JOURNAL OF
ENVIRONMENTAL HYDROLOGY

The Electronic Journal of the International Association for Environmental Hydrology
On the World Wide Web at http://www.hydroweb.com

VOLUME 19 2011

# EVALUATING THE HYDROLOGIC EFFECTS OF FOREST HARVESTING AND REGROWTH USING A SIMPLE RAINFALL-RUNOFF MODEL

**Nicolas Zegre**
Division of Forestry & Natural Resources
West Virginia University
Morgantown, WV, USA

*Much of what is known about the effects of forest management on catchment-scale hydrology comes from the paired watershed study approach. However, it is often impractical or impossible to establish suitable control watersheds with respect to time, land ownership, expense, and timber market pressure. As an alternative, a simple rainfall-runoff model is used to explore the hydrologic response of a watershed to forest harvesting, herbicide treatments, and natural regrowth. The model is applied and tested to a managed watershed at the Fernow Experimental Forest, West Virginia. Long-term daily precipitation, air temperature, and streamflow records were used to generate 14 models that successfully represented hydrologic responses over fifty years of landcover changes. The model parameter governing transpiration losses changed following harvesting and herbicide application. Parameters that govern the rate of recession of water from the watershed exhibited little change. This study shows the utility of rainfall-runoff models to discern the effects of forest management on watershed hydrology and can be a useful tool for resource managers where paired watershed studies are not possible.*

## INTRODUCTION

The effect of forest management on catchment-scale hydrology remains a central research interest in water resources management worldwide (Bosch and Hewlett, 1982; Eisenbies et al., 2007). The sustainability of water resources depends on both the ability to detect changes that occur following forest harvesting and understanding changes in processes that control runoff, storage, and movement of water through forested catchments. Here we focus on the second: understanding how forest management changes the water balance and processes at the catchment scale.

Traditional approaches for discerning the effects of forest management on hydrology have focused on the paired watershed approach, where statistical models relate streamflow in a harvested watershed to streamflow in an undisturbed watershed. Results from several decades of these studies conducted across the globe generally show streamflow increases following harvesting (e.g. Bosch and Hewlett, 1982; Eisenbies et al., 2007; Moore and Wondzell, 2005). Though this method has been particularly useful for quantifying the impact of harvesting in terms of increases or decreases in streamflow (Andréassian et al., 2003), the approach is limited in that it requires a control watershed that serves as a climatic reference for the duration of the experiment. Control watersheds are seldom available in practice due to harvesting schedules, timber market pressures, land ownership, and the identification of watersheds appropriately similar to warrant pairing. In this study a simple rainfall-runoff model is used to model and assess the effects of forest management of watershed hydrology. The model is applied to Watershed 7 in the Fernow Experimental Forest during 14 time periods that represent preharvest, harvesting and herbicide, and regrowth conditions over the fifty year period.

## METHODS

### Study site

The Fernow Experimental Forest was established in 1934 by the USDA Forest Service to study the effects of forest and watershed management in the northern and central Appalachian Mountains (Figure 1). Since gauging started in the 1950's the Fernow maintains nearly continuous climatic and hydrologic records and offers a unique opportunity to study the impacts of forest management on the environment.

The Fernow receives on average 1,480 mm of precipitation annually 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, and is 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 Watershed 7 (WS7). WS7 is a small (0.24 km2) east-facing headwater catchment and has been continually monitored since November 1956. The timeline of management in WS7 is shown in Table 1. The first harvesting entry consisted of clearcutting 49 percent of basal area from the upper half of WS7from 11/1963-3/64 and was maintained barren from 5/64-10/69 using herbicides. The remaining 51% basal area in the lower half of WS7 was harvested from 5/64-3/67 and the entire watershed was maintained barren from 5/67-10/69. WS7 has been naturally regenerated and growth has continued to the present with no management. The period considered in this study is from 11/56 – 10/2006.

