Chapter 5 - Hydrology

5.1 Hydrology

The process of designing drainage facilities, including culverts, pipelines, and stormwater management systems, requires the engineer to determine the peak rate and maximum volume of flow to be transported by the drainage facility. Numerous textbooks and manuals have been developed to guide the design engineer. In addition, many agencies for which drainage facilities are being designed have developed their own standard procedures for hydrologic analysis.

Practices do vary from state to state, and often within states, and this chapter is not intended to provide comprehensive design procedures. It is intended to identify common procedures for determining the design flow. Manuals or texts that include detailed design procedures are referenced.

When considering the specific focus of the drainage engineer, hydrology is the science which deals with estimating the rate of precipitation or rainfall, estimating the spatial distribution of the rainfall, and quantifying the flow or runoff (both peak rate and total volume) that reaches a particular location. This location is labeled the “point of solution.” The point of solution can be a catch basin, inlet, culvert entrance, or any other point within a watershed where detailed analysis is desired.

There are several factors that directly impact runoff. These include the rainfall intensity, the type of ground cover of the drainage area, the time of concentration for the rainfall event, and the size of the contributing drainage area.

It is important to note that estimating the above parameters requires significant experience and judgement. Additionally, different techniques commonly used to estimate runoff can produce considerably different results for identical hydrologic design parameters. Therefore, the level of effort spent on estimating the runoff, and the storm interval selected for the design of a drainage facility must be commensurate with the risk of damage from flooding.

5.2 Rainfall Intensity, Duration, and Frequency Data

Rainfall is typically measured as the total amount (in. or cm) of rainfall coupled with the duration of the rainfall event. Rainfall intensity, measured in inches or cm per hour, is dependent upon the duration of the rainfall and the frequency of the storm event. Short duration storms and storms of longer return periods are often more intense than longer, more frequent storms.

When describing rainfall events, both the duration and frequency are needed to fully describe the rainfall intensity. The frequency of the storm event, or recurrence interval, is a statement of the statistical likelihood of a rainfall event occurring in a given year. Consider a rainfall event with a 10-year recurrence interval. It would indicate that there is a 0.10 or 10% chance of a rainfall event of this intensity and duration occurring in any given year. It does not indicate that this event will only occur once in every 10-years, but rather that it will occur every 10 years on average. The design frequency used in the design of drainage facilities is typically provided by the facility owner or jurisdictional regulatory agency. Typical design year frequencies for various roadway classes are provided in Table 5.1.

Table 5.1: Design storm selection guidelines (1)

Roadway Classification	Exceedence Probability (%)	Return Period (Year)
Interstate, Freeways (Urban/Rural)[a]	2%	50
Principal Arterial	2%	50
Minor Arterial System with ADT >3,000 VPD	2%	50
Minor Arterial System with ADT = <3,000 VPD	4%	25
Collector System with ADT >3,000 VPD	4%	25
Collector System with ADT = <3,000 VPD	10%	10
Local Road System[b]	20%–10%	5–10

[a] Federal regulation requires Interstate highways to be provided with protection from the two percent flood event. Underpasses and depressed roadways should also be designed to accommodate the two percent flood. Where no embankment overflow relief is available, drainage structures should be designed for at least the one percent or 100-yr event.

[b] At the discretion of the designer, based on Risk Analysis and Design Hourly Volume (DHV).

Rainfall intensity/duration/frequency (IDF) curves are statistically-developed from rain gauge recordings of rainfall data over time. IDF curves are available from the National Weather Service, most State DOTs, local flood control agencies, and other governmental agencies. The National Oceanic and Atmospheric Administration (NOAA) has developed a web-based Precipitation Frequency Data Server. This website is based on NOAA Atlas 14, Precipitation-Frequency Atlas of the United States (2). The website provides the user with rainfall intensity, duration, and frequency data along with rainfall confidence intervals. Figure 5.1 illustrates a typical IDF curve.

