NATIONAL ENGINEERING HANDBOOK

SECTION 4

HYDROLOGY

CHAPTER 15. TRAVEL TIME, TIME OF CONCENTRATION AND LAG

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NATIONAL ENGINEERING HANDBOOK

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Introduction

There is a delay in time, after a brief heavy rain over a watershed, before the runoff reaches its maximum peak. This delay is a watershed characteristic called lag. It must be known before computing a peak flow time and rate for an ungaged watershed. Lag is related to time of concentration and may be estimated from it. Both lag and time of concentration are made up of travel times, which are also used in flood routings and hydrograph construction. This chapter contains methods for estimating travel time, lag, and time of concentration.

Types of Flow

Figure 15.1 shows four types of flow that may occur singly or in combination on a watershed.

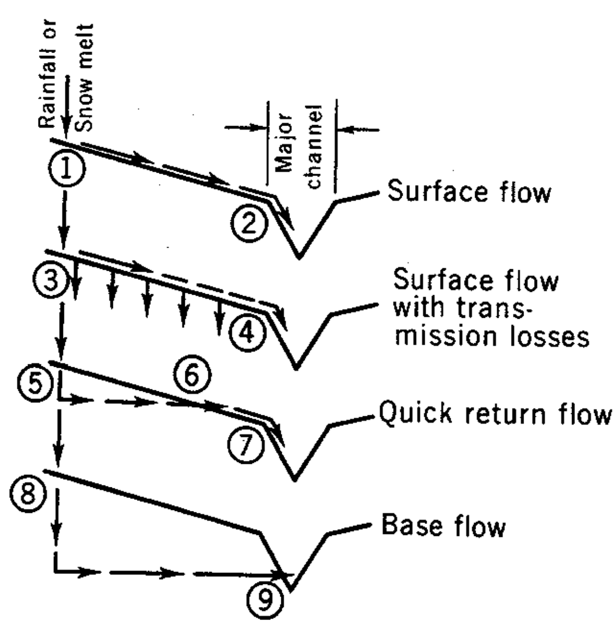

Figure 15. 1.--Types of flow

Surface Flow. - - Travel from point 1 to point 2 in figure 15.1 is along the surface of the watershed. This is surface runoff (also see Chapter 10). The flow takes place as overland flow or channel flow. This type is commonly discussed in hydrograph analysis but it seldom occurs in its ideal form.

Surface Flow with Transmission Losses. - - Water traveling toward the watershed outlet is infiltrated into the soil or channel material. This type is common in arid, semiarid, and subhumid climates. When the infiltration takes place in a channel, it is called a transmission loss (see Chapter 19). The distance from point 3 to point 4 in figure 15.1 will depend on the amount of runoff, the moisture characteristics of the soil and on hydraulic features of the flow.

Interflow or Quick Return Flow. - - Water infiltrated at point 5, figure 15.1, eventually returns to the surface at point 6, continuing as surface flow to point 7. This flow reappears rapidly in comparison to base flow and is generally much in excess of normal base flow. Springs or seeps that add to flood flows are of this type. It is common in humid climates and in watersheds with soils of high infiltration capacities and moderate to steep slopes.

Base Flow. - - Rainfall entering at point 8, figure 15.1, goes directly to the ground water table, eventually entering a stream at point 9. This type of flow has little effect on flood peaks in small watersheds. However, if it is a factor, it is usually added to the hydrograph as a constant discharge.

Measurement of flow

On figure 15.1, flows from points 1 to 2, 3 to 4, and 6 to 7 can be measured directly (see Chapter 14). Flows 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. The distance from point 3 to 4 in figure 15.1 will depend on the amount and rate of runoff, moisture condition in the soil and the hydraulic features of the flow. Such water cannot be measured except indirectly by analyses of precipitation, soil moisture movements, and evapotranspiration.

