Hydrologic Evaluation of the Curve Number Method for Forest Management in West Virginia

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Findings and Recommendations

A test of the curve number method for hydrologic analysis selected by the West Virginia Flood Advisory Technical Taskforce shows that

1. Additional investigation is necessary to determine if the curve number method is applicable for forested watersheds in West Virginia.
2. A curve number protocol is then necessary to define how hydrologists and engineers should select curve numbers for West Virginia forests if the method is applicable.
3. Any proposals for hydrologic analysis in the regulatory process for forest harvesting based on the curve number method should be defined with specific application protocols and sensitivity analysis so that it can be determined if the method is adequately accurate and precise for the purposes at hand.

Curve numbers derived for the Fernow Experimental Forest in West Virginia establish significant uncertainty in the method that would seem to lead to uncertainty greater than the 0 to 6 percent effects of forest harvest that the Flood Advisory Technical Taskforce found for three watersheds in southern West Virginia. To reach these findings, two tests were performed as follows:

1. The standard Soil Conservation Service (now the National Resource Conservation Service) protocol was used to select a curve number of 55 for an uncut Watershed 4 and periodically harvested Watershed 2 in the Fernow Forest.
2. The HEC-1 model selected by the Flood Advisory Technical Taskforce was calibrated to determine the curve numbers that best simulated the peak flows measured at Fernow for a few storms selected by the U.S. Forest Service based on similarity with July 8, 2002 event that flooded southern West Virginia.

Analysis of the two watersheds, one last cut in 1910 and the other subject to a diameter-limited cut on a periodic basis (as most private West Virginia timberlands are managed), provide uncertain information about the appropriate curve numbers for analysis of forest hydrology in West Virginia. The standard method of selecting curve numbers does not adequately reflect forest management practices and leads to errors in peak flood simulations of up to 77 percent when applied to West Virginia forested watersheds in the Fernow Forest on the Allegheny Plateau. The difficulty in selecting a lag time and calibrating the curve number method to the timing and value of peak runoff indicates that the method may not be applicable for some forested watersheds in West Virginia. The calibration problems also imply significant uncertainty in the hydrologic analysis of mixed land uses. The curve numbers for the mature forest (Watershed 4) of 65 ± 11 and 62 ± 7.5 for the forest harvested of timber (Watershed 2) were indistinguishable statistically because West Virginia best management practices were applied to achieve a
good hydrologic soil cover condition quickly after harvest. Because of the high degree of imprecision in the calibrated values, the curve number of 55 is not significantly different from 62 or 65, nor are the values of 70 and 73 used by the Taskforce for the class C soils in southern West Virginia significantly different from 62 and 65 for Class B soils in the Fernow Forest. The high uncertainty may be due to lag time estimates that are known to be imprecise, seasonal effects, antecedent runoff conditions, calibration to peak runoff instead of runoff volume, and perhaps other effects.

These large uncertainties from two different watersheds establishes the need to analyze additional data from Fernow and other sites in and around West Virginia to be sure that the method is applicable, and then designate how curve numbers should be selected for forested watersheds. The curve number method has not been formally and scientifically adapted to forest hydrology and management and is known to be notoriously unreliable for some forests. When the standard procedure assigns the same curve number of 55 to cut and uncut forests based on sound observations consistent with applying West Virginia best management practices, the need for a formal protocol for the analysis of forest hydrology is also clear. Furthermore, lacking an uncertainty and sensitivity analysis of forest management practices in the southern West Virginia watersheds makes it difficult to be sure that the effects reported by the Flood Advisory Technical Taskforce are greater than the noise or uncertainty in the curve number method. Once the Taskforce better defines the sensitivity of the models used and how the curve number approach should be used in a hydrologic analysis of forestry management, it will be possible to determine if the method has the precision to make some useful calculations.
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Glossary

Antecedent moisture conditions: Amount of soil wetness prior to a rainfall event. The more modern concept used in the curve number method is the antecedent runoff condition (Woodward et al. 2002) that is the average watershed conditions when floods occur, which includes more that just soil moisture conditions.

Calibration: Process of changing uncertain parameters such as the curve number until an optimum parameter value is found so that simulated values of selected variables match measurements as in the case of calculated peak flood heights compared to measured flood heights.

Cull: Inferior tree expected to produce a grade of lumber below the lowest common grade.

Curve number: Simplified index used by hydrologists to determine how much rainfall becomes runoff and thus enters the land drainage network. Given the influences on infiltration and runoff such as antecedent moisture conditions, slope, runoff path, soil physical conditions, impacts of vegetative, and some metrological conditions the curve numbers should not be overly simplified, but clearly these index values are related to land cover. Urban runoff from parking lots with very little infiltration has curve numbers as high as 98, for example. A range of curve numbers, 30 to 79, depending upon the soil type, condition, and coverage, represents some but not all forests.

Diameter-limited cut: Forest harvesting method that involved cutting only those trees of certain diameter (e.g., 17 inches or 43 centimeters).

Hyetograph: Distribution of rainfall volume or intensity in time.

Hydrograph: Distribution of runoff in time.

Interflow: Lateral flow towards a stream occurring just below the surface and due to variability in wetting soils caused by layering, interfaces, and lenses. The concept may be defined in other ways (e.g., quick return flow).

Initial abstraction of rainfall: Amount of rainfall required to wet watershed surfaces including all vegetation, litter, and bare ground normally before infiltration occurs. For pavements and other impervious surfaces, the initial abstraction is the amount required to wet the surface before water accumulates and begins to flow. For forested
watersheds, typically 0.2 to 0.5 inches (5.1 to 13 millimeters) are required to wet all surfaces (Chow 1964). This amount is rarely measured and thus the SCS (1985) assumes that the initial abstraction is 20 percent of the maximum soil moisture storage.

Lag time: Period between the beginning of rainfall or center of mass of the hyetograph and the occurrence of the peak in the hydrograph. The center of the hyetograph is considered the more accurate starting point to define watershed response to rainfall. The HEC-1 model uses the time from the peak of the excess precipitation or runoff on the watershed surface or from the midpoint of the runoff duration to the time the peak flow occurs at the watershed outlet (HEC 1990).

Recurrence or return periods or intervals: Terms used to describe precipitation or flood frequency as in 100-year flood. This does not mean that only one big storm occurs every 100 years. If the 100-year storm occurred in the preceding year, 99 years will not necessarily transpire before the next such storm. The 100-year event may happen the next year or not at all in the next 100 years. The American Meteorological Society Glossary of Meteorology defines rainfall frequency as: "The probability distribution specifying the exceedance probability of different rainfall depths for a given duration. The exceedance frequency is often reported as a return period in years, which is the reciprocal of the annual exceedance frequency." The 100-year event is therefore an event which has a 1 percent chance of being exceeded in any year; not one event every 100 years (http://weather.gov/oh/hdsc/studies/prepfreq.html).

Travel Time: Time it takes runoff at any given point in the watershed to reach the outlet or some other specified location along the runoff pathway. Time of travel is vital in the estimation of lag times to define hydrograph peaks.

Uncertainty or reliability: A measure or qualitative estimate (at least a discussion of unknown or poorly understood critical factors that must be considered in decision making) of the known or possible deviations of a parameter or variable comparable to a true condition or state. Absolute true conditions can only rarely be defined mathematically and logically. Thus, most often uncertainty is estimated from comparing calculations, statistical results, simulations, predictions, forecasts, hindcasts, and other assessment or analysis results to measurements. Measurements of a condition or state are by definition also uncertain (see the uncertainty principle of quantum mechanics). Uncertainty encompasses both estimation, simulation, or assessment bias and precision. Uncertainty can be defined by a number of statistical tools. The simpler tools include measures of the central tendency (mean, median, and other measures) and the distribution about a central tendency (standard deviation, standard error, and other measures) of the differences with measurements. Methods that are more elaborate include sensitivity analyses, Monte Carlo analysis, and similar analysis techniques that define probability.
distributions and propagate these uncertainties through a simulation or analysis; this includes a first order error analysis.

