Carlo simulations to randomly sample values for each parameter from non-informative uniform distributions to generate 5,000 candidate models. The Nash-Sutcliffe measure of efficiency (NSE) (Nash and Sutcliffe 1970) was used to evaluate the goodness of fit between observed and simulated streamflow and identify populations of the best performing models. We used a NSE > 0.4 to define behavioral models, those models that acceptably reflect the behavior of the modeled system (Beven 2001).

PARAMETER CHANGE DETECTION

The populations of model parameters identified from the best fitting models (Monte-Carlo) were used to develop 'behavioral' distributions that show probable and acceptable ranges of the likely model parameters that have good agreement between simulated and observed streamflow for the pre- and post-harvest periods. Box and whisker plots and the nonparametric two-sided Wilcoxon rank sum test were used to test the null hypothesis that there are no differences between pre- and post-harvest parameter distributions. As model parameters are proxy for the state variable responsible for streamflow generation, rejection of the null hypothesis suggests changes in the underlying processes that control the timing and distribution of runoff during respective periods.

RESULTS

ANNUAL PRECIPITATION AND STREAMFLOW CHANGES

Precipitation and streamflow varied by year and season (Fig. 3). Water year 1958 (1 October 1957 - 30 September 1958) (WY 58) and WY 57 were the wettest and driest years during this study with approximately 1,751 and 1,287 mm, respectively. The largest peakflow event (52 mm) occurred on 5 March 1963, during the preharvest period. Runoff ratios, calculated as the ratio of total streamflow to total precipitation, averaged 56 percent (51-59 percent) and 52 percent (40-61 percent) during the pre- and post-harvest periods, respectively. Streamflow measured during WY 60 exhibited nonstationarity and was excluded from analyses. Nonstationarity implies systematic change in mean and/or variance over time and violates assumptions of time-series analysis.

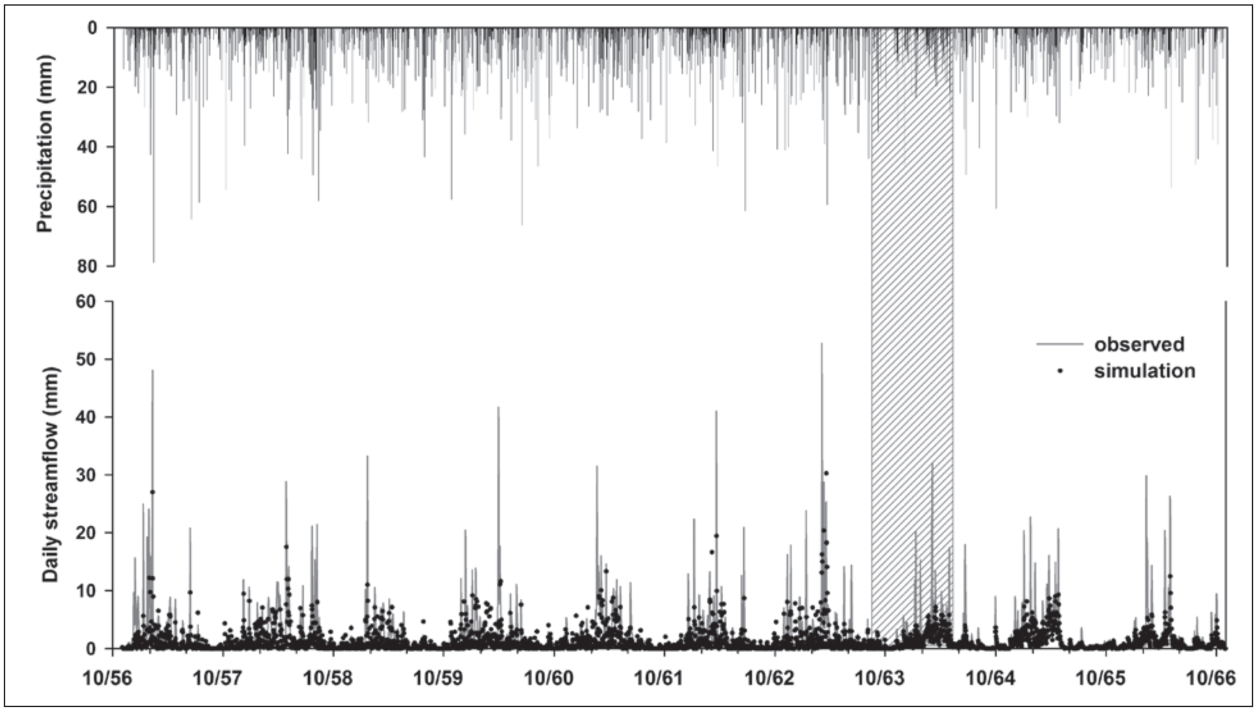

Figure 3.—Daily precipitation and observed and simulated streamflow during study period for Watershed 7 of the Fernow Experimental Forest, WV. The plotted simulated streamflow represents the median streamflow of all behavioral models identified by GLUE. Shaded area notes harvest treatment period.