Travel Time, Lag and Time of Concentration

Travel time

Travel time (T_t) is the time it takes water to travel from one location in a watershed to another location downstream. The travel may occur on the surface of the ground or below it or in a combination of the two. T_t is affected by hydraulic factors and storage. It is a component part of lag (L) and time of concentration (T_c). It can be estimated by equation 15.1.

$$T_t = \frac{\ell}{3600\ V} \quad \text{. . . . . Eq. 15.1}$$

Where T_t = travel time in hours
ℓ = hydraulic length in feet
V = velocity in feet per second

<u>Lag</u>
The lag (L) of a watershed may be thought of as a weighted time of concentration. If for a given storm the watershed is divided into increments, and the travel times from the centers of the increments to the main watershed outlet are determined, then the lag is:

$$L = \frac{\Sigma(a_x\ Q_x\ \ T_{t_x})}{A\ \ Q_a} \quad \text{. Eq. 15.2a}$$

$$L = \frac{\Sigma(a_x\ Q_x\ T_{t_x})}{\Sigma(a_x\ Q_x)} \quad \text{. Eq. 15.2b}$$

where L = lag in hours

a_x = the x-th increment of watershed area in square miles

Q_x = runoff in inches from area a_x

T_{t_x} = travel time in hours from the center of a_x to the point of reference

A = total area of the watershed above the point of reference

Q_a = average runoff in inches from the total area (A), or $\Sigma(a_x\ Q_x)/A$

Equation 15.2 will give the watershed lag for all the types of flow shown in figure 15.1. However, the difficulties of obtaining accurate estimates of underground flow rates and paths limits the use of the equation. Instead, the approach in general practice is to develop a hydrograph for each of the subareas (A_x) in equation 15.2 and route the hydrographs downstream to the point of reference. The subareas are usually a subdivision of a hydrologic unit as described in Chapter 6. A lag time (L) or time of concentration (T_c) is usually estimated for each hydrologic unit by one of the methods in this Chapter. Hydrographs are then developed for each by a method of Chapter 16 and routed to the point of reference by a method of Chapter 17.

In simple hydrograph analysis, lag is the time from the center of mass of excessive rainfall to the peak rate of runoff (see Chapter 16). When combinations of flow occur together, a compound hydrograph with more than one peak and lag time may result. Ideally the various types of flow should be separated for lag analysis and combined at the end of the study. Water exists in a watershed system as a shapeless mass occurring in varying combinations of surface runoff, interflow and ground water flow. These components are characterized by the path the water takes from where it is generated to the point of reference, downstream. The velocity distribution varies both horizontally and vertically and lacks constant boundaries, thus the flow pattern cannot be evaluated by simple hydraulic analysis. In practice, lag is usually determined only for the direct runoff portion of flow.

The role of channel and valley storage are 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, so that an average lag may have a large error. The problem of evaluating lag is sufficiently complex that theoretical hydraulic analysis must be complemented with a hydrologic appraisal of the relative effect of basin characteristics in order to make the best estimate.

Time of concentration

This is the time it takes for runoff to travel from the hydraulically most distant part of the storm area to the watershed outlet or other point of reference downstream. In hydrograph analysis, T_c is the time from the end of excessive rainfall to the point on the falling limb of the hydrograph (point of inflection) where the recession curve begins (see Chapter 16). T_c is generally understood as applying to surface runoff.

The implication in the definitions of L and T_c, that the time factor is only a case of calculating a theoretical velocity of a segment of water moving through a hydraulic system, is an over-simplification. As with lag, T_c may vary because of changes in hydraulic and storage conditions.

Estimating T_c, T_t and L

Each method presented here is in effect a short-cut from which one or more watershed characteristics have been omitted. It is a good practice to consider more than one method, choosing the one that best fits the characteristics of a given watershed. It is not worthwhile averaging estimates made using two or three methods. Instead, the method that appears most applicable because of field and data conditions should be used.

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 coefficient; 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.

Indications of channel stability can sometimes be used to bracket the range of velocities that normally occur in the stream channels. Because high sediment concentrations frequently affect both channel velocities and peak rates of runoff, it is important to note when this potential exists.

Intensity of investigations
The purpose for which a study is made is a guide to the amount of work that should be done in securing data to serve as a basis for estimating T_c (Chapter 6). Where the hydrograph is to be the basis for design or for an important conclusion in planning, sufficient surveys should be made to serve as a basis for (a) dividing the main drainage course into reaches that are approximately uniform as to channel sizes, slopes and characteristics and (b) determining average cross sections, roughness coefficients and slopes for each reach. Where the hydrograph is to be the basis for preliminary conclusions, T_c may be estimated by taking the travel distance from maps or aerial photographs and estimating average velocity from general knowledge of the approximate sizes and characteristics of channels in the area under consideration.