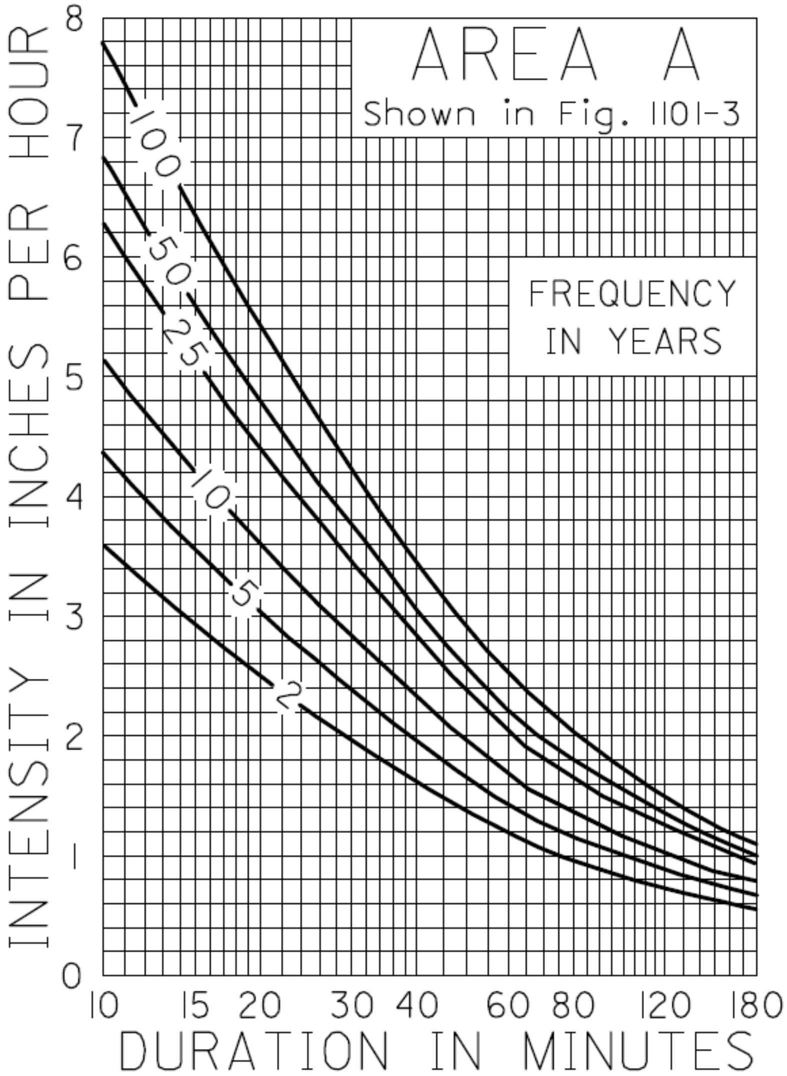


Figure 5.1: Typical IDF curve (3)

5.3 Estimating Time of Concentration

The time of concentration is the time required for stormwater runoff to travel from the most hydraulically distant point in a watershed to the point of solution. The time of concentration (t_t) is comprised of three distinct components: overland flow time (t_o); shallow concentrated flow time (t_s); and, concentrated flow time (t_c). There are many ways to estimate t_t and formulas exist for the prediction of all three subcomponents of the time of concentration. The time of concentration is the total time for water to move through each flow regime until it reaches the point of solution.

Time of Overland Flow

Overland flow time t_o is the first component of the time of concentration. It typically occurs at the most remote point in the watershed and is characterized by sheet flow. It is thought to occur for no more than 300 ft (91 m), though some limit no further than 100 ft (31 m).

Kirpich Equation

The time of concentration of overland flow t_o can be estimated from the Kirpich equation, as given in Eqn. 5.1:

$$t_o = 0.00013\,L^{0.77}S^{-0.385} \qquad \text{(Eqn. 5.1)}$$

where:

t_o = concentration time, hrs;
L = the longest length of water travel, ft (m);
S = ground surface slope = H/L, ft/ft (m/m); and,
H = difference in elevation between the most remote point on the basin and the collection point, ft. (m).

The Kirpich empirical equation is normally used for natural drainage basins with well-defined overland flow routes along bare soil. For overland flow on impervious surfaces, the t_o obtained should be reduced by 60%. For overland flow on grass surfaces, the computed t_o should be increased by 100%.

Kinematic Wave Equation

The kinematic wave equation may also be used to determine t_o. Eqn. 5.2 shows the form:

$$t_o = \frac{0.93(L^{0.6})(n^{0.6})}{(i^{0.4})(S^{0.3})} \qquad \text{(Eqn. 5.2)}$$