Uncertainty analysis: In environmental and engineering modeling and assessment, a formal uncertainty analysis is an absolute requirement to define precision (including the nebulous model noise or better defined white noise or threshold precision below which the model approximations are unreliable for decision making) and bias over practical ranges that decision makers need to make decisions. Uncertainty analysis is a vital component of all known decision making, formal or informal (using experience as a crude guide in informal settings). As a result, all analysts must define the uncertainty of all simulations, assessments, and other investigations to have a rational impact on human decision making, whether the analysis involves resource and environmental resources or not. Lacking a formal uncertainty analysis, decision makers must use past experience, make assumptions, conduct an analysis themselves, or commission another analyst to finish the task. Ideally, an iterative process is usually necessary where decision makers (which may be the dual role of the analyst in a few cases but is avoided for objectivity in most cases) define reliability objectives or goals for information, especially critical knowledge, which the analyst can convert into probabilities of error or other criteria. Otherwise, the analyst uses trial and error guided by professional experience to select analytical tools and quantifies or describes potential uncertainty. For legal proceedings, criminal trials rely upon “beyond a shadow of reasonable doubt” that many expert witnesses seem to translate into 95 to 99 or higher percent probabilities. In civil cases, the standard is “more likely than not” or greater than 50 percent probabilities (normally viewed as higher by many juries and judges depending on the economic severity of potential errors). Design standards of professions and government agencies are normally accepted as producing a minimal probability of error or the effects of uncertainty have been minimized with safety factors and can be used with confidence in standard decision making for which the design or assessment process or protocol was intended to support. In this case, the uncertainty analysis is done once in creating a standard and the communication is reduced to a review of the limitations of the protocol is a reminder of the range of conditions the decision can cover. The probability of loss of human life, renewable and non-renewable resources, and quality of life, and the economics associated with other formal decisions are used in a general fashion or integrated into professional practices and protocols as criteria for analysts. Neither the analyst nor decision maker can afford to use profession practices or protocols outside the range of established limitations without additional uncertainty analysis and expect to maintain full credibility. One final absolute from the uncertainty principle is that all practical analytical tools for assessments, forecasts, simulations, and other analyses are only approximations of real conditions or targets. Professional practices, formal agency and organization protocols and procedures, uncertainty or error analysis, and other means must be used to define the degree of approximation and the analyst clearly and explicitly convey the reliability to decision makers and society.
Unit hydrograph: Unit runoff response to a standard rainfall volume of 1-inch or 1-centimeter occurring over 1 hour or other selected standard rainfall durations that are summed for different durations of rainfall and multiplied by the ratio of the actual rainfall volume to the standard 1-inch or 1-centimeter storm volumes to estimate an actual hydrograph for a given watershed.
Acknowledgments

This investigation was performed under contact to the West Virginia Division of Forestry. The guidance and management of State Forester Charles R. Dye is very much appreciated. Mary Beth Adams of the U.S. Forest Service Timber and Watershed Laboratory in Parsons, West Virginia and Wayne Swank, retired from the U.S. Forest Service Coweta Hydrologic Laboratory in Franklin, North Carolina reviewed a draft of this report and their comments were much appreciated. Mary Beth Adams, Jim Kochenderfer, and Frederica Wood of the U.S. Forest Service Timber and Watershed Laboratory and Fernow Experimental Forest headquartered in Parsons, West Virginia provided background information on the Fernow watersheds and data for select storms in a HEC-1 format for this analysis; this report has not been reviewed by all of those scientists. The Fernow Experimental Forest is operated and maintained by the Northeastern Research Station, Forest Service, U.S. Department of Agriculture, Newtown Square, Pennsylvania. The U.S. Forest Service and the scientists associated with the Experimental Forest are to be complimented for the foresight in the collection of important hydrologic data over the years that are vital to the current West Virginia policy deliberations on flood plain, forestry, and mining management in the State. The use of trade, firm, or corporation names is for the information and convenience of the reader. Such use in the original information or in this report does not constitute an endorsement or official approval by the U.S. Department of Agriculture or the Forest Service of any product or service to the exclusion of others that may be suitable. Some information in this report about the Fernow Experimental Forest was taken from (http://www.fs.fed.us/ne/parsons/fefhome.htm) and (http://www.fs.fed.us/r9/mnf/general_info/intro.shtml). Richard Hawkins of the University of Arizona provided insightful background information on the use and limitations of the curve number method in forested watersheds and how best to interpret curve numbers.
Introduction

Following the devastating floods in southern West Virginia of May and July 2001, an executive order by Governor Bob Wise directed the formation of the Flood Advisory Technical Taskforce. The Flood Advisory Technical Taskforce selected a peak flood modeling approach based on the Watershed Management System developed by the U.S. Army Corps of Engineers and U.S. Environmental Protection Agency. The Taskforce further selected three watersheds for analysis from the flooded counties in southern West Virginia. The three watersheds included Seng Creek, Scrabble Creek, and Sycamore Creek. The first two watersheds involve a mix of mining, silviculture, and other land uses. Sycamore Creek watershed is largely free of mining and logging currently.

The Flood Advisory Technical Taskforce selected methods for rainfall-runoff analysis based on the curve number method by the U.S. Soil Conservation Service (now the National Resource Conservation Service), initially based on runoff relationships observed for agricultural plots. More recently, the method has been expanded to the analysis of urban land uses and other mixed land uses that include some forested areas. The curve number method is applied in the Watershed Management System Model HEC-1 (HEC 1990), a standard watershed analysis tool by the U.S. Army Corps of Engineers. Flows were routed in these three watersheds using HEC-RAS, another standard model of the Corps of Engineers.

As the comments of reviewers Wayne Swank and Rhett Jackson state, and the Flood Advisory Technical Taskforce (2002) acknowledges, the application of the curve number approach to forested catchments and some other watersheds is controversial and uncertain. The method has not been formally adapted to rainfall-runoff analysis in catchments with forestry as the dominant land use. In fact, the guidance is very limited in applying curve numbers for forest cover and little guidance has been developed for modifying curve numbers for different forestry management approaches, including different harvest practices.

The primary concern that hydrologists have regarding the curve number method is that distinct runoff is rarely observed in forests, contrasted with the rill and sheet flow occurring over the more uniform agricultural and urban land covers, respectively. On parking lots and other impervious surfaces, and most fields, surface runoff shows up quickly and distinctly. The floor of a forest is more like a sponge and the vegetation above can be equally irregular in density and wetting capacity so that the moisture that reaches the forest litter is quite uneven to start with. Nevertheless, runoff occurs from forests whether moving from one wet spot to the next (variable source area concept pioneered by forest hydrologist) to reach a stream channel or whether by wetting the
spongy forest litter that does begin to drain into stream channels, by a process known as interflow or quick return flow.

For at least 135 years, foresters and hydrologists have investigated the effects of forests on runoff (Lull and Reinhart 1972, also see brief history by Wayne Swank in FATT 2002) but the Flood Advisory Technical Taskforce (2002) seems to have misinterpreted these findings. A number of investigators, including those working with data from the Fernow Experimental Forest (Hornbeck et al. 1993, Kochenderfer et al. 1997), Coweeta Hydrologic Laboratory in North Carolina (see the numerous references cited by Wayne Swank in FATT 2002), and similar settings from New Hampshire to South Carolina (Hewlett and Helvey 1970, Hornbeck 1973, Settergren and Krstansky 1987) have found hydrologic effects from logging during the next growing season for small storms on smaller catchments. To date, no one seems to have measured peak runoff effects on large floods of the type analyzed by the Flood Advisory Technical Taskforce. The reason is that logging effects on transpiration are important during the initial growing season on small catchments for small storms, but not for major flood volumes (Jim Kochenderfer, personal communication, January 27, 2003, U.S. Forest Service Timber and Watershed Laboratory, Parsons, West Virginia).

This report takes a focused look at whether the curve number approach and other methods adopted by the Flood Advisory Technical Taskforce work in the forested watersheds of the Fernow Experimental Forest compared to Seng, Scrabble, and Sycamore watersheds. Watersheds 2 and 4 are smaller than the three watershed investigated by Flood Advisory Technical Taskforce, 0.1495 and 0.0598 square miles (38.9 and 15.50 hectares) versus 4.2, 5.1, and 5.4 square miles (1090, 1320, and 1399 hectares). Thus, the Fernow watersheds are more comparable to one of the catchments contributing to Seng, Scrabble, and Sycamore creek watersheds except that the Fernow catchments are gauged. Thus, the peak flow simulated using the curve number and unit hydrograph method implemented in the HEC-1 model can be compared to actual peak flow measurements to assess and determine curve number indices and lag time estimates. Watershed 4 is a very mature undistributed forest (last cut 1910) and Watershed 2 has been periodically harvested for large trees (diameter-limited cut). Because the Fernow Experimental Forest was not as impacted by the July 8, 2001 rainfall, other comparable storms were selected by the U.S. Forest Service and used in this investigation to evaluate the HEC-1 curve number approach selected by the Flood Advisory Technical Taskforce.

Fernow Experimental Forest

In 1934 a portion of forest that would eventually become the Monongahela National Forest, was recognized as representative of much of the timberland in West Virginia and adjacent states, in terms of topography, history of cuttings, climate, and variety of species. This representative forest was set aside for research use until 1951 when
monitoring installations were built and calibrated for 6 years, and different forest management practices begun on select watersheds in 1957 (Reinhart et al. 1963). The experimental forest was named in memory of Bernhard E. Fernow, a pioneer in American forestry research. The Fernow Experimental Forest (shown in Figure 1), with recent land acquisitions from the Monongahela National Forest, now totals approximately 4700 acres (1902 hectares).

Today the Fernow Experimental Forest is a thriving field laboratory for the research project "Sustainable Forest Ecosystems in the Central Appalachians." This project of the U.S. Forest Service is headquartered at the Timber and Watershed Laboratory at Parsons, West Virginia.