Many natural streams have considerable sinuosity, meander, etc. as well as overfalls and eddies. Tendencies are therefore, to underestimate the length of channels and overestimate average velocities through reaches.

Stream hydraulics for estimating travel time and T_c
This method is recommended for the usual case where no usable hydrographs are available. This procedure is most applicable for areas where surface runoff predominates. It can result in too short of T_c for areas where interflow and ground water flow are a major part of runoff.

Stream or valley lengths and flow velocities are used, being taken from field survey data. It is assumed the stream has been divided into reaches.

1. Estimate the 2-year frequency discharge in the stream. When this cannot be done, use the approximate bankfull discharge of the low flow channel.

2. Compute the average velocity. In watersheds with narrow flood plains where the depth of overbank flow may be 10 to 20 feet during a major flood event, it may be desirable to use correspondingly higher velocities for frequencies of 10 to 100 years or greater.

3. Use the average velocity and the valley length of the reach to compute the travel time through the reach by equation 15.1.

4. Add the travel times of step 3 to get the T_c for the watershed. Use of the low flow channel bankfull discharges with valley lengths is a compromise that gives a T_c for average floods. For special cases (channel design, for instance) use whatever average velocities and lengths are appropriate.

In most cases the hydraulic data do not extend upstream to the watershed ridge. The remaining time (to add in step 4) can be estimated by adding the time obtained by the upland method or the T_c obtained by the curve number method. See figures 15.2 and 15.3 respectively. Use the one most applicable to the upper watershed characteristics.

Lag may be estimated in terms of T_c using the empirical relation:

$$L = 0.6\ T_c \quad \text{Eq. 15.3}$$

This is for average natural watershed conditions and for an approximately uniform distribution of runoff on the watershed. When runoff is not uniformly distributed the watershed can be subdivided into areas within which the runoff is nearly uniform, enough so that equation 15.3 can be applied.

Upland method

Types of flow considered in the upland method are: overland; through grassed waterways; over paved areas; and through small upland gullies. Upland flow employed in this method can be a combination of these various surface runoff conditions. The velocity is determined using figure 15.2.

The most remote segment of runoff that becomes part of the total time of concentration may occur in wide sheets overland rather than in defined channels. This type of flow is of practical importance only in very small watersheds because runoff is usually concentrated into small gullies or terrace channels within less than a thousand feet of its origin. The velocity of overland flow varies greatly with the surface cover and tillage as demonstrated in figure 15.2.

Surface runoff along terrace channels is another type of upland flow. The velocity and distance of flow that relate to time of concentration is based on the terrace gradient and length. A velocity of 1.5 feet per second can be assumed for the average terrace channel. Runoff soon concentrates from sheet flow into small gullies. Their path of flow and location may change from one flood to the next. Ordinary tillage operations may obliterate them after each period of runoff. Still larger gullies are formed which under a good conservation practice are transformed into permanent grassed waterways.

The travel time (T_t) for each type of upland flow can be computed using equation 15.1. The summation of these travel times will equal the T_c in the upland or subwatershed, to the watershed outlet, or down to the point where hydraulic cross sections have been made for the stream hydraulics method.

In a small watershed the elapsed time for overland flow in figure 15.2 may be a substantial percent of the total watershed time of concentration. Conversely, it is a much smaller portion of the total time of concentration in larger watersheds. In watersheds larger than 2000 acres, it can usually be ignored by extrapolating the average measured velocity over the entire hydraulic distance as previously described.

The upland method should be limited to small watersheds (2000 acres or less) and to the sub-watershed portions of larger watersheds above and beyond the point where it is impractical to survey cross sections and make other detailed hydraulic measurements. This upstream limit is usually selected where natural reach storage ceases to be an important element in shaping a unit hydrograph for the watershed in question.

<u>Curve number method</u>
This method was developed for areas of less than 2000 acres.

Equation 15.4 was developed from research watershed data:

$$L = \frac{\ell^{0.8}\,(S+1)^{0.7}}{1900\,Y^{0.5}} \quad \text{. . . . . Eq. 15.4}$$

Where L = lag in hours

ℓ = hydraulic length of watershed in feet

$S = \frac{1000}{CN'} - 10$ where $CN' \cong$ hydrologic soil cover complex number (CN) in Chapter 9.

