Chapter 26

An Alternate Method of Finding the USDA Soil Conservation Service Runoff Curve Number for a Small Watershed

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Currently, one of the most widely-used methods for estimating losses for a watershed is the Soil Conservation Service (SCS) runoff curve number method (Chow et al, 1988; Viessman et al, 1989). This method requires the identification of the hydrologic soil group, cover type, treatment, hydrologic condition, and antecedent runoff condition of a watershed (McCuen, 1982; USDA, 1986). These factors are used to select a representative curve number (CN) which, in turn, is used to estimate runoff for a given rainfall event.

Selecting a value for all of the watershed parameters listed above involves individual judgment and therefore introduces errors that might otherwise be avoided. The primary focus of this chapter was to test the hypothesis that a more accurate assessment of the curve number could be found by measuring multiple rainfall events using a recording flow meter and a rain gauge.

HEC-1 was used to analyze the hydrographs and determine an SCS runoff curve number and lag time for the watershed being studied. The work was conducted using a watershed with an area of 49 km² (19 mi²) and an estimated time of concentration of 4.8 hours. Although a probable range of curve numbers (78 to 84) and lag times (3.4 to 3.8 hours) was identified, the variation in curve numbers among the five storms studied was 14. The variation in lag times was 4 hours.

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26.1 Introduction

The Soil Conservation Service (SCS) runoff curve number method (USDA, 1985) was empirically developed in the 1950's from studies of small agricultural watersheds and revised several times over the last forty years. It was intended to be used to determine key hydrologic parameters like peak flow, time to peak, and volume of runoff for design events. This method requires the watershed to be characterized by the hydrologic soil group, cover type, treatment, hydrologic condition, and antecedent runoff condition. These factors are used to select a runoff curve number that is ultimately used to estimate losses and precipitation excess or runoff for a given rainfall event (USDA, 1986).

The process by which these factors are selected is a weakness of the method. For each factor listed above, the user is forced to use a discrete classification such as “Fair” or “Antecedent Moisture Condition III”. In reality, watershed properties, such as cover type, tend to be variable and continuous, not discrete, values. Ultimately, the curve number is found by using a series of educated guesses rather than by direct measurement. Using the current method, errors in the value of the curve number are introduced by errors in judgment. These could be avoided by a direct measurement technique.

It is possible to derive the SCS runoff curve number and lag time for a watershed directly using the hydrograph of one or more measured rainfall events. Since it is relatively easy to accurately measure rainfall and flow, if a curve number can be found successfully in this manner, then SCS methods of calculating losses and generating a runoff hydrograph for a design storm would be improved. Measured values would replace estimation and educated guesses.

An accurate SCS runoff curve number and lag time value is important in the computation of design flows. The hydrograph developed from using the SCS runoff curve number and lag time is used to predict what the flow will be for a given rainfall event such as the 50-year storm or 100-yr storm. This data is then used for the mapping of flood plains, design of bridges and flood control structures, and for risk assessment. Using a SCS curve number that is too low will underestimate the risk of flooding and cause structures to be under-designed. Conversely, using a SCS curve number that is too high will overestimate the risk of flooding and cause structures to be over-designed.

26.2 Study Objective

The objective of this work was to investigate whether the SCS runoff curve number and lag time could be found directly by measuring the rainfall and flow at the outlet of a watershed in a reasonably short time frame rather than by using

the traditional SCS runoff curve number method of finding the hydrologic soil group, cover type, treatment, hydrologic condition, and antecedent runoff condition.

26.3 Methodology

The first step was the selection of a watershed. The requirements of the watershed were that it be local, well defined, and predominantly of a single land use. These criteria were necessary in order to avoid placing multiple rain gauges and flow meters in the basin. The Fishing Creek watershed in Dauphin County, Pennsylvania met all these requirements. The drainage area is approximately 30.6 km² (11.8 mi²). The watershed is located in a narrow valley between Blue Mountain and Second Mountain. Fishing Creek runs east to west the length of the valley and flows into the Susquehanna River 16.1 km (10.0 mi.) north of Harrisburg, Pennsylvania. The watershed comprises mostly forest.

Equally important to the selection of a watershed was the location of the equipment. It was desirable for the equipment to be located where flow in the stream was subcritical. In addition, the equipment had to be placed in a location that was accessible for maintenance yet secure from vandalism.

