

# Estimation of Time of Concentration for Maryland Streams

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The time of concentration (TC) is an important input to most hydrologic models and is usually estimated by travel-time computations or by using rainfall-runoff data. Average TCs were determined for 78 rural and urban watersheds in Maryland and related to watershed characteristics using regression analysis. The regression equation is based on the channel length and slope; the percentage of the watershed covered with forests, lakes, and ponds; and the percentage of the watershed with impervious areas. The equation is applicable for estimating TCs for rural and urban watersheds in Maryland with watershed characteristics similar to the gauging station data. TC values computed at Maryland gauging stations were compared with estimates from an equation developed by Kirpich and the Soil Conservation Service (SCS) lag equation, and with basin lag times determined by the U.S. Geological Survey (USGS). The average TC values computed in this analysis were about 5 percent higher than the basin lag-time estimates, which is consistent with the USGS's definition of lag time. TC estimates from the Kirpich or SCS equations were consistently lower than the values computed from gauging station data. The tendency to underestimate TCs is a major reason why hydrologic models often provide conservative estimates of design discharges compared with regional regression equations and gauging station data.

Today's methods for the hydraulic design of bridges, culverts, embankments, and storm water management structures require knowledge of flood discharges and volumes or times of inundation related to such structures. Hydrologic models are used to estimate flood hydrographs for design purposes. The hydrologic model most often used in Maryland is the TR-20 model developed by the Soil Conservation Service (SCS) (1). An important input to the TR-20 model is the watershed time of concentration (TC), which is a function of watershed characteristics such as its length, slope, and land coverage and affects the shape and peakedness of the flood hydrograph.

Rainfall-runoff data compiled by the U.S. Geological Survey (USGS) were used to compute the average TC values for 78 rural and urban watersheds in Maryland. The computed TC values and watershed characteristics were used to develop a regression equation for estimating TC at ungauged watersheds in Maryland.

## DATABASE

Two TC definitions are commonly accepted. First, the TC can be defined as the time required for a particle of water to flow from the most hydraulically distance point in the watershed to the outlet or

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design point. The method of estimating this travel time is usually accomplished as a combination of sheet flow, shallow concentrated flow, and open channel flow, as described in the SCS TR-55 manual (2).

Second, the TC can be defined from an observed rainfall hyetograph (graph of rainfall versus time) and the resulting observed discharge hydrograph. The rainfall excess and direct runoff are computed from the observed hyetograph and hydrograph. The TC is the time between the end of rainfall excess and the first inflection point on the recession of the runoff hydrograph. The inflection point represents the time when surface runoff ceases and subsequent flow is sustained by releases from watershed storage.

The second TC definition was used in this study. The inflection point was located visually by plotting the discharge hydrograph on semilogarithmic paper (discharge is logarithmic, time is arithmetic). Generally, the recession has two distinct slopes, representing direct immediate runoff and the storage component or delayed runoff. A schematic defining TC is given in Figure 1.

The rainfall-runoff data in Figure 1 are from the gauging station at Western Run, Maryland (Station 01583500) for the flood of December 25, 1986. The total rainfall was 41.91 mm (1.65 in.), and the peak discharge was 54.2 m<sup>3</sup>/s (1,914 ft<sup>3</sup>/s), approximately a 2-year event. The discharge ordinate in Figure 1 is plotted on an arithmetic scale, rather than the logarithmic scale, for better representing the discharge hydrograph.

TC values were computed from rainfall-runoff data compiled by the USGS as part of a flood hydrograph study for the Maryland State Highway Administration (3). The USGS compiled data for 278 rainfall-runoff events during from 1981 to 1993 at 81 gauging stations in Maryland. This time period was chosen because the unit-values hydrograph data from more recent years were more accessible than the older data. Not all of the 278 events were suitable for defining the TC. For some rainfall-runoff events, an inflection point could not be detected on the recession of the hydrograph. On average, about three events were used in determining the average TC for a watershed. For three gauging stations, no rainfall-runoff events were suitable for determining TC. Therefore, data for 78 gauging stations were used in developing a regression equation for estimating TC at ungauged watersheds.