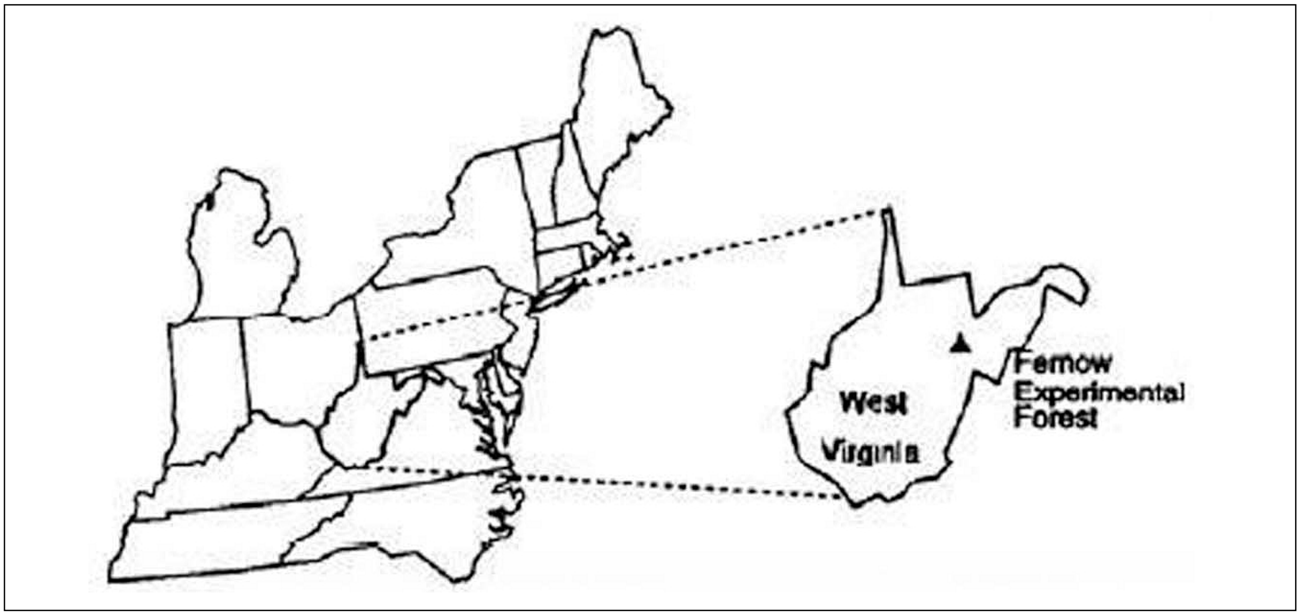

Figure 1. Location of the Fernow Experimental Forest, West Virginia, USA.

## Description of the IHACRES hydrologic model

The Identification of Unit Hydrographs And Component flows from Rainfall, Evaporation, and Streamflow data (IHACRES) (Jakeman et al., 1990) model was used to simulate daily streamflow during preharvest, harvesting and herbicide application, and regrowth conditions in WS7. This simple rainfall-runoff model can be run from a standard desktop personal computer and requires daily inputs of precipitation and air temperature to simulate daily streamflow. The model consists of a non-linear module that converts rainfall into effective or excess rainfall and a linear module that represents the transformation of effective rainfall into streamflow (Figure 2). Parameters *tw*, *f* and *1/c* in the non-linear module govern effective rainfall generation and parameters *tq*, *ts*, *vs* partition flow into quick and slowflow reservoirs in the linear module (Post and Jakeman, 1999). Parameter *tw* (days) is the time constant governing rate of water loss from the catchment or inversely the rate at which the catchment dries in the absence of rainfall; *f* (unitless) varies the rate of catchment water loss due to a unit change in temperature; *1/c* (mm) is calculated such that total effective rainfall equals total observed streamflow and can be considered to be the maximum volume of potential evaporative store. Therefore decreases in *1/c* convey decreases in transpiration whereas increases in *1/c* convey increases in transpiration. *tq* (days) is the time constant governing the rate of quickflow recession of streamflow; *ts* (days) is the time constant governing the rate of slowflow or baseflow recession of streamflow; and vs is ratio of slowflow to total flow. The parameter set, *tau* = {*tw, f, tq, ts, vs*} is determined directly from the observed rainfall, temperature, and streamflow, whereas *1/c* is optimized so that the mass balance between effective rainfall and

Table 1. Timeline of treatment activities in watershed 7 in the Fernow Experimental Forest, WV. WY= water year (October 1 – September 31); model = model calibrated over 3-4 year periods (total of 14 periods) to account for interannual variability; activity – management activity modeled during model period.

| | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | lower clearcut (0.12 km$^2$) | | | | | | | | | | | | | |
| activity | pre-harvest | | | | | | | upper clearcut (0.12 km$^2$) | upper maintained barren herbicides | | | entire watershed barren herbicides | | | regrowth | | | | | | | | | |
| WY | 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 | 64 | 65 | 66 | 67 | 68 | 69 | 70-72 | 73-76 | 77-79 | 80-82 | 83-86 | 87-90 | 91-95 | 96-99 | 00-03 | 04-06 |
| model | 1 | | | | 2 | | | 3 | | | | 4 | | | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |

