Chapter 5
Rainfall

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1.0 Overview

The purpose of this chapter is to provide rainfall depth, duration, intensity, and frequency data and analytical methods used to develop the rainfall information needed to carry out the hydrological analyses described in the *Runoff* chapter of the Urban Storm Drainage Criteria Manual (USDCM). Specifically, this chapter describes:

- The basis of point precipitation values for locations within the Urban Drainage and Flood Control District (UDFCD),
- Temporal distributions of point rainfall to develop the hyetographs necessary for the Colorado Urban Hydrograph Procedure (CUHP) hydrological modeling, and
- Intensity-duration-frequency (IDF) data and relationships used in Rational Method hydrologic computations.

This chapter includes analysis of the 2-, 5-, 10-, 25-, 50-, 100-, and 500-year return storm events. If information is needed regarding other storm return periods or for areas in Colorado but outside UDFCD, the reader is directed to NOAA Atlas 14 Precipitation-Frequency Atlas of the United States, Volume 8 Version 2.0 (NOAA Atlas 14) published by the National Oceanic and Atmospheric Administration (NOAA) in 2013, which contains a more complete description of rainfall analysis in the State of Colorado.

History of the Rainfall Chapter

The USDCM that was originally published in 1969 contained rainfall depth-duration-frequency maps for the 2-, 10-, and 100-year events and guidelines for developing design rainstorms and I-D-F curves for any location within UDFCD. The NOAA Atlas 2, Volume III, published in 1973, was based on a longer period of record and a large number of gages. Unfortunately, the maps in the USDCM and the NOAA Atlas did not agree.

Since 1977 UDFCD has studied the rainfall and runoff relationships in the Denver metropolitan area, including analysis of the (then) 73-year period at the Denver rain gage. This analysis indicated that the NOAA Atlas 2 maps, although not perfect, were more in line with the rainfall frequency distribution of the long-term record than the maps in the original USDCM.

As the 1982 version of CUHP was being developed, UDFCD developed methods to convert the information in the NOAA Atlas 2 into a family of design rainstorms by distributing these design storms in a manner that yielded peak runoff recurrence frequency distributions consistent with observed rainfall-runoff characteristics in the Denver metropolitan area. For the above-stated reasons and to use rainfall information consistent with the information being used by the State of Colorado, it was concluded that the NOAA Atlas 2 rainfall information should also be used within UDFCD.

In 2013, the new *NOAA Atlas 14 Precipitation-Frequency Atlas of the United States, Volume 8-Midwestern States* was published with new precipitation values. UDFCD provided peer review of NOAA's work. In 2016, UDFCD used *NOAA Atlas 14* values in a CUHP recalibration effort and decided to adopt the new values at that time.

2.0 Rainfall Depth-Duration-Frequency

To apply CUHP or the Rational Method as outlined in the *Runoff* Chapter, 1-hour point rainfall data for the area of interest are needed. To apply CUHP to watersheds larger than 15-square miles in size, 3-hour and 6-hour point rainfall depths are also required.

2.1 Rainfall Depth-Duration-Frequency

Access NOAA Atlas 14 at http://hdsc.nws.noaa.gov/hdsc/pfds/ to obtain rainfall depth-duration-frequency values for the UDFCD region. The website includes durations of 5, 10, 15, 30, and 60 minutes as well as 2, 3, 6, 12, and 24 hours. It also includes several durations from 2 to 60 days. Recurrence intervals included in the new Atlas include intervals of 1, 2, 5, 10, 25, 50, 100, 200, 500, and 1000 years. New with the Atlas 14 update, 2-hour and 3-hour depths are now provided. Previous versions of this manual provided equations to calculate these depths based on the 1-hour and 6-hour depths. These equations are still used in CUHP to calculate the third hour of the 3-hour temporal distribution as described in Section 3.1.