Geography and Geology

The Fernow Experimental Forest lies in the Allegheny Mountain section of the unglaciated Allegheny Plateau. Elevation ranges from 1750 to 3650 feet (533 to 1113 meters above the U.S. National Geodetic Vertical Datum or sea level), and slopes are generally steep (10 to 40 percent or more, Reinhart et al. 1963).

A rock layer composed of fractured hard sandstone and softer shale underlies most of the Forest. Apparently, little water is stored in the underlying rock layer. A majority of the Fernow soil is of the Calvin and Dekalb series that originate from these rocky materials. At one point, beyond Big Spring Gap, a belt of Greenbriar limestone outcrops in places to produce a mid-slope zone of limestone soil of the Belmont series. Almost all Fernow soils, including the sandstone, shale, and limestone soils, are well drained, medium textured loams and silt loams notable for stoniness. Average soil depth is about 3 feet (1 meter). Undistributed soils have high infiltration and permeability capacity. The three soils found in Watersheds 2 and 4 are the Calvin, Dekalb, and Ernest series. Humus, a medium mull, is approximately 2.5 inches (1.0 centimeters) deep (Reinhart et al. 1963). All three soils are in hydrologic soil group B and are classified by the U.S. Forest Service as having a hydrologic condition of good.

Tree Species

The Fernow Experimental Forest is primarily a hardwood forest. Upland oaks are the most common species. Northern red oak (Quercus rubra L.), which is found in all stands, is very abundant. Chestnut oak (Quercus prinus L.) and white oak (Quercus alba L.) are the next most abundant oaks. These two species, although seldom found in the excellent stands, are more common than red oak in the fair stands. Scarlet oak (Quercus coccinea Muenchh.) and some black oak (Quercus velutina Lam.) can also be found in fair stands.
Figure 1. Location of Watersheds 1 through 7 in the Fernow Experimental Forest, near Parsons, West Virginia. The locations of recording rain gauges are marked by a triangle. Standard rain gauges are located with a circle. Elk Lick Run flows north into the Black Fork River. Modified from U.S. Forest Service (http://www.fs.fed.us/ne/parsons/webdata/strmdoc.htm) for which no scale was provided.

Beech (*Fagus grandifolia* Ehrh.) and sugar maple (*Acer saccharum* Marsh.) are numerous in all but the poor stands. Yellow poplar (*Liriodendron tulipifera* L.) makes up
a large part of excellent and good-site stands, along with black cherry (*Prunus serotina* Ehrh.), white ash (*Fraxinus americana* L.), and basswood (*Tilia americana* L.). Scattered trees include yellow birch (*Betula alleghaniensis* Britton), cucumber tree (*Magnolia acuminata*), butternut (*Juglans cinerea* L.), black walnut (*Juglans nigra* L.), and elm (*Ulmus americana* L.).

Red maple (*Acer rubrum* L.), black locust (*Robinia pseudoacacia* L.), sweet birch (*Betula lenta* L.), and, to a lesser extent, Fraser magnolia (*Magnolia fraseri* Walt.) are consistent, but generally minor, components of the forest. Black gum (*Nyssa sylvatica* Marsh.), sassafras [*Sassafras albidum* (Nutt.) Nees.], and sourwood [*Oxydendrum arboreum* (L.) DC.] are poor-stand trees of little commercial importance. Among the shrubby tree species are flowering dogwood (*Cornus florida* L.), pin cherry (*Prunus pensylvanica* L. f.), striped maple (*Acer pensylvanicum* L.), and downy serviceberry [*Amelanchier arborea* (Michx. f.) Fern.].

**Climate and Precipitation**

The Fernow Experimental Forest has a rainy and cool climate. The mean annual temperature is about 48 degrees Fahrenheit (9 degrees Centigrade), and the length of the frost-free season is about 145 days (September 30 to May 7, Reinhart *et al.* 1963). Because of elevation, winters are more severe in the Fernow Forest than in lower surrounding areas. Annual snowfall is heavy. Temperatures between 10 and 20 degrees Fahrenheit below zero (-29 to -23 degrees Centigrade) are not uncommon.

The mean annual precipitation is 58 inches (1470 millimeters), concentrated in the winter, spring, and summer months. At least three types of low frequency precipitation events lead to high flows in the Fernow Forest. These include (1) tropical depressions producing extensive rain over longer periods, (2) rainfall on snow, and (3) higher-intensity, shorter-duration rainfall (*e.g.*, large thunderstorms) when the soil is free of snow. The higher-intensity, shorter-duration rainfall events are similar to the events of May and July 2001 that caused extensive flooding in southern West Virginia. Table 1 provides the recurrence periods for various duration storms. Because the recurrence intervals for southern West Virginia (see National Weather Service Technical Report 40, 1961) investigated by the Flood Advisory Technical Taskforce (2002) are very similar, only differing by 0.1 inches (2.5 millimeters) for some rainfall totals, the climatic regimes influencing flooding must be very similar. Therefore, the definition of two climatic regimes for West Virginia by the National Oceanic and Atmospheric Administration (FATT 2002) does not seem pertinent unless those regimes are based on a need to project flooding conditions. Even then careful selection of storms at Fernow to be analyzed, and the focus on curve number indices of runoff that is inherently applicable to different rainfall conditions nationwide, indicate that any climate differences are probably moot for this evaluation.
<table>
<thead>
<tr>
<th>Duration in hours</th>
<th>Recurrence interval in years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>24</td>
<td>2.4 (61.0)</td>
</tr>
<tr>
<td>12</td>
<td>2.0 (50.8)</td>
</tr>
<tr>
<td>6</td>
<td>1.8 (45.7)</td>
</tr>
</tbody>
</table>


A network of four universal recording rain gauges (Belfort 780 series) and seven standard (8-inch or 200-centimeter) rain gauges (Belfort model 5-400) are used to measure daily and weekly precipitation amounts. See Brakensiek et al. (1979) for details on how these measurements are made. The locations of these gages in the Experimental Forest are shown in Figure 1.

**Drainage and Hydrology**

The Fernow Experimental Forest encompasses practically the entire Elk Lick Run drainage -- about 3.8 miles long and 2.3 miles across (6.12 by 3.70 kilometers) at the widest point. Elk Lick Run has seven major tributaries including Big Spring, which drains a headwater limestone formation. Headwater areas on two of these tributaries have been gaged to show how forest management influences streamflow.

The seven experimental watersheds shown in Figure 1 have been managed in the following manner to determine hydrologic impacts:

1. May 1957 through June 1958 harvest of all trees 6 inches (15 centimeters) or greater in basal diameter except culls that removed 74 percent of the basal area.
2. Periodic cutting of all trees with a 17-inch (43-centimeters) or greater diameter.
3. Harvest of all trees 6 inches (15 centimeters) or greater in diameter including culls October 1958 through February 1959 that removed 13 percent of the basal area and September 1963 through October 1963 that removed 8 percent of the basal area. July 1969 through May 1970 clear-cut of all trees greater than 1 inch (2.54 centimeters) in diameter (except for the stream riparian zone) that removed 91 percent of the basal area and the riparian strip was cut during November 1972. Since January 1989, an acidification study has been ongoing.
4. Control of approximately century-old second growth that was last cut in 1910.
5. Diameter-limited cut of 11-inch (27.9-centimeter) or greater diameter trees including culls approximately every ten years starting in 1958 to remove about 20 percent of the basal area.
6 From March 1964 to October 1969, clear cut in two phases, both maintained as barren using herbicides, and then planted in April 1973 with Norway spruce (Picea abies).

7 Clear cut in two phases and maintained as barren using herbicides from November 1963 to October 1969.

Streamflow and precipitation measurement began May through July 1951 except for Watersheds 6 and 7 for which streamflow measurements began November 1, 1956. These measurements are ongoing as of publication of this report, but not all the gages have been maintained continuously. Stage monitoring for Watershed 2 was inactive from November 1979 through April 1988 and for Watershed 5, monitoring was not conducted from November 1973 through September 1990.

All watersheds are gaged with 120-degree V-notch weirs instrumented with Belfort FW-1 water level recorders. Water surface height is measured continuously. Recorder charts are changed weekly and digitized annually at the Timber and Watershed Laboratory. Stream discharge (Q in cubic feet per second) is calculated from height (H in feet) using a standard equation calibrated to each installation. The empirical equation for Watershed 2 is

\[
Q = 4.3963 H^{2.449}
\]

and for Watershed 4 the rating curve is

\[
Q = 4.4178 H^{2.449}
\]

The Fernow watersheds respond quickly to rainfall and have limited base flows because of the shallow soils on steep slopes (approximate slopes of 10 to 40 percent) underlain by shale and sandstone that stores relatively little ground water. Runoff is rarely observed in the undistributed forests. Most of the approximately 40 percent of the precipitation that becomes runoff, moves to the streams as near-surface interflow. About two-thirds of the runoff occurs in the dormant season (Reinhart et al. 1963).

