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**Natural
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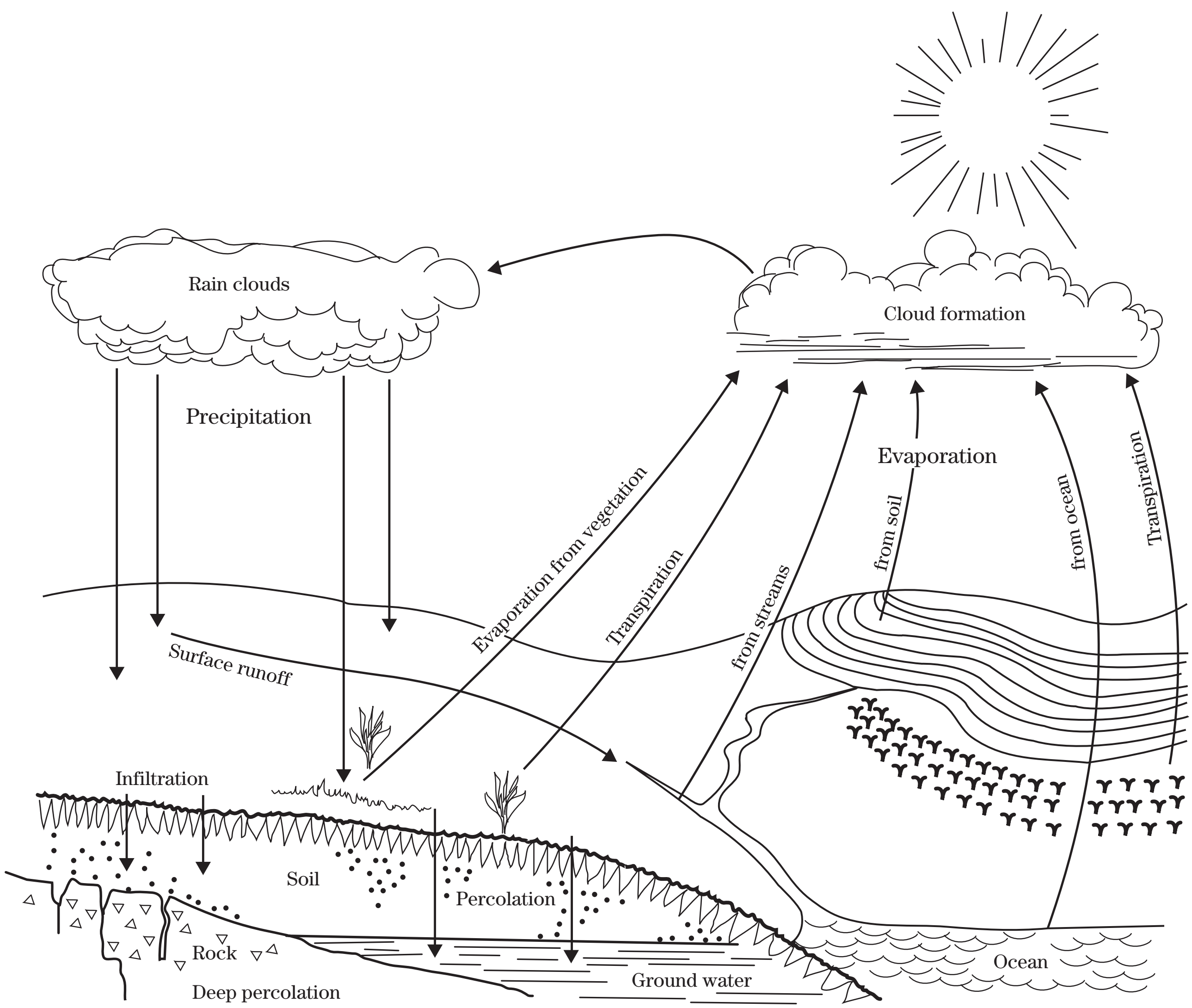
Conservation
Service**

Part 630 Hydrology
National Engineering Handbook

Chapter 15 Time of Concentration



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Chapter 15 Time of Concentration

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630.1500 Introduction

This chapter contains information on the watershed characteristics called travel time, lag, and time of concentration. These watershed characteristics influence the shape and peak of the runoff hydrograph. The National Engineering Handbook, Part 630, Hydrology, Chapter 16, Hydrographs (NEH630.16) contains information on development of runoff hydrographs. The methods presented in this chapter are suitable for use with any hydrologic model which uses time of concentration or lag as an input parameter. Users of models are cautioned to be mindful of specific model input parameters and limitations, which may not be the same as limitations of a particular time of concentration estimation tool. Limitations of specific models are not described in this chapter.

630.1501 Definitions and basic relations

(a) Types of flow

Rainfall over a watershed that reaches the ground will follow one of four potential paths. Some will be intercepted by vegetation and evaporate into the atmosphere. Some will fall onto the ground surface and evaporate. Some will infiltrate into the soil. Some will run directly off from the ground surface. Depending on total storm rainfall and a variety of other factors, a portion of the water will find its way to the stream system. Of the portion that makes its way to the stream system, there are four types of flow that may occur singly or in combination throughout the watershed. Figure 15–1 illustrates these types of flow.

Surface flow—In figure 15–1, point 1 represents a location where precipitation falls on a watershed. Surface runoff is represented by lines with arrows showing travel along the surface of the watershed from point 1 to point 2. Surface flow takes the form of sheet flow, shallow concentrated flow, and/or channel flow.

Surface flow with transmission losses—In figure 15–1, point 3 represents a location where precipitation falls on a watershed. Surface flow is represented by the lines with arrows showing travel along the surface of the watershed from point 3 to point 4, while the transmission losses are represented by the lines with arrows indicating water infiltrating into the ground surface. In this type of flow, runoff is largely infiltrated into the ground before reaching the stream channel. This type of flow is common in arid, semiarid and subhumid climates, and in karst areas. The distance from point 3 to point 4 depends on the amount of runoff, moisture characteristics of the soil, topography, and hydraulic features of the flow.

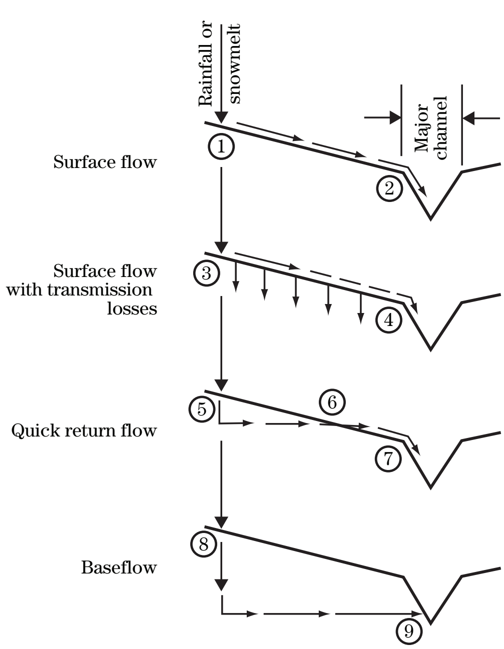
Interflow or quick return flow—In figure 15–1, point 5 represents a location where precipitation falls on a watershed. Water is infiltrated at this point, flows rapidly underground, and eventually returns to the surface at point 6. From point 6, it continues as surface flow until reaching the stream channel at point 7. This flow appears rapidly in comparison to baseflow and is generally much in excess of normal baseflow. It

is common in humid climates and in watersheds with soils having high infiltration capacities and moderate to steep slopes.

Baseflow—In figure 15–1, point 8 represents a location where precipitation falls on a watershed, infiltrates directly into the ground, and enters the ground water table. From there, it flows slowly until it eventually reappears, entering a stream channel at point 9. This type of flow has little effect on flood peaks in small watersheds. However, if baseflow is a factor in flood flows, it is usually added to the base of the hydrograph.