## DATA ANALYSIS

Stepwise regression analysis was used to relate the average TC value computed at 78 gauging stations to the watershed characteristics. The watershed characteristics used in this analysis were taken from Dillow (3). Some characteristics that highly correlate with TC also highly correlate with each other. For example, drainage area has a correlation coefficient of 0.98 with channel length. Because of their high correlation, both variables are not significant in the regression

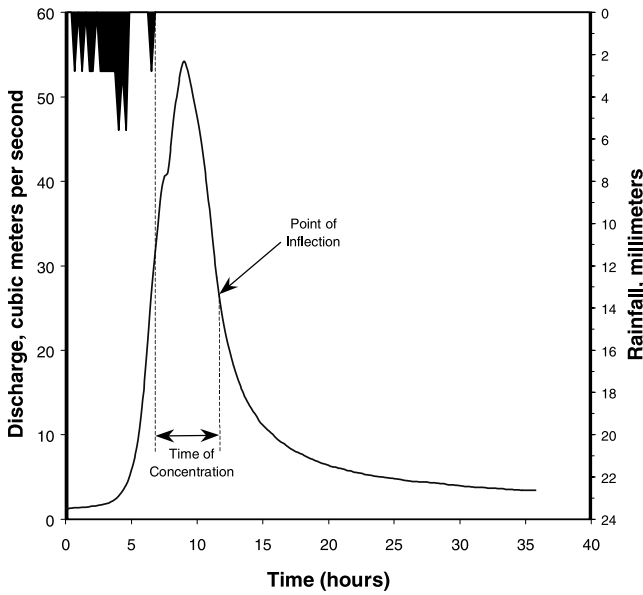


FIGURE 1 Definition of the time of concentration for a given rainfall-runoff event.

analysis—they essentially explain the same variation in TC. The regression equation based on channel length has a slightly lower standard error than the one with drainage area, and so channel length is used in the final equation. Channel length also provides a better estimate of travel time for a variety of watershed shapes.

Following Dillow’s approach, qualitative variables were used in the regression analysis to identify gauging stations in different hydrologic regions in Maryland (3). Dillow determined that three hydrologic regions can be used for estimating flood hydrographs for

Maryland streams—the Appalachian Plateau, Piedmont, and Coastal Plain. These same regions are assumed applicable in this analysis and are shown in Figure 2. The qualitative-variables approach is superior to defining different equations for each geographic region because only 10 gauging stations exist in the Appalachian Plateau.

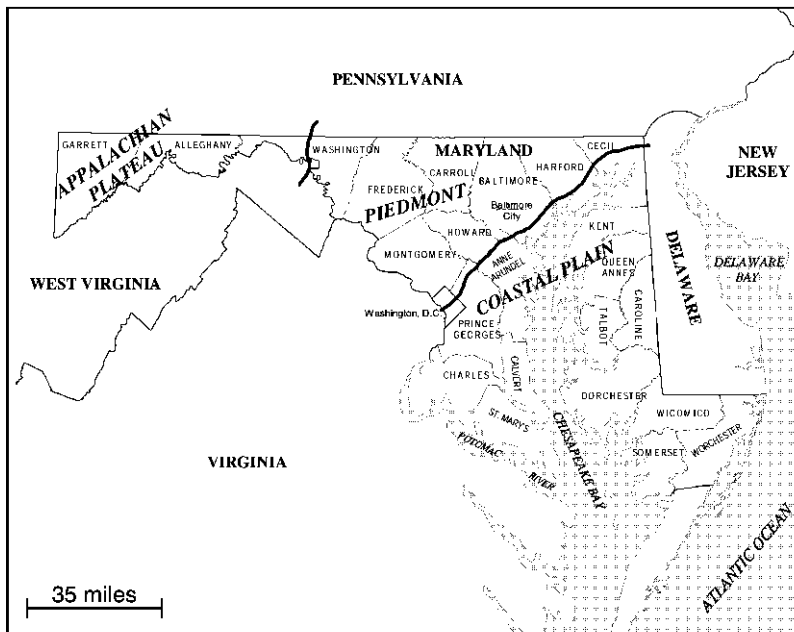
The qualitative variables Appalachian Plateau (AP) and Coastal Plain (CP) are used in the regression equation to account for TC variability not explained by the available explanatory variables. An AP value of 1 specifies that the watershed is in the Appalachian Plateau, a CP value of 1 specifies that the watershed is in the Coastal Plain, and 0 values for AP and CP specify that the watershed is in the Piedmont. The TC values for watersheds in the Appalachian Plateau and Coastal Plain are larger than watersheds in the Piedmont for a given set of watershed characteristics. The qualitative variables also account for regional TC differences related to watershed characteristics not available for analysis. Both AP and CP are highly significant in the regression analysis.

