6.0 Introduction

This chapter summarizes methodology for determining rainfall and runoff information for the design of stormwater management facilities in the City. The methodology is based on the procedures presented in the UDFCD Manual in the Rainfall and Runoff sections. The design procedures outlined in the UDFCD Manual, supplemented by the information provided in this section, apply to all projects in the City.

6.0.1 Stormwater Quality Considerations. One of the most significant impacts of urbanization is the increase in peak flow rates, runoff volumes, and frequency of runoff from impervious areas. This increase in runoff can lead to severe stream erosion, habitat disruption, and increased pollutant loading. At the same time, with proper planning, the increased runoff volumes can be managed to create or supplement existing wetland areas or riparian habitats, which may provide significant benefits to the watershed. The increase in runoff from development is especially pronounced when drainage systems are designed to quickly and “efficiently” convey runoff off paved areas and roofs directly into inlets and storm sewers, discharging eventually into drainageways that are typically designed to convey flows at maximum acceptable velocities. Whether for one site or for a whole watershed, this increase in runoff and acceleration of flood peaks is reflected accurately by the hydrologic methods discussed herein.

As discussed in Chapter 14, Stormwater Quality, effective stormwater management today seeks to disconnect impervious surfaces, slow down flows, and convey runoff over vegetated ground surfaces, leading to filtering, infiltration, and attenuation of flows. These principles can also be reflected in the hydrologic variables discussed in this chapter, yielding longer times of concentration and reduced peak runoff. Specifically, Section 6.6 provides design guidance to account for the hydrologic effects of minimizing directly connected impervious areas.

6.1 Design Rainfall

Rainfall data to be used in the City of Centennial is based on the *National Oceanic and Atmospheric Administration Precipitation-Frequency Atlas of the Western United States, Volume III-Colorado* (NOAA Atlas), published in 1973. Precipitation depth maps shown in the NOAA Atlas were used to determine representative 1-hour and 6-hour point rainfall values for the City. Following the guidelines in the NOAA Atlas, these point values were used to develop 2-hour and 3-hour values as well as the intensity-duration curves for use in the City. The Rainfall chapter of the UDFCD Manual provides additional discussion on the use of rainfall data obtained from the NOAA Atlas.

6.1.1 One-hour Rainfall. There is very little variation in the NOAA Atlas isopluvial (equal precipitation depth) map within the City of Centennial; therefore, one set of one hour design point rainfall values, indicated in Table 6-1, applies to the City.

TABLE 6-1
1-HOUR POINT RAINFALL VALUES
FOR THE CITY OF CENTENNIAL (INCHES)

2- YR	5-YR	10-YR	50-YR	100-YR
0.97	1.38	1.65	2.32	2.67

The one-hour rainfall depths are the basis of the City's intensity-duration rainfall curves and are used to formulate design storm distributions.

6.1.2 Intensity-Duration Curves. Rainfall intensity-duration curves based on storm duration for a variety of storm return periods can be found on Figure 6-1 at the end of this chapter. These curves were developed using distribution factors provided in the NOAA Atlas and also provided in Table RA-4 of the UDFCD Manual.

6.1.3 Six-hour Rainfall. In order to use the Colorado Urban Hydrograph Procedure (CUHP), 2-, 3- or 6-hour rainfall distributions are required, depending on watershed area. Table RA-1 in the UDFCD Manual summarizes storm durations, area adjustments, and incremental rainfall depths to be used in CUHP based on watershed area. The UD-Raincurve Spreadsheet included in the UDFCD Manual shall be used to generate the rainfall distribution curves necessary for a CUHP model. In order to generate these distribution curves, the 1-hour and 6-hour rainfall depths for the design return periods are necessary. . The 1-hour point values can be found in Table 6-1 of this chapter. The 6-hour point values are as follows:

TABLE 6-2
6-HOUR POINT RAINFALL VALUES
FOR THE CITY OF CENTENNIAL (INCHES)

2- YR	5-YR	10-YR	50-YR	100-YR
1.4	1.9	2.2	3.0	3.4

The UD-Raincurve spreadsheet shall be used for all portions of the City, including non-urban areas. Once the rainfall distribution curves are generated using the District's UD-Raincurve Spreadsheet, the CUHP model is to be set up following the procedures provided in the "Runoff" chapter of the UDFCD Manual.

6.2 Selecting a Method to Estimate Runoff

Two primary methods for estimating storm runoff, peak flow rates and total volumes are used in the City.

