Appendix C - Time Of Concentration

6.C.1 Introduction

Travel time (T_t) is the time it takes runoff to travel from one location to another in a watershed (subreach) and is a component of time of concentration (T_c), which is the time for runoff to travel from the hydraulically most distant point of the watershed to a point of interest within the watershed. **T_c is computed by summing all the travel times for consecutive components of the drainage conveyance system**.

Following is a discussion of procedures and equations for calculating time of concentration and travel time.

6.C.2 Time Of Concentration

The time of concentration, which is denoted as T_c ,is defined as the time required for a particle of runoff to flow from the hydraulically most distant point in the watershed to the outlet or design point. Factors that affect the time of concentration are the length of flow, the slope of the flow path, and the roughness of the flow path. For flow at the upper reaches of a watershed, rainfall characteristics, most notably the intensity, may also influence the velocity of the runoff.

The time of concentration equals the sum of the travel times on each segment of the principal flow path, accordingly, it is useful to describe the segments of flow paths. Sheet flow occurs in the upper reaches of a watershed. Such flow occurs over short distances and at shallow depths prior to the point where topography and surface characteristics cause the flow to concentrate in rills and swales. The depth of such flow is usually 20 to 30mm (3/4 in to 1 in) or less. Concentrated flow is runoff that occurs in rills and swales and has depths on the order to 40 to 100 mm (1.5 in to 4 in). Part of the principal flow path may include pipes or small streams. The travel time through these segments would be computed separately. Velocities in open channels are usually determined assuming bank-full depths.

The following equation represents the time of concentration which is the sum of the travel times (T_t) values for the various consecutive flow segments:

$$\mathbf{T_c = T_{t1} + T_{t2} + \ldots T_{tm}} \qquad \textbf{(6.C.1)}$$

Where T_c = time of concentration, h
m = number of flow segments
T_{tm} = travel time segment, h

6.C.3 Travel Time, T_t

Water moves through a watershed as sheet flow, shallow concentrated flow, open channel flow, or some combination of these. The type that occurs is a function of the conveyance system and is best determined by field inspection.

6.C.4 Sheet-Flow Travel Time, T_t

Sheet flow is a shallow mass of runoff on a plane surface with the depth uniform across the sloping surface. **Typically flow depths will not exceed 30mm (1 in). Such flow occurs over relatively short distances, rarely more than about 91.4m (300 ft), but most likely less than 46m (150 ft)**. Sheet flow rates are commonly estimated using the NRCS TR-55 (1986) variation of the kinematic wave equation:

$$T_t = \frac{0.091(nL)^{0.8}}{P_2^{\,0.5} S^{0.4}} \qquad \left(T_t = \frac{0.007(nL)^{0.8}}{P_2^{\,0.5} S^{0.4}} \right) \qquad \textbf{(6.C.2)}$$

Where T_t = travel time, h
n = Manning's roughness coefficient (values of n can be obtained from Table C.1)
L = flow length, m (ft)
S = slope of the hydraulic grade line (land slope), m/m (ft/ft)
P_2 = 2 year, 24 hour rainfall depth, mm (in) (See Table B-1.)

TR-55 recommends an upper limit of L=91.4m (300 ft) for using Equation 6.C.2, although others have suggested that 91.4m (300 ft) is too long of a flow length for Connecticut so **engineering judgement should be used when selecting the flow length**.

Travel time is the ratio of flow length to flow velocity:

$$\mathbf{T_t = L/(3600V)} \qquad \textbf{(6.C.3)}$$

Where: T_t = travel time, h
L = flow length, m (ft)
V = average velocity, m/s (ft/s)
3600 = conversion factor from seconds to hours.

n	Surface Description
0.011	Smooth asphalt
0.012	Smooth concrete
0.05	Fallow (no residue)
	Cultivated soils
0.06	Residue cover = 20%
0.17	Residue cover >20%
0.13	Range (natural)
	Grass
0.15	Short grass prairie
0.24	Dense grasses
0.41	Bermuda grass
	Woods**
0.40	Light underbrush
0.80	Dense underbrush

Table C-1 Mannings's Roughness Coefficient (n) for Overland Sheet Flow*

* Values obtained from NRCS TR-55 (1986) and McCuen (1989).

** When selecting n for woody underbrush, consider cover to a height of about 25mm (1in). This is the only part of the plant cover that will obstruct sheet flow.

6.C.5 Shallow Concentrated Flow Travel Time

After a maximum of 91.4 m (300 ft), sheet flow usually becomes shallow concentrated flow. The average velocity for this flow can be determined from equations 6.C.4 and 6.C.5, in which average velocity is a function of watercourse slope and type of channel.

Unpaved $\mathbf{V = 4.9178(s)^{0.5}}$ $\mathbf{(V = 16.1345(s)^{0.5})}$ **(6.C.4)**

Paved $\mathbf{V = 6.1961(s)^{0.5}}$ $\mathbf{(V = 20.3284(s)^{0.5})}$ **(6.C.5)**

Where: V = average velocity, m/s (ft/s)
s = slope of hydraulic grade line (watercourse slope), m/m (ft/ft)

These two equations are based on the solution of Manning's equation with different assumptions for n (Manning's roughness coefficient) and r (hydraulic radius, m (ft)). For unpaved areas, n is 0.05 and r is 0.12 m (0.4 ft); for paved areas, n is 0.025 and r is 0.06 m (0.2 ft).

After determining average velocity, use equation 6.C.3 to estimate travel time, T_t for the shallow concentrated flow segment.