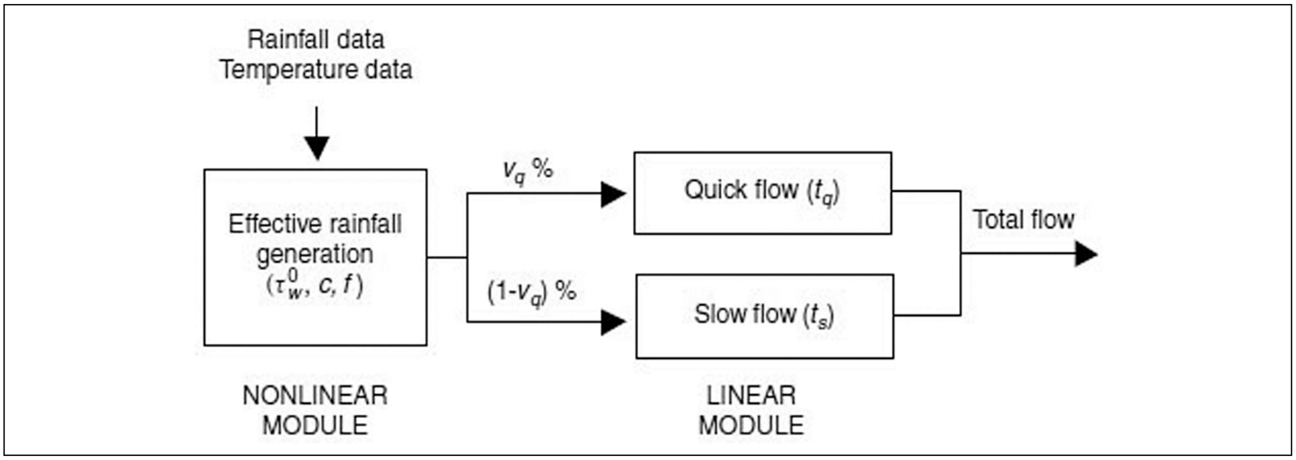

Figure 2. Schematic of the IHACRES rainfall-runoff model. Parameters are defined as: *tw* is the time constant (days) governing rate of water loss from the catchment a 20 C; *f* is the rate of catchment water loss due to a unit change in temperature (unitless); *1/c*(mm) is a scale parameter used to minimize bias so that the volume of effective rainfall is equal to the total streamflow; *tq* is the time constant (days) governing the rate of quickflow recession of streamflow; *ts* is the time constant (days) governing the rate of slowflow or baseflow recession of streamflow; and *vs* is ratio of slowflow to total flow (from Kokkonen et al. 2003).

runoff is preserved (Post and Jakeman, 1996). Detailed descriptions of the IHACRES model can be found in (Post and Jakeman, 1996; 1999).

### Model calibration and identification

IHACRES was used to simulate daily streamflow in WS7 using longterm daily precipitation and air temperature records measured at the weather station in the Fernow. The IHACRES model was calibrated using observed daily streamflow measured at the outlet of WS7 prior to and following harvesting over the fifty year period. Models were estimated over 2-4 water years (WY: October 1 – September 31) periods to account for annual variability and management activity. In total, 14 models were used to simulate hydrologic responses of WS7; 2 models before harvesting, 2 models during harvesting and herbicide treatments, and 10 models during natural regeneration and stand establishment (Table 1).

Many studies have demonstrated the difficulty of identifying, calibrating, and validating hydrologic models (Beven and Binley, 1992; Oreskes et al., 1994). To find the best fitting models, Monte Carlo simulations were used to randomly sample parameter values from non-informative uniform distributions to generate 5,000 models for each period. The Nash-Sutcliffe (1970) measure of efficiency (NSE) was used to evaluate the goodness of fit between observed and simulated streamflow and identify the best performing models.

### Parameter change detection

The populations of model parameters identified from the best fitting models were used to develop ‘behavioral’ distributions that show probable and acceptable ranges of the model parameters that have good agreement between simulated and observed streamflow for each period. Three approaches were used to discern the effects of harvesting on hydrologic model parameters: (1) comparison of parameter distribution median values; (2) Box plots; and (3) the non-parametric two-sided Wilcoxon rank sum test (alpha = 0.05) to test the null hypothesis that there are no differences between parameter distributions for different periods. Rank sum tests were calculated between period (t) and period (t-1) to test changes in parameter distributions through time. 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 (Figure 3). Water year 1996 (WY 96) and WY 65 were the wettest and driest years during this study with approximately 1,982 and 1,121 mm of total annual precipitation, respectively. The largest peakflow event (82 mm) occurred on 9 February 1994, during a period of forest regrowth. Runoff ratio, calculated as the proportion of total streamflow to total precipitation, increased from a preharvest (periods 1&2) mean of 55% to 68% following harvesting (periods 3&4), then decreased to 61% during periods of regeneration (Table 2). The smallest runoff ratio of 51% occurred during period 13, while the largest runoff ratio of 72% occurred during period 5.