Y = average watershed land slope in percent

The curve number method was developed to span a broad set of conditions ranging from heavily forested watersheds with steep channels and a high percent of the runoff resulting from subsurface or inter-flow and meadows providing a high retardance to surface runoff, to smooth land surfaces and large paved parking areas. The CN' is a measure of the

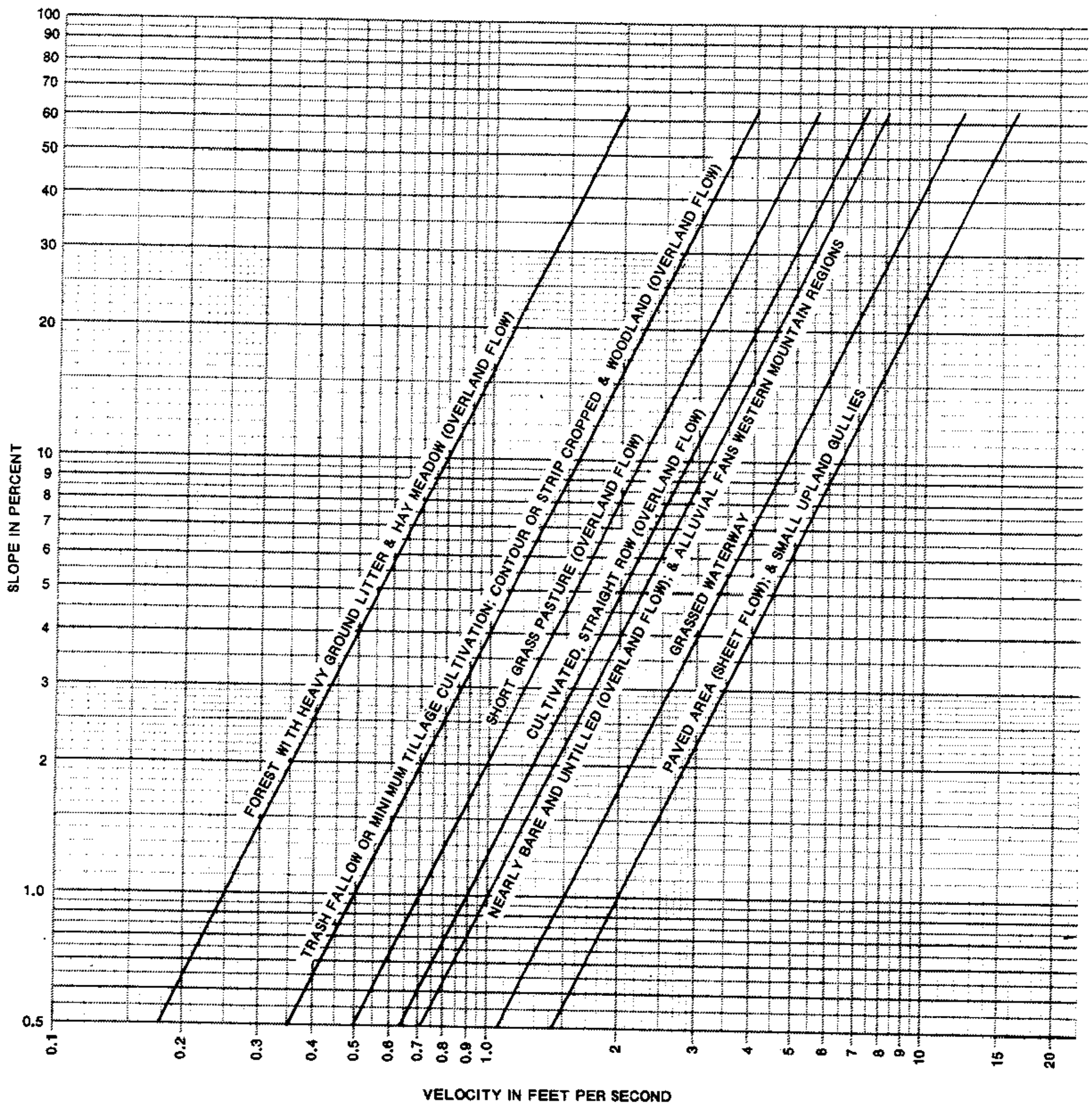

Figure 15.2.--Velocities for upland method of estimating T_c

retardance of surface conditions on the rate at which runoff concentrates at some point in question. This retardance factor (CN') is approximately the same as the CN in Chapter 9. A thick mulch in a forest is associated with a low CN in Chapter 9 and reflects a high degree of retardance as well as a high infiltration rate. A hay meadow has a relative low CN, other factors being equal, and like a thick mulch in a forest provides a high degree of retardance to overland flow in small watersheds. Conversely, bare surfaces with very little retardance to overland flow are represented by a high CN'. Runoff curve number tables in Chapter 9 can be used for approximating the CN' for the "S" in equation 15.4. A CN' of less than 50 or greater than 95 should not be used in the solution of equation 15.4.