The hydrology varies significantly from the Coastal Plain of Maryland to the mountainous Appalachian Plateau. Therefore, several watershed characteristics are statistically significant in predicting the TC. In the following equation, all explanatory variables are significant at the 5 percent level. The coefficient of determination ( $R^2$ ) is 88.8 percent, implying that the equation explains 88.8 percent of the variation in the computed TC value. The standard error of estimate (SE) is 30 percent.

$$TC = 0.133(CL^{0.475})(SL^{-0.187})(101 - FOR)^{-0.144} (101 - IA)^{0.861}(ST + 1)^{0.154}(10^{0.194AP})(10^{0.366CP}) \quad (1)$$

where

- TC = time of concentration (h),
- CL = total channel length to the watershed divide (km or mi),



NOTE: 1 mi = 1.6093 km.

FIGURE 2 Study area and hydrologic regions in Maryland.

- SL = channel slope between points 10 and 85 percent of the distance upstream from the watershed outlet (m/km or ft/mi),
- FOR = forest cover in percentage of the drainage area of the watershed,
- IA = impervious area in percentage of the drainage area of the watershed,
- ST = lakes and ponds in percentage of the drainage area of the watershed,
- AP = 1 if the watershed is in the Appalachian Plateau (0 otherwise),
- C = 1 if the watershed is in the Coastal Plain (0 otherwise), and
- AP and CP = 0 for watersheds in the Piedmont.

Equation 1 was computed using customary units, and thus customary units are given first, followed by the SI units in parentheses.

Equation 1 was computed by transforming the TC and watershed characteristics to logarithms and fitting a linear regression model to the transformed data. This transformation is somewhat standard in hydrology because the logarithmic transformation tends to stabilize the variance of the residuals, normalize the distribution of the residuals about the regression equation, and linearize the equation. The standard error of the log-transformed equation is 0.12755 log units, which converts to a standard error of 30 percent.

The FOR, IA, and ST percentages can be 0 for a given watershed. Therefore, constants must be added to these variables before the logarithmic transformation or these variables must be subtracted from a constant to avoid a logarithm of 0. For this analysis, subtracting the percentages from 101 provided more reasonable estimates of the regression coefficients and slightly reduced the standard error of the regression equation.

Any regression equation, such as Equation 1, should be used only at ungauged watersheds that have characteristics within the range of those used to develop the equation. The upper and lower limits for the watershed characteristics are given in Table 1 for each hydrologic region to define the applicability of Equation 1.

Equation 1 can be used to estimate TCs for rural and urban watersheds in Maryland. The IA percentage is a measure of the urbanization or development in the watershed. Also, urban watersheds would have less forest cover.