- Rational Method
- CUHP/UDSWMM

The Rational Method is a simpler approach generally used for smaller sub-watersheds where hydrograph information is not required. CUHP and UDSWMM are computer models that are typically run sequentially; CUHP generates runoff hydrographs from individual subwatersheds and UDSWMM combines and routes individual hydrographs through channels and detention basins. Additional information on the CUHP and UDSWMM computer programs is provided in the UDFCD Manual.

Table 6-3 compares the Rational Method with CUHP/UDSWMM and provides information useful for selecting one of the approaches for a particular project. Additional information on each method is provided in Sections 6.3 and 6.4.

TABLE 6-3
COMPARISON OF HYDROLOGICAL METHODS

	Is the Rational Method Applicable?	**Is CUHP/UDSWMM Applicable?**
Hydrologic Information Desired:		
Runoff peak discharge.	Yes	Yes
Combining peak flows from separate sub-watersheds.	Yes	Yes
Runoff volume (V=I*A*Duration).	Yes	Yes
Runoff hydrograph.	No	Yes
Watershed Size (Acres)[1]		
0 to 5	Yes	No
5 to 90	Yes	Yes[2]
90 to 160	Yes	Yes
160 to 3,000	No	Yes
Greater than 3,000	No	Yes

[1] Subdividing watersheds into smaller sub-watersheds may be desirable to obtain runoff information at multiple design points or to accurately model areas of different character. The maximum sub-watershed size shall be approximately 130-acres in accordance with UDFCD master planning guidance. Methods to combine flows from individual sub-watersheds are discussed in Sections 6.3 and 6.4.
[2] Time of concentration must be estimated and entered into CUHP.

As shown Table 6-3, either the Rational Method or CUHP/UDSWMM may be used for watershed sizes from 5- to 160-acres. The following considerations may direct the user to one or the other of these methods.

- If no detention facilities are planned or if detention facilities are to be sized using simplified methods shown in Chapter 13, hydrograph information is not required and the Rational Method would be the simpler of the two methods.
- If detention facilities are to be sized based on hydrograph routing, or if hydrograph information is desired for any other reason, CUHP/UDSWMM must be used.
- If more detailed information on time to peak, duration of flow, rainfall losses, or infiltration is desired, CUHP/UDSWMM offers this information.

Regardless of the method used, the maximum sub-watershed size shall be approximately 130-acres in accordance with UDFCD master planning guidelines. This is to reduce discrepancies in peak flow predictions between master plan hydrology and flow estimates based on single sub-watersheds significantly larger than 130-acres.

6.3 Rational Method

The Rational Method is used to determine runoff peak discharges for watersheds up to 160-acres in size (see Table 6-3). Sections 2.2 and 2.3 in the Runoff chapter of the UDFCD Manual provide detailed explanations of the Rational Method, assumptions behind its use and its limitations.

All Rational Method design calculations for projects in the City of Centennial shall be completed using Standard Form 2 (SF-2) and Standard Form 3 (SF-3) which are located at the end of this chapter as Figure 6-2 and Figure 6-3, respectively. The UD-Rational spreadsheet or the UDSEWER software can also be used to complete Rational Method calculations and can be found at the UDFCD website, www.udfcd.org. The SF-3 form is used to estimate accumulated peak discharges from multiple basins as storm runoff flows downstream in a channel or pipe. Results from the Rational Method calculations shall be included with the drainage report submittal.

6.3.1 Rational Method Equation. The Rational Method is based on the direct relationship between rainfall and runoff, and is expressed by the following equation:

$$Q = CIA$$

In which:

Q = the maximum rate of runoff (cubic feet per second [cfs])

C = the runoff coefficient that is the ratio between the runoff volume from an area and the average rainfall depth over a given duration for that area

I = the average intensity of rainfall for a duration equal to the time of concentration (inches/hour)

A = basin area (acres)

6.3.2 Time of Concentration (t_c). The time of concentration, used to determine the average intensity of rainfall, is equivalent to the amount of time needed for runoff to travel from the most remote point of the basin to the design point. The time of concentration consists of two components, the initial or overland flow time "t_i" (usually as sheet flow) and the time of travel "t_t" in a concentrated form (i.e., in a storm sewer, gutter, swale, channel, etc.). The time of concentration is summarized by the following equation:

$$t_c = t_i + t_t$$

In which:

t_c = time of concentration (minutes)
t_i = overland flow time (minutes)
t_t = travel time in the ditch, channel, gutter, storm sewer, etc. (minutes)