In figure 15–1, flows from points 1 to 2, 3 to 4, and 6 to 7 can be measured directly. Flow from points 5 to 6 and 8 to 9 are usually determined indirectly by storm and hydrograph analyses or by field observation of rainfall and runoff. Ground water movement is determined indirectly by analyses of precipitation, soil moisture movements, and evapotranspiration.

Figure 15–1 Types of flow



(b) Travel time

Travel time (T_t) is the time it takes water to travel from one location to another. Travel time between two points is determined using the following relationship:

$$T_t = \frac{\ell}{3{,}600V} \qquad \text{(eq. 15–1)}$$

where:
T_t = travel time, h
ℓ = distance between the two points under consideration, ft
V = average velocity of flow between the two points, ft/s
3,600 = conversion factor, s to h

(c) Lag

Lag is the delay between the time runoff from a rainfall event over a watershed begins until runoff reaches its maximum peak. Conceptually, lag may be thought of as a weighted time of concentration where, if for a given storm, the watershed is divided into bands of area (fig. 15–2), the travel times from the centroids of the areas to the main watershed outlet may be represented by the following relationship:

$$L = \frac{\sum\left(a_x Q_x T_{tx}\right)}{\sum\left(a_x Q_x\right)} \qquad \text{(eq. 15–2a)}$$

$$L = \frac{\sum\left(a_x Q_x T_{tx}\right)}{AQ_a} \qquad \text{(eq. 15–2b)}$$

where:
L = lag, h
a_x = increment of watershed area, mi^2
Q_x = runoff in inches from area a_x, in
T_{tx} = travel time from the centroid of a_x to the point of reference, h
A = total area of the watershed above the point of reference, mi^2
Q_a = total runoff, in

In general hydrologic modeling practice, lag is not computed using equation 15–2a or 15–2b. Instead, time of concentration is estimated using one of the methods in this chapter. In cases where only a peak discharge and/or hydrograph are desired at the watershed outlet and watershed characteristics are fairly homogenous, the watershed may be treated as a single area. A time

of concentration for that single area is required. A hydrograph is then developed using the methods described in NEH630.16. However, if land use, hydrologic soil group, slope, or other watershed characteristics are not homogeneous throughout the watershed, the approach is to divide the watershed into a number of smaller subareas, which requires a time of concentration estimation for each subarea. Hydrographs are then developed for each subarea by the methods described in NEH630.16 and routed appropriately to a point of reference using the methods described in NEH630.17, Flood Routing.

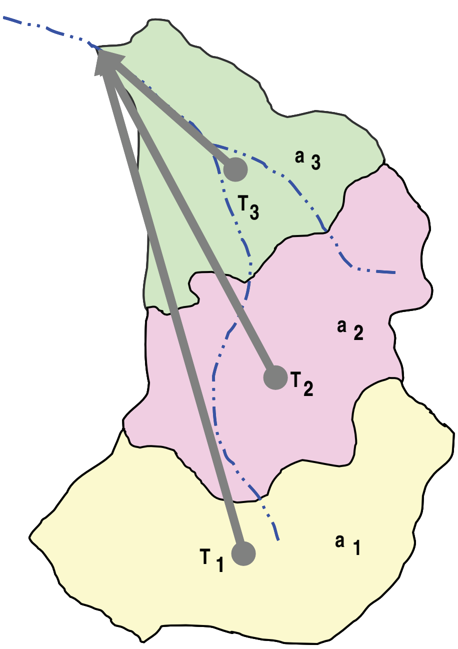
In hydrograph analysis, lag is the time interval between the center of mass of the excess rainfall and the peak runoff rate (fig. 15–3).

(d) Time of concentration

Time of concentration (T_c) is the time required for runoff to travel from the hydraulically most distant point in the watershed to the outlet. The hydraulically most distant point is the point with the longest travel time to the watershed outlet, and not necessarily the point with the longest flow distance to the outlet. Time of concentration is generally applied only to surface runoff and may be computed using many different methods. Time of concentration will vary depending upon slope and character of the watershed and the flow path.

In hydrograph analysis, time of concentration is the time from the end of excess rainfall to the point on the falling limb of the dimensionless unit hydrograph (point of inflection) where the recession curve begins (fig. 15–3).

Figure 15–2 Conceptual watershed illustrating travel time from the centroid (gray dot) of each band of area to the watershed outlet



(e) Relation between lag and time of concentration

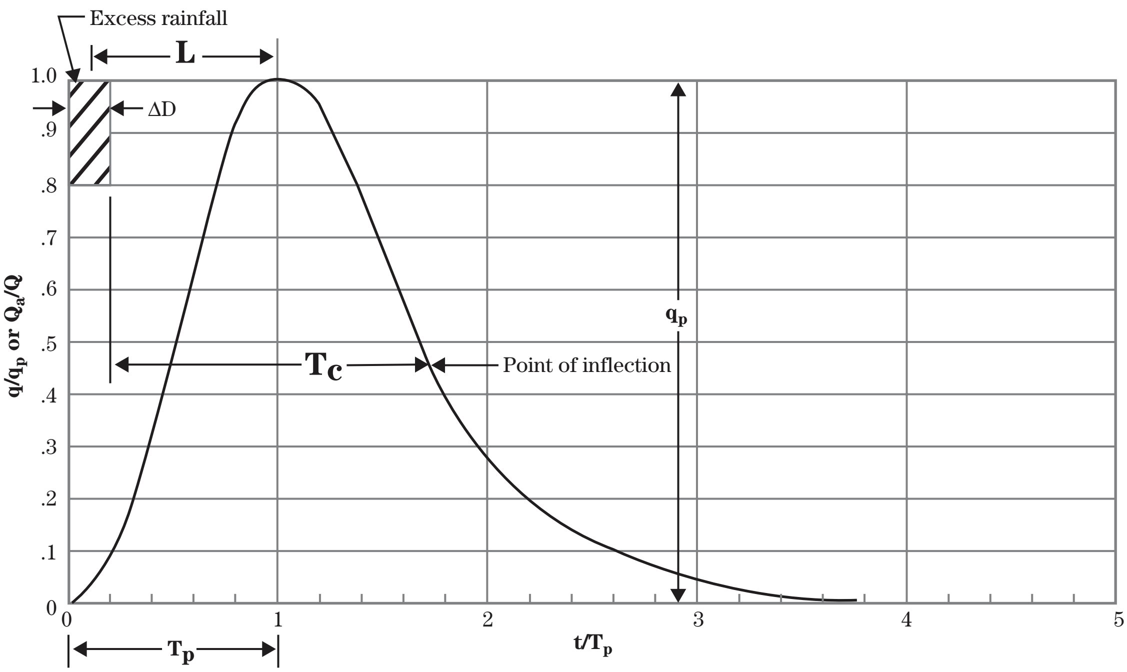
Various researchers (Mockus 1957; Simas 1996) found that for average natural watershed conditions and an approximately uniform distribution of runoff:

$$L = 0.6T_c \qquad \text{(eq. 15–3)}$$

where:
L = lag, h
T_c = time of concentration, h

When runoff is not uniformly distributed, the watershed can be subdivided into areas with nearly uniform flow so that equation 15–3 can be applied to each of the subareas.

Figure 15–3 The relation of time of concentration (T_c) and lag (L) to the dimensionless unit hydrograph



where:

- L = Lag, h
- T_c = time of concentration, h
- T_p = time to peak, h
- ΔD = duration of excess rainfall, h
- t/T_p = dimensionless ratio of any time to time to peak
- q = discharge rate at time t, ft^3/s
- q_p = peak discharge rate at time T_p, ft^3/s
- Q_a = runoff volume up to t, in
- Q = total runoff volume, in

630.1502 Methods for estimating time of concentration

Two primary methods of computing time of concentration were developed by the Natural Resources Conservation Service (NRCS) (formerly the Soil Conservation Service (SCS)).