### Model performance and parameter sensitivity

Five thousand Monte Carlo simulations were used to generate probable distributions of model parameters for the 14 calibration periods. Acceptable agreement was obtained between observed and simulated streamflow (Figure 4); NSE values ranged from 0.51 - 0.78 for all models. Of the six model parameters, *tw* and *1/c* from the non-linear module consistently showed the greatest sensitivity during all treatment periods. Model performance showed little sensitivity to the remaining parameters.

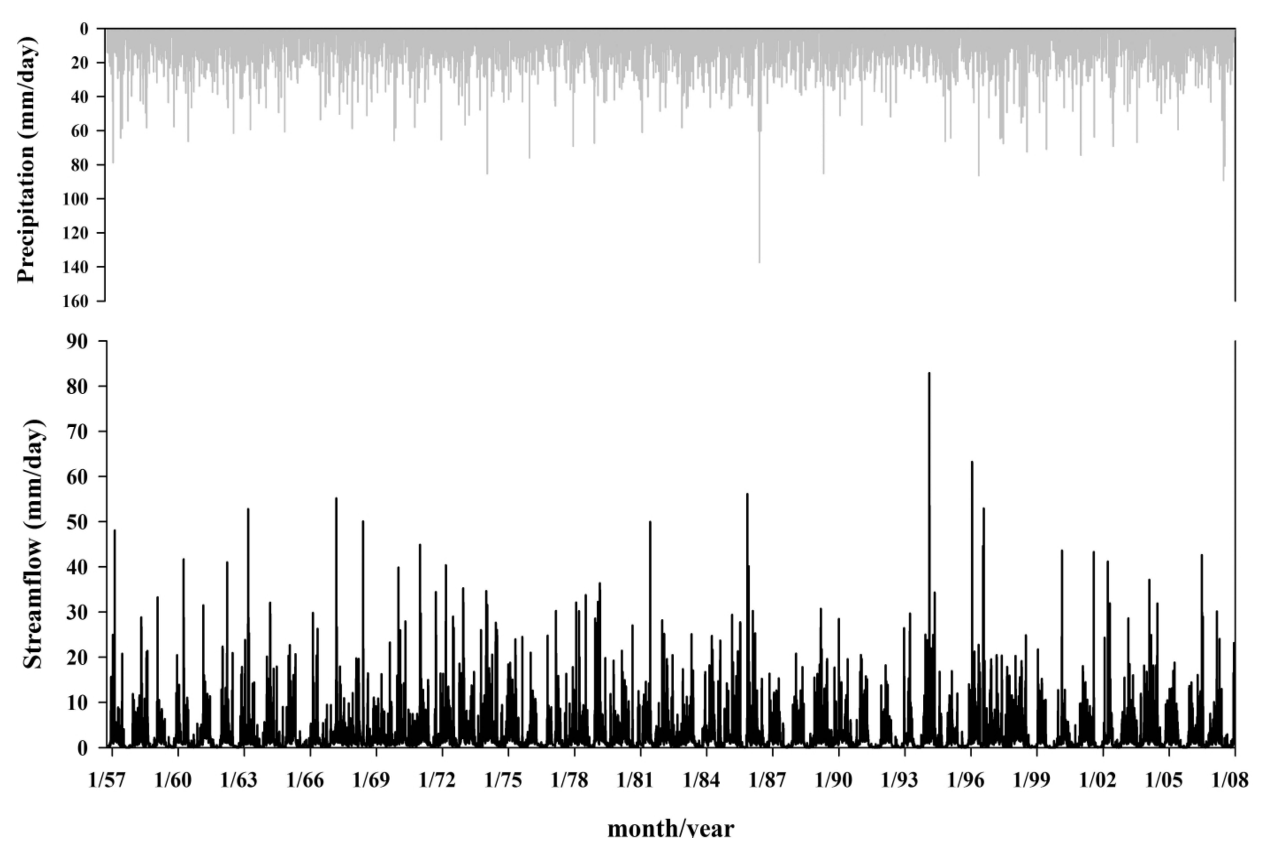

Figure 3. Daily precipitation and observed streamflow during study period for Watershed 7 of the Fernow Experimental Forest, WV.