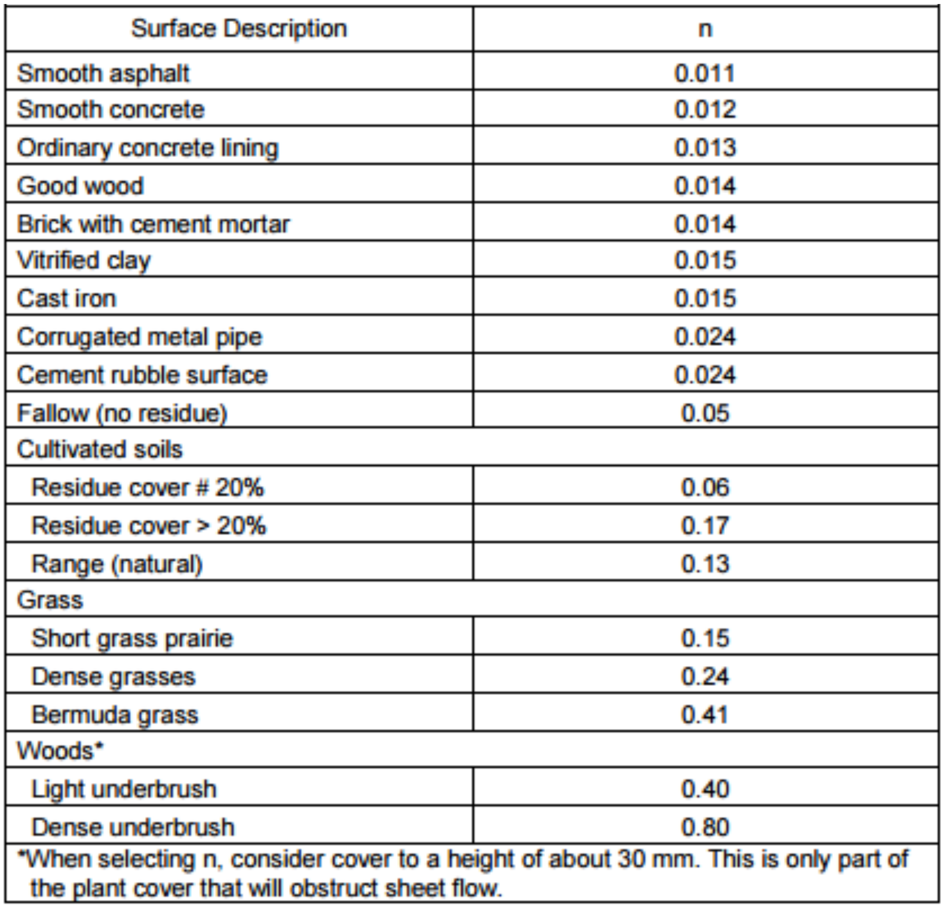
where:

t_o = travel time, minutes;
n = Manning's roughness coefficient;
L = flow length, ft (m);
i = rainfall intensity, inch/hr (cm/hr); and,
S = slope of hydraulic grade line (land slope), ft/100 ft (m100).

Obtaining a solution for the kinematic wave equation is an iterative procedure because the t_o is a function of the rainfall intensity, while the rainfall intensity is a function of the total time of concentration.

Manning's roughness coefficient is a function of the depth of flow. For very shallow depths, such as overland flow, a modified roughness coefficient must be utilized and typical values are provided in Table 5.2.

Table 5.2 Manning's roughness coefficient (n) for overland sheet flow (4)



Surface Description	n
Smooth asphalt	0.011
Smooth concrete	0.012
Ordinary concrete lining	0.013
Good wood	0.014
Brick with cement mortar	0.014
Vitrified clay	0.015
Cast iron	0.015
Corrugated metal pipe	0.024
Cement rubble surface	0.024
Fallow (no residue)	0.05
Cultivated soils	
Residue cover # 20%	0.06
Residue cover > 20%	0.17
Range (natural)	0.13
Grass	
Short grass prairie	0.15
Dense grasses	0.24
Bermuda grass	0.41
Woods*	
Light underbrush	0.40
Dense underbrush	0.80

*When selecting n, consider cover to a height of about 30 mm. This is only part of the plant cover that will obstruct sheet flow.

Upland Method

The Upland method is a graphical solution for finding the average overland flow velocity and can be used for overland flow in basins with a variety of land covers. This method relates t_o to the basin slope and to the length and type of ground cover. A graphical solution for finding the average overland flow velocity can be obtained from Figure 5.2. The t_o is commonly estimated as the longest length of flow travel divided by the average velocity of flow.