The specific parameters and equations for calculating the overland travel time (t_i) and the channelized travel time (t_t) are provided in the UDFCD Manual. For an urbanized catchment, the time of concentration shall not exceed the value determined from equation RO-5 in the UDFCD Manual. The minimum time of concentration is as follows:

t_c *(min)* = 5 minutes for urbanized watersheds
t_c *(min)* = 10 minutes for non-urban watersheds

A common error in estimating the time of concentration occurs when a designer does not check the peak runoff generated from smaller portions of the catchment that may have a significantly shorter time of concentration (and a higher intensity) than the watershed as a whole. Sometimes calculations using the Rational Method for a lower, urbanized portion of a watershed will produce a higher peak runoff than the calculations for the watershed as a whole, especially if the watershed is long or the upper portion has little or no impervious cover. UDSEWER software checks for these eventualities as long as the sub-catchment is properly subdivided.

The Rational Method can be used for estimating peak runoff rates for multiple design points. The time of concentration for a downstream design point is calculated by adding the travel times from the previous design point to the time of concentration for the previous point. This cumulative relationship is represented by the following equation:

$$t_{cn} = t_{c1} + t_{t2} + \ldots + t_{tn}$$

In which:

t_{cn} = total time of concentration at the design point of the n^{th} subwatershed area
t_{c1} = time of concentration at the design point of the first subwatershed area
t_{t2} = travel time from the design point of the first subwatershed area to the design point of the second subwatershed area.
t_{tn} = travel time from the design point of the n-1 subwatershed area to the design point of n^{th} subwatershed area

6.3.3 Rainfall Intensity (I). The average rainfall intensity (I), in inches per hour, for a storm duration equal to the time of concentration for the City of Centennial can be found in Figure 6-1. Once the time of concentration has been calculated, the rainfall intensity can be read from the intensity-duration curve and then used in the Rational Method equation.

6.3.4 Runoff Coefficient (C). The runoff coefficient represents the integrated effects of infiltration, detention storage, evaporation, retention, flow routing, and interception, all of which affect the time distribution and peak rate of runoff. Runoff coefficients are based on the imperviousness of a particular land use and the hydrologic soil type of the area and are to be selected in accordance with the information shown in Section 2.7 of the Runoff chapter in the UDFCD Manual. The procedure is as follows:

1. Categorize the site area into one or more similar land uses, each with a representative imperviousness, according to the information in Table RO-3.
2. Find the percent imperviousness for single-family residential developments using Figures RO-3 through RO-5.
3. Based on the dominant hydrologic soil type in the area, use Figures RO-6 through RO-8 or Table RO-5 to estimate the runoff coefficient for the particular land use category for the design storms of interest.
4. Calculate an area-weighted average runoff coefficient for the site based on the runoff coefficients from individual land use areas of the site.

Runoff coefficients for the 5-year and smaller storms may be reduced for sites that incorporate grass buffers and swales to minimize directly connected impervious area (MDCIA), as described in Volume 3 of the UDFCD Manual. See Section 6.6 for additional information.

When analyzing an area for design purposes, urbanization of the full watershed, including both onsite and off-site areas, shall be assumed. See Section 6.7 for further discussion.

Weighted runoff coefficients are not acceptable in single land use areas, such as commercial or single family residential areas. In single land use areas, the landscaping and the impervious areas cannot be separated and a new weighted coefficient calculated. Only the accepted values for individual land use classifications can be used, even if they appear to be on the high side for a given situation.

All weighted runoff coefficient calculations for projects in the City shall be completed using the UD-Rational spreadsheet provided with the UDFCD Manual.

There are some circumstances where the selection of impervious percentage values may require additional investigation due to unique land characteristics (i.e. recent burn areas). When these circumstances arise, it is the designer's responsibility to verify that the correct land use assumptions are made.

6.3.5 Basin Area (A). The size of a sub-watershed contributing runoff to a design point, in acres, is used to calculate peak runoff in the Rational Method. The area may be determined through the use of planimetric-topographic maps, supplemented by field surveys where topographic data has changed or where the contour interval is too great to distinguish the direction of flow. The drainage basin lines are determined by the pavement slopes, locations of downspouts and inlets, paved and unpaved yards, grading of lawns, and many other features found on the urban landscape.