Table 2 lists the 20 most significant runoff events measured on the control Watershed 4. These events are produced by at least three different types of precipitation as noted in the section Climate and Precipitation. From these and lesser storms, the U.S. Forest Service selected and made available 15-minute rainfall data and peak runoff for four storms on Watershed 4 that could be used in this curve number analysis. Due to a discontinuous flow record on Watershed 2, the Forest Service only monitored three of the runoff events. The selected storms cover a range of rainfall conditions representative of the short, intense precipitation, including the October 15, 1954 storm that occurred as a result of Hurricane Hazel. This selection process excluded storms of longer durations due to tropical depressions and rain on snow events in favor of the shorter-duration July 8, 2001-type rainfall event analyzed by the Flood Advisory Technical Taskforce for
southern West Virginia (Frederica Wood, personal communication, January 24, 2003, U.S. Forest Service Timber and Watershed Laboratory, Parsons, West Virginia).

Table 2. Peak Flow and Recurrence Intervals for the Top 20 Largest Storms that Occurred on Watershed 4 from 1951 to 2000 (from Jim Kochenderfer and Frederica Wood, January 24, 2003, U.S. Forest Service Timber and Watershed Laboratory, Parsons, West Virginia).

<table>
<thead>
<tr>
<th>Rank</th>
<th>Date of peak flow</th>
<th>Peak flow in cubic feet per second (cubic meters per second)</th>
<th>Recurrence interval in years</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>November 4, 1985</td>
<td>25.44 (0.72038)</td>
<td>52</td>
</tr>
<tr>
<td>2</td>
<td>February 9, 1994</td>
<td>18.41 (0.5213)</td>
<td>26</td>
</tr>
<tr>
<td>3</td>
<td>October 15, 1954</td>
<td>18.06 (0.5114)</td>
<td>17</td>
</tr>
<tr>
<td>4</td>
<td>July 19, 1996</td>
<td>17.59 (0.498)</td>
<td>13</td>
</tr>
<tr>
<td>5</td>
<td>June 6, 1981</td>
<td>17.18 (0.4865)</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>January 19, 1996</td>
<td>15.88 (0.4497)</td>
<td>8.7</td>
</tr>
<tr>
<td>7</td>
<td>May 7, 1994</td>
<td>15.58 (0.4412)</td>
<td>7.4</td>
</tr>
<tr>
<td>8</td>
<td>February 10, 1957</td>
<td>15.49 (0.4386)</td>
<td>6.5</td>
</tr>
<tr>
<td>9</td>
<td>February 19, 2000</td>
<td>13.33 (0.3775)</td>
<td>5.8</td>
</tr>
<tr>
<td>10</td>
<td>May 24, 1968</td>
<td>13.19 (0.373)</td>
<td>5.2</td>
</tr>
<tr>
<td>11</td>
<td>July 29, 2001</td>
<td>11.92 (0.3375)</td>
<td>4.7</td>
</tr>
<tr>
<td>12</td>
<td>March 5, 1963</td>
<td>11.67 (0.3305)</td>
<td>4.3</td>
</tr>
<tr>
<td>13</td>
<td>March 6, 1967</td>
<td>11.35 (0.3214)</td>
<td>4.0</td>
</tr>
<tr>
<td>14</td>
<td>July 31, 1996</td>
<td>11.2 (0.317)</td>
<td>3.7a</td>
</tr>
<tr>
<td>15</td>
<td>December 22, 1970</td>
<td>10.99 (0.3112)</td>
<td>3.7</td>
</tr>
<tr>
<td>16</td>
<td>May 28, 1956</td>
<td>10.5 (0.299)</td>
<td>3.4a</td>
</tr>
<tr>
<td>17</td>
<td>August 11, 1984</td>
<td>9.97 (0.2832)</td>
<td>3.5</td>
</tr>
<tr>
<td>18</td>
<td>May 30, 1966</td>
<td>9.90 (0.2803)</td>
<td>3.3</td>
</tr>
<tr>
<td>19</td>
<td>January 22, 1959</td>
<td>9.67 (0.2738)</td>
<td>3.1</td>
</tr>
<tr>
<td>20</td>
<td>March 21, 1962</td>
<td>9.40 (0.2662)</td>
<td>2.9</td>
</tr>
</tbody>
</table>

a Because a larger storm occurred in this May to April water year, these return intervals were calculated from a nonlinear equation fit to the 1951 to 2000 annual peak flow versus recurrence interval or exceedance probability.

Watershed 2

Established in 1951, Watershed 2 has an area of 38.30 acres or 0.0598 square miles (15.50 hectares) with drainage generally from the north to the south. As shown in Figure 2, elevations range approximately from 2330 to 2670 feet (710 to 815 meters). Mixed hardwoods cover the watershed. The weir is located at 39.05387N 79.68258W but was inactive during November 1979 to April 1988.
The Watershed was divided into two treatment Areas A and B (see Figure 2). Within Area A, trees 17 inches (43.2 centimeters) in diameter and greater including culls were harvested during June to November 1958 removing 43 percent of the basal area, during August 1972 removing 23 percent of the basal area, and during May to July 1988 removing 34 percent of the basal area. Within Area B, the same practice removed 22 percent of the basal area during June to August 1958, 10 percent of the basal area during January 1978, and 34 percent of the basal area during September 1996. Beginning in November 1990, ground, agricultural-grade limestone was been applied every other year at the rate of 3 tons per acre (6700 kilograms per hectare) to the 11.3-acre (4.573 hectare) riparian zone around the stream. The purpose was to investigate reducing the acidity of stream water. The effects of liming on stream flow and soil chemistry are still being investigated.

Table 3 provides information for the three rainfall events on Watershed 2 selected by the U.S. Forest Service for which 15-minute rainfall data and peak runoff were provided. The West Virginia Division of Forestry and the U.S. Forest Service selected Watershed 2 because the periodic removal of larger trees best fits practices typically used on private landholdings in the State. Clear cutting is only rarely used on large tracts by large timber companies for the regeneration of forests and is also very different from the stripping of soil and vegetation for mining (Mary Beth Adams, personal communication, January 30, 2003, U.S. Forest Service Timber and Watershed Laboratory, Parsons, West Virginia). For Watershed 2, the three storms selected by the U.S. Forest Service (Table 3) may not strongly reflect the effects of tree harvest. The October 15, 1954 storm occurred 20 years after the Fernow Forest was established and before cutting began on this watershed. The September 29, 1973 storm occurred 25 years after the June to November 1958 harvest of
37 percent of the tree basal area. The July 30, 1996 storm occurred 18 years after the May to July 1978 24 percent (on a watershed basis) harvest of the tree basal area.

**TABLE 3.** Comparison of Watershed Characteristics for the Flood Advisory Technical Taskforce Basins and Fernow Watersheds 2 and 4

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Area in square miles (square kilometers)</th>
<th>Curve number</th>
<th>Dates when rainfall began for the events analyzed</th>
<th>Total precipitation in inches (millimeters)</th>
<th>Return interval in years</th>
<th>Peak flow in cubic feet per second (cubic meters per second)</th>
<th>Return interval in years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fernow 2</td>
<td>0.0598 (0.1549)</td>
<td>55</td>
<td>7/30/1996, 9/29/1973, 10/15/1954</td>
<td>3.34 (84.84), 3.35 (85.09), 4.47 (113.5)</td>
<td>4, 14, 20</td>
<td>5.54 (0.1569), 3.70 (0.1048), 10.59 (0.29988)</td>
<td>4, 4, 14</td>
</tr>
<tr>
<td>Fernow 4</td>
<td>0.1495 (0.38721)</td>
<td>55</td>
<td>7/30/1996, 6/5/1981, 9/29/1973, 10/15/1954</td>
<td>3.34 (84.84), 3.53 (89.7), 3.35 (85.09), 4.47 (113.5)</td>
<td>4, 4, 14, 20</td>
<td>11.23 (0.3180), 17.18 (0.48649), 4.06 (0.1150), 18.06 (0.51141)</td>
<td>3.7, 10, &lt;2, 17</td>
</tr>
<tr>
<td>Seng</td>
<td>5.4 (14.0)</td>
<td>70-73</td>
<td>7/8/2001</td>
<td>3.9 (99.1)</td>
<td>40</td>
<td>2595 (73.483)</td>
<td>&lt;25</td>
</tr>
<tr>
<td>Scrabble</td>
<td>4.2 (10.9)</td>
<td>70-73</td>
<td>7/8/2001</td>
<td>4.1 (104)</td>
<td>50</td>
<td>2045 (57.908)</td>
<td>&lt;25</td>
</tr>
<tr>
<td>Sycamore</td>
<td>5.1 (13.2)</td>
<td>70-73</td>
<td>7/8/2001</td>
<td>2.6 (66.0)</td>
<td>4</td>
<td>1211 (34.292)</td>
<td>&lt;25</td>
</tr>
</tbody>
</table>

*a Information from U.S. Forest Service for Watersheds 2 and 4 and from LIDAR coverage of Seng, Scrabble, and Sycamore watersheds interpreted by the Flood Advisory Technical Taskforce (2002) in Part III.