CHANGES IN PARAMETER DISTRIBUTIONS

The two-sided Wilcoxon rank sum test was used to detect decreasing and increasing shifts between pre- and post-harvest parameter distributions. Significant differences (alpha = 0.05) between pre- and post-harvest distributions were detected for linear module components while parameters in the nonlinear effective rainfall module were robust to change (Table 1). Parameter distributions for v_s and t_q increased while ts decreased following forest harvesting (Fig. 4). Median values for post-harvest parameter distributions increased by 31 and 141 percent, respectively, for v_s and t_q, and decreased by 33 percent for the parameter t_s.

Table 1.—Pre- and post-harvest model parameter distributions from Monte-Carlo simulations. +++ (---) signify significant increases (decreases) or no change (n/c) between pre- and post-harvest distributions. See methods section for definition of IHACRES model parameters.

Model Parameter	Median value of pre-harvest parameter distributions (1956-1963)	Median value of post-harvest parameter distributions (1963-1966)	Change in post-harvest parameter distributions relative to pre-harvest
t_w	15	15	n/c
f	2	2	n/c
v_s	0.6	0.8	+++
t_s	7	5	---
t_q	0.5	1	+++

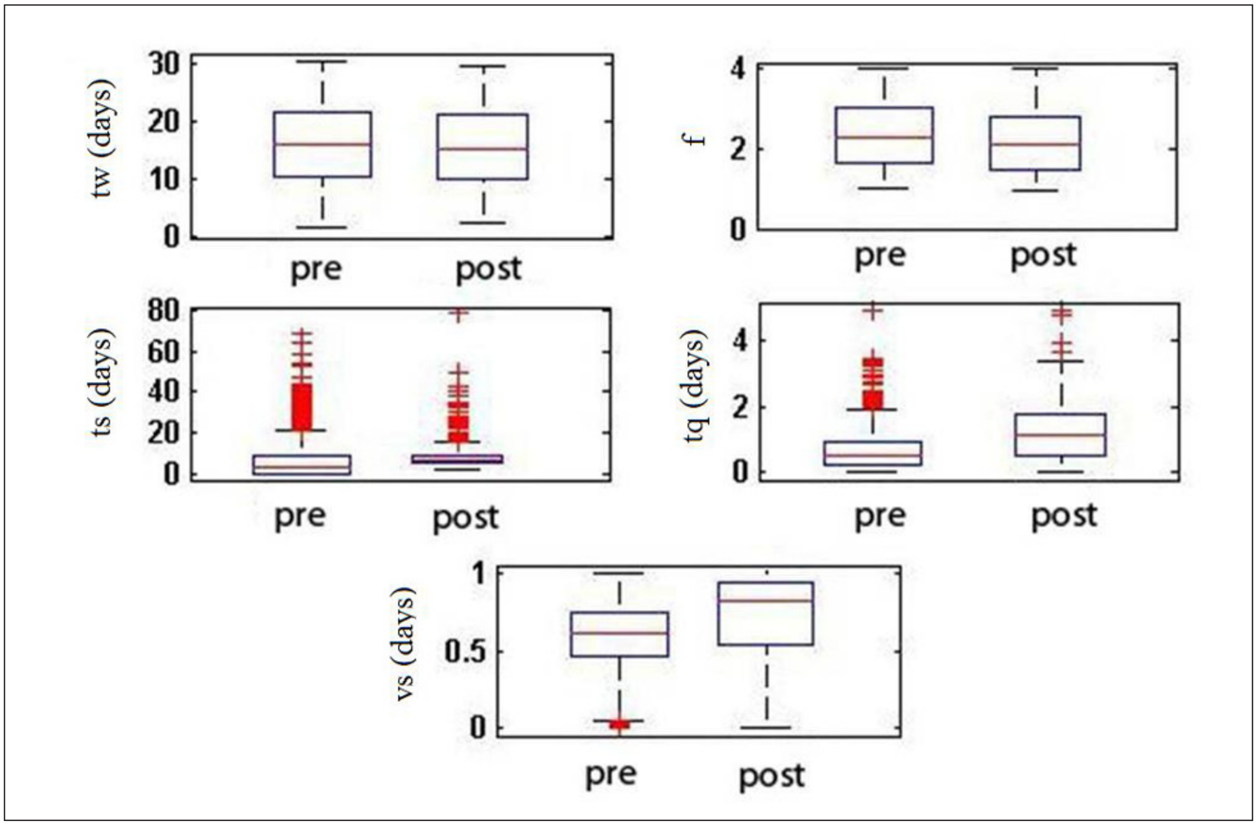

Figure 4.—Box and whisker plots for pre- and post-harvest parameter distributions for model simulations using the IHACRES model.