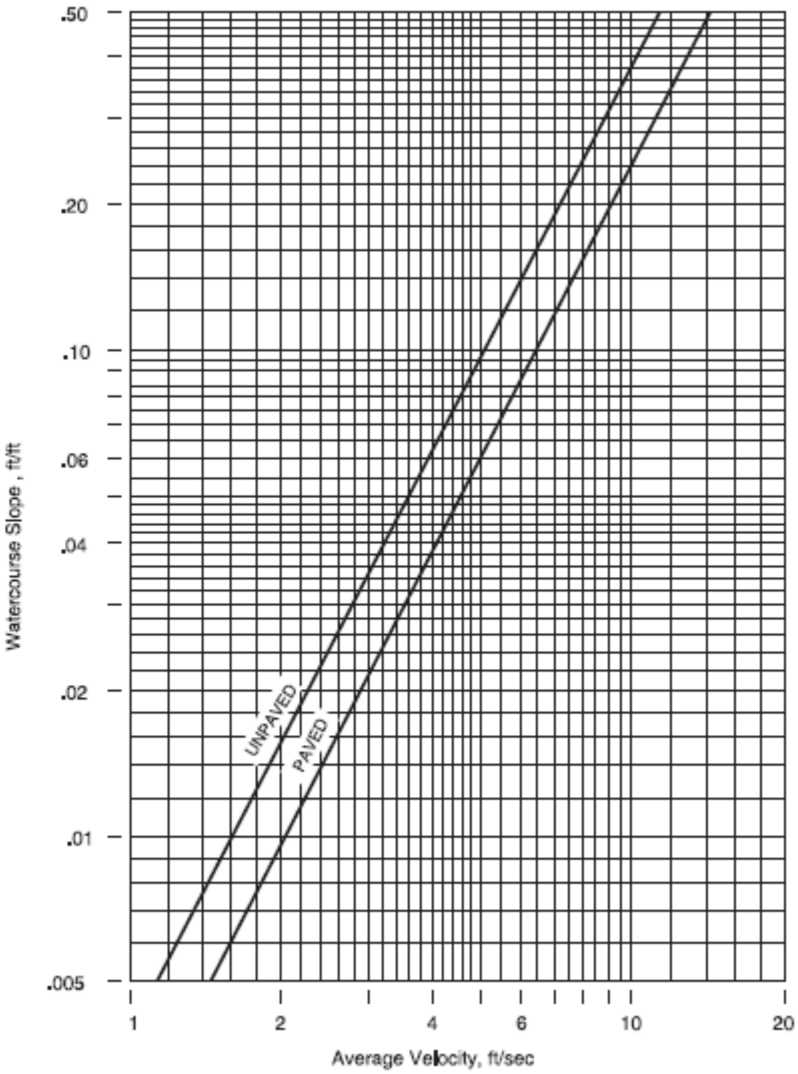


Figure 5.2: Average velocities for estimating travel time for shallow concentrated flow (5)

Shallow Concentrated Flow

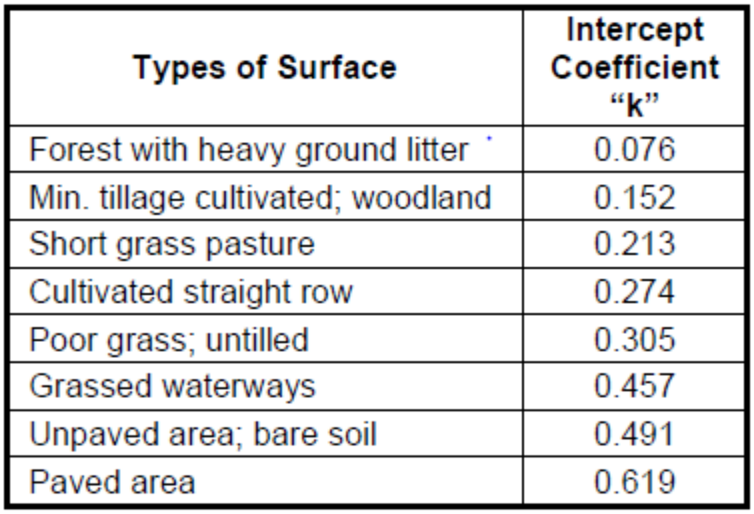
As runoff moves towards the point of solution, it concentrates into rills and gullies. Flow of this type is more efficient than overland flow and occurs with increased velocity. This type of flow is identified as shallow concentrated flow. The velocity of t_s can be determined using the equation shown in Eqn. 5.3:

$$V = 3.281\, k\, \sqrt{S} \qquad \text{(Eqn. 5.3)}$$

where:

V = Velocity, ft/sec. (m/sec);
K = intercept coefficient (seen in Table 5.3); and,
S = overland slope, ft/100 ft (m/100 m).

Table 5.3: Intercept coefficients for shallow concentrated flow (4)



Types of Surface	Intercept Coefficient "k"
Forest with heavy ground litter	0.076
Min. tillage cultivated; woodland	0.152
Short grass pasture	0.213
Cultivated straight row	0.274
Poor grass; untilled	0.305
Grassed waterways	0.457
Unpaved area; bare soil	0.491
Paved area	0.619

Once the velocity of flow has been determined the time of shallow concentrated flow t_s can be computed as shown in Eqn. 5.4:

$$t_s = \frac{L}{60\,V} \qquad \text{(Eqn. 5.4)}$$

where:

t_s = time of shallow concentrated flow, min;
L = overland flow length, ft (m); and,
V = velocity of overland flow, ft/sec (m/sec).