The slope (Y) in percent is the average land slope of the watershed. Theoretically, it would be as if slopes were obtained for each corner of a grid system placed over the watershed, and then averaged.

Figure 15.3 provides a quick solution to equation 15.4.

Variations in Lag and T_c Due to Urbanization

Investigations have indicated that a significant increase in peak discharge can result from urbanization of a watershed. Such increases in the peak discharge are generally attributed to the construction of collection systems that are more efficient in a hydraulic sense than those provided in nature. These systems increase conveyance velocities so that greater amounts of discharge tend to reach points of concentration concurrently. Where flow once prevailed over a rough terrain and along field gullies and stream channels, urbanization provides hydraulically smooth concrete gutters, streets, storm drains and open channel floodways that convey runoff rapidly to downstream points.

The amount of imperviousness due to urbanization in a watershed varies from about 20 percent in the case of low density residential areas to about 90 percent where business and commercial land use predominates.

Table 15.1 illustrates the degree of imperviousness with land use for typical urban development.

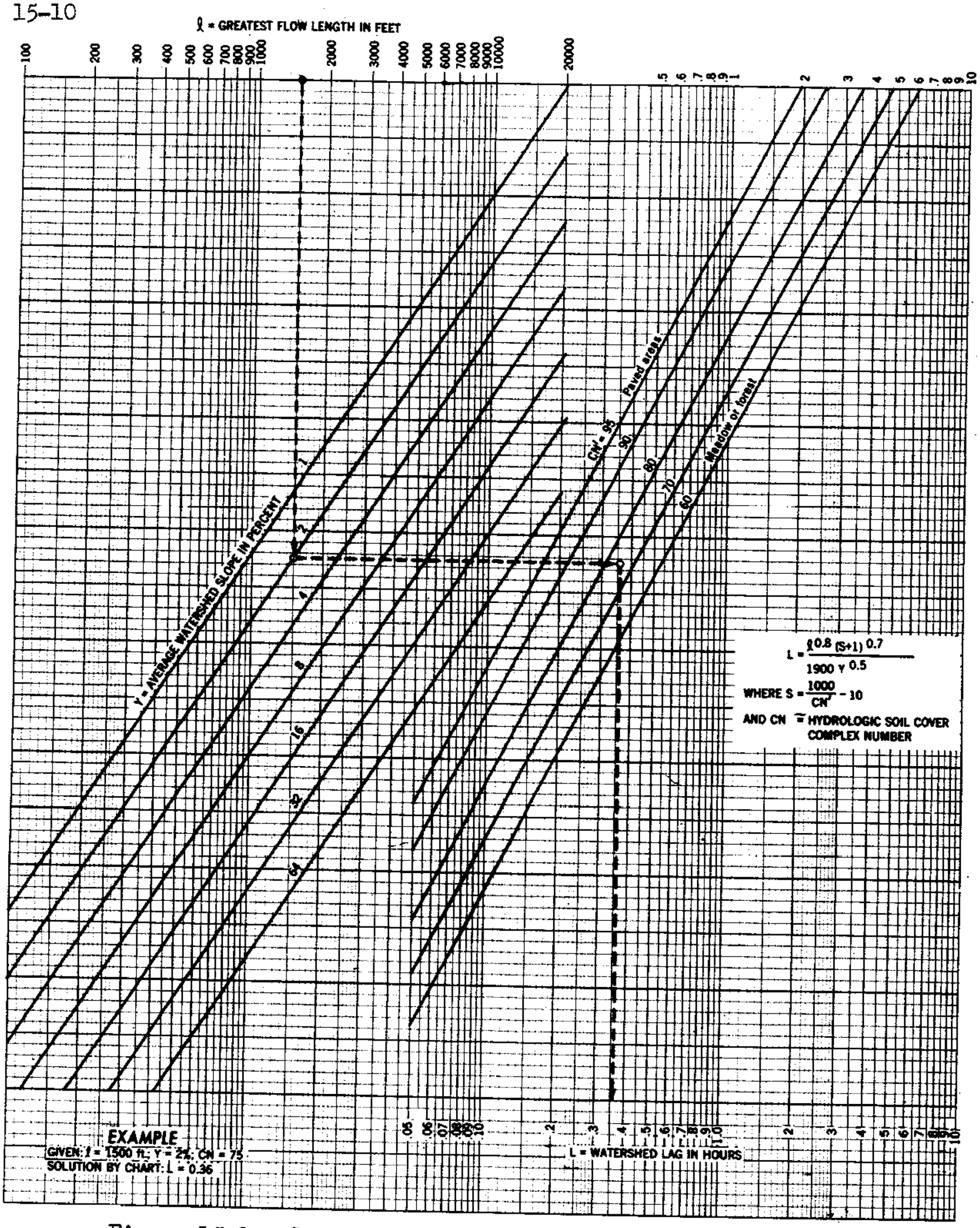

Figure 15.3.--Curve number method for estimating lag (L)

Table 15.1.--Percent of imperviousness for various densities of urban occupancy.

Land Use	% Imperviousness[1]
Low Density Residential	20 - 30
Medium Density Residential	25 - 35
High Density Residential	30 - 40
Business - Commercial	40 - 90
Light Industrial	45 - 65
Heavy Industrial	50 - 70

1/ Effects of Urbanization on Storm Runoff - Cudworth and Bottorf - South Pacific Division - Corps of Engineers. Presented to Water Management Subcommittee, PSIAC, March 1969.

A CN' of 90 or 95 can be used to estimate the impervious portion. CN' for lawns, parks, etc. can be selected from one of the curve number tables in Chapter 9.

Travel Time Through Reservoirs, Lakes, and Swamps

It is sometimes necessary to compute a T_c for a watershed having a relatively large body of water in the flow path. In such cases, T_c is computed by one of the above methods to the upstream end of the lake or reservoir, and for the body of water the travel time is computed using the equation:

$$V_w = \sqrt{gD_m} \qquad \text{Eq. 15.5}$$

Where V_w = the wave velocity, in fps, across the water

g = 32.2 feet/sec/sec

D_m = mean depth of lake or reservoir in feet

Generally, V_w will be high, as shown in table 15.2.

One must not overlook the fact that equation 15.5 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's outlet. This time is generally much longer than and is added to the travel time across the lake. The travel time through lake storage and its outlet can be determined by one of the storage routing procedures in Chapter 17.

For additional discussion of equation 15.5 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.

Equation 15.5 can be used for swamps with much open water, but where the vegetation or debris is relatively thick (less than about 25 percent open water), Manning's equation is more appropriate.

Table 15.2.--Wave velocities on lakes and reservoirs

Mean depth, D_m (feet)	Wave velocities, V_w (fps)	(mph)
2	8.0	5.45
4	11.3	7.70
8	16.0	10.9
16	22.7	15.5
32	32.1	21.9

Examples

The following examples illustrate the use of the methods previously described to estimate travel time (T_t), time of concentration (T_c) and lag (L). The sample watershed of Chapter 6 showing the subdivision of a hydrologic unit is repeated here as figure 15.4 for the examples that follow.

Example 15.1, Upland Method.--Subdivision (1) in figure 15.4 has a diversion terrace below a short grass pasture outletting into a grassed waterway down to a road crossing. The overland flow length across the pasture down to the diversion terrace is 900 feet.

The length of the longer diversion terrace is 2100 feet. The average slope of the pasture is 8 percent. The grassed waterway is 2400 feet long with an average slope of 4 percent. A raw gully extends from the road crossing where the grassed waterway terminates, down to the point where a grade stabilization structure is planned. The length of the gully is 2700 feet with a 3 percent grade.

1. Read the following velocities from figure 15.2:

   Short grass pasture @ 8 percent . . . . 2 ft./sec.
   Grassed waterway @ 4 percent . . . . 3 ft./sec.
   Gully @ 3 percent . . . . 3.5 ft./sec.