(a) Watershed lag method

The SCS method for watershed lag was developed by Mockus in 1961. It spans a broad set of conditions ranging from heavily forested watersheds with steep channels and a high percent of runoff resulting from subsurface flow, to meadows providing a high retardance to surface runoff, to smooth land surfaces and large paved areas.

$$L = \frac{\ell^{0.8}(S+1)^{0.7}}{1{,}900Y^{0.5}} \qquad \text{(eq. 15–4a)}$$

Applying equation 15–3, L=0.6T$_c$, yields:

$$T_c = \frac{\ell^{0.8}(S+1)^{0.7}}{1{,}140Y^{0.5}} \qquad \text{(eq. 15–4b)}$$

where:
L = lag, h
T_c = time of concentration, h
ℓ = flow length, ft
Y = average watershed land slope, %
S = maximum potential retention, in

$$= \frac{1{,}000}{cn'} - 10$$

where:
cn′ = the retardance factor

Flow length (ℓ)—In the watershed lag method of computing time of concentration, flow length is defined as the longest path along which water flows from the watershed divide to the outlet. In developing the regression equation for the lag method, the longest flow path was used to represent the hydraulically most distant point in the watershed. Flow length can be measured using aerial photographs, quadrangle sheets, or GIS techniques. Mockus (USDA 1973) developed an empirical relationship between flow length and drainage area using data from Agricultural Research Service (ARS) watersheds. This relationship is:

$$\ell = 209A^{0.6} \qquad \text{(eq. 15–5)}$$

where:
ℓ = flow length, ft
A = drainage area, acres

Land slope (Y), percent—The average land slope of the watershed, as used in the lag method, not to be confused with the slope of the flow path, can be determined in several different ways:

- by assuming land slope is equal to a weighted average of soil map unit slopes, determined using the local soil survey
- by using a clinometer for field measurement to determine an estimated representative average land slope
- by drawing three to four lines on a topographic map perpendicular to the contour lines and determining the average weighted slope of these lines
- by determining the average of the land slope from grid points using a dot counter
- by using the following equation (Chow 1964):

$$Y = \frac{100(CI)}{A} \qquad \text{(eq. 15–6)}$$

where:
Y = average land slope, %
C = summation of the length of the contour lines that pass through the watershed drainage area on the quad sheet, ft
I = contour interval used, ft
A = drainage area, ft^2 (1 acre = 43,560 ft^2)

Retardance factor—The retardance factor, cn´, is a measure of surface conditions relating to the rate at which runoff concentrates at some point of interest. The term “retardance factor” expresses an inverse relationship to “flow retardance.” Low retardance factors are associated with rough surfaces having high degrees of flow retardance, or surfaces over which flow will be impeded. High retardance factors are associated with smooth surfaces having low degrees of flow retardance, or surfaces over which flow moves rapidly.

Thick mulches in forests are associated with low retardance factors and reflect high degrees of retardance, as well as high infiltration rates. Hay meadows have relatively low retardance factors. Like thick mulches in forests, stem densities in meadows provide a high degree of retardance to overland flow in small watersheds. Conversely, bare surfaces with little retardance to overland flows are represented by high retardance factors.

The retardance factor is approximately the same as the curve number (CN) as defined in NEH630.09, Hydrologic Soil-Cover Complexes. In practical usage, CN is used as a surrogate for cn´, and the CN tables in NEH 630.09 may be used to approximate cn´ in equations 15–4a and 15–4b. A CN of less than 50, or greater than 95 should not be used in the solution of equations 15–4a and 15–4b (Mockus 1961).

Applications and limitations—The watershed lag equation was developed using data from 24 watersheds ranging in size from 1.3 acres to 9.2 square miles, with the majority of the watersheds being less than 2,000 acres in size (Mockus 1961). Folmar and Miller (2000) revisited the development of this equation using additional watershed data and found that a reasonable upper limit may be as much as 19 square miles.

(b) Velocity method

Another method for determining time of concentration normally used within the NRCS is called the velocity method. The velocity method assumes that time of concentration is the sum of travel times for segments along the hydraulically most distant flow path.

$$T_c = T_{t1} + T_{t2} + T_{t3} + \dots T_{tn} \qquad \text{(eq. 15–7)}$$

where:
T_c = time of concentration, h
T_{tn} = travel time of a segment n, h
n = number of segments comprising the total hydraulic length

The segments used in the velocity method may be of three types: sheet flow, shallow concentrated flow, and open channel flow.

Sheet flow—Sheet flow is defined as flow over plane surfaces. Sheet flow usually occurs in the headwaters of a stream near the ridgeline that defines the watershed boundary. Typically, sheet flow occurs for no more than 100 feet before transitioning to shallow concentrated flow (Merkel 2001).

A simplified version of the Manning's kinematic solution may be used to compute travel time for sheet flow. This simplified form of the kinematic equation was developed by Welle and Woodward (1986) after studying the impact of various parameters on the estimates.

$$T_t = \frac{0.007(n\ell)^{0.8}}{(P_2)^{0.5} S^{0.4}} \qquad \text{(eq. 15–8)}$$

where:
T_t = travel time, h
n = Manning's roughness coefficient (table 15–1)
ℓ = sheet flow length, ft
P_2 = 2-year, 24-hour rainfall, in
S = slope of land surface, ft/ft

Table 15–1 Manning's roughness coefficients for sheet flow (flow depth generally ≤ 0.1 ft)

Surface description	*n* [1]
Smooth surface (concrete, asphalt, gravel, or bare soil)	0.011
Fallow (no residue)	0.05
Cultivated soils:	
Residue cover ≤ 20%	0.06
Residue cover > 20%	0.17
Grass:	
Short-grass prairie	0.15
Dense grasses [2]	0.24
Bermudagrass	0.41
Range (natural)	0.13
Woods: [3]	
Light underbrush	0.40
Dense underbrush	0.80

1 The Manning's *n* values are a composite of information compiled by Engman (1986).
2 Includes species such as weeping lovegrass, bluegrass, buffalo grass, blue grama grass, and native grass mixtures.
3 When selecting *n*, consider cover to a height of about 0.1 ft. This is the only part of the plant cover that will obstruct sheet flow.

This simplification is based on the following assumptions:

- shallow steady uniform flow
- constant rainfall excess intensity (that part of a rain available for runoff) both temporally and spatially
- 2-year, 24-hour rainfall assuming standard NRCS rainfall intensity-duration relations apply (Types I, II, and III)
- minor effect of infiltration on travel time

For sheet flow, the roughness coefficient includes the effects of roughness and the effects of raindrop impact including drag over the surface; obstacles such as litter, crop ridges, and rocks; and erosion and transport of sediment. These *n* values are only applicable for flow depths of approximately 0.1 foot or less, where sheet flow occurs. Table 15–1 gives roughness coefficient values for sheet flow for various surface conditions.

Kibler and Aron (1982) and others indicated the maximum sheet flow length is less than 100 feet. To support the sheet flow limit of 100 feet, Merkel (2001) reviewed a number of technical papers on sheet flow. McCuen and Spiess (1995) indicated that use of flow length as the limiting variable in the equation 15–8 could lead to less accurate designs, and proposed that the limitation should instead be based on:

$$\ell = \frac{100\sqrt{S}}{n} \qquad \text{(eq. 15–9)}$$

where:
n = Manning's roughness coefficient
ℓ = limiting length of flow, ft
S = slope, ft/ft

Table 15–2 provides maximum sheet flow lengths based on the McCuen-Spiess limiting criteria for various cover type—*n* value—slope combinations.