6.C.6 Open Channel Flow Travel Time

Open channels are assumed to begin where surveyed cross section information has been obtained, where channels are visible on aerial photographs, or where blue lines (indicating streams) appear on United States 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 bank-full elevation but may change with respect to stream reach.

Manning's equation is

$$\mathbf{V = (r^{2/3}\, s^{1/2})/n \quad (V = (1.49 r^{2/3}\, s^{1/2})/n)} \qquad \textbf{(6.C.6)}$$

where: V = average velocity, m/s (ft/s)
r = hydraulic radius, m (ft) (equal to a/p_w)
a = cross sectional flow area, m^2 (ft^2)
p_w = wetted perimeter, m (ft)
s = slope of the hydraulic grade line (watercourse slope), m/m (ft/ft)
n = Manning's roughness coefficient (see Appendix A of Chapter 8, Culverts and Table 7-1 of Chapter 7, Channels)

After average velocity is computed using equation 6.C.6, T_t for the channel segment can be estimated using equation 6.C.3.

6.C.7 Reservoir Or Lake Flow Travel Time

Sometimes it is necessary to compute a T_t for a watershed having a relatively large body of water in the flow path. In such cases, T_t is computed to the upstream end of the lake or reservoir, and for the body of water the travel time is computed using the equation:

$$\mathbf{V_w = (g D_m)^{0.5}} \qquad \textbf{(6.C.7)}$$

Where: V_w = the wave velocity across the water, m/s (ft/s)
g = 9.81 m/s^2 (32.2 ft/s^2)
D_m = mean depth of lake or reservoir, m (ft)

Generally, V_w will be high 2.44 - 9.14 m/s (8-30 ft/s).

One must not overlook the fact that equation 6.C.7 only provides for estimating travel time across the lake and for the inflow hydrograph to the lake's outlet. It does not account for the travel time involved with the passage of the inflow hydrograph through spillway storage and the reservoir or lake outlet. This time is generally much longer and is added to the travel time across the lake. The travel time through lake storage and its outlet can be determined by the storage routing procedures in the Storage Chapter. Equation 6.C.7 can be used for swamps with much open water, but where the vegetation or debris is relatively thick (less than about 25% open water), Manning's equation is more appropriate. For additional discussion of equation 6.C.7 see King's Handbook of Hydraulics, fourth edition, page 8-50, or Elementary Mechanics of Fluids, by Hunter Rouse, John Wiley and Sons, Inc., 1946, page 142.

After wave velocity is computed using equation 6.C.7, T_t for the reservoir or lake can be estimated using equation 6.C.3.

6.C.8 Limitations

- Manning's kinematic solution should not be used for sheet flow longer than 91.4 m (300 ft). Equation 6.C.2 was developed for use with the four standard rainfall intensity-duration relationships.
- In watersheds with storm drains, carefully identify the appropriate hydraulic flow path to estimate T_c. Storm drains generally handle only a small portion of a large event. The rest of the peak flow travels by streets, lawns, and so on, to the outlet. Consult a standard hydraulics textbook to determine average velocity in pipes for either pressure or nonpressure flow.
- A culvert or bridge can act as a reservoir outlet if there is significant storage behind it. Detailed storage routing procedures should be used to determine the outflow through the culvert.

Time of Concentration Worksheet (Page 1 of 3)

Project No. ______________________ By ________________ Date _______________

Location ________________________ Checked ___________ Date _______________

Circle one: Present Developed

Circle one: metric units English units

NOTES: Space for as many as two segments per flow type can be used for each worksheet.
Must include a map showing travel time flow paths.

Sheet flow (Applicable to T_c only)		Segment ID					
1	Surface description (Table 6.C.1)						
2	Manning's roughness coeff., n (Table 6.C.1)						
3	Flow length, L (See Section 6.C.4)	m (ft)					
4	Two-yr 24-hr rainfall, P_2 (Table B-1)	mm (in)					
5	Land slope, s	m/m (ft/ft)					
6	Travel Time, T_t (Equation 6.C.2)	h		+		=	

Shallow concentrated flow		Segment ID					
7	Surface description (paved or unpaved)						
8	Flow length, L	m (ft)					
9	Watercourse slope, s	m/m (ft/ft)					
10	Average velocity, V (Equation 6.C.4 or 6.C.5)	m/s (ft/s)					
11	Travel Time, T_t (Equation 6.C.3)	h		+		=	

Time of Concentration Worksheet (Page 2 of 3)

Channel flow		Segment ID					
12	Cross sectional flow area, a	m^2 (ft^2)					
13	Wetted perimeter, p_w	m (ft)					
14	Hydraulic radius, $r = a/p_w$	m (ft)					
15	Channel slope, s	m/m (ft/ft)					
16	Manning's roughness coeff., n (Table 7-1 & Append. A, Ch. 8)						
17	Average velocity, v (Equation 6.C.6)	m/s (ft/s)					
18	Flow length, L	m (ft)					
19	Travel Time, T_t (Equation 6.C.3)	h		+		=	

Channel Section ID Schematic

Channel Section ID Schematic

Time of Concentration Worksheet (Page 3 of 3)

Reservior or lake flow		Segment ID					
20	Mean depth of lake or reservoir, D_m	m (ft)					
21	Wave velocity across the water, V_w	m/s (ft/s)					
22	Travel time, T_t (Equation 6.C.3)	h		+		=	

Total T_c = (add T_t in steps 6, 11, 19, and 22)……………………………