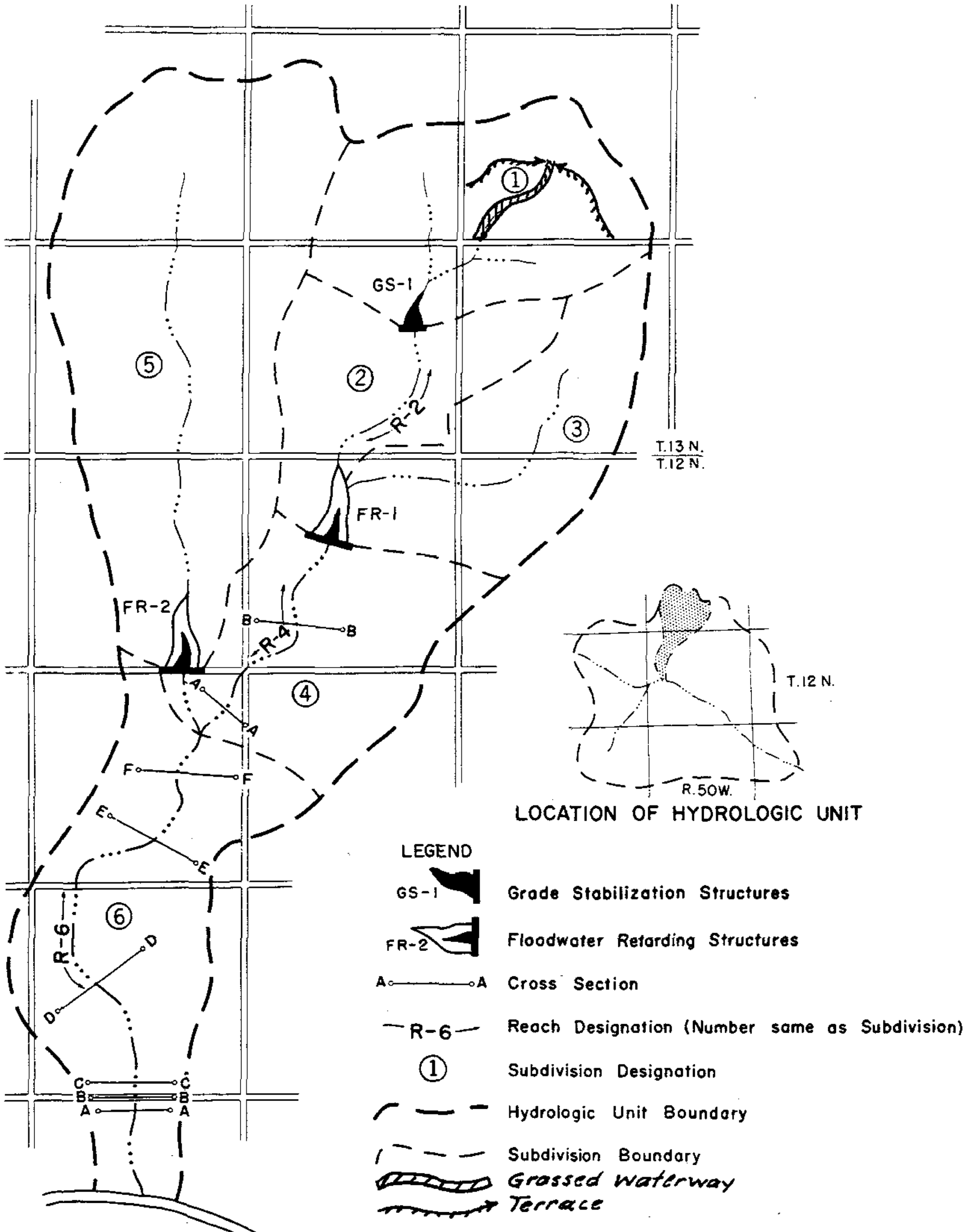

FIGURE 15.4-HYDROLOGIC UNIT HAVING DETAIL FOR USE AS A SAMPLE WATERSHED

2. The average velocity for terraces is 1.5 ft./sec.

3. Substituting velocity and length in equation 15.1:

   T_t (pasture) = (900/3600) ÷ 2 = 0.125 hr.
   T_t (terrace) = (2100/3600) ÷ 1.5 = 0.390 hr.
   T_t (waterway) = (2400/3600) ÷ 3 = 0.222 hr.
   T_t (gully) = (2700/3600) ÷ 3.5 = 0.215 hr.