Table 15–2 Maximum sheet flow lengths using the McCuen-Spiess limitation criterion

Cover type	*n* values	Slope (ft/ft)	Length (ft)
Range	0.13	0.01	77
Grass	0.41	0.01	24
Woods	0.80	0.01	12.5
Range	0.13	0.05	172
Grass	0.41	0.05	55
Woods	0.80	0.05	28

Shallow concentrated flow—After approximately 100 feet, sheet flow usually becomes shallow concentrated flow collecting in swales, small rills, and gullies. Shallow concentrated flow is assumed not to have a well-defined channel and has flow depths of 0.1 to 0.5 feet. It is assumed that shallow concentrated flow can be represented by one of seven flow types. The curves in figure 15–4 were used to develop the information in table 15–3.

To estimate shallow concentrated flow travel time, velocities are developed using figure 15–4, in which average velocity is a function of watercourse slope and type of channel (Kent 1964). For slopes less than 0.005 foot per foot, the equations in table 15–3 may be used.

After estimating average velocity using figure 15–4, use equation 15–1 to estimate travel time for the shallow concentrated flow segment.

Open channel flow— Shallow concentrated flow is assumed to occur after sheet flow ends at shallow depths of 0.1 to 0.5 feet. Beyond that channel flow is assumed to occur. Open channels are assumed to begin where surveyed cross-sectional information has been obtained, where channels are visible on aerial photographs, or where bluelines (indicating streams) appear on U.S. Geological Survey (USGS) quadrangle sheets.

Manning's equation or water surface profile information can be used to estimate average flow velocity. Average flow velocity is usually determined for the bankfull elevation.

Manning's equation is:

$$V = \frac{1.49 r^{\frac{2}{3}} s^{\frac{1}{2}}}{n} \qquad \text{(eq. 15–10)}$$

Figure 15–4 Velocity versus slope for shallow concentrated flow

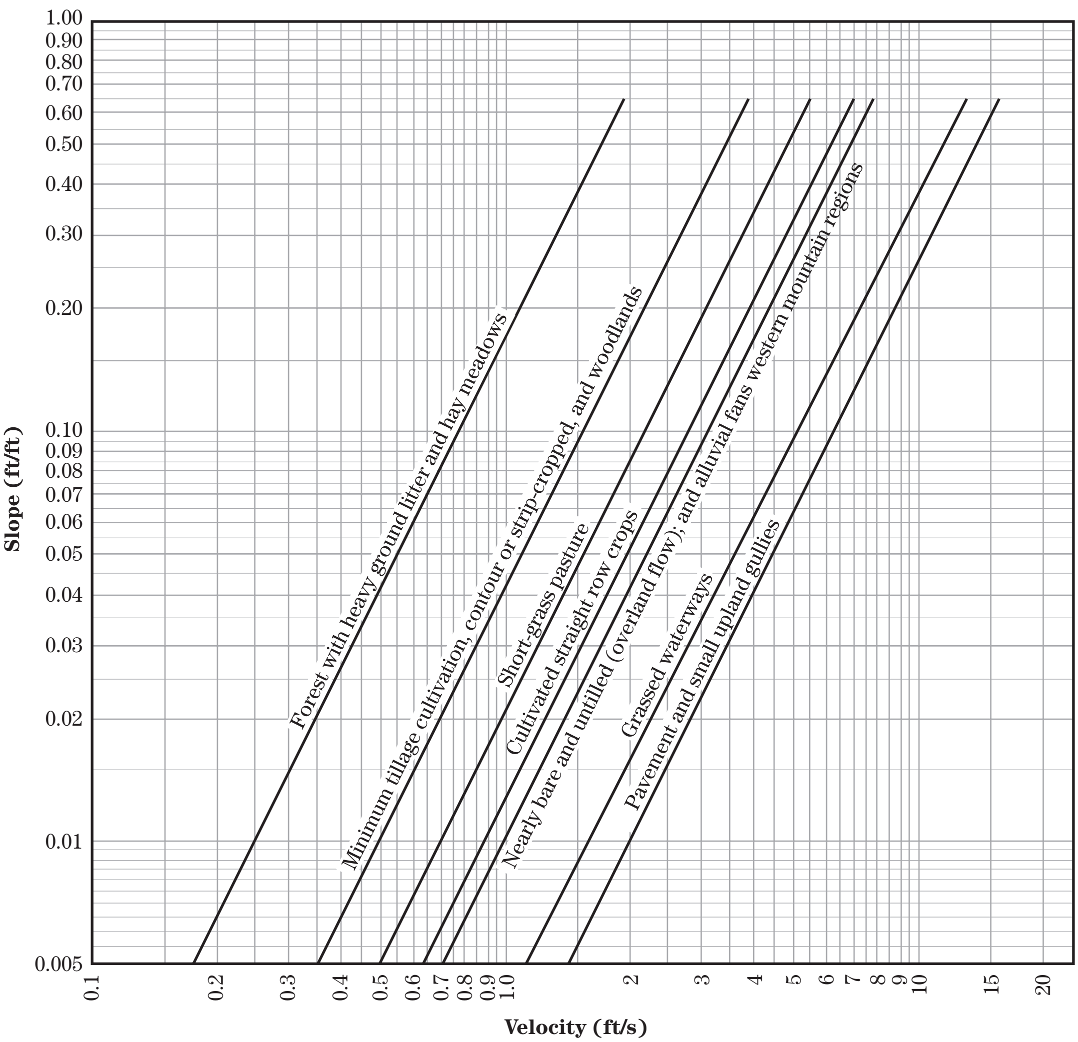


Table 15–3 Equations and assumptions developed from figure 15–4

Flow type	Depth (ft)	Manning's *n*	Velocity equation (ft/s)
Pavement and small upland gullies	0.2	0.025	$V = 20.328(s)^{0.5}$
Grassed waterways	0.4	0.050	$V=16.135(s)^{0.5}$
Nearly bare and untilled (overland flow); and alluvial fans in western mountain regions	0.2	0.051	$V=9.965(s)^{0.5}$
Cultivated straight row crops	0.2	0.058	$V=8.762(s)^{0.5}$
Short-grass pasture	0.2	0.073	$V=6.962(s)^{0.5}$
Minimum tillage cultivation, contour or strip-cropped, and woodlands	0.2	0.101	$V=5.032(s)^{0.5}$
Forest with heavy ground litter and hay meadows	0.2	0.202	$V=2.516(s)^{0.5}$

where:
V = average velocity, ft/s
r = hydraulic radius, ft
$= \frac{a}{P_w}$
a = cross-sectional flow area, ft^2
P_w = wetted perimeter, ft
s = slope of the hydraulic grade line (channel slope), ft/ft
n = Manning's *n* value for open channel flow

Manning's *n* values for open channel flow can be obtained from standard hydraulics textbooks, such as Chow (1959), and Linsley, Kohler, and Paulhus (1982). Publications dealing specifically with Manning's *n* values are Barnes (1967); Arcement and Schneider (1989); Phillips and Ingersoll (1998); and Cowen (1956). For guidance on calculating Manning's *n* values, see NEH630.14, Stage Discharge Relations.

Applications and limitations—The velocity method of computing time of concentration is hydraulically sound and provides the opportunity to incorporate changes in individual flow segments if needed. The velocity method is the best method for calculating time of concentration for an urbanizing watershed or if hydraulic changes to the watercourse are being considered.

Often, the average velocity and valley length of a reach are used to compute travel time through the reach using equation 15–1. If the stream is quite sinuous, the channel length and valley length may be significantly different and it is up to the modeler to determine which is the appropriate length to use for the depth of flow of the event under consideration.