**TABLE 1 Upper and Lower Limits for Watershed Characteristics by Hydrologic Region**

Region	Variable	Upper limit	Lower limit
Appalachian Plateau	Drainage area (mi <sup>2</sup> )	295	1.6
Appalachian Plateau	Channel length (mi)	40.8	2.1
Appalachian Plateau	Channel slope (ft/mi)	195	6.1
Appalachian Plateau	Storage (%)	3.2	0.0
Appalachian Plateau	Forest cover (%)	89	54
Appalachian Plateau	Impervious area (%)	1.25	0.0
Piedmont	Drainage area (mi <sup>2</sup> )	494	2.1
Piedmont	Channel length (mi)	70	2.2
Piedmont	Channel slope (ft/mi)	336	11
Piedmont	Storage (%)	1.16	0.0
Piedmont	Forest cover (%)	92	2.0
Piedmont	Impervious area (%)	41	0.0
Coastal Plain	Drainage area (mi <sup>2</sup> )	113	2.0
Coastal Plain	Channel length (mi)	18.3	2.0
Coastal Plain	Channel slope (ft/mi)	41.8	1.5
Coastal Plain	Storage (%)	26.0	0.0
Coastal Plain	Forest cover (%)	79	5.0
Coastal Plain	Impervious area (%)	35	0.0

NOTE: 1 mi<sup>2</sup> = 2.5900 km<sup>2</sup>  
 1 mi = 1.6093 km.  
 1 ft = 0.3048 m.

The TC values computed using rainfall-runoff events in this study were generally larger than those computed by SCS procedures for a given watershed size (2). One possible hypothesis is that the TC may be inversely related to the size of the flood event. In this study, the recurrence intervals of peak discharges of the hydrographs used to compute TCs were generally shorter than for a 2-year event. About 30 events for the 78 gauging stations had a peak discharge for a 5-year or longer event. An evaluation of the TC values as a function of recurrence interval revealed that the TC values did not vary with the recurrence interval in any consistent pattern. Sometimes the larger flood events had smaller TC values, and the converse was true in other instances. The use of larger flood events would not necessarily result in smaller TC values. Unit-hydrograph theory assumes that the TC is a constant for a watershed and is independent of flow magnitude and frequency. This assumption is the basis for several empirical equations for estimating the TC as a function of watershed characteristics, such as Equation 1 and other equations that follow. The rainfall-runoff data compiled by Dillow and used in this study are reasonably consistent with the assumption of a constant TC for a given watershed (3).

### COMPARATIVE ANALYSES

Many empirical equations can be used for estimating the TC. McCallum and Hotchkiss described and reviewed 21 methods for estimating the TC and evaluated 7 methods using data at seven small stream sites in Nebraska (4). Two of the methods evaluated were an equation developed by Kirpich, which is often used in conjunction with the Rational method and the SCS Lag Equation (4–6). Estimates from these two methods were compared with TC values computed at gauging stations in Maryland.

#### Kirpich Equation

Kirpich calibrated two equations for estimating TC using small watershed data in Pennsylvania and Tennessee (5). The most frequently used equation was the one developed using Tennessee watersheds ranging in size from 4 046 m<sup>2</sup> to 453 152 m<sup>2</sup> (1 to 112 acres), with slopes from 3 to 10 percent. This equation is

$$TC_k = 0.00013 CL^{0.77} SL^{-0.385} \tag{2}$$

where

- TC<sub>k</sub> = TC from Kirpich's equation (h),
- CL = channel length (m or ft), and
- SL = channel slope (m/m or ft/ft).

The constant in Equation 2 is based on customary units, and thus these units are shown first, followed by the SI units in parentheses. Kirpich's equation was applied to 14 gauging stations in Maryland whose drainage areas were less than 10 km<sup>2</sup> (3.85 mi<sup>2</sup>). TC estimates from Kirpich's equation and Equation 1 were plotted against the computed (gauging station) TC values, as shown in Figure 3.