Table 2. Model calibration periods, runoff ratios, non-linear and linear module parameters for the IHACRES model applied to watershed 7, Fernow Experimental Forest, during preharvest, harvest and herbicides, and regrowth periods. Parameter values represent median values for each parameter distribution generated using 5,000 Monte Carlo simulations.

| Model number | Calibration period | Runoff ratio | *non-linear module* | | | *linear module* | | |
|---|---|---|---|---|---|---|---|---|
| | | | *tw* | *f* | *1/c* | *vs* | *ts* | *tq* |
| | (wy) | (%) | (days) | | (mm) | (%) | (days) | (days) |
| 1 | 1957-59 | 54 | 15 | 2.3 | 424 | 0.6 | 7 | 0.5 |
| 2 | 1960-62 | 55 | 17 | 2.4 | 476 | 0.7 | 8 | 0.5 |
| 3 | 1963-66 | 64 | 16 | 2.4 | 345 | 0.6 | 7 | 0.5 |
| 4 | 1967-69 | 71 | 17 | 2.3 | 255 | 0.6 | 9 | 0.4 |
| 5 | 1970-72 | 72 | 15 | 2.2 | 290 | 0.7 | 8 | 0.5 |
| 6 | 1973-76 | 67 | 15 | 2.2 | 310 | 0.7 | 7 | 0.5 |
| 7 | 1977-79 | 65 | 16 | 2.6 | 274 | 0.6 | 8 | 0.5 |
| 8 | 1980-82 | 63 | 15 | 2.6 | 250 | 0.7 | 8 | 0.5 |
| 9 | 1983-86 | 62 | 19 | 2.6 | 355 | 0.6 | 8 | 0.5 |
| 10 | 1987-90 | 57 | 17 | 2.6 | 304 | 0.7 | 8 | 0.5 |
| 11 | 1991-95 | 56 | 15 | 2.5 | 332 | 0.6 | 8 | 0.4 |
| 12 | 1996-99 | 60 | 18 | 2.6 | 350 | 0.6 | 8 | 0.5 |
| 13 | 2000-03 | 51 | 16 | 2.6 | 302 | 0.7 | 8 | 0.5 |
| 14 | 2004-06 | 61 | 17 | 2.6 | 328 | 0.7 | 9 | 0.4 |

### Changes in parameter distributions

In this study the IHACRES rainfall-runoff model was used to assess the hydrologic impact of forest harvesting and regrowth by evaluating changes in model parameter distributions calibrated for each period. Median parameter values for *tw* and *f* exhibited relatively small changes between periods, ranging from 15 - 19 and 2.2 - 2.6, respectively, whereas median values for *1/c* showed the greatest variation with median values ranging from 476 mm to 250 mm (Table 2). Median values for non-linear module parameters *vs*, *ts*, and *tq* show little variation over the 14 calibration periods. Box plots of parameter distributions show variation between periods for each parameter. However, statistically significant differences between parameter distributions for specific periods (Figure 5) were only detected for parameters *tw* and *1/c* using the Wilcoxon rank sum test. Significant differences were not detected for parameters *f*, *vs*, *ts*, and *tq*.

## DISCUSSION AND CONCLUSIONS

### Modeling the effects of forest harvesting on streamflow

Behavioral populations of the IHACRES model fit the observed data acceptably well. NSE measure of efficiency, the proportion of observed streamflow variance explained by the hydrologic model, ranged from 0.51 to 0.78. Figure 4 shows an example of the agreement between observed and simulated streamflow for period 1 (11/56 – 9/59), a preharvest period and period 9 (10/82 – 9/86), a regrowth period. Generally, the IHACRES model under simulated peak stormflow and over estimated lowflow. Errors in simulated streamflow are attributed to model structure, parameterization, uncertainty, as well as measurement error in input and calibration data.

The parameter set *tau* characterizes the dynamic hydrologic response of a catchment (Figure 2) (Kokkonen et al., 2003). Monte Carlo simulations were used to construct distributions of *tau* and optimize *1/c* to model the hydrologic responses of WS7 during different periods that reflect