The role of channel and valley storage is important in the development and translation of a flood wave and the estimation of lag. Both the hydraulics and storage may change from storm to storm and the velocity distribution may vary considerably both horizontally and vertically. As a result, actual lag for a watershed may have a large variation. In practice, calculations are typically based on the 2-year frequency discharge event since it is normally assumed that the time of concentration computed using these characteristics is representative of travel time conditions for a wide range of storm events. Welle and Woodward's simplification of Manning's kinematic equation was developed assuming the 2-year, 24-hour precipitation value.

630.1503 Other considerations

(a) Field observations

At the time field surveys to obtain channel data are made, there is a need to observe the channel system and note items that may affect channel efficiency. Observations such as the type of soil materials in the banks and bottoms of the channel; an estimate of Manning's roughness coefficients; the apparent stability or lack of stability of channel; indications of debris flows as evidenced by deposition of coarse sediments adjacent to channels, size of deposited materials, etc., may be significant.

(b) Multiple subarea watersheds

For multiple subarea watersheds, the time of concentration must be computed for each subarea individually, and consideration must be given to the travel time through downstream subareas from upstream subareas. Travel time and attenuation of hydrographs in valley reaches and reservoirs are accounted for using channel and reservoir routing procedures addressed in NEH630.17.

(c) Surface flow

Both of the standard methods for estimating time of concentration, as well as most other methods, assume that flow reaching the channel as surface flow or quick return flow adds directly to the peak of the subarea hydrograph. Locally derived procedures might be developed from data where a major portion of the contributing flow is other than surface flow. This is normally determined by making a site visit to the watershed.

(d) Travel time through bodies of water

The potential for detention is the factor that most strongly influences travel time through a body of water. It is best to divide the watershed such that any potential storage area is modeled as storage.

In many cases, the travel time for a water droplet through a body of water is assumed to be nearly instantaneous. An assumption is made that at the instant the droplet arrives at the upstream end of the lake, reservoir, or wetland the water level is raised a small amount and this same amount of water leaves the water body via the outlet. In such cases, time of concentration is computed using standard methods to the upstream end of the water body, and travel time through the water body is ignored.

In other cases, such as with a watershed having a relatively large body of water in the flow path, time of concentration is computed to the upstream end of the water body using standard methods, and velocity for the flow segment through the water body may be computed using the wave velocity equation coupled with equation 15–1 to convert the velocity to a travel time through the water body. The wave equation is:

$$V_w = \sqrt{gD_m} \qquad \text{(eq. 15–11)}$$

where
V_w = wave velocity, ft/s
g = 32.2 ft/s^2
D_m = mean depth of lake or reservoir, ft

Generally, V_w will be high; however, equation 15–11 only provides for estimating travel time through the water body and for the inflow hydrograph to reach the outlet. It does not account for the time required for the passage of the inflow hydrograph through reservoir storage and spillway outflow. The time required for the passage of the inflow hydrograph through the reservoir storage and spillway outflow can be determined using storage routing procedures described in NEH630.17.

Equation 15–11 can be used for wetlands with much open water, but where the vegetation or debris is relatively thick (less than about 25 percent open water), Manning's equation may be more appropriate.

(e) Variation in lag and time of concentration

Rao and Delleur (1974) concluded that lag time, and hence time of concentration, is not a unique watershed characteristic and varies from storm to storm. Reasons for the variation in lag time may include amount, duration and intensity of rainfall; vegetative growth stage and available temporary storage. However, without further examination and study of these characteristics, no obvious trend may be readily observed to explain the variation. Table 15–4 illustrates that lag is not a constant for a single watershed, but does vary from storm to storm. The lag times in table 15–4 were developed by Thomas, Monde, and Davis (2000) for three watersheds in Maryland using USGS stream gage data.

Table 15–4 Variation in lag time for selected events for selected streams on three watersheds in Maryland

Stream	USGS number	Area (mi^2)	Date	Storm duration (min)	Precipitation (in)	Lag (h)
Brien Run	1585400	1.97	8/21/1986	30	1.85	2.35
			8/22/1986	45	0.32	1.94
			9/8/1987	120	1.03	2.44
Jones Falls	1589440	26.2	8/10/1984	15	1.84	4.16
			2/12/1985	285	1.59	6.91
			12/24/1986	165	2.47	5.20
Deer Creek	1580000	94.4	9/8/1987	75	2.2	5.06
			9/18/1987	15	1.02	7.15
			5/6/1989	60	5.00	9.67

Folmar and Miller (2008) found that the watershed lag method and the velocity method tended to underpredict or underestimate time of concentration. Underestimation of lag or time of concentration by the velocity method may be attributed to:

- low estimates of stream length from not considering sinuosity
- overestimated flow velocities from not considering pools in the stream
- underestimated Manning's *n* values within the reach

When used in conjunction with unit hydrograph procedures (NEH630.16), this results in overestimated design discharges. It was determined from 52 nonurbanized watersheds that both the lag method and the velocity method may underpredict the time of concentration.

(f) Effects of urbanization

- **Surface roughness**—One of the most significant effects of urban development on overland flow is the lowering of retardance to flow causing higher velocities. Undeveloped areas with very slow and shallow overland flow (sheet flow and shallow concentrated flow) through vegetation become modified by urban development. Flow is then delivered to streets, gutters, and storm sewers that transport runoff downstream more rapidly. Travel time through the watershed is generally decreased.
- **Channel shape and flow patterns**—In small, nonurban watersheds, much of the travel time results from overland flow in upstream areas. Typically, urbanization reduces overland flow lengths by conveying storm runoff into a channel as soon as possible. Since constructed channel designs have efficient hydraulic characteristics, runoff flow velocity increases and travel time decreases.
- **Watersheds with storm sewers**—In watersheds with storm sewers, it is important to carefully identify the appropriate hydraulic flow path to estimate time of concentration. Storm sewers generally handle only a small portion of a large event. The rest of the peak flow travels by streets and lawns to the outlet. Any standard hydraulics textbook contains methods to determine average velocity in pipes for either pressure or nonpressure flow.
- **Slope**—Slopes may be increased or decreased by urbanization, depending on the extent of site grading and the extent to which storm sewers and street ditches are used in the design of the water management system. Slopes may increase when channels are straightened and decrease when overland flow is directed through storm sewers, street gutters, and diversions, or when land is graded to develop nearly level lots.

(g) Geographic information systems

Geographic information systems (GIS) can be used to estimate watershed features, such as watershed boundaries and drainage areas; flow path lengths and slopes; stream and flood plain reach lengths; average watershed land slopes; land cover; and, in some cases, stream cross-sectional features. This information can then be imported into a number of hydrology computer programs, which use the data to estimate times of concentration for watersheds. One example of this is the NRCS Geo-Hydro program.

630.1504 Examples

(a) Example of watershed lag method

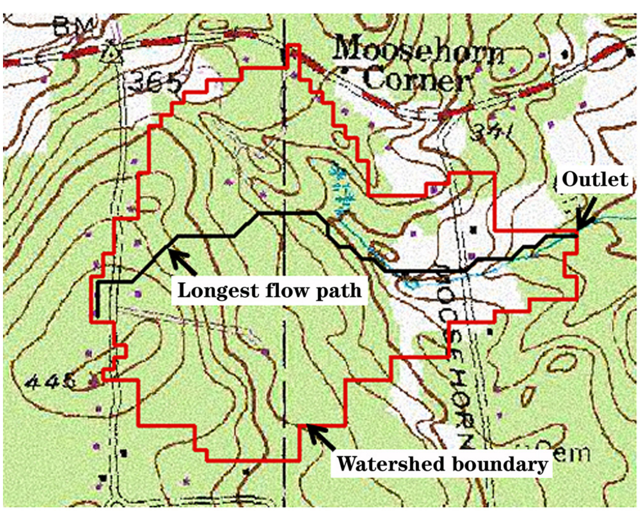
Compute the time of concentration using the watershed lag method for Mawney Brook Watershed in Kent County, Rhode Island. The topographic map for the watershed is shown in figure 15–5. The watershed has the following attributes:

Drainage area, A	=	0.17 mi^2
Curve number, CN	=	63–used as a surrogate for cn′
Longest flow path, ℓ	=	3,865 ft
Watershed slope, Y	=	4.79%

Time of concentration is computed using equation 15–4b:

$$T_c = \frac{\ell^{0.8}(S+1)^{0.7}}{1{,}140Y^{0.5}}$$

Figure 15–5 Mawney Brook Watershed, Kent County, RI



S is computed using the relationship:

$$S = \frac{1{,}000}{cn'} - 10$$

$$S = \frac{1{,}000}{63} - 10$$

$$S = 5.87$$

Substituting into the time of concentration equation gives:

$$T_c = \frac{3{,}865^{0.8}(5.87+1)^{0.7}}{1{,}140(4.79)^{0.5}}$$

$$T_c = 1.14 \text{ h}$$

(b) Example of velocity method

The time of concentration flow path for the watershed shown in figure 15–6 is split into three reaches based upon similar hydraulic characteristics within the reaches. Computation of the watershed time of concentration follows.