6.4 CUHP/UDSWMM

6.4.1 CUHP. The Colorado Urban Hydrograph Procedure (CUHP) is a hydrologic analysis method based upon the Snyder's unit hydrograph principle. It has been calibrated by UDFCD for this region using local simulations of rainfall-runoff data collected over an eight-year period in the 1970's. Table 6-3 provides information to help the designer determine if CUHP is appropriate for a particular project and watershed area.

Procedures, assumptions, and equations used for a CUHP computer model shall conform to the protocols described in the Runoff Chapter of the UDFCD Manual. The CUHP program users' manual (distributed by UDFCD) may also be used for reference.

6.4.2 UDSWMM. UDSWMM is used to route the hydrographs generated by CUHP through conveyance and storage facilities located within a drainage basin. Large watersheds may be divided into smaller sub-watersheds that contain a number of different conveyance and storage elements. UDSWMM will add and combine the hydrographs from sub-watersheds and conveyance elements as the flow proceeds downstream. The UDFCD Manual may be used as a reference for this software and the latest version of UDSWMM may be downloaded from the UDFCD website, www.udfcd.org.

6.5 Other Hydrologic Methods

6.5.1 Published Hydrologic Information. The UDFCD has prepared Major Drainageway Planning Reports, Outfall Systems Planning Reports and/or Flood Hazard Area Delineation Reports that contain hydrologic studies for most of the major drainageways and watersheds within the UDFCD boundaries. These reports contain information regarding peak flow and runoff volume from the 2-year through 100-year storm events at numerous design points within the study watersheds. These studies, available at the UDFCD, contain information about watershed and sub-watershed boundaries, soil types, percent imperviousness, and rainfall. If there are published flow rate values available from the UDFCD for any drainageway of interest, these values shall be used for design unless there are compelling reasons to use other values or approaches. Use of other values shall be approved in writing by SEMSWA in advance of any related design work.

Published hydrologic information for major drainageways can also be found in Federal Emergency Management Agency (FEMA) Flood Insurance Studies (FIS). For all FEMA related projects, the FEMA hydrologic data shall be consulted. Flow rates published in FEMA FIS studies typically represent existing conditions at the time the study was completed and generally do not incorporate any future development. SEMSWA's policy is to analyze and design stormwater facilities based on future development flow rates; therefore, FEMA flow rates shall not be used for design without the written approval of SEMSWA.

6.5.2 Statistical Methods. In some situations, statistical analysis of measured stream flow data provides an acceptable means of determining design runoff rates. Statistical analyses are to be limited to drainageways with a long period of flow data (30-year minimum) that had no significant changes occur in land-uses within the tributary watershed during the flow record. Statistical methods may be useful in calibrating a hydrologic model for existing development conditions, but are not suited for estimating the flow for expected future watershed development conditions.

6.5.3 Retention Volume. In order to calculate an appropriate storage volume for a basin designed to retain the 100-year runoff, the 24-hour rainfall depth is to be used. These data may be found in the maps provided in the Colorado NOAA Atlas.

6.6 Runoff Reduction Associated with Minimizing Directly Connected Impervious Area

Imperviousness and runoff coefficients for the 5-year and smaller, more frequent storms may be reduced for sites that incorporate grass buffers and swales to minimize directly connected impervious area, as described in Volume 3 of the UDFCD Manual. Figure ND-1 may be used to estimate a reduced impervious value for practices that qualify for Level 1 or 2 minimizing directly connected impervious area. The reduced impervious value may be used to estimate applicable runoff coefficients for 5-year and smaller storms (see Section 6.3.4). The reduced imperviousness may also be used to calculate Water Quality Capture Volume for stormwater quality facilities (discussed in Chapter 14). Depending on the amount of imperviousness of a site, Level 2 minimizing directly connected impervious area may reduce imperviousness by as much as half.

6.7 Design Hydrology Based on Future Development Conditions

6.7.1 On-site Flow Analysis. Full site development shall be considered when the design engineer selects runoff coefficients or impervious percentage values and performs the hydrologic analyses for on-site areas. Changes in flow patterns and sub-basin boundaries due to site grading and proposed street and roadway locations must be considered. Time of concentration calculations must reflect increased surface flow velocities and velocities associated with proposed runoff conveyance facilities.

6.7.2 Off-site Flow Analysis. Fully developed conditions shall be considered when the design engineer selects runoff coefficients or impervious percentage values and performs the hydrologic analyses for off-site areas. Where the off-site area is undeveloped, fully developed conditions shall be projected using the best available land use information, current zoning information, or approved land use applications. SEMSWA shall be consulted to verify all assumptions regarding future development in off-site areas. If information is not available, runoff calculations shall be based on the impervious percentage value presented in Table RO-3, found in the Runoff chapter of UDFCD Manual Volume 1, for off-site flow analysis.