Concentrated Flow

The concentrated flow, t_c, is flow that is confined by sidewalls, natural or constructed, and free to travel under the influence of gravity. When runoff flows in an open channel or pipe, the length of the channel or pipe and the velocity are used to determine the time of concentration, t_t, for that portion of the watershed. Manning's equation may be used to determine the average velocity of open channel flow, as shown in Eqn. 5.5:

$$V = \frac{1.49\,r^{2/3}s^{1/2}}{n} \qquad \text{(Eqn. 5.5)}$$

where:

V = velocity, ft/sec (m/sec);
r = hydraulic radius in ft (equal to the cross-sectional area of the flow divided by the wetted perimeter, ft^2/P);
P = wetted perimeter, ft (m);
s = slope of the channel, ft/ft (m/m); and,
n = Manning's roughness coefficient for open channel flow (seen in Table 5.4).

Table 5.4: Typical values for Manning's roughness coefficient (4)

Typical Values for Manning's Roughness Coefficient	
Conduit Material	Manning's n
Closed Conduits	
Concrete Pipe (Smooth)	0.010-0.011
Concrete Boxes (Smooth)	0.012-0.015
Spiral Rib Metal Pipe (Smooth)	0.012-0.013
Corrugated Metal Pipe (Helical Corrugations 2-2/3 X 1/2 in)	0.011-0.023
Corrugated Metal Pipe (Helical Corrugations 6 X 1 in)	0.022-0.025
Corrugated Metal Pipe, Pipe-Arch and Box (Annular Corrugations 2-2/3 X 1/2 in)	0.022-0.027
Corrugated Metal Pipe, Pipe-Arch and Box (Annular Corrugations)	0.025-0.026
Corrugated Metal Pipe, Pipe-Arch and Box (Annular Corrugations 5 X 1 in)	0.027-0.028
Corrugated Metal Structural Plate (Annular Corrugations 6 X 2 in)	0.033-0.035
Corrugated Metal Structural Plate (Annular Corrugations 9 X 2-1/2 in)	0.033-0.037
Corrugated Polyethylene (Smooth)	0.009-0.015
Corrugated Polyethylene (Corrugated)	0.018-0.025
Polyvinyl chloride (PVC) (Smooth)	0.009-0.011
Open Channels	
Lined channels	
Asphalt	0.013 - 0.017
Brick	0.012 - 0.018
Concrete	0.011 - 0.020
Rubble or riprap	0.020 - 0.035
Vegetal	0.030 - 0.400
Excavated or dredged	
Earth, straight and uniform	0.020 - 0.030
Earth, winding, fairly uniform	0.025 - 0.040
Rock	0.030 - 0.045
Unmaintained	0.050 - 0.140
Natural channels (minor streams, top width at flood stage < 100 ft)	
Fairly regular section	0.030 - 0.070
Irregular section with pools	0.040 - 0.100

Once the velocity of concentrated flow has been determined, the t_c can be computed using the same procedure as described for shallow concentrated flow.

5.4 Estimating Rainfall Runoff

In many situations, it is sufficient to calculate the peak rate of runoff and the distribution of runoff, as a function of time is not necessary. There are many methods available for determining the peak rates of stormwater runoff. Two of the most popular are the Rational Method and the NRCS method.

Rational Method

The rational method has been used to estimate runoff since the late 1800's, named for the rational approach to estimating runoff. When using the rational method, the peak runoff is found by the relationship between the size of the drainage area, the amount of rainfall, and the proportion of rainfall that is converted into runoff. A fundamental assumption of the rational method is that the rainfall intensity is uniform over the entire contributing drainage area and lasts for the entire storm duration. This assumption limits the applicability of the rational method to relatively small drainage basins, which are usually considered to be in the range of 200 to 300 acres (81 to 121 hectares).

The rational method takes the form:

$$Q = C\ i\ A \qquad \text{(Eqn. 5.6)}$$

where:

Q = peak rate of runoff, cfs (cms);
C = runoff coefficient;
i = rainfall intensity, for selected recurrence interval and duration equal to the time of concentration in./hr (cm/hr); and,
A = area, acres (hectares).

The runoff coefficient, C, is the percentage of rainfall which is converted into runoff. The reasons for rainfall not being converted into runoff include evapotranspiration, infiltration, and localized depression storage. Many factors or variables affect the magnitude of C, including the slope of the ground, type of ground cover, soil moisture, travel length and velocity of overland flow, travel length and velocity of stream flow, rainfall intensity, and other phenomena. Generally, it is necessary to use higher C values for greater rainfall intensities and for steeper slopes. The selection of an appropriate C value requires careful judgment on the part of the design engineer. Typical ranges for C values can be found in Table 5.5.