Part A: Travel time through reach 1 (designated R-1—from the watershed divide to cross section A-A)

Reach 1 (R–1) consists of sheet flow and shallow concentrated flow from the watershed divide to cross section A–A. The flow segments are as follows:

- Flow segment from the watershed divide to the diversion terrace consists of 100 feet of sheet flow and 800 feet of shallow concentrated flow across pasture at a slope of 8 percent.
- The diversion terrace is 2,100 feet long with a design velocity of 1.5 feet per second.
- The grassed waterway is 2,400 feet long with an average slope of 4 percent.
- The grassed waterway terminates at a road crossing and a raw gully extends from the road crossing to a point where a grade stabilization structure (GS–1) is planned (but not yet installed). The length of the gully is 2,700 feet with a 3 percent grade.

Sheet flow segment—The travel time for the sheet flow segment through the short-grass pasture is computed using equation 15–8. The 2-year, 24-hour precipitation for the watershed is 3.6 inches. The *n* value for short grass pasture from table 15–1 is 0.15.

$$T_t = \frac{0.007(n\ell)^{0.8}}{[(P_2)^{0.5}S^{0.4}]}$$

$$= \frac{0.007[(0.15)(100)]^{0.8}}{[(3.6)^{0.5}(0.08)^{0.4}]}$$

$$= 0.09 \text{ h}$$

Shallow concentrated flow segments—The travel times for the remaining portions along the flow path are based on shallow concentrated flow velocities. Given that the majority of conservation practices are not intended to handle large flow depths, this is a reasonable assumption. For those flow segments for which velocity is not given, velocity is determined using figure 15–4 and converted to a travel time for each flow segment using equation 15–1:

- Short grass pasture: ℓ = 800 feet, V = 2 ft/s

$$T_t = \frac{\ell}{3,600V} = \frac{800}{3,600(2)} = 0.11 \text{ hr}$$

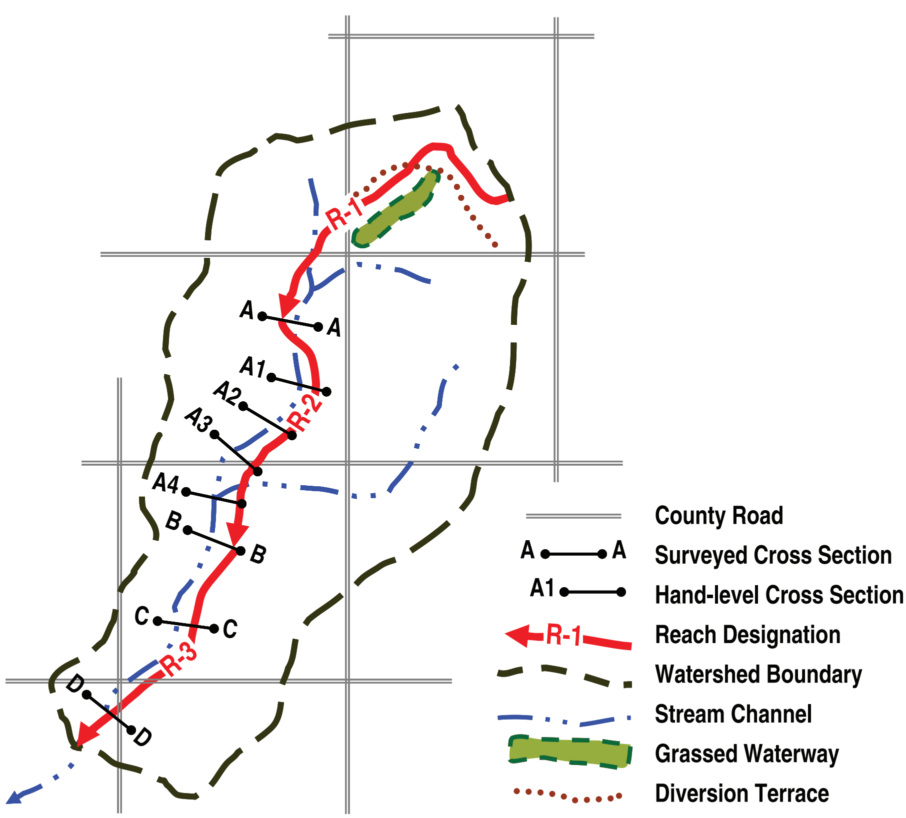
- Terrace: ℓ = 2,100 ft, V = 1.5 ft/s

$$T_t = \frac{\ell}{3,600V} = \frac{2,100}{3,600(1.5)} = 0.39 \text{ h}$$

- Grassed waterway: ℓ = 2,400 ft, V = 3.4 ft/s

$$T_t = \frac{\ell}{3,600V} = \frac{2,400}{3,600(3.4)} = 0.20 \text{ h}$$

Figure 15–6 Sample watershed for velocity method example



- Gully: ℓ = 2,700, V = 3.5 ft/s

$$T_t = \frac{\ell}{3{,}600V} = \frac{2{,}700}{3{,}600(3.5)} = 0.21 \text{ h}$$

Add the travel times for each flow segment to get the total travel time for Reach 1:

$$\begin{aligned} T_{t(R-1)} &= 0.09 + 0.11 + 0.39 + 0.20 + 0.21 \\ &= 1.00 \text{ h} \end{aligned}$$

Part B: Travel time through Reach 2 (designated R–2—from cross section A–A to cross section B–B)

Reach 2 (R–2) consists of channel flow from cross section A–A to cross section B–B and has a total reach length of 6,000 feet.

A surveyed cross section was available at A–A, but no other cross sections were surveyed upstream of B–B. Instead, hand-level sections were made at four intermediate locations in reach 2, and an overall gradient estimated. These four hand-level sections were taken at approximately equal intervals through the reach between cross sections A–A and B–B (and are identified on figure 15–6 as cross sections A1, A2, A3, and A4). Table 15–5 summarizes estimated velocity at these cross sections, including the field data obtained for

Table 15–5 Field data and computed velocities at each cross section in reach R-2

Cross section	Bankfull area (a) ft^2	Wetted perimeter (P_w) ft	Hydraulic radius (r) ft	$r^{2/3}$	Manning's *n*	Slope (S) ft/ft	$S^{1/2}$	Velocity (V) ft/s
A–A	48	22	2.18	1.68	0.040	0.01	0.10	6.3
A1	55	35	1.57	1.35	0.055	0.01	0.10	3.7
A2	55	39	1.41	1.26	0.055	0.01	0.10	3.4
A3	50	26	1.92	1.54	0.040	0.01	0.10	5.7
A4	56	28	2.00	1.59	0.040	0.01	0.10	5.9
B–B	Obtained from water surface profiles							6.1

Table 15–6 Travel times for flow segments along reach R–3

Segment	Length	Velocity	Travel time
Cross section B–B to cross section C–C	2,400 ft	3.6 ft/s	0.19 h
Cross section C–C to cross section D–D	2,800 ft	3.8 ft/s	0.20 h
Cross section D–D to watershed outlet	900 ft	6.1 ft/s	0.04 h
T_t (R–3)			0.43 h

estimating mean velocity at each of the hand level sections. The velocities were computed using Manning's equation for open channel flow (eq. 15–10).