Where the off-site area is full or partially developed, the hydrologic analysis shall be based on existing platted land uses, constructed conveyance facilities, and developed topographic characteristics. Consideration of potential benefits related to detention provided in off-site areas depends on the type of detention provided and whether or not the off-site tributary area is part of a major drainageway basin, as discussed in Section 6.8 of this chapter.

6.8 Consideration of Detention Benefits in Off-Site Flow Analysis

6.8.1 Major Drainageway Basin Distinction. When determining whether on-site detention benefits may be recognized in off-site flow analysis, a distinction is made between systems that are a part of the major drainageway basin system (generally greater than 130-acres of tributary area) and for those that are higher upstream in the watershed (generally less than 130-acres of tributary area), and are not considered a part of the major drainageway basin system.

6.8.2 Analysis when System is Part of a Major Drainageway Basin. When determining minor storm event peak flow rates from off-site areas, no benefit shall be recognized for detention in the off-site areas.

For determination of peak flow rates from the major storm event and other less frequent events, no benefit shall be recognized for on-site detention in the off-site areas. While the smaller on-site detention ponds provide some benefit immediately downstream, it has been shown that the benefit diminishes as the number of relatively small ponds increases with the accumulation of more tributary area. It has been suggested that there may be very little benefit along the major drainageway when numerous on-site detention ponds are provided in the upstream watershed. The technical paper, “Potential Effectiveness of Detention Policies”, by Ben Urbonas and Mark Glidden, provides more information regarding this subject. The paper is available on-line at www.udfcd.org.

For determination of peak flow rates from the major storm event and other less frequent events, the benefits provided by constructed, publicly operated and maintained, regional detention facilities in the off-site areas may be recognized, if approved by SEMSWA. On-site and regional detention facilities are discussed in more detail in Chapter 13, Storage.

Conveyance of runoff along major drainageway basins is also subject to the additional requirements outlined in Section 6.8.4.

6.8.3 Analysis when System is not a Part of a Major Drainageway Basin. When determining minor storm event peak flow rates from off-site areas, no benefit shall be recognized for detention in the off-site areas.

For determination of peak flow rates from the major storm event and other less frequent events, runoff may be calculated assuming historic runoff rates computed in accordance with procedures outlined in Chapter 13, if the off-site area is undeveloped. Benefits of constructed and SEMSWA accepted on-site detention facilities in the off-site area can be recognized if the off-site area is partially or fully developed.

6.8.4 Analysis when System is a Part of a Master-Planned Regional Detention Drainageway Basin. In areas where there is a master-planned regional drainage system, with regional detention facilities, the outfall collector systems are typically designed for the future, fully developed flow rates from the major storm event. On-site detention is not necessary in this situation. The analysis of off-site flows in these areas must conform with the approved master plan for the drainage basin, and must consider the status and design requirements of the future and existing outfall collector systems within the project area.