If a watershed is comprised of several subareas of differing land use, a weighted C value should be computed as shown in Eqn. 5.7:

$$C_w = \frac{\sum_{i=1}^{n} C_i A_i}{\sum_{i=1}^{n} A_i} \qquad \text{(Eqn. 5.7)}$$

where:

C_w = weighted runoff coefficient;
C_i = runoff coefficient for i^{th} subarea;
A_i = area of i^{th} subarea, acres (hectares); and,
n = number of unique subareas.

The engineer responsible for the design of drainage facilities must anticipate and assess the most likely effects of future development of all of the land in the watershed of interest. Urban development will generally increase the volumes of stormwater runoff due to reduced infiltration and greater peak discharges, due to decreased flow travel time.

Table 5.5: Runoff coefficient for various land uses (6)

Business:	
Downtown area	0.70-0.95
Neighborhood areas	0.50-0.70
Residential:	
Single-family areas	0.30-0.50
Multi-units, detached	0.40-0.60
Multi-units, attached	0.60-0.75
Suburban	0.25-0.40
Apartment dwelling areas	0.50-0.70
Industrial:	
Light areas	0.50-0.80
Heavy areas	0.60-0.90
Parks, cemeteries	0.10-0.25
Playgrounds	0.20-0.40
Railroad yard areas	0.20-0.40
Unimproved areas	0.10-0.30
Lawns:	
Sandy soil, flat, < 2%	0.05-0.10
Sandy soil, average, 2 to 7%	0.10-0.15
Sandy soil, steep, > 7%	0.15-0.20
Heavy soil, flat, < 2%	0.13-0.17
Heavy soil, average 2 to 7%	0.18-0.22
Heavy soil, steep, > 7%	0.25-0.35
Streets:	
Asphalt	0.70-0.95
Concrete	0.70-0.95
Brick	0.70-0.85
Drives and walks	0.70-0.85
Roofs	0.70-0.95
Rural:	
Meadow areas	0.10-0.40
Forested areas	0.10-0.30
Cultivated fields	0.20-0.40

NRCS Method (5)

In 1964, the Natural Resources Conservation Service (NCRS) developed a computer program for watershed modeling. That watershed model was presented in Technical Release 20. The model is used for watershed evaluation and flood plain studies. To estimate runoff and peak rates of flow in small watersheds, a simplified method was developed and presented in Technical Release 55 TR-55 (5). For small watersheds, stream flow records are often unavailable, and when they are available, urban development may result in inaccurate statistical analysis. The TR-55 method allows for the development of hydrologic models using watershed characteristics to estimate peak discharge from the watershed.

The TR-55 model begins with a rainfall amount uniformly imposed on a watershed for a 24-hour distribution period. The period of 24 hours was used because of the availability of daily rainfall data that could be used to estimate 24-hour rainfall amounts.

Rainfall is then converted into mass rainfall using a runoff curve number (CN). The runoff curve numbers developed in TR-55 are based upon watershed characteristics including soil type, type and amount of plant cover, amount of impervious area, runoff interception, and surface storage. Runoff is then transformed into a hydrograph using a graphical or tabular computation method. The result is a peak discharge or design flow that can be used for the design of drainage structures.

The TR-55 model can be used for any location in the United States. It provides a nationally-consistent method of determining peak flow and can be used to check of peak flow computations made by other methods. If major discrepancies are found, a more thorough evaluation of the computations may be warranted.

Hydrologic Soil Group

Soils are classified into hydrologic soil groups (HSG) to indicate the rate of infiltration and the rate at which water moves within the soil. The HSGs are defined in TR-55 as follows:

Group A soils have low runoff potential and high infiltration rates even when thoroughly wetted. They consist mainly of deep, well-to-excessively drained sands or gravels and have a high rate of water transmission (i.e., greater that 0.30 in./hr (0.76 cm/hr));

Group B soils have moderate infiltration rates when thoroughly wetted and consist mostly of moderately-deep to deep, moderately-well to well-drained soils with moderately-fine to moderately-coarse textures. These soils have a moderate rate of water transmission (i..e., 0.15 to 0.30 in./hr (0.38 to 0.76 cm/hr));

Group C soils have low infiltration rates when thoroughly wetted and consist mainly of soils with a layer that impedes downward movement of water, and soils with moderately-fine to fine texture. These soils have a low rate of water transmission (i.e., 0.05 to 0.15 in./hr (0.13 to 0.38 cm/hr)); and,

Group D soils have high runoff potential. They have very low infiltration rates when thoroughly wetted and consist primarily of clay soils with a high swelling potential, soils with a permanent high water table, soils with a clay pan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very low rate of water transmission (i.e., 0 to 0.05 in./hr (0 to 0.13 cm/hr)).