*b The curve numbers for the Fernow watersheds (soil hydrologic class B and good cover conditions) were derived using the standard Soil Conservation Service (now the National Resource Conservation Service) procedure as were the curve numbers for forested areas [with soils in hydrologic class C and the hydrologic cover condition good (70) or fair (73)] derived by the by Flood Advisory Technical Taskforce for the Seng, Scrabble, and Sycamore watersheds. Different curve numbers were applied to mined and residential areas in the Seng, Scrabble, and Sycamore watersheds (FATT 2002).

*c Extrapolated from National Weather Service Technical Report 40 for durations of 17 hours for the July 30, 1996 storm, 23.5 hours for the June 5, 1981 storm, 7 hours for the September 29, 1973 storm [excluding the first 11 hours and 15 minutes of drizzle totaling 0.05 inches (1.3 millimeters)], and 17.25 hours for the October 15, 1954 storm. FATT (2002) shows that the July 8, 2001 storm lasted 8 hours on the Seng and Scrabble watersheds, and 6 hours on Sycamore.

*d Return intervals have not been calculated but these values should be approximately 4 to 20 years, estimated from frequency analysis of runoff in the nearby Watershed 4 for the same storms.

*e From Flood Advisory Technical Taskforce (2002 and Responsive Summary, August 6, 2002) for a 24-hour design period based on observations of sediment-control basins in Seng and Scrabble watersheds. The return interval for the Sycamore Creek out-of-bank flows does not seem to be reported, but see return intervals reported in FATT (2002) from provision records from the U.S. Geological Survey for several gaging stations in the area that ranged from less than 2-year to greater than 500-year occurrences.
Watershed 4

Established in 1951, Watershed 4 was designated as a control watershed in 1956. The forest cover is 92 to 97-year-old second growth with some poles that replaced dead chestnut trees (Castanea dentata) that were harvested in the 1930s. Records establish that these stands have not been subjected to fire or grazing since at least 1928 (Reinhart et al. 1963). The area is 95.70 acres or 0.1495 square miles (38.73 hectares). The aspect is southeast; the drainage generally occurs from the northwest or west to the southeast. Watershed elevation ranges from 2425 to 2840 feet (740 to 865 meters) as shown in Figure 3 and the weir is located at 39.05397N 79.68714W.

Figure 3. Topography and catchment boundaries for Fernow Experimental Forest Watershed 4, near Parsons, West Virginia. The elevation contours are in feet (1 foot equals 0.3048 meters) and increments of 40 feet (12.2 meters). The gray shading or green color denotes complete mixed hardwood forest cover growing since the last known logging of 1905 to 1910. The doubled dashed lines represent an access road in the upper part of the catchment. North is from the bottom to the top. From U.S. Forest Service (www.fs.fed.us/ne/parsons/webdata). Scale not provided.

Table 3 shows four rainfall events on Watershed 4 selected by the U.S. Forest Service for which 15-minute rainfall data and peak runoff are available. The West Virginia
Division of Forestry and the U.S. Forest Service selected Watershed 4 to represent a sound test of the curve number method. The 92 to 97-year-old second growth is one of the most mature stands in the region. This condition represents private forests that have not been logged for more than 25 years. Watershed 4 is also a control that can be used to put the hydrologic response of Watershed 2 and the other experimental watersheds into a broader context.

**Models Selected by Flood Advisory Technical Taskforce**

The Watershed Management System selected by the Flood Advisory Technical Taskforce (2002) is a comprehensive watershed simulation framework that uses a number of watershed rainfall-runoff models and flow routing techniques (Brigham Young University 1998). The framework includes a number of modules or stand-alone computer codes that simulate different process, including overland runoff and channel routing of flows.

Within the Watershed Management System, the Flood Advisory Technical Taskforce selected the HEC-1 model to develop rainfall-runoff relationships for the Seng, Scrabble, and Sycamore watersheds. The Flood Advisory Technical Taskforce also used the HEC-RAS model to route flows in the three watersheds.

From the Watershed Management System, the Flood Advisory Technical Taskforce used the following capabilities and procedures:
1. Watershed software that handles geographic information and uses digital elevation terrain models to delineate and partially characterize watersheds and to set setup irregular flow networks
2. Watershed conceptualization involving digital elevation models (DEM) and laser or light detection and ranging (LIDAR) to define watershed characteristics (drainage area, slope, and flow directions and paths and a stream network) were used with the Watershed Management System module, topographic parameterization (TOPAZ) program, to perform a drainage analysis
3. Definition of related coverage features such as soil types, land uses, and other information
4. Development of input files for and execution of the HEC-1 model to define rainfall-runoff relationships and route flows using the Muskingum method and normal depths
5. Development of composite curve numbers for different subwatersheds
6. Computation of lag time and time of concentration for subwatersheds using Soil Conservation Service methods in HEC-1
7. Distribution of rainfall uniformly over watersheds and use of the module Gages to establish the position of rainfall gages
8. Application of the U.S. Soil Conservation Service (National Resource Conservation Service) loss method and development of the Soil Conservation Service dimensionless unit hydrograph
9. Evaluation of input data sets using HEC-1 checker

The separate BOSS RiverCAD® software was used to calibrate to actual peak flows derived from observed high water marks after the July 8, 2001 flood. The standard U.S. Army Corps of Engineers HEC-RAS code was used to route peak flows downstream of significant tributaries. Because the Fernow Watersheds 2 and 4 do not require flow routing simulations, the Flood Advisory Technical Taskforce (2002) routing approach is not reviewed in this report.

The Flood Advisory Technical Taskforce determined that an antecedent runoff condition II and a normal type II storm distribution best described the July 8, 2001 flood in southern West Virginia. Rainfall was assumed to be uniformly spread over each watershed simulated. The runoff volume computed using the curve number method was converted to a peak flow using the Soil Conservation Service (now National Resource Conservation Service) dimensionless unit hydrograph and separate lag time equation. This was done for each catchment simulated. The Muskingum routing method was used for catchment routing as needed.

**Hydrologic Analysis of Watersheds 2 and 4**

**Testing Approach**

The basic data for Watersheds 2 and 4 were used in two evaluations. First, the data, derived by the same Soil Conservation Service procedure as used by the Flood Advisory Technical Taskforce were used to evaluate the applicability to and what uncertainty might be involved in simulating forested watersheds on the Allegany Plateau in West Virginia. Second, values of the curve number were derived for Watersheds 2 and 4 by calibration of the HEC-1 model.

Because Watersheds 2 and 4 are homogenous in land cover, condition, and hydrologic soil conditions (forest growing on class B soils in good hydrologic condition), the watersheds are best evaluated and compared as separate contributing catchments in which stream routing is not necessary. For this reason, the runoff from Watershed 2 and the runoff from Watershed 4 were simulated using HEC-1 from the Watershed Management System, but not HEC-RAS that the Flood Advisory Technical Taskforce found necessary in the larger Seng, Scrabble, and Sycamore watersheds of mixed land use.
The curve number method requires a precipitation distribution (hyetograph), watershed area, land cover, and soil types. These data are readily available for Watersheds 2 and 4, and most watersheds nationwide and in West Virginia. The rainfall data are based on reliable measurements (made with well defined and published procedures of the U.S. Forest Service for experimental watersheds or other standard practices, Reinhart et al. 1963, Brakensiek et al. 1979). The soil type and cover are used to define soil and cover hydrologic conditions, which in turn are used to select a curve number for an antecedent runoff condition, following a standard protocol (SCS 1985). Unless soil moisture data are available, the standard procedure is to assume that the initial abstraction of rainfall is 20 percent of maximum probable moisture storage in the soil. These same procedures were used by the Flood Advisory Technical Taskforce (2002). Normally, antecedent runoff conditions are not well defined as the Flood Advisory Technical Taskforce (2002) found for southern West Virginia in July 2001. For the Fernow Forest, indirect measurements of antecedent soil moisture were available (Table 4). These include base flow measurements and antecedent rainfall. Unfortunately, the National Resource Conservation Service (see Hawkins et al. 2001b and http://www.wcc.nrcs.usda.gov/water/quality/common/neh630/4content.html) has recently withdrawn the procedure to relate antecedent rainfall for 5 days prior to a storm, to the antecedent runoff condition. Table 4 illustrates that the out-of-date procedure of the Soil Conservation Service (1986) based on antecedent rainfall would have put all storms on Watersheds 2 and 4 into the drier-than-average antecedent runoff condition. This is despite the fact that watershed base flows were two to three orders of magnitude different before the storms.