The location chosen was 3.2 km (2.0 mi.) upstream from the creek's outlet into the Susquehanna River and just downstream from a roadway structure. The stream in this location flows subcritically. The location was accessible since it was within 30.5 m (100 ft.) of the roadway and at a location where there was a parking area along the roadway. Vandalism was not a large concern since the equipment was not easily visible from the roadway, especially after the trees bloomed, and there were few houses in the area.

After a watershed and equipment location were selected, a rating curve for the stream was developed using an average Manning's n , a surveyed cross-section, and assuming uniform flow.

The next step was to collect rainfall and flow data for various rainfall events. An Isco Model 3210 Portable Recording Flow Meter and Isco Model 674 Rain Gauge were used. The system was powered by a rechargeable nickel-cadmium battery pack which was attached to the flow meter. The level of flow was measured by an ultrasonic level sensor. It was mounted approximately 1.2 m (4 ft.) above the water surface. Data was collected for nine measurable storms from April 8, 1995 through May 29, 1995 and entered into a spreadsheet. Flow data was reduced to average hourly flows in the spreadsheet.

Five of the nine storms had rainfall amounts of 6.4 mm (0.25 in.) or more. The data for these five events were used in input data files for the HEC-1 program (U.S. Army, 1987). HEC-1 is a flood hydrograph package that computes the surface rainfall-runoff response of a watershed. Of particular interest in this

study was the program's ability to calibrate watershed parameters using data from observed events. In this case, the SCS curve number, SCS lag time, and initial abstraction were the optimized parameters.

Initially, two sets of HEC-1 analyses were made using data from the five rainfall events. The first set (Set 1) produced values of curve number (CN), lag time (t_p), and initial abstraction (IA) for each rainfall event using optimization algorithms found in HEC-1. The initial abstraction in the SCS Curve Number method of estimating losses is taken to be $0.2S$ where:

$$S = \frac{1000 - 10CN}{CN} \quad (26.1)$$

and CN is the SCS runoff curve number. As described in the following section, this set of runs resulted in values for these variables that were significantly different from storm to storm.

A second set of runs (Set 2) was made to calibrate the model and get more consistent results. HEC-1 was run for all five storms inserting selected values for SCS curve number and SCS lag time. The goal was to minimize errors and to match the peak flows.

An additional two sets of HEC-1 runs were made using values of CN, t_p , and IA optimized by HEC-1 for the 5/28/95 storm and the 4/12/95 storm (Sets 3 and 4, respectively). These storms were selected because they had the largest rainfall of the five recorded storms and, coincidentally, runoff curve numbers that were the closest to the curve number obtained when using the traditional SCS Method.

26.4 Results

26.4.1 Parameter Calibration

In general, the recession flows in the HEC-1 generated hydrographs based upon optimized parameters and the observed hydrograph matched well for each of the five recorded events. However, the peak flows did not match. In all cases, the peak flow generated by HEC-1 exceeded the observed peak flow rates. The time to peak flow rate was the same for the optimized and observed hydrographs; the optimized hydrographs peaked and receded at a faster rate than the observed hydrographs.

The optimized runoff parameters showed a large variation in the SCS curve number, SCS lag time, and initial abstraction among the five storms. A summary is displayed in Table 26.1. The SCS curve numbers ranged between 79 and 93, and the lag times ranged between 1.7 and 5.7 hours. The third optimized runoff parameter, initial abstraction (IA), varied from 4.3 mm (0.17 in.) to 10.4 mm

Table 26.1: HEC-1 optimization results summary.

Date of Storm	4/08/95	4/09/95	4/12/95	5/02/95	5/28/95
Rainfall [mm (in)]	7.6 (0.30)	9.1 (0.36)	32.0 (1.26)	13.2 (0.52)	17.3 (0.68)
SCS Curve Number	88	93	82	92	79
SCS Unitgraph Lag (hr)	1.7	5.7	3.8	5.7	3.4
Init. Abstraction [mm (in)]	4.3 (0.17)	4.3 (0.17)	10.4 (0.41)	5.8 (0.23)	7.4 (0.29)
Average Absolute Error [m ³ /s (cfs)]	0.08 (3)	0.08 (3)	0.42 (15)	0.17 (6)	0.14 (5)
Average Percent Absolute Error (%)	3.6	3.5	6.9	4.6	5.0

(0.41 in.). Table 26.1 also displays an interesting relationship between curve number and rainfall amount. Higher values of the curve number are associated with smaller storm events (lower rainfall amounts).