FIGURE 6-1
RAINFALL INTENSITY-DURATION CURVE
CITY OF CENTENNIAL, COLORADO

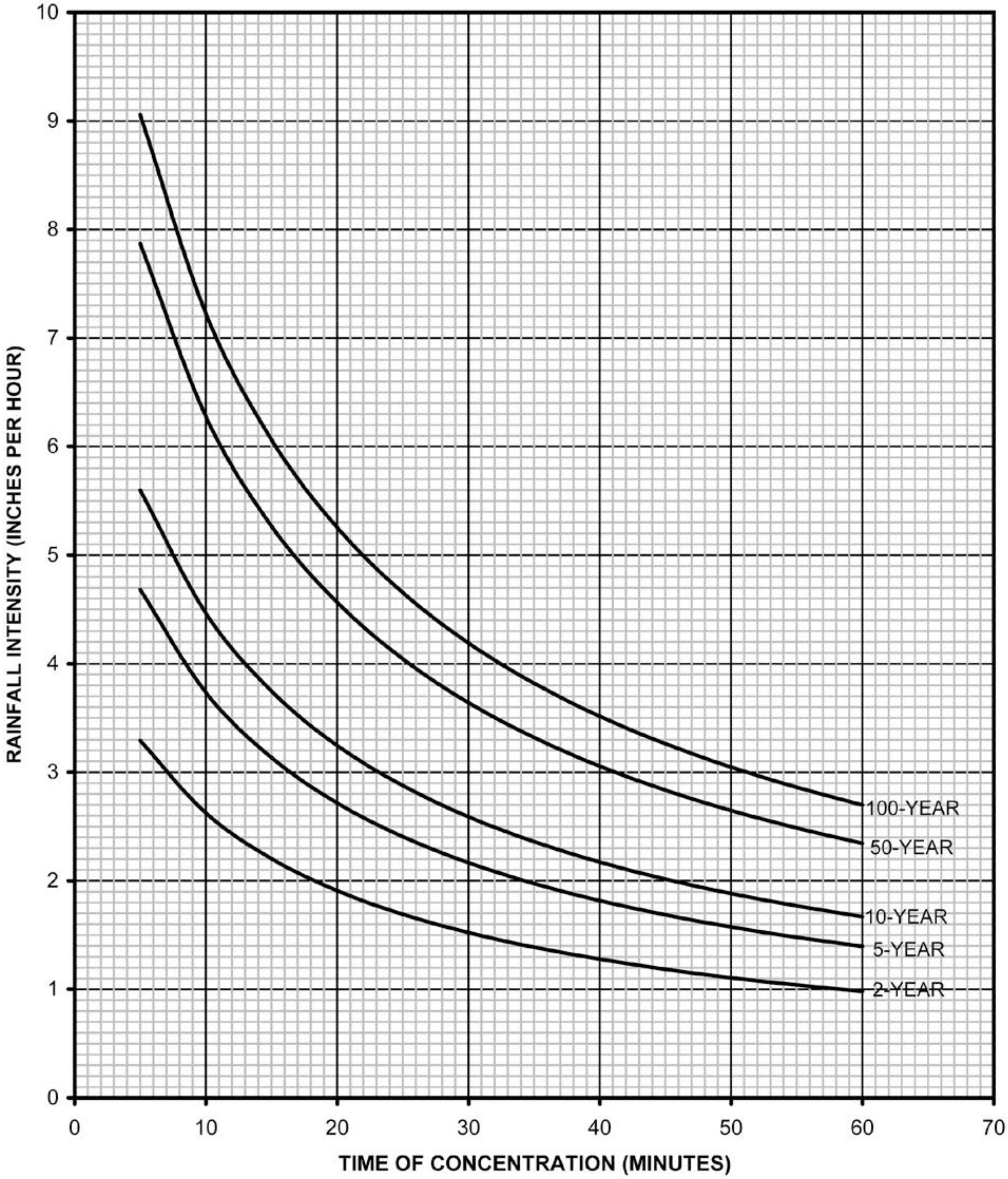

FIGURE 6-2
STANDARD SF-2 FORM

STANDARD FORM SF-2
TIME OF CONCENTRATION

DEVELOPMENT ____________________

CALCULATED BY ________ DATE ________

SUB-BASIN DATA			TIME OF CONCENTRATION ESTIMATE								MINIMUM T_C IN URBAN AREAS			FINAL Tc	REMARKS
			INITIAL/OVERLAND TIME (Ti)			TRAVEL TIME (Tt)					Tc CHECK (urbanized basins)				
DESIG: (1)	AREA Ac (2)	C5 (3)	LENGTH Ft (4)	SLOPE % (5)	Ti Min (6)	LENGTH Ft (7)	SLOPE % (8)	VEL Ft/Sec (9)	Tt Min (10)	Tc Min (11)	COMP. Tc (12)	TOTAL LENGTH Ft (13)	Tc(urban) Min (14)	Min (15)	

FIGURE 6-3
STANDARD SF-3 FORM

STANDARD FORM SF-3
STORM DRAINAGE SYSTEM DESIGN
(RATIONAL METHOD PROCEDURE)

CALCULATED BY: ________
DATE: ________

JOB #: ________
PROJECT: ________
DESIGN STORM: ________

		DIRECT RUNOFF							TOTAL RUNOFF				STREET		PIPE			TRAVEL TIME					
STREET	DESIGN POINT	AREA DESIGN.	AREA (Ac)	COEFF C	Tc (min)	C*A (Ac)	I	Q (CFS)	Tc (min)	Sum C*A (Ac)	I (In/Hr)	Q (CFS)	Slope (%)	Street Q (CFS)	Design Q (CFS)	Slope (%)	PIPE SIZE	L (Ft)	VEL (Ft/Sec)	Tt (min)	Q add'l	Q tot	REMARKS
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)			(22)