### Table 4. Antecedent Runoff Conditions

<table>
<thead>
<tr>
<th>Beginning of rainfall event</th>
<th>Pre-storm base flow in cubic feet per second (meters per second)</th>
<th>Antecedent precipitation in inches (millimeters) for different periods</th>
<th>Antecedent runoff condition</th>
<th>Modified curve number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Watershed 2</td>
<td>Watershed 4</td>
<td>7 days</td>
<td>14 days</td>
</tr>
<tr>
<td>7/30/1996</td>
<td>0.075 (0.00212)</td>
<td>0.232 (0.00657)</td>
<td>1.23 (31.42)</td>
<td>7.50 (190.5)</td>
</tr>
<tr>
<td>6/5/1981</td>
<td>Not measured</td>
<td>0.592 (0.01678)</td>
<td>1.25 (31.75)</td>
<td>3.15 (80.01)</td>
</tr>
<tr>
<td>9/29/1973</td>
<td>0.004 (0.00011)</td>
<td>0.004 (0.00011)</td>
<td>1.13 (28.70)</td>
<td>1.96 (49.78)</td>
</tr>
<tr>
<td>10/15/1954</td>
<td>0.010 (0.00028)</td>
<td>0.086 (0.00244)</td>
<td>0 (0)</td>
<td>4.05 (102.9)</td>
</tr>
</tbody>
</table>

Note: The antecedent runoff condition is derived from out-of-date criteria published in SCS (1985) that must not be used in design and assessment. For 5 days before the rainfall event, Condition I was formerly used if the total antecedent rainfall was 1.4 inches (35.5 millimeters) or less during growing season and 0.5 inches (13 millimeters) during dormancy.

The SCS (1985) provides a relation between curve numbers for antecedent runoff conditions I, II, and III. For a curve number of 55 for condition II (average runoff conditions), the condition I curve number is 35 and the condition III number is 75. When the modified curve numbers are used in the HEC-1 model, peak flow simulations are even smaller than those measured such that the method underpredicts peak flow for all
storms on both watersheds. These discrepancies highlight another procedural problem with the selection for curve numbers for forested watersheds. Because the National Resource Conservation Service guidance (National Engineering Handbook updated from SCS 1985, http://www.wcc.nrcs.usda.gov/water/quality/common/neh630/4content.html) does not give specific guidance on how to assess antecedent runoff conditions, this analysis uses the same assumption that the Flood Advisory Technical Taskforce (2002) used for the July 8, 2001 storm in southern West Virginia – antecedent runoff condition II.

Clearly from the base flow data in Table 4, conditions on both Watersheds 2 and 4 were drier before the September 9, 1973 runoff event than the other storms. Nevertheless, there is no standard procedure for quantifying these differences. Clearly, this part of the procedure is a problem in general, and specifically a gap in the hydrologic analysis of forested watersheds by the curve number method.

The only other model parameter in the process applied by the Flood Advisory Technical Taskforce (2002) is the lag time necessary to define the peak occurrence of the Soil Conservation Service (1985) unit hydrograph. The lag time as applied in the HEC-1 model is the time from the peak of the excess precipitation or runoff on the watershed surface or from the midpoint of the runoff duration to the time the peak flow occurs at the watershed outlet (HEC 1990).

The Flood Advisory Technical Taskforce (2002) selected the Soil Conservation Service (1985) lag time equation, which for homogenous catchments such as Watersheds 2 and 4, is the travel time for the catchment. The travel time is the time it takes runoff to travel through the basin to the watershed outlet for which the channel length is divided by the typical channel velocity. There is also the stream hydraulics method for estimating time of concentration from the time of travel, which seems to be same calculation as the lag time, except 60 percent of the time of concentration is taken to be the lag time. The third method of estimating the lag time is based on the watershed flow lengths and slope, and the curve number. The standard procedure (SCS 1985) is to use the method best adapted to the watershed of interest. The travel time estimate seems to be more realistic because the lag is very directly related to travel time for runoff to move out of the watershed. The curve number method was derived from research watersheds, but SCS (1985) does not say how many of the watersheds involved forest cover.

The problem with the travel time based calculations is that reliable channel velocity estimates are difficult to establish. In Table 5, the U.S. Forest Service followed the standard guidance (SCS 1985) in defining bank-full flows, estimating the recurrence interval as 1.5 years for bank-full flows in Fernow, using the Manning equation to relate flow rate to depth, and then deriving average channel velocities from the continuity equation (flow equals velocity times the cross-sectional area). In southern West Virginia, the Flood Advisory Technical Taskforce did an excellent job in surveying the flooded cross sections every 500 feet (150 meters) or so and derived slopes from digital elevation
models (data bases and simulation packages that reliably define land surface topography) using the Watershed Management System. The Fernow watersheds have not been defined quite as well for this specific purpose but can be for follow up work that is necessary to establish that the curve number is appropriate for West Virginia forests.

Table 5. Lag Time Estimates for Fernow Watersheds 2 and 4 near Parsons, West Virginia

<table>
<thead>
<tr>
<th>Water-shed</th>
<th>Channel length in feet (meters)</th>
<th>Slope in percent</th>
<th>Average bank full channel velocity in feet per second (meters per second)</th>
<th>Distributed flow length in feet (meters)</th>
<th>Slope in percent</th>
<th>Velocity in feet per second (meters per second)</th>
<th>Lag from time of travel in hours</th>
<th>Curve number based lag in hours</th>
<th>Lag (60 percent of stream plus distributed flow time) in hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2000 (610)</td>
<td>15</td>
<td>1 (0.30)</td>
<td>100 (30)</td>
<td>15</td>
<td>1 (0.30)</td>
<td>0.6</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>4</td>
<td>2000 (610)</td>
<td>1.3 (0.396)</td>
<td>700 (210)</td>
<td>14</td>
<td>1.1 (0.34)</td>
<td>1.6</td>
<td>0.4</td>
<td>1.0</td>
<td></td>
</tr>
</tbody>
</table>

*From Reinhart et al. (1963)*

*From Figures 2 and 3 and Reinhart et al. (1963)*

*Data from U.S. Forest Service Timber and Watershed Laboratory. The Watershed 2 velocity was estimated from a cross section of the stream. The Watershed 4 velocity was estimated from cross sections on two adjacent watersheds of similar size and topography. Bank-full sections were defined by scour and exposed roots and the bank-full discharge was taken to have a recurrence interval of 1.5 years. The HEC-RAS model was used to derive cross-section areas from coordinates data and depth of flow from the bank-full flow with an estimated roughness coefficient n of 0.25 to solve the Manning equation. Velocity was derived from the continuity equation – velocity = flow/cross-section area.

*Velocity derived from SCS (1985) Figure 15-2 for forest with heavy ground litter (overland flow).*

*Calculated from SCS (1985) as

\[
S = \frac{1000/(\text{curve number}) + 10}{1900 (\text{slope})^{0.5}}
\]

*Channel slope for 1200 upstream of the watershed outlet (Reinhart et al. 1963). The channel slope remaining upstream is 14 percent.*

For watersheds that involve significant overland flow path lengths, the Soil Conservation Service (1985) provides a chart to estimate velocities from land surface slope and cover. The overland flow path length divided by the chart velocity is the overland travel time that is added to the stream channel time of travel for the total lag time. The Soil Conservation Service (1985) chart has a specific curve for forests and meadows. Unfortunately, most of the flow in the Fernow watersheds has been observed to be interflow or quick return flow (Reinhart et al. 1963) and not overland flow to which the chart pertains.
Because none of the three lag time estimates for Fernow Watersheds 2 and 4 clearly stood out as the most appropriate, observed lag times were compared to the estimates and the sensitivity of peak flow rates to lag times investigated. From observations in Table 6, only the lag time of the shortest duration storm in 1973 is similar to the estimates in Table 5. However, the comparison and averaging of the lag times are complicated by the fact that the 1996 and 1981 rainfall events are multi-modal in that two or more rainfall events occurred in short periods and the runoff from these separate rainfalls have not been separated. This would require more elaborate hydrologic modeling of the watersheds or use of hydrograph separation techniques that were not possible in the limited time for this investigation. As a result, the 1954 and 1973 storms are the most useful, but the other two will be examined using extensions of the Flood Advisory Technical Taskforce (2002) approach to illustrate the uncertainty in the method as applied in southern West Virginia. Thus, the lag time estimate based on time of travel was used for a consistent analysis of all four storms following the Flood Advisory Technical Taskforce approach. The effects of lag time estimates on peak flow simulations were examined for the 1954 and 1973 storms. This proved to be useful because the HEC-1 code (HEC 1990) actually applies a different lag time estimate. Instead of the using the standard definition based on the rainfall distribution, the HEC-1 code actually defines the point of reference in time as the mid point of the duration of the excess precipitation or runoff generated on the land surface, or the peak excess runoff. Therefore, several watershed simulations were run for the 1954 and 1973 storms to calibrate the HEC-1 defined lag to the occurrence of the actual hydrograph peaks for Watersheds 2 and 4. Based on this logical determination, sensitivity and calibration tests were conducted for lag times and the curve number.