The parameter optimization routines in HEC-1 calculate and report the average absolute error and average percent absolute error. The average absolute error is the average of the absolute value of the differences between the observed and computed hydrographs. The average percent absolute error is the average of the absolute value of percent difference between the computed and observed hydrograph ordinates.

The average absolute error ranged between 0.08 m³/s (3 cfs) and 0.42 m³/s (15 cfs). The average percent absolute error ranged between 3% and 7%. A second set of runs was made to try to determine a set of watershed parameters that would be consistent for all storms. This time, HEC-1 was run inserting values for SCS curve number and SCS lag time to calibrate the model, in essence, abandoning the HEC-1 optimization routines. A summary of results is listed in Table 26.2. Like the previous set of runs, the recession flows matched closely between the two hydrographs. In addition, the peak flows matched. Although the time of maximum flow rate was the same for the optimized and observed hydrographs, the optimized hydrographs peaked and receded at a faster rate than the observed hydrographs.

The second set of runs produced the same variation in SCS curve number and SCS lag time as the first set. The curve numbers ranged between 78 and 91. The lag time varied from 2.0 hours to 5.0 hours.

The average absolute error and average percentage absolute error were similar to the optimization runs. The average absolute errors ranged between 0.08 m³/s (3 cfs) and 0.42 m³/s (15 cfs). The average absolute percentage errors ranged between 3% and 7%.

Table 26.2: HEC-1 results summary - selected watershed parameters.

Date of Storm	4/08/95	4/09/95	4/12/95	5/02/95	5/28/95
Rainfall [mm (in)]	7.6 (0.30)	9.1 (0.36)	32.0 (1.26)	13.2 (0.52)	17.3 (0.68)
SCS Curve Number	91	91	78	88	84
SCS Unitgraph Lag (hr)	3.5	5.0	2.6	4.0	2.0
Init. Abstraction [mm (in)]	5.1 (0.20)	5.1 (0.20)	14.2 (0.56)	6.9 (0.27)	9.7 (0.38)
Average Absolute Error [m ³ /s (cfs)]	0.08 (3)	0.11 (4)	0.42 (15)	0.14 (5)	0.17 (6)
Average Percent Absolute Error (%)	3.4	3.9	7.2	4.5	6.3

26.4.2. Comparing Generated Hydrograph to Other Storms

Comparison using the 5/28/94 optimized runoff parameters

A summary for the third set of HEC-1 runs is given in Table 26.3. The storm hydrographs for 5/28/95 matched closely. Since the optimized values for SCS curve number, SCS lag, and initial abstraction were used, the computed hydrograph was identical to the one produced in the first set of runs. Graphically, the 4/12/95 storm hydrographs also matched fairly well. The recession flows, total volume, and time of peak matched between the two hydrographs. As observed previously, the computed hydrograph peaked and receded at a faster rate than the observed hydrograph. The hydrographs for the other storms did not match. In all three cases, the computed hydrograph was considerably lower than the observed hydrograph.

The errors produced were higher than the previous two sets of runs. The average absolute error ranged between 0.25 m³/s (9 cfs) and 0.42 m³/s (15 cfs). The average absolute percent error ranged from 5% to 11%.

Comparison using the 4/12/94 optimized runoff parameters

A summary for the fourth set of HEC-1 runs is in Table 26.4. Like the third set of HEC-1 runs, the 4/12/95 storm hydrographs matched closely although this was expected since the optimized values were used. The recession flows and time of peak flow for the two hydrographs matched, however, the computed peak

Table 26.3 HEC-1 results summary using 5/28/95 storm optimized parameters for all storms.