Runoff Curve Number

The Runoff Curve Number (CN) is used to define the amount of rainfall which is not converted into runoff. CN values vary from 0 to 100. The CN for various ground covers and HSGs have been tabulated by NRCS and are widely available in engineering publications. Composite CNs can be calculated for drainage areas of varying soil cover and HSG using a weighting procedure similar to that which is used for the rational method.

Initial Abstraction

Initial abstraction (I_a) is the total of all losses before runoff begins. It includes water retained in surface depressions, water intercepted by vegetation, evaporation, and infiltration. The I_a is highly variable, but generally is correlated with soil and cover parameters. Through the studies conducted on many small agricultural watersheds, I_a was found to be approximated by the empirical equation shown in Eqn. 5.8:

$$I_a = 0.2S \qquad \text{(Eqn. 5.8)}$$

Where CN and S are related by:

$$S = \frac{1000}{CN} - 10$$

The I_a is dependent upon the CN value only. Using the calculated CN, the I_a can be found in tabular form in TR-55 (5) or by using the relationship defined in Eqn. 5.8.

Peak Unit Discharge

The peak unit discharge, q_u, is an empirical parameter which considers the rainfall distribution, the time of concentration, and initial losses. The TR-55 model provides graphical methods of determining the q_u, by using the following information:

1. Determine the time of concentration. This is the summation of the flow travel time through each consecutive segment of the watershed area. Travel time for sheet flow, shallow concentrated flow, and open channel flow can be calculated as discussed earlier in this chapter.
2. Determine the rainfall distribution. Different rainfall distributions can be developed for each watershed to emphasize the critical rainfall duration for the peak discharges. However, in order to avoid the use of a different set of rainfall intensities for each drainage area size, it is common practice in rainfall runoff analysis to develop a set of synthetic rainfall distributions. For the small-sized drainage areas, a storm period of 24 hours is appropriate for determining runoff volumes (even though 24 hours is a longer period than needed to determine the peak runoff).
3. The TR-55 model provides synthetic rainfall distributions for various intensities. A geographic depiction of rainfall distribution types is provided in TR-55. Types I, IA, II, and III are dependent upon the location of the watershed within the United States.
4. Determine the relationship I_a/P where P is the rainfall depth for the watershed measured in in. or cm. Then rainfall with a 24-hour duration and at various intensities can be obtained from the NOAA Precipitation Frequency Data Server or from local weather or water resource agencies.

Excess Rainfall

Excess rainfall is the depth of rainfall that is potentially available for runoff, after adjusting for initial losses. It should be computed as shown in Eqn. 5.9:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \quad \text{(Eqn. 5.9)}$$

where:

Q = runoff, in. (mm) (note: not the same parameter, Q, used for peak rate of runoff in the rational method);
P = rainfall, in. (mm);
S = potential maximum retention after runoff begins, in. (mm); and,
I_a = initial abstraction, in. (mm).

Peak Discharge

Peak discharge can be computed using Eqn. 5.10:

$$Q_p = q_u A_m Q \quad \text{(Eqn. 5.10)}$$

where:

Q_p = peak discharge, cfs (cms);
q_u = unit peak discharge, cfs per square mile per in. (cms per square km per cm);
A_m = drainage area, square miles (square km); and,
Q = direct runoff, in. (mm).

5.5 Rainfall Runoff Hydrograph

A rainfall runoff hydrograph provides the relationship between the discharge and the time for the entire duration of a storm event. A typical hydrograph is presented in Figure 5.3. The shape of the hydrograph differs from basin to basin. It is a function of the physical characteristics of the drainage basin, rainfall intensities and distribution pattern, land uses, soil type, and the initial moisture condition of the soil.