As illustrated in Figure 3, estimates from Kirpich's equation tended to vary little and to be significantly lower than TC values computed from gauging station data. One reason for the apparent bias of the Kirpich equation is its application well beyond the range of data used to develop it. Most of the Maryland watersheds had slopes less than 10 percent, consistent with Kirpich's data. To obtain

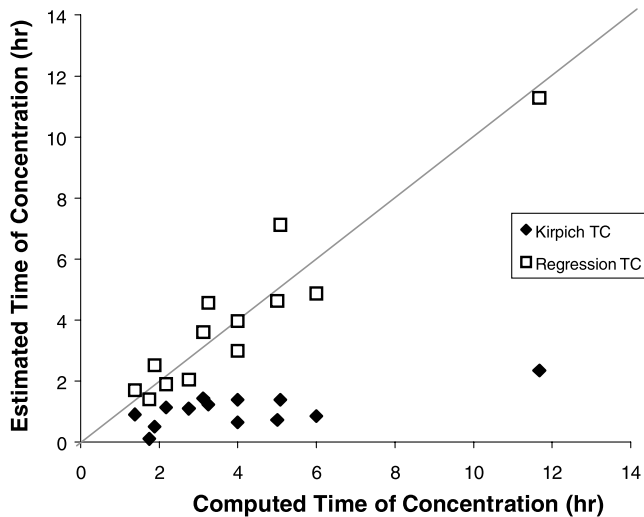


FIGURE 3 Comparison of the estimated time of concentration from Kirpich's equation and the seven-parameter regression equation with computed values of the time of concentration.

an adequate sample for comparison, however, an upper limit of 10 km<sup>2</sup> (3.85 mi<sup>2</sup>) was used for drainage areas beyond the limit of data used by Kirpich. Figure 3 shows that Kirpich's estimate tended to deviate more from the regression estimate as the watershed got larger (increasing TC). The TC estimates from Equation 1 are consistent with the computed values because the equation is based on these data.

The comparisons are consistent with those of McCallum and Hotchkiss, who found that 1.5 times the Kirpich estimate still underestimated the TC based on the gauging station data (4). The Kirpich equation is representative of several empirical equations that estimate the TC as a function of channel length and slope.

**SCS Lag Equation**

The SCS lag equation is applicable for estimating the basin lag time for watersheds with drainage areas less than 8.1 km<sup>2</sup> (2,000 acres) (6). SCS defines basin lag time as the time from the centroid of rainfall excess to the peak of the hydrograph. The TC was estimated as 1.67 times the basin lag time, and this multiplier is shown at the end of Equation 3. The TC estimated from the SCS lag equation is defined as

$$TC_{SCS} = 0.000526CL^{0.80}(1000 - 9 * RCN)^{0.70} S^{-0.50}RCN^{-0.70}(1.67) \tag{3}$$

where

- TC<sub>scs</sub> = time of concentration from the SCS lag equation (h),
- CL = channel length (m or ft),
- RCN = runoff curve number as defined by SCS, and
- S = watershed slope (perpendicular to the channel) (%).

The constant in Equation 3 is based on customary units, and thus these units are shown first, followed by the SI units in parentheses. The SCS lag equation was applied to data from 13 gauging stations

with drainage areas less than 25.9 km<sup>2</sup> (10 mi<sup>2</sup>) for which RCN and S were defined. The SCS lag equation was also applied to watersheds beyond the recommended limit of 8.1 km<sup>2</sup> (2,000 acres) to obtain an adequate sample for comparison. TC estimates from the SCS lag equation and Equation 1 were plotted against computed values for the 13 gauging stations, as shown in Figure 4.

The comparisons in Figure 4 are similar to those for the Kirpich equation but are more consistent with the computed data. On average, the SCS lag equation underestimated the TC values computed from the gauging station data. Figure 4 shows that the SCS estimates tended to deviate more from the regression estimate as the watershed got larger (increasing TC). The TC estimates from Equation 1 are consistent with the computed values because the equation is based on these data.