Date of Storm	4/08/95	4/09/95	4/12/95	5/02/95	5/28/95
Rainfall [mm (in)]	7.6 (0.30)	9.1 (0.36)	32.0 (1.26)	13.2 (0.52)	17.3 (0.68)
SCS Curve Number	79	79	79	79	79
SCS Unitgraph Lag (hr.)	3.4	3.4	3.4	3.4	3.4
Init. Abstraction [mm (in)]	7.4 (0.29)	7.4 (0.29)	7.4 (0.29)	7.4 (0.29)	7.4 (0.29)
Average Absolute Error [m ³ /s (cfs)]	0.25 (9)	0.28 (10)	0.42 (15)	0.28 (10)	0.14 (5)
Average Percent Absolute Error (%)	11.1	11.0	7.8	7.6	5.0

Table 26.4 HEC-1 results summary using 4/12/95 storm optimized parameters for all storms.

Date of Storm	4/08/95	4/09/95	4/12/95	5/02/95	5/28/95
Rainfall [mm (in)]	7.6 (0.30)	9.1 (0.36)	32.0 (1.26)	13.2 (0.52)	17.3 (0.68)
SCS Curve Number	82	82	82	82	82
SCS Unitgraph Lag (hr.)	3.8	3.8	3.8	3.8	3.8
Init. Abstraction [mm (in)]	10.4 (0.41)	10.4 (0.41)	10.4 (0.41)	10.4 (0.41)	10.4 (0.41)
Average Absolute Error [m ³ /s (cfs)]	0.25 (9)	0.37 (13)	0.45 (16)	0.51 (18)	0.23 (8)
Average Percent Absolute Error (%)	11.1	14.6	7.1	14.8	8.8

flow exceeded the observed peak flow. Once again, the computed hydrograph peaked and receded at a faster rate than the observed hydrograph.

The hydrographs for the other storms did not match. In all four cases, the computed hydrograph was lower than the observed hydrograph. For the 4/08/95 and 4/09/95 storms, the flow receded over the entire period. This was due to the initial abstraction of 10.4 mm (0.41 in) being greater than the total rainfall for those events.

The errors produced were slightly higher than for the previous set of runs. The average absolute error ranged between 0.25 m³/s (9 cfs) and 0.51 m³/s (18 cfs). The average absolute percent error ranged from 7% to 15%.

26.5 Discussion

From the results presented, it appears that the methodology did not yield a single SCS runoff curve number or SCS lag time but a wide range of values. In the case where the runoff parameters were optimized by HEC-1 for each storm (Set 1, Table 26.1), the SCS curve number varied by a factor of 14, and the SCS Unitgraph Lag varied by 4 hours. When HEC-1 was calibrated to match peak flows (Set 2, Table 26.2), the variation was 13 for the SCS curve number and 3 hours for the lag time. When using the HEC-1 output from the optimization run of the 5/28/95 and 4/12/95 storms in the HEC-1 input for the five storms, the computed and observed hydrographs did not match.

Despite the varied results, we cannot conclude that a SCS curve number and SCS lag time cannot be successfully found. If a factor or factors can be found that are responsible for the variation, then a correction can be applied which can improve the consistency between values.

The first factors to examine are those that are known to affect the SCS curve number using the traditional approach. These factors are hydrologic soil group, cover type, treatment, hydrologic condition, and antecedent runoff conditions. Each of these factors is briefly discussed.

Hydrologic soil group - The predominant soil types of the basin are the Calvin Series and the Dekalb Series (USDA, 1972). Both are classified as Type C soils and did not change over the course of the study.

Cover type - The cover type for the basin is classified as woods and did not change over the study period.

Treatment - Treatment pertains mainly to agricultural lands and therefore was not a factor for this study.

Hydrologic condition - Although the entire watershed is classified as being in “good” hydrologic condition, the hydrologic condition did change over the study period. At the start of the project in April 1994, the trees and shrubs had not bloomed. By the beginning of May, the trees had bloomed, and by mid to late May, the ground cover had thickened considerably.

The addition of foliage to the trees and shrubs would cause the hydrologic condition to improve and the SCS curve number to decrease. According to the SCS charts, the difference in SCS curve number between “fair” and “good” for a type C wooded soil is a decrease of 3. The optimized HEC-1 runs found that the 5/28/95 curve number was 3 less than the 4/12/95 which means that if the addition of foliage was enough to change the condition from “fair” to “good”,

then the difference between the 4/12/95 and 5/28/95 storm is accounted for. Although the hydrologic condition probably did not change from “fair” to “good”, it definitely improved, and therefore, a difference in SCS curve numbers of 1 or 2 may be reasonable.