**Table 6. Observed Lag Times for Selected Storms on Fernow Watersheds 2 and 4**

<table>
<thead>
<tr>
<th>Date the rainfall event began</th>
<th>Watershed 2</th>
<th>Watershed 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time from beginning of rainfall to the hyetograph center of mass in hours</td>
<td>Time from beginning runoff to peak flow in hours</td>
</tr>
<tr>
<td>7/30/1996</td>
<td>6.75</td>
<td>15.9</td>
</tr>
<tr>
<td>6/5/1981</td>
<td>4.5</td>
<td>N/A</td>
</tr>
<tr>
<td>9/29/1973</td>
<td>0.75</td>
<td>1.4</td>
</tr>
<tr>
<td>10/15/1954</td>
<td>6.0</td>
<td>11.1</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>5.3</strong></td>
<td><strong>Average</strong></td>
</tr>
<tr>
<td><strong>Standard error</strong></td>
<td><strong>81%</strong></td>
<td><strong>Standard error</strong></td>
</tr>
</tbody>
</table>

*Note: N/A is not available due to discontinuous monitoring record.*
Results

The first test of the curve number method illustrates a significant flaw in the standard procedure defined by the U.S. Soil Conservation Service (now the National Resource Conservation Service), and large uncertainty in calculating peak flow rates. The flaw is that different forest management techniques, the seminal difference between Watersheds 2 and 4, cannot be reliably distinguished by selecting different curve numbers to reflect any difference in rainfall-runoff relationships for the catchments due to different forest management techniques. For catchments with the same type of forest, soils hydrologic class (A, B, C, or D), and surface hydrologic condition (good, fair, or poor), the same curve number is derived from Soil Conservation Service guidance (SCS 1985, 1986). In the case of Watersheds 2 and 4, a curve number of 55 is applicable for both catchments, a value of which is derived from SCS (1995, 1996). The same curve number of 55 would result from the procedure if the watershed had been clear cut and best management practices used to recovery the soil cover hydrologic condition of good, as occurred on other Fernow watersheds (Jim Kochenderfer and Frederica Wood, personal communications, January 23 and 27, 2003, U.S. Forest Service Timber and Watershed Laboratory, Parsons, West Virginia).

The selection procedure for the curve number fails to distinguish forest harvest practices, especially when proper best management practices are used, because a formal procedure has not been derived for forested watersheds (SCS 1985 as updated, despite some reference to U.S. Forest Service work in the 1950s). As soon as the timber harvest was finished on Watershed 2, haul roads, skid trails, and landing areas devoted to piling and loading timber were re-seeded. This includes management of berms, debris or slash piles, and other practices that concentrate runoff and cause erosion (thus preventing runoff from spreading out for filtration and control by indigenous vegetation). When West Virginia best management practices (Forestry Division 2001) were tested on the Fernow Forest (Kochenderfer et al. 1997), logging only had a small influence on both peak and total runoff of smaller storms in the next growing season. The Flood Advisory Technical Taskforce (2002) cites observations of isolated bare spots on logging roads for up to five years in Fernow (Kochenderfer et al. 1997). The Taskforce also cites studies of other watersheds in which hydrologic effects seem to persist from 4 to 17 years or up to 20 years for clear cutting. Unfortunately, the Taskforce does not provide a citation of these later studies nor do they indicate if these studies involved flood flows or smaller storms as others have observed, including the reviewers of FATT (2002). In the case of Watershed 2 and the other logged watersheds in Fernow, Kochenderfer and Wood of Kochenderfer et al. (1997) are adamant that the good hydrologic condition that existed before the logging of Watershed 2 and the other watersheds was achieved within a much shorter time – no more than one growing season at most. Therefore, development of any West Virginia procedure for hydrologic analysis of logging operations would need to focus on the dynamic road building (Reinhart 1964) and logging period, restoration and reseeding, and the following recovery until the preceding hydrologic conditions are
achieved. Chiefly, the effects of these operations need to be related to hydrologic condition, an alternative selection procedure for the curve number derived, or a different hydrologic analysis technique developed.

The fact that the curve number method is not well adapted to forest hydrology, especially the short, dynamic period of logging and the following restoration, is not a new finding. Hydrologist have known for some time that the method only does comparatively well for agricultural and urban runoff, marginally well for rangeland or pasture, but not well for forested watersheds (Woodward et al. 2002, Hawkins et al. 2002b). In fact, experts in the field find that "the failure to develop formal methods of applying the curve number to forested watersheds is a gaping professional embarrassment" that is not general known in practice. While some forested watersheds across the country do follow a curve number relationship approximately, many others do not because of the inherent limitations of the method, the small and subtle effects on runoff from logging being difficult to quantify, and the uniqueness of forest runoff (Woodward et al. 2002, Van Mullem et al. 2002, Hawkins et al. 2002a, 2002b, W. Swank in FATT 2002, R.H. Hawkins, University of Arizona, personal communication, January 24, 2003).

In the case of the four events on Watershed 4, peak flood simulations are different from measured flows by -48 to 77 percent or -2 to 13 cubic feet per second (-0.057 to 0.37 cubic meters per second). For Watershed 2, the stage recorder was not operational during the September 29, 1973 flood. During the other three storms, peak flow simulations differed from measurements by -20 to 55 percent or -1 to 4 cubic feet per second (-0.028 to 0.11 cubic meters per second). See Figures 4 and 5. These discrepancies may be due to seasonal effects on the curve number and differences in antecedent moisture from antecedent runoff condition II that the curve number method does not represent too well (Hawkins et al. 2002b). The effect of rainfall amounts on the curve number (Van Mullem et al. 2002) is not evident from the four storms selected by the U.S. Forest Service but these storms are biased towards larger events for the purpose of having information comparable to the July 8, 2001 flood in southern West Virginia.

Using the standard method to select a curve number 55 for Watersheds 2 and 4, the curve number method typically under predicts peak flows. The exception occurred during the September 29, 1973 flood. Prior to this storm, Watersheds 2 and 4 were evidently drier compared to conditions before the other three storms. For Watershed 2, the base flow was 0.001 cubic feet per second (0.000028 cubic meters per second) before the September 29, 1973 storm compared to 0.01 and 0.074 cubic feet per second (0.00028 to 0.00201 cubic meters per second) for the other two storms. The base flow was only 0.004 cubic feet per second (0.00011 cubic meters per second) for Watershed 4, compared to 0.09 to 0.6 cubic feet per second (0.0025 to 0.017 cubic meters per second) before the other three storms. The method as applied by the Flood Advisory Technical Taskforce assumes a constant 20 percent initial abstraction and that the antecedent runoff condition can be described for all runoff events by condition II.
Figure 4. Measured versus simulated Watershed 2 peak flows based on a curve number of 55. Note that 1 cubic foot per second is 0.028317 cubic meters per second.

In terms of water surface height differences behind the weir, the range is -0.5 to 1 feet (0.15 to 0.30 meters) for Watershed 2, and -0.7 to 1.6 feet (0.21 to 0.49 meters) for Watershed 4. In larger watersheds, these errors in simulating flood heights will normally be magnified depending on the increase in watershed area and the timing of peak flows from contributing subbasins.

The Flood Advisory Technical Taskforce (2002) noted that the curve number method was best calibrated. The second test performed for this analysis involved calibration of the HEC-1 model for the homogenous Watersheds 2 and 4. Both the lag time and curve numbers were investigated.

The 1954 storm with a single runoff peak represents the best opportunity to test what lag times may be appropriate for Watersheds 2 and 4. The 1973 storm has a secondary peak occurring during the initial recession but this should not interfere with the lag time to the initials and dominant runoff peak. The multi-peaked storms of 1981 and 1996 cannot be analyzed for lag time without hydrograph separation. The use of lag time to
control the timing and magnitude of the simulated 1954 peak runoff on Watershed 4 does not work well for a curve number of 55. A HEC-1 defined lag time of 4 hours simulates the peak observed at 1900 hours on October 15, 1954 but the magnitude of 8 cubic feet per second (0.23 cubic meters per second) is significantly different from the measured peak of 18.06 cubic feet per second (0.51141 cubic meters per second). If the lag time is reduced to 0.3 hours, the simulated peak matches the observed peak flow, but this lag seems unrealistic. For Watershed 2, a lag does not exist that simulates the magnitude of the 1954 storm peak.

Figure 5. Measured versus simulated Watershed 4 peak flows based on a curve number of 55. Note that 1 cubic foot per second is 0.028317 cubic meters per second.

For the 1973 storm on Watershed 4 using a curve number of 55, the simulated peak matched the observed with a HEC-1 lag of 3.1 hours but missing the timing by almost three hours. A lag of 0.5 hours is required to match the timing, but with this timing, the magnitude of the peak is over predicted by almost 200 percent. On Watershed 2 for the same storm, it is possible change the HEC-1 lag to 0.7 hours to reproduce the peak of 4.06 cubic feet per second (0.1150 cubic meters per second), but the simulated peak is
about 30 minutes late. Using an unrealistic HEC-1 lag of 0.2 hours matches the timing of the observed peak but the simulated flow is 65 percent too high.

Using more optimal curve numbers, lag times are better behaved for the 1954 storm on Watershed 4. However, significant discrepancies with the magnitude and timing of peaks persist, implying the underlying runoff volume calculated using the curve number is not correct.