4. $T_c = \Sigma T_t = 0.125 + 0.390 + 0.222 + 0.215 = 0.952$ hr.
   Round to 1.0 hr (to the nearest tenth hour).

Example 15.2, Curve Number Method.--Subdivision (5) in figure 15.4 is a wooded area with soils primarily in hydrologic group B. The hydrologic condition is good, having a heavy cover of litter. The slopes are steep, averaging about 16 percent. The hydraulic length according to map measurement is 16,000 feet.

1. The soil cover number from table 9-1 (Chapter 9) for this subdivision would be 55. $CN \cong CN' = 55$

2. Using figure 15.3, L = 1.4 hrs.

3. Use equation 15.3 to convert lag to T_c:

   $T_c = 1.4/0.6 = 2.3$ hrs.

Example 15.3, Stream Hydraulics Method.--It can be assumed that back water curves (or water surface profiles) have been computed by methods in Chapter 14 from the river outlet of the sample watershed in figure 15.4 up stream to the proposed floodwater retarding structure sites FR-1 and FR-2. Example 15.2 provided the T_c for developing inflow hydrographs to the proposed FR-2 site and example 15.1 provided the T_c for inflow hydrographs to the proposed grade stabilization structure, GS-1 site. A flood hydrograph for present conditions (without structures) is desired at the junction below subdivisions (4) and (5). Therefore a simple flood hydrograph is needed at the outlet of subdivision (4) to combine with the hydrograph at the proposed FR-2 site and outlet of subdivision (5). To develop a simple hydrograph at the lower end of subdivision (4), the travel time (T_t) is needed for reaches R-2 and R-4 and each added to the T_c for the GS-1 site. There floodplain lengths are:

GS-1 to FR-1	6000'
FR-1 to B-B	2400'
B-B to A-A	2800'
A-A to junction	900'

The bankfull discharge and cross sectional area obtained from the W.S. profile rating curves at surveyed sections A-A and B-B give a mean velocity of 3.6 and 3.8 feet per second respectively. Similarly, the velocity obtained from the water surface profile at the FR-1 site is 6.1 feet per second. A surveyed cross section was available at the GS-1 site but other than that surveyed cross sections were not made beyond the upstream point of site FR-1. They were not considered necessary for the sole purpose of estimating travel time in this upper reach. Instead, handlevel channel cross sections were made at four intermediate locations in reach R-2 and an overall gradient estimated. These data appear in the following steps.

1. A table is made showing the field data obtained in R-2 and the estimated mean velocities for each section therein computed from Manning's formula, $V = \frac{1.486}{n} r^{2/3} S^{1/2}$

X-Section	Bankfull area (a)	Wetted Perimeter (P)	Hydraulic Radius (r)	$r^{2/3}$	n	$S^{1/2}$	V
	ft	ft	ft			ft/ft	ft/sec
GS-1	48	22	2.18	1.68	0.040	0.10	6.2
hde-1	55	35	1.57	1.35	0.055	0.10	3.7
hde-2	55	39	1.42	1.26	0.055	0.10	3.4
hde-3	50	26	1.92	1.55	0.040	0.10	5.8
hde-4	56	28	2.00	1.59	0.040	0.10	5.9
FR-1	(obtain from water surface profile rating)						6.1

2. Since the handlevel sections were taken at approximately equal intervals, the velocities are averaged without weighting them with respect to length. The average velocity for reach R-2 is 5.2 ft/sec.

3. Applying equation 15.1:

$$T_t = (6000/3600) \div 5.2 = 0.32 \text{ hrs.}$$

4. Obtain T_t for R-4 by equation 15.2:

From	To	Distance (d)	Velocity (V)	T_t (hr)
FR-1	Midway to B-B	1200	6.1	0.051
Midway between FR-1 & B-B	Midway between B-B & A-A junction	2600	3.8	0.190
Midway between B-B & A-A		2300	3.6	0.181
			Total	0.422

5. T_c for subdivisions (1), (2), (3) and (4):

T_c for subdivision (1) from example 15.1 . . . . . 0.95
T_t for R-2 . . . . 0.32
T_t for R-4 . . . . 0.42
T_c (total) 1.69
Round to 1.7 hrs.

A hydrograph developed at the junction by combining the two tributary areas and using the longer T_c of 2.3 hours would be less accurate than by estimating the T_c for each tributary, as was done in the examples above, and then combining the two hydrographs developed for each.