The hydrologic condition does not account for the variance between the other storms. The 4/08/95 and 4/09/95 storms occurred in the same week as the 4/12/95, but the curve numbers differ with the 4/12/95 storm by 6 and 11 respectively. The 5/02/95 storm occurred three weeks after the 4/12/95 storm but has a higher SCS curve number.

Antecedent runoff condition - The antecedent runoff condition can change the curve number of a watershed substantially. According to SCS charts, a watershed with a SCS curve number of 80 under normal conditions (Condition II) will have a curve number of 94 under Condition III. A watershed with a curve number of 90 under normal conditions will have a curve number of 78 under Condition I. Consequently, the antecedent runoff condition could account for the difference in curve numbers.

To verify the antecedent runoff condition, rainfall and temperature data is needed. Since the rain gauge was not activated for the entire study period, and temperature data was not recorded, data was obtained from the National Weather Service. The data although recorded 24.1 km (15.0 mi.) away from the study area should be accurate enough to indicate the soil condition for each storm. The total rainfall and average temperature for the five-day period before every storm are shown in Table 26.5.

Table 26.5 Temperature and rainfall data for Harrisburg.

Storm	Average Temperature (Previous 5 Days)	Normal Average Temperature (Previous 5 Days)	Rainfall (Previous 5 days)
4/08/95	7°C (45°F)	9°C (48°F)	0.0 mm (0.00 in)
4/09/95	8°C (47°F)	9°C (48°F)	6.1 mm (0.24 in)
4/12/95	11°C (51°F)	10°C (50°F)	23.9 mm (0.94 in)
5/02/95	12°C (53°F)	14°C (57°F)	11.9 mm (0.47 in)
5/28/95	21°C (69°F)	18°C (65°F)	2.3 mm (0.09 in)

The traditional SCS runoff curve method classifies conditions with rainfall less than 12.7 mm (0.5 in.) in the previous five days as Condition I. Rainfall of 12.7 mm (0.5 in.) to 27.9 mm (1.1 in.) is Condition II, and rainfall exceeding 27.9 mm (1.1 in.) or less than 27.9 mm (1.1 in.) with low temperatures is Condition

III. Following this criteria, the 4/08/95, 4/08/95, and 5/28/95 storms are Condition I, and the 4/12/95 and 5/02/95 storms are Condition II.

As mentioned in the introduction, the largest downfall with the SCS method is having to classify each factor into one category or another. For example, the soil at the time of the 4/12/95 storm although officially classified as Condition II was probably somewhere between Condition II and Condition III because there were two rainstorms in the previous five days. For this reason, the SCS conditions are backed away from and the following statements are made:

- the soil conditions on 4/08/95 were generally dry making the SCS curve lower than normal;
- the soil conditions on 4/09/95 were also dry, so the SCS curve number is low;
- the soil conditions on 4/12/95 were generally average bordering on wet (meaning the SCS curve number is slightly higher than normal);
- the soil conditions on 5/02/95 were average, therefore, the SCS curve number does not need to be adjusted; and
- the soil conditions on 5/28/95 were normal to dry lowering the SCS curve number.

The antecedent moisture condition does not entirely account for the large variation in SCS curve numbers. The 4/08/95 and 4/09/95 storms had a high SCS curve number to begin with, and are adjusted even higher. The 4/12/95 had a low curve number and is adjusted lower. The 5/02/95 storm had a high curve number but would not be adjusted.

Another possible explanation in the variation of SCS curve numbers is the limitations of the SCS curve number method. TR-55 (USDA, 1972) states that the SCS curve number method is less accurate for runoffs under 12.7 mm (0.5 in.). Runoff is related to the amount of rainfall and initial abstraction by the following equation:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + 5I_a} \quad (26.2)$$

where:

- Q = the runoff in millimeters
 P = the rainfall in millimeters
 I_a = the initial abstraction in millimeters

This results in runoff values for the sequence of five storms of 0.5 mm (0.02 in.), 0.8 mm (0.03 in.), 6.4 mm (0.25 in.), 1.5 mm (0.06 in.), and 2.0 mm (0.08 in.) respectively. All are below the 12.7 mm (0.5 in.) value. Since runoff decreases with rainfall, it can be said that the runoff values are less accurate for smaller storms. Therefore, the accuracy of the 4/08/95 and 4/09/95 curve numbers is much less than the others, and the curve number found from the 4/12/95 is the most accurate.