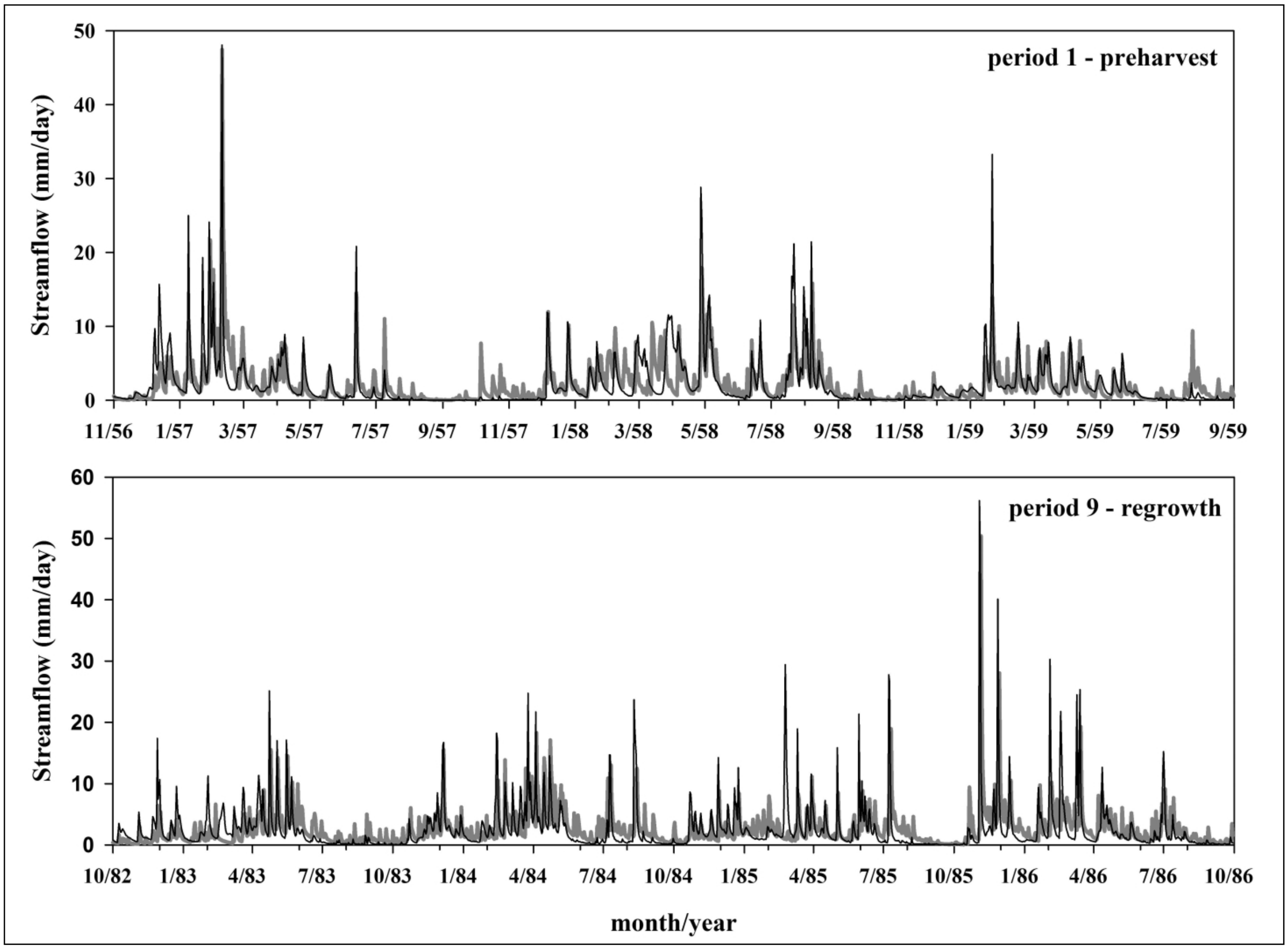

Figure 4. Example comparison of observed (black) and simulated (grey) daily streamflow for watershed 7 in the Fernow Experimental Forest, WV, during preharvest period 1 (11/56 – 9/59) and regrowth period 9 (10/82 – 9/86).

preharvest, harvesting and herbicide application, and regrowth conditions. Change detection is performed by comparing the distributions of *tau* and *1/c* generated for each landuse treatment period; significant differences between distributions are proxy for changes in catchment processes that govern runoff and streamflow generation.

Parameter distributions for parameters *f*, *vs*, *ts*, and *tq* showed little differences between preharvest, harvesting and regrowth periods (Figure 5, Table 2). This is similar to the findings of Post et al. (1996) who applied the IHACRES model to evaluate forest harvesting changes on the hydrologic responses of Picaninny Creek in southeast Australia. The insensitivity of these parameters to landcover changes in these two studies suggest that harvesting-induced changes on the rate which water drains from the respective watersheds were relatively small compared to natural variability of the modeled watersheds (Post and Jakeman, 1996).