**USGS Basin Lag Time**

Dillow computed basin lag time using essentially the same rainfall-runoff data as used in this study to determine the TC (3). The lag time as used by Dillow was the time from the centroid of rainfall excess to the centroid of the direct runoff hydrograph. The average lag time values were 0.95 times the TC values, and, conversely, the average TC values were 5 percent higher than the lag times. This difference is consistent with the definitions of lag time and TC. For 90 percent of the gauging stations, the ratio of the lag time to the TC was between 0.70 and 1.40. A comparison of lag time with TC values is given in Figure 5. As the figure shows, the lag time and TC values tended to be nearly equal for small values of the parameters and deviate for large values.

**CONCLUSIONS**

TC values estimated from empirical equations, such as Kirpich or SCS, tended to be lower than values computed from rainfall-runoff data for 78 gauging stations in Maryland. These equations

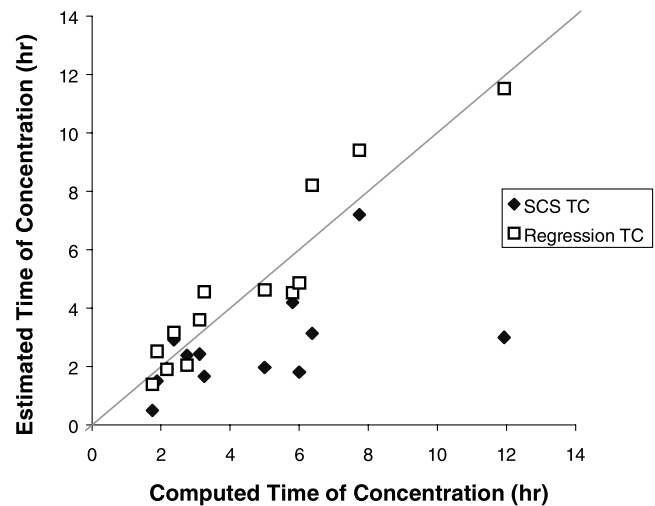


FIGURE 4 Comparison of the estimated time of concentration from the SCS lag equation and the seven-parameter regression equation with computed values of time of concentration.

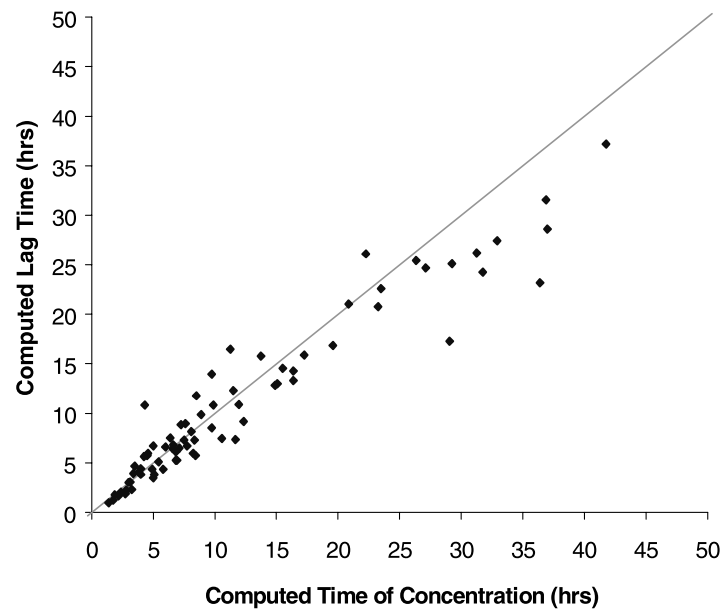


FIGURE 5 Comparison of basin lag time and the time of concentration computed from the same rainfall-runoff events.

are indicative of other empirical equations not evaluated in this study. The tendency to underestimate the TC is directly related to conservative estimates of design discharges from hydrologic models compared with regional regression equations and gauging station data, as presented in a U.S. Water Resources Council report (7). This report further illustrated the high variability associated with the TC estimates used as input to rainfall-runoff procedures. Further research is needed to improve the estimation of TC that would ultimately provide more accurate estimates of design discharges from hydrologic models.

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Publication of this paper sponsored by Committee on Hydrology, Hydraulics, and Water Quality.