This suggests that the SCS curve number for Fishing Creek is probably in the low eighties, although the smaller storms' data suggests that it is higher. The SCS lag time is probably between 3.5 and 4 hours. As a comparison, using the traditional SCS runoff curve method the curve number is 70 and the lag time is 2.9 hours. This indicates that the results of the traditional method are low, but lacking consistent results, a corrected value cannot be recommended.

Although the main discussion centers around the variation in the SCS curve numbers for the five storms, there are other results that should be explained. The first is the failure of the HEC-1 optimization procedure to match peak flows. The optimized peak flow always exceeded the observed peak flow. This is because HEC-1's optimization procedure minimizes the difference in total flow between the computed and observed hydrographs. Since the SCS hydrograph peaked and receded at a faster rate and in a shorter time period than the observed hydrograph, to minimize the difference in total flow, the computed hydrograph had a greater maximum flow rate than the observed.

The observed hydrographs and computed hydrographs never had the same shape. The computed hydrograph always peaked and receded at a faster rate than the observed hydrograph. This is due to the fact that the method selected in the optimization runs used the SCS dimensionless unit hydrograph. The SCS dimensionless unit hydrograph is based on the equations:

$$TPEAK = 0.5t + TLAG \quad (26.3)$$

$$QPEAK = \frac{44269 \times AREA}{TPEAK} \quad (26.4)$$

where:

- $TPEAK$ = the time to the peak flow in hours
- t = the duration of excess in hours
- $TLAG$ = 0.6 x the time of concentration in hours
- $QPEAK$ = the peak flow in m³/s
- $AREA$ = the basin area in km²

The SCS dimensionless hydrograph may not have had the same shape as the observed hydrographs, therefore, regardless of which value for SCS curve number, SCS lag, and initial abstraction are input, the computed and observed hydrographs will not match.

The final item of discussion is the error found for the 4/08/95 and 4/09/95 storms in the third and fourth set of HEC-1 runs. The errors for the third and fourth runs match exactly for the two storms. The reason for this is that the SCS curve numbers used were so low that for a small rainfall, there was no runoff. Consequently, the hydrograph only consisted of recession flow.

Heuristically calibrating the model was as successful as using HEC-1's optimization routines in determining a single curve number and lag time for the watershed. In some cases, varying the parameters may improve the overall solution. In this study, the results did not change substantially between the two methods. Still, it is recommended that the optimization results be compared to a heuristic calibration since there is an opportunity to improve the values of the parameters with respect to some other optimization goal, such as matching peak flows.

26.6 Conclusions and Recommendations

Overall, the process of measuring rainfall and stream flow for multiple storms in the Fishing Creek basin and using the data in HEC-1 was unsuccessful in determining a single SCS runoff curve number and lag time. The SCS curve numbers and SCS lag times found by parameter calibration varied considerably from storm to storm. The hydrograph produced from running HEC-1 using the optimized values did not match the observed hydrographs. Although some of the discrepancies could be rationalized, only a broad SCS curve number range and lag time range resulted from the analysis. Nevertheless, based upon the experience of measuring flow and rainfall over a relatively short period using readily available, mobile equipment, the authors were able to identify a likely range of curve numbers for the watershed ($78 \leq CN \leq 84$) and for the basin's lag time ($3.4 \text{ hr} \leq t_p \leq 3.8 \text{ hr}$).

Even so, some of the factors used in the SCS runoff curve method such as the hydrologic condition and antecedent runoff condition must be accounted for even when directly measuring the rainfall and stream flow.

Since the SCS curve number method is most accurate for runoffs of 12.7 mm (0.5 in.) or more, large rainfall events are needed to assure accuracy especially in non-developed areas where the runoff is generally low. It is recommended that data for three rainfall events each exceeding 12.7 mm (0.5 in.) and occurring under antecedent runoff soil Condition II be collected to achieve a consistent SCS runoff curve number and lag time. Although the data could take weeks or months to collect, it is important to record data under these conditions. If these conditions cannot be accommodated, adjustments will have to be made which, in essence, would make this direct method no better than the traditional method of determining curve number and lag time.

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