Significant differences were detected between periods in the distributions for non-linear module parameters *tw* and *1/c*. Significant differences in tw were detected between all periods which can be explained by its dependence on rainfall and antecedent moisture conditions. Significant differences in parameter *1/c*, however, clearly reflect the hydrologic response of WS7 to forest harvesting. *1/c* decreases from 424 and 476 mm for the two preharvest periods to 345 mm to 255 mm during the two periods of harvesting and herbicides treatments (Figure 5, Table 2). Decreases in *1/c* are commensurate with decreases in transpiration (Post and Jakeman, 1996).

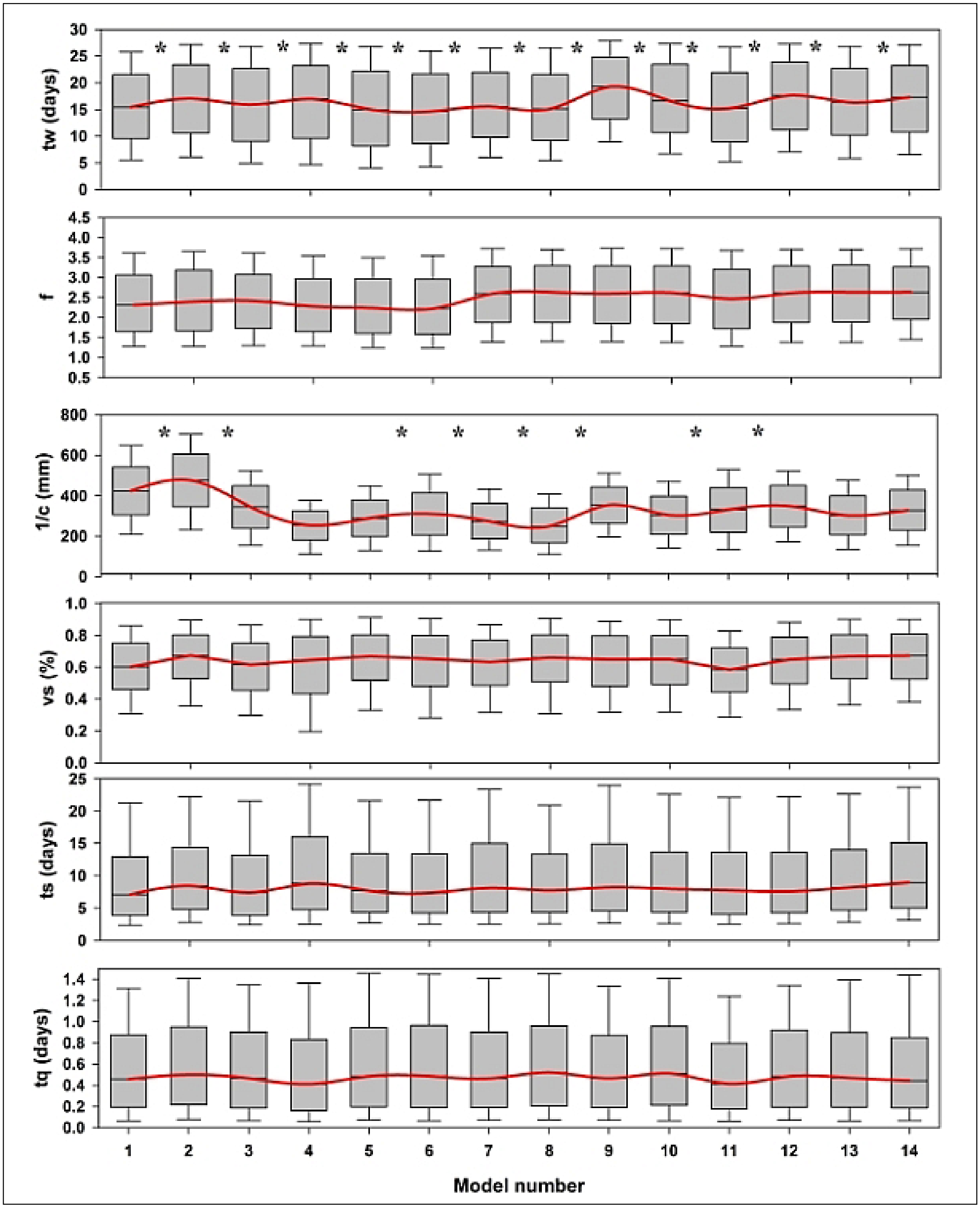

Figure 5. Box plots for parameter distributions for model simulations using the IHACRES model. Monte Carlo simulations were used to randomly sample parameter values from non-informative uniform distributions to generate 5,000 candidate models for each period. Boxes represent inter-quartile range (median solid line); whiskers are 95% confidence intervals. (*) denotes statistical differences between periods based on the Wilcoxon rank sum test at the 0.05 significance level. Model parameters are described in Figure 3. See Table 1 for specific day in each calibration period.