Since the hand-level cross sections were taken at approximately equal intervals through reach 2, the velocities can be averaged without weighting them with respect to length. The average velocity of all six cross sections in reach 2 is 5.2 feet per second.

Travel time through reach 2 can then be computed by applying equation 15–1:

$$
\begin{aligned}
T_{t(R\text{-}2)} &= \frac{\ell}{3{,}600V} \\
&= \frac{6{,}000}{3{,}600(5.2)} \\
&= 0.32 \text{ h}
\end{aligned}
$$

Part C: Travel time through Reach 3 (designated R–3— from cross section B–B to the watershed outlet)

Reach 3 (R–3) consists of channel flow from cross section B–B to the watershed outlet and is split into three flow segments. Mean velocity for each of the flow segments was determined using a computer program to develop a water surface profile model (such as HEC–RAS). Applying equation 15–1 to flow length and velocity data the travel times were estimated for each of the flow segments and summed to obtain a travel time through reach 3 as summarized in table 15–6.

Part D The total travel time for reaches R-1, R-2 and R-3

T_t for reach R-1	1.00 h
T_t for reach R-2	0.32 h
T_t for reach R-3	0.43 h
Total	1.75 h

The total time of concentration for the watershed is the sum of the travel times and equals 1.75 hours.

630.1505 References

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Appendix 15A Other Methods for Computing Time of Concentration

This appendix includes regression equations for estimating time of concentration developed by various researchers in different regions of the United States. These procedures may have an application for NRCS in limited areas or for special studies. In general, these equations are for existing conditions and cannot be adapted to future conditions or urbanization changes that might occur in a watershed. These methods are included here for information and to provide a broad overview of other types of time of concentration calculation methods that are available.

Whenever possible, an effort was made to maintain the form of equations as published by the author. Therefore, the various methods illustrated here may use different units.

Kirpich equation—The Kirpich equation (Maidment 1993) was developed using data from seven rural watersheds on a farm in Tennessee with well-defined channels and steep slopes. Drainage areas ranged from 1.25 to 112.0 acres.

$$T_c = 0.007\ell^{0.77}S^{-0.385} \qquad \text{(eq. 15A–1)}$$

where:
T_c = time of concentration, min
ℓ = length of channel from headwater to outlet, ft
S = slope of the longest hydraulic length, ft/ft

Kerby equation—The Kerby (1959) equation was developed from a very small watershed in which overland flow dominated. Some references suggest that it should be used for watersheds having flow lengths less than 1,000 feet.

$$T_c = \left[\frac{2.2n\ell}{S^{0.5}}\right]^{0.324} \qquad \text{(eq. 15A–2)}$$

where:
T_c = time of concentration, min
ℓ = length of channel from headwater to outlet, ft
S = average slope, ft/ft
n = Manning's channel roughness coefficient

Drainage area equations—The drainage area equations in table 15A–1 were developed by the Soil Conservation Service using small watershed data.

Simas equations—Simas (1996), in a nationwide analysis of 116 small agricultural watersheds, developed several regression equations for watershed lag. Lag was defined by Simas as the time between the centroid of effective rainfall and the centroid of direct runoff. Equations were modified to time of concentration using the relationship of lag = $0.6T_c$ or T_c = 1.67 lag.

The simplest form of the equation Simas developed is:

$$T_c = 0.0481A^{0.324} \qquad \text{(eq. 15A–5)}$$

where:
T_c = time of concentration, h
A = the drainage area, acre

The equation exhibiting the highest degree of correlation (R^2) developed by Simas is:

$$T_c = 0.0085W^{0.5937}S^{-0.1505}S_{nat}^{0.3131} \qquad \text{(eq. 15A–6)}$$

where:
T_c = time of concentration, h
W = watershed width, ft
$= \dfrac{\text{drainage area } (\text{ft}^2)}{\text{watershed length } (\text{ft})}$
S = average watershed slope, ft/ft
S_{nat} = storage coefficient used in the curve number method
where:
S_{nat} = (1,000/CN)–10
CN = runoff curve number

Sheridan equation—Sheridan (1994) performed a study on nine flatland watersheds located in Georgia and Florida and ranging in size from 2.62 to 334.34

Table 15A–1 SCS Drainage area equations

Region of applicability	Time of concentration equation	
Texas	$T_c = 2.4A^{0.6}$	(eq. 15A–3)
Ohio	$T_c = 0.9A^{0.6}$	(eq. 15A–4)

where:
T_c = time of concentration, h
A = drainage area, mi^2

km². A regression analysis was performed using many basin characteristics to determine a timing equation. However, it was found that the main channel length was the overwhelming characteristic that correlated with the timing parameter. Therefore, an equation was developed based solely on main channel length to estimate the time of concentration. The equation had a correlation coefficient (R^2) of 96 percent.

$$T_c = 2.20\ell^{0.92} \qquad \text{(eq. 15A–7)}$$

where:
T_c = time of concentration, h
ℓ = main channel length, km

Folmar and Miller equation—Folmar and Miller (2008) developed an equation for lag time from 52 agricultural watersheds throughout the country. Lag was measured from the centroid of excess precipitation to the peak of the hydrograph. Watersheds ranged in size from approximately 3 acres to 20 square miles. Similar to what was determined by Sheridan (1994), it was found that only the longest hydraulic length as determined by comparing travel times was needed to determine an estimate of lag time. The developed equation had an R^2 value of 89 percent.

$$T_l = \frac{\ell^{0.65}}{83.4} \qquad \text{(eq. 15A–8)}$$

where:
T_l = lag time, h
ℓ = longest hydraulic length, m

Papadakis and Kazan—Papadakis and Kazan (1986), from the University of Cincinnati, developed regression equations using data from 84 small ARS watersheds with drainage areas less than 500 acres across the United States.

$$T_c = 0.66L^{0.5}n^{0.52}S^{-0.31}i^{-.38} \qquad \text{(eq. 15A–9)}$$

where:
T_c = time of concentration, min
L = length of the longest waterway, ft
S = slope of the flow path, ft/ft
i = intensity of the rainfall excess, in/h
n = roughness coefficient (Manning's n value for channel)

Appendix 15B Shallow Concentrated Flow Alternatives

Recently there has been much discussion over the reasonableness of limiting shallow concentrated flow to only a paved or unpaved condition. The following provides an alternate methodology for developing shallow concentrated flow estimates if so desired.

The shallow concentrated flow curves shown in figure 15B–1 correspond to the grassed waterway and paved area sheet flow curves from figure 15–4. The curves in figure 15B–1 were developed based upon solutions to Manning's equation assuming trapezoidal shaped channels with n = 0.05 and R = 0.4 foot for the unpaved condition and n = 0.025 and R = 0.2 foot for the paved condition. Figure 15B–1 appeared in the 1986 Technical Release Number 55, Urban Hydrology for Small Watersheds (TR–55). Because TR–55 was specifically recommended for use in evaluating urban hydrology, it was assumed that in a majority of cases, shallow concentrated flow would occur either in paved areas or in grassed areas and there was no need to include the entire range of curves shown in figure 15–4. However, the velocity method of computing time of concentration is applicable across a broad range of land uses and the additional curves in figure 15–4 are quite beneficial.