Table 7 shows the calibrated curve numbers for a lag time estimate based on the travel time (0.6 and 1.6 hours for Watersheds 2 and 4, respectively). These values are quite uncertain. The curve number for mature hardwood forests growing in soils of class B and good hydrologic condition found on the unglaciated Allegheny Plateau is $65 \pm 11$. Watershed 2 that has been managed to cut the larger trees on three occasions since 1958, the curve number is $62 \pm 7.5$. A student $t$ test of the two populations based on a difference in the variances of the two populations as applied by the Microsoft Excel® spreadsheet indicates a 64 percent probability that the two populations are from the same population. Furthermore, it is not possible to distinguish between the values of 55 derived by standard procedure versus $65 \pm 11$ or $62 \pm 7.5$ derived by calibration of the HEC-1 model. Nor is it possible to distinguish the curve number of 70 used by the Flood Advisory Technical Taskforce (Table 3) for a different soil hydrologic class C for forested areas in Seng, Scrabble, and Sycamore watersheds, from $62 \pm 7.5$ or $65 \pm 11$. The reason is due to the high degree of uncertainty of few curve numbers derived from calibration of the HEC-1 model for peak flows in Fernow Watersheds 2 and 4. Many more storms need to be analyzed by calibrating the actual runoff volume computed with curve number rainfall runoff relationship, to avoid complications of the HEC-1 model calibration that translates runoff volume into peak flows with the Soil Conservation Service unit hydrograph. However, these high levels of uncertainty in curve numbers are expected due to the approximate nature of this lump-parameter method. Figure 6 illustrates the inherent uncertainty in curve numbers.

Based on these results, a design methodology such as the curve number approach can produce large uncertainties for forest hydrologic response. The lack of a formal procedure to adapt the method to forest practices compounds the inherent uncertainty. As a result, the imprecision in the curve number method must be carefully evaluated before changing and managing forestry practices based on such simulations.

**Recommendations for Additional Study**

Five other experimental watersheds and the stream draining all the experimental watersheds are instrumented to also measure rainfall and runoff carefully. The other catchments have undergone varying degrees of forest harvest, including clear cuts and thus the monitoring data capture the hydrologic effects of a wider range of forest management practices. If the curve number method is determined to be appropriate for
forested areas in West Virginia, many more of the storms, including those with smaller volumes will need to be evaluated for Watersheds 2 and 4. This initial assessment only establishes that the method is quite uncertain and cannot be justified without additional investigation. If a curve number rainfall-runoff relationship can be established for forested watersheds in West Virginia, then the State needs the formal development of the method to resolve the effects of various forestry practices as was done to adapt the method to urban hydrology. This formal development must not only attempt to resolve the hydrologic effects of different harvesting practices, but may also need to be formally adapted to estimate hydrologic effects during the short, dynamic period of logging and restoration.

**TABLE 7.** Curve Numbers for Fernow Experimental Forest Watersheds 2 and 4 Determined by Calibration of the HEC-1 Model Using an Average Antecedent Runoff Condition II

<table>
<thead>
<tr>
<th>Date the rainfall event began</th>
<th>Watershed 2</th>
<th>Watershed 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peak flow in cubic feet per second (cubic meters per second)</td>
<td>Lag in hours</td>
</tr>
<tr>
<td>7/30/1996</td>
<td>5.54 (0.1569)</td>
<td>0.6</td>
</tr>
<tr>
<td>6/5/1981</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>9/29/1973</td>
<td>3.7 (0.105)</td>
<td>0.6</td>
</tr>
<tr>
<td>10/15/1954</td>
<td>10.59 (0.29988)</td>
<td>0.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>62</th>
<th>Average</th>
<th>65</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard error</td>
<td>12%</td>
<td></td>
<td>Standard error</td>
<td>17%</td>
</tr>
</tbody>
</table>

Notes: Precipitation and base and peak flow data from U.S. Forest Service for Fernow Experimental Forest. The Watershed 2 gaging station was inactive during the 6/5/1981 storm. These calculations are based on antecedent runoff conditions II and a 20 percent initial abstraction.

Finally, an investigation of all Fernow Forest watersheds in concert, could test the routing procedures selected and used by Flood Advisory Technical Taskforce in a forested watershed. The HEC-RAS and Muskingum routing procedures are anticipated to be adequate, especially when a typical cross section spacing of 500 feet (150 meters) is available, but the routing technique is semi-empirical and could be tested with upstream and downstream gages that the Fernow data provides, but that Seng, Scrabble, and Sycamore watersheds lacked.
Figure 6. Typical uncertainty in curve numbers. These data are from 110 watersheds in the U.S. The 21 agricultural watershed curve numbers have a mean bias of 4.2 and standard deviation of 9.5, the 32 range curve numbers -1.5 and 7.4, and 51 forested watershed curve numbers -12.5 and 18.2. From Hawkins (1984, 2002b).

Limitations of this Analysis

Highly accurate rainfall data and peak runoff were available from the U.S. Forest Service – typically accurate to within 1 to 5 percent or less. The flow measuring weirs were carefully installed to avoid significant seepage underneath according to the U.S.
Forest Service. The hydrological analysis indicates that most if not all significant runoff was captured.

Watersheds 2 and 4 were well instrumented with a recording and standard rain gage in the upper catchment of Watershed 4. Nine other gages at different elevations were nearby to both watersheds. All four precipitation events were selected that involved intense, shorter-duration summer and early fall rainfall; no snowmelt was involved, nor were longer duration rainfalls from tropical depressions. The durations of 7 to 24 hours over the Fernow Forest were similar to the 6 to 8 hour durations on Seng, Scrabble, and Sycamore watersheds for the July 8, 2001 flood.

Antecedent moisture of the soil prior to rainfall was not measured. Only indirect measurements of base flow and antecedent rainfall are available (Table 4). The lack of this information precludes, in part, deriving specific curve numbers for West Virginia forests. This was overcome by using the same procedure as the Flood Advisory Technical Taskforce to set up a relative comparison that defines the uncertainty of the curve number method.

In general, the major sources of error for the curve number method are determinations of rainfall depths (which were well known for the Fernow watersheds) and the curve number (SCS 1985). For a wide range of rainfall depths, runoff calculated by the method is more sensitive to the value of the curve number, than to the amount of precipitation (Van Mullem et al. 2002). The largest uncertainty in the curve number derived for Watersheds 2 and 4 by the calibration of the HEC-1 model seems to be due to the use of a standard lag time equation, a standard antecedent runoff condition, the assumption that the initial abstraction of rainfall is 20 percent of the potential maximum retention, and the failure to account for potential seasonality of curve numbers for forested watersheds. The calibration of the HEC-1 model optimizes the fit of simulated peak runoff to measured peak runoff. The HEC-1 model uses a unit hydrograph based on a lag time estimate to translate peak runoff from the runoff volume calculated directly from the curve number. As is normally the case, the lag time is very uncertain and effects the calibration of the curve number for the Fernow Watersheds 2 and 4. Because of this, the curve number calibrations presented in this report are primarily for illustration of the uncertainty of the method overall to calculate peak flows. These curve numbers should not be used in design or hydrologic assessments without additional confirmation of validity. The uncertainty involved can be reduced in additional investigations by directly solving the U.S. Soil Conservation Service (National Resource Conservation Service) rainfall-runoff equation for the curve number for each storm runoff volume or all the storms monitored in Fernow and by examining the antecedent runoff condition selected by the Flood Advisory Technical Taskforce and the 20 percent assumption for initial abstraction (Hawkins et al. 2002a). Other effects may also be present but have not been investigated in the limited time available for this analysis.
Neither Watershed 2 nor Watershed 4 was divided into smaller catchments to numerically check the U.S. Forest Service experimental forest study design and determine if some flow should routed out of the lower catchment. This seems contrary to the standard practice of using the largest (thus simplest) segmentation of a watershed with consistent cover and soil conditions. Both catchments are homogenous in forest cover, hydrologic soil class (B), and soil cover condition (good). Nothing in the hydrologic response to the storms selected by the U.S. Forest Service indicate a problem, but this was not confirmed by breaking the watersheds into smaller catchments and confirming that routing on a smaller scale was not necessary.

The decisions of the Flood Advisory Technical Taskforce to use the U.S. Soil Conservation Service (National Resource Conservation Service) lag time calculation and the use of other unit hydrograph and relationships were investigated. The sensitivity of the peak runoff calculations to the lag time in the HEC-1 simulations was evaluated using the data for Watersheds 2 and 4 to conclude that runoff volumes are not correctly calculated. Without the complete hydrographs for each storm, it is not possible to fully quantify the uncertainty in the curve method. This report can only conclude that the indirect calibration of peak flows does not produce reliable curve numbers and that the reason is probably due to the inherent uncertainty illustrated in Figure 6.

The data and parameters used in this report were based on standard measurement and selection procedures, and when the simulations did not exactly match measured runoff, the sensitivity to the lag time investigated and curve number was calibrated with data from up to four major storms. The storms were selected by the U.S. Forest Service to approximate the volume and 6 to 8-hour duration of the July 8, 2001 storm that flooded southern West Virginia. This involved excluding events due to rain on snow and longer-duration rains from tropical depressions.

References


Forestry Division (2001) Best management practices for controlling soil erosion and sedimentation from logging operations in West Virginia. State of West Virginia, Charleston.