*1/c* continues to drop to 290 mm during period 5, the first period following harvesting. As natural regeneration occurs during the regrowth periods, *1/c* gradually rises, reflecting increases in transpiration, and ultimately reductions in streamflow. These changes are similar to the findings of Post and Jakeman, (1996) that show similar trends in *1/c* during preharvest, harvest, and regrowth conditions.

Parameter distribution changes for *1/c* connote that a larger proportion of rainfall is contributed to catchment storage and subsequently streamflow, rather than lost through evaporation and transpiration, and are further corroborated with changes in runoff ratio, the proportion of streamflow to precipitation. Runoff ratio is lower during the preharvest period, increases during harvesting periods, and shows a generally decreasing trend through the regrowth period (Table 1). The modeling and runoff ratio results are consistent with empirical watershed studies showing that forest harvesting augments streamflow by reducing canopy interception and transpiration, thereby modifying soil moisture conditions and increasing streamflow (Eisenbies et al., 2007).

### Model change detection: A tool for managers

The modeling approach presented in this study can be a useful alternative to overcome some of the limitations of the paired watershed approach, particularly where paired watersheds are not practical. The change in parameter distributions in our study clearly show that forest harvesting alters the hydrologic response of WS7. This change detection approach is a useful way to advance our understanding of the hydrologic response to disturbance. 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 harvesting and regrowth 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.

## ACKNOWLEDGMENTS

The author is grateful to Dr. Joshua Faulkner, Agricultural Engineer, West Virginia University Extension and Dr. Samuel Lamont, Research Hydrologist, Natural Resources Analysis Center (NRAC) for their constructive comments and suggested editing. West Virginia Agricultural and Forestry Experiment Station Scientific Article No. 3087.

## REFERENCES

Andréassian, V., E. Parent, and C. Michel. 2003. A distribution-free test to detect gradual changes in watershed behavior, Water Resources Research, 39(9), doi:10.1029 2003WR002081.

Beven, K., and A. Binley. 1992. The future of distributed models: Model calibration and uncertainty prediction, Hydrological Processes, 6(3), 279-298.

Bosch, J.M., and J.D. Hewlett. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration, Journal of Hydrology, 55(1), 3-23.

Eisenbies, M.H., W.M. Aust, J.A. Burger, and M.B. Adams. 2007. Forest operations, extreme flooding events, and considerations for hydrologic modeling in the Appalachians—A review Forest Ecology and Management, 242(2-3), doi:10.1016/j.foreco.2007.1001.1051.

Jakeman, A.J., I.G. Littlewood, and P.G. Whitehead. 1990. Computation of the instantaneous unit hydrograph and identifiable component flows with application to two small upland catchments Journal of Hydrology, 114(1-4), 275-300.

Kokkonen, T.S., A.J. Jakeman, P.C. Young, and H.J. Koivusalo. 2003. Predicting daily flows in ungauged catchments: model regionalization from catchment descriptors at the Coweeta Hydrologic Laboratory, North Carolina, Hydrologic Processes, 17(11), 2219-2238.

Moore, R.D., and S.M. Wondzell. 2005. Physical Hydrology and the Effects of Forest Harvesting in the Pacific Northwest: A Review, Journal of the American Water Resources Association, 41(4), 763-784.

Nash, J.E., and J.V. Sutcliffe. 1970. River flow forecasting through conceptual models. Part I: a discussion of principles, Journal of Hydrology, 10, 282-290.

Oreskes, N., K. Shrader-Frechette, and K. Beli. 1994. Verification, Validation, and Confirmation of Numerical Models in the Earth Sciences, Science, 263(5147), 641 - 646.

Post, D.A., and A.J. Jakeman. 1996. Relationships between catchment attributes and hydrological response characteristics in small Australian mountain ash catchments, Hydrological Processes, 10(6), 877-892.

Post, D.A., and A.J. Jakeman. 1999. Predicting the daily streamflow of ungauged catchments in S.E. Australia by regionalising the parameters of a lumped conceptual rainfall-runoff model Ecological Modelling, 123(2-3), doi:10.1016/S0304-3800(1099)00125-128

ADDRESS FOR CORRESPONDENCE
Nicolas Zegre
Division of Forestry & Natural Resources
West Virginia University
322 Percival Hall
Morgantown, WV 26506, USA

Email: nicolas.zegre@mail.wvu.edu