DISCUSSION

MODELING THE EFFECTS OF FOREST HARVESTING ON STREAMFLOW

Behavioral populations of the IHACRES model successfully captured the shape and timing of the hydrograph during pre- and post-harvest periods but consistently underestimated peak stormflows. Errors in simulated streamflow were attributed to model structure, parameterization, and uncertainty and measurement error in input data.

The parameter set tau = $\{t_w, f, v_s, t_s, t_q\}$ characterizes the dynamic hydrologic response of a catchment (Fig. 2) (Kokkonen and others 2003). Monte-Carlo simulations were used to construct probable distributions of tau to model the hydrologic responses of WS7 during pre- and post-harvest periods. Different distributions of tau between these periods are proxy for changes in the catchment processes resulting from forest harvesting.

Significant changes in linear module parameters indicate that a larger proportion of rainfall is contributed to catchment storage and streamflow generation. Forest harvesting typically augments streamflow by reducing canopy interception and transpiration, and modifying soil moisture conditions (e.g., Bosch and Hewlett 1982, Eisenbies and others 2007). These effects are reflected by increases in parameters v_s, the proportion of streamflow derived from baseflow, and t_q, the rate of quickflow recession; and by decreases in t_s, the rate of baseflow recession. Changes in model parameters, therefore, show that harvesting increases the volume of water contributed to catchment storage, thereby increasing baseflow volume (v_s), decreasing the time for the catchment to drain (t_s), and increasing stormflow response (t_q). These responses were shown by Rothacher (1973) and Adams and others (1991). Rothacher (1973) showed increases in soil moisture and streamflow following partial (25-percent area) clear-cut harvesting of a forested catchment in the Pacific Northwest. Soil moisture averaged more than 10 cm greater in harvested areas of the watershed and streamflow increased by as much as 160 mm.

Our results contrast with those of Post and others (1996), who used the IHACRES model to evaluate land-cover changes on the hydrologic responses of Picaninny Creek, a mountain ash (*Eucalyptus regnans*)-dominated catchment in south east Australia. Model parameters that govern the rate of catchment drying (t_w), recession (t_q and t_s), and volumetric throughput of quickflow and slowflow (v_s) did not change between pre- and post-harvest periods. These outcomes suggest that (1) harvesting-induced changes were relatively small compared to natural variability (Post and Jakeman 1996); and/or (2) the presence or absence of mountain ash was not important in determining the hydrologic response of Picaninny Creek (Post and Jakeman 1996).

The changes in parameter distributions in our study clearly show that forest harvesting altered the hydrologic response of WS7 in the Fernow Experimental Forest during the first harvesting period. Differences in hydrologic responses between WS7 and Picaninny Creek are explained mostly by differences in soil depth and harvesting treatments and in part by vegetation and location. For example, soil depth in the Fernow averages 1 meter (Adams and others 2004), in contrast with 10 to 15 meters in Picaninny Creek (Post and Jakeman 1996). Soil depth is a primary factor determining how fast subsurface water moves through a catchment. The deeper soils in Picanniny Creek translate to a baseflow recession of ~45 days (Post and Jakeman 1996), compared to 5 days during the post-harvest period in WS7 (Table 1). In addition, Picaninny Creek was burned and reseeded immediately following harvesting, whereas WS7 was treated with herbicides and left barren for 5 years following harvesting.

WHERE DO WE GO FROM HERE?

This study serves as a useful proof-of-concept to show the utility of hydrologic modeling for detecting and discerning the effects of forest management on catchment hydrology. The next step is to extend our approach to model the effects of the subsequent management activities, such as harvesting, on the lower half of the catchment (1966) and on the natural recovery period commencing in 1969. In addition, we are conducting catchment- and hillslope-scale experiments using stable isotopes to characterize residence time, partition hydrographs, and identify the sources of streamflow generation.

CONCLUSION

The change detection approach presented in this study is a useful way to advance our understanding of catchment processes and the effects of disturbance on hydrology. Results from this study corroborate the hypothesis that forest harvesting increases streamflow by decreasing the volume of precipitation lost to interception and transpiration, thereby increasing antecedent soil moisture and streamflow. Though our approach was developed and tested to evaluate the effects of disturbance in a managed forest ecosystem, we contend that our method is applicable for evaluating and forecasting the effects of other disturbances, such as insect denudation and directional climate change, on streamflow and catchment processes.

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