G. Cerrelli (Professional notes, 1990) developed a set of curves to supplement the shallow concentrated flow curves which appear in figure 15B–1. Cerrelli's curves were developed using the concepts in Technical Paper 61, Handbook of Channel Design for Soil and Water Conservation. Cerrelli used assumptions with regards to flow shape, width, and depth in conjunction with the VR versus n curves from TP–61 on a trial and error basis to determine a relationship of V versus slope. For paved surfaces and row crops with conventional tillage, Cerrelli used Manning's equation with a fixed n value to determine a V versus slope curve.

A.A. Humpal (Professional notes, 2008) verified Cerrelli's curves but used a slightly different set of assumptions with regards to flow shape, width, and depth. Table 15B–1 and figure 15B–2 are a compilation of agreed upon values by Humpal and Cerrelli (2009).

A third alternative for estimating shallow concentrated flow velocities for very unique conditions is to use the procedures in Agricultural Handbook 667, Stability Design of Grass-Lined Open Channels.

Figure 15B–1 TR–55 shallow concentrated flow curves

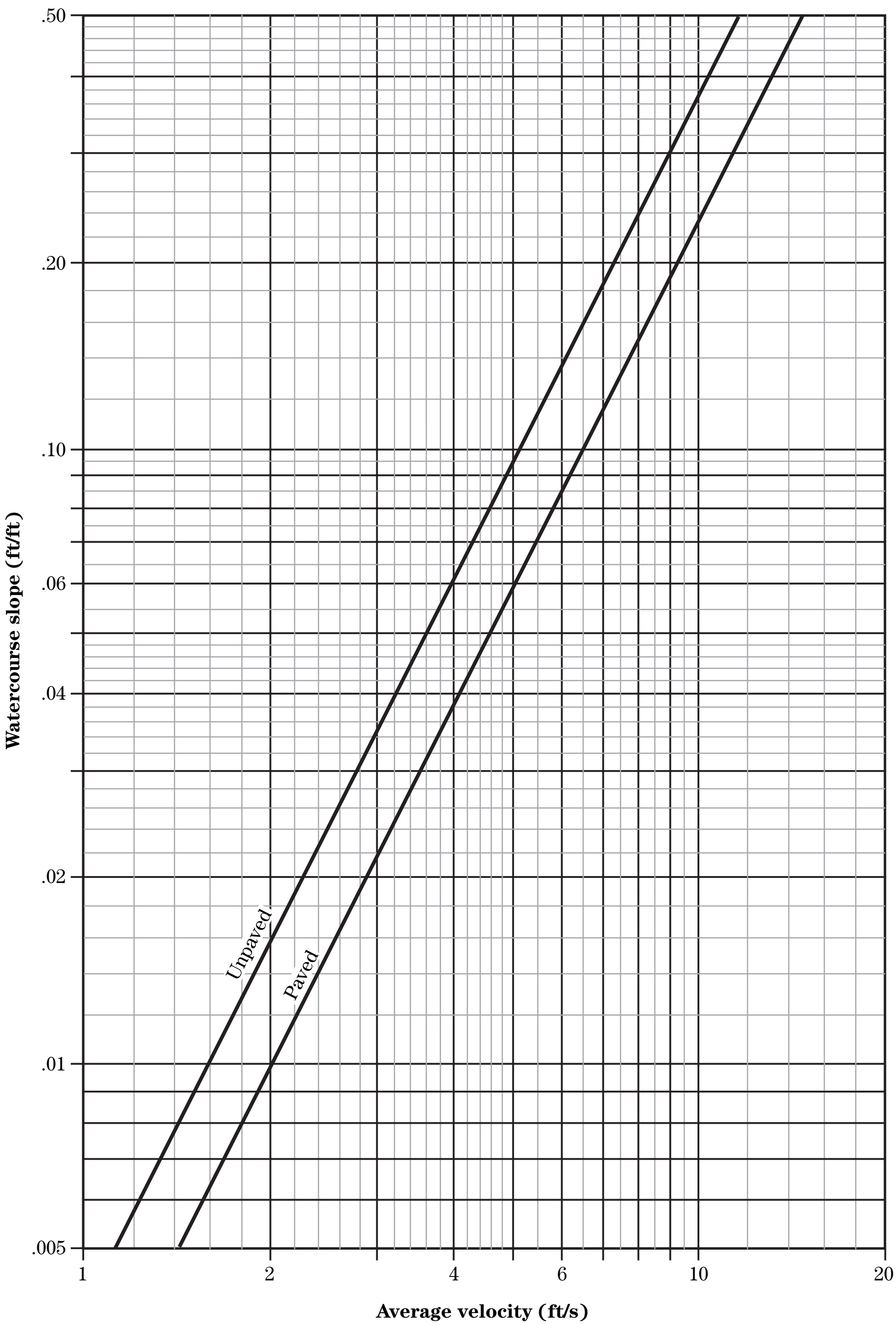

Figure 15B–2 Cerrelli's and Humpal's shallow concentrated flow curves

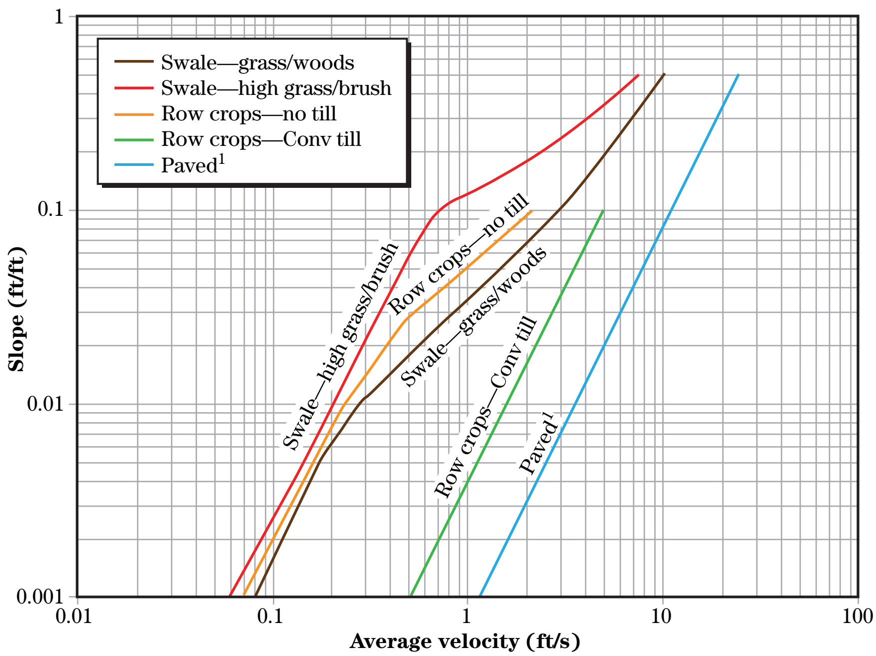

Table 15B–1 Assumptions used by Cerrelli and Humpal to develop shallow concentrated flow curves

Cover type	**Flow shape**	**Width (ft)**	**Depth (ft)**	**Hydraulic radius, R (ft)**	**Retardance**	***n* value**
Wide swale—lawn/mature woods	Parabolic	10	0.4	0.27	D	
Wide swale—high grass/brushy	Parabolic	10	0.4	0.27	C	
Row crops—no till	Parabolic	7.5	0.3	0.23	D	
Row crops—conventional tillage/bare gully	Parabolic	7.5	0.3	0.23		0.035
Paved 1/	Triangular	12	0.4	0.19		0.014

1 The assumptions and limits for the paved condition used to define the paved line in figure 15B–2 are not the same as those used for the pavement and small upland gullies line shown in figure 15–4. Velocities obtained using figure 15–4 and/or table 15–3 should not be combined with those obtained from figure 15B–2.