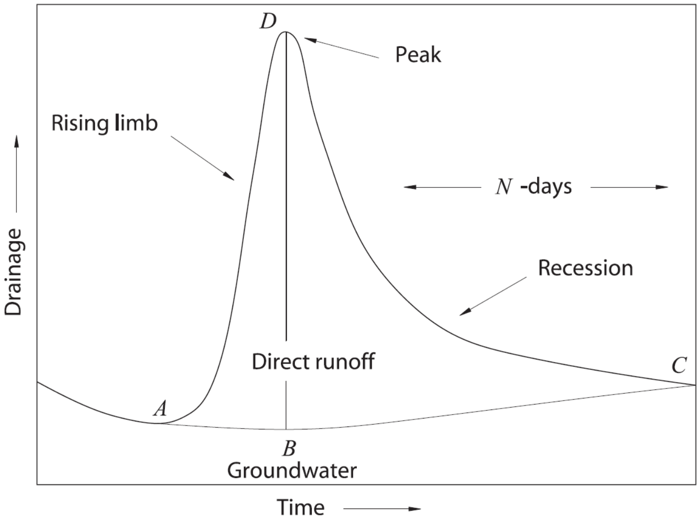


Figure 5.3: Typical runoff hydrograph

The types of hydrographs are typically either direct or synthetic. A direct hydrograph is based on the statistical analysis of long-term rainfall records within a given watershed. This method is generally applicable to very large watersheds and is only applicable to that specific watershed. A synthetic hydrograph represents an estimate of the discharge versus time relationship developed to approximate the response of a typical watershed in a given geographic location. The synthetic hydrograph is then converted to represent a unit of 1 in. (2.5 cm) of precipitation. For the vast majority of projects, the use of synthetic hydrographs is suitable.

The NRCS has developed unit synthetic hydrographs for each of the four geographic locations. The NRCS unit hydrograph is converted to represent a unit of 1 in. (2.5 cm) of precipitation and for 1 square mile (2.6 square km) of drainage area. Each time step value of the unit hydrograph is then multiplied by the peak discharge, Q_p, to determine the ordered pairs (time, discharge) for the runoff hydrograph.

5.6 Computer Models

The NRCS has provided a computer version of the TR-55 for use in computing peak rates of runoff and runoff hydrographs. For large, complex watersheds and for high-profile or high-risk culvert installations, it may be necessary to utilize a sophisticated computer solution for determining runoff hydrographs and peak runoff rates.

The U.S. Army Corps of Engineers Hydraulics Engineering Center has developed a set of hydraulic models for use in watershed management. The Hydraulic Engineering Center-Hydrologic Modeling System (HEC-HMS) is widely used for modelling watershed hydrology and is capable of simulating a large number of separate sub-shed areas, actual storm events, infiltration methods, and methods for routing flows from point-to-point within the watershed (7).

Both the NRCS and U.S. Army Corps of Engineers software products are available for free download from their respective governmental agency websites. The TR-55 model is accessible from www.nrcs.usda.gov, while the HEC-HMS program can be downloaded from hec.usace.army.mil. However, it is important to note that the results from computer-based models must be based on sound input values and should be reviewed for accuracy by an experienced design engineer.

5.7 Example Problem

Given:
A parcel of land is scheduled for development and has the following land use characteristics for the pre- and post-developed conditions, as shown in Tables 5.6 and 5.7.

Table 5.6: Example problem – Pre-developed conditions

Land Use	Area (acres)	Runoff Coefficient (C)	Time of Concentration (min)
Forested Area	5	0.20	
Meadow	15	0.25	
Total =	20		20

Table 5.7: Example problem - Post-developed conditions

Land Use	Area (acres)	Runoff Coefficient (C)	Time of Concentration (min)
Forested Area	0.5	0.20	
Meadow	1.5	0.25	
Paved	1.5	0.90	
Single Family Residential	16.5	0.40	
Total =	20		15

Find:
The peak 10-year runoff for the pre- and post-developed condition using the rational method

1. Use the equation, $C_w = \frac{\sum_{i=1}^{n} C_i A_i}{\sum_{i=1}^{n} A_i}$, and determine the weighted runoff coefficient for pre-developed conditions:

$$C_w = \frac{5(0.20)+15(025)}{20} = 0.238$$

2. Use the equation, $C_w = \frac{\sum_{i=1}^{n} C_i A_i}{\sum_{i=1}^{n} A_i}$, and determine the weighted runoff coefficient for post-developed conditions:

$$C_w = \frac{0.5(0.20)+1.5(0.25)+1.5(0.90)+16.5(0.40)}{20} = 0.421$$

3. Utilize Figure 5.1 to determine the rainfall intensity, I, for a 10-year recurrence interval for the pre- and post-developed conditions:

   i_{10pre} = 3.6 in./hr (10.7 cm/hr)
   i_{10post} = 4.2 in./hr (9.1 cm/hr)

4. Utilize the rational equation, $Q = C\ i\ A$, and determine the peak 10-year runoff for the pre-developed conditions:

   $Q = 0.238(3.6)(20) = 17.1\ cfs$ (0.5 cms)

5. Utilize the rational equation, $Q = C\ i\ A$, to determine the peak 10-year runoff for the post-developed condition:

   $Q = 0.421(4.2)(20) = 35.4\ cfs$ (1.0 cms)

The proposed land development results in the doubling of the peak discharge from the parcel, primarily because land development typically increases the imperviousness of the land. This creates an effect by increasing the proportion of runoff that travels overland, as evidenced by the rational equation and the increased runoff coefficient value. The land use conversion also increased the time of concentration, which resulted in an increase in the rainfall intensity.

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