3.0 Design Storm Distribution for CUHP

The 1-hour point precipitation values from NOAA Atlas 14 are distributed into 5-minute increments (see Table 5-2) to develop temporal distributions for use with CUHP. The rainfall duration used with CUHP varies with the size of the watershed being analyzed as shown in Table 5-1. For larger storms, Depth Reduction Factors (DRFs)[1] are applied to the incremental precipitation depths to take into account averaging effects for larger watershed sizes. For the 2-, 5-, and 10-year events (minor events), DRFs can be applied to watersheds 2-square miles or larger. For the 25-, 50-, 100-, and 500-year events, DRFs are applicable to watersheds 15-square miles and larger. Table 5-1 provides design storm durations and applicability of DRFs based on watershed area.

Table 5-1. Storm duration and area adjustment for CUHP modeling

Design Storm	Watershed Area (square miles)	Recommended Storm Duration	Apply DRF?
2-, 5-, and 10-Year	$A \leq 2.0$	2 hours	No
	$2.0 < A < 15.0$	2 hours	Yes – Use Table 5-3
	$A \geq 15.0$	6 hours	Yes – Use Table 5-3
25-, 50-, 100-, and 500-Year	$A < 15.0$	2 hours	No
	$A \geq 15.0$	6 hours	Yes – Use Table 5-4

[1] The term Depth Reduction Factor (DRF) is used in this text but is interchangeable with the terms Depth Area Reduction Factor (DARF) and Area Reduction Factor (ARF) used by others.

3.1 Temporal Distribution

The current version of CUHP was designed to be used with the 1-hour rainfall depths from NOAA Atlas 14. To obtain a temporal distribution for a design storm, the 1-hour depth is converted into a 2-hour design storm by multiplying the 1-hour depth(s) by the percentages for each time increment given in Table 5-2. This conversion is handled automatically in CUHP for the 1-hour depth specified in the CUHP input file.

The temporal distribution presented in Table 5-2 represents a design storm for use with a distributed rainfall-runoff routing model. The distribution is the result of a calibration process performed by UDFCD to provide, in conjunction with the use of CUHP, peak runoff rates and runoff volumes of the same return period as the design storm (Urbonas 1978). The 1-hour values are “embedded” in the 2-hour and other duration design storms. The first hour of the rainfall distribution includes the most intense rainfall (25% of the 1-hour point rainfall depth is assumed to occur over a 5-minute period). The 2-hour precipitation total is approximately 116% of the 1-hour rainfall depth for all recurrence intervals included in this chapter, as shown in the totals at the bottom of Table 5-2. It should be noted that the 2-hour point rainfall depth provided in the NOAA Atlas may differ slightly from the summation of the incremental depths from the 2-hour distribution in CUHP.

CUHP prepares a temporal distribution of the Design Rainfall for the 2-, 5-, 10-, 25-, 50-, 100- and 500-yr events within the UDFCD boundary including depth reduction factors (DRFs) for use with SWMM modeling. CUHP may provide slightly different results for the rainfall distribution than the procedure outlined in this chapter due to a smoothing method implemented in the programming which eliminates potential dips in the hyetograph.

To develop the temporal distribution for the 6-hour design storm (watersheds greater than 15.0 square miles), first prepare a 3-hour design storm. Developing the 3-hour storm is an intermediate step in deriving the 6-hour temporal distribution. To develop the temporal distribution for the 3-hour design storm, first prepare the 2-hour design storm distribution using the 1-hour storm point precipitation and the temporal percentage distribution shown in Table 5-2. The 2-hour distribution provides the first two hours of the 3-hour design storm. The difference between the 3-hour point precipitation and the 2-hour point precipitation is then distributed evenly over the third hour of the storm (i.e., the period of 125 minutes to 180 minutes). It should be noted that CUHP uses equations derived from NOAA Atlas 2, Volume III (1973) to calculate the difference between the 3-hour and 2-hour point precipitation values. For this reason, the values used by CUHP may not match the published values in NOAA Atlas 14.

The 3-hour distribution provides the first three hours of the 6-hour design storm. The difference between the 6-hour point precipitation (provided on the NOAA website) and the 3-hour point precipitation (calculated by summation of the incremental depths from the 3-hour distribution) is distributed evenly over the period of 185 minutes to 360 minutes (i.e. the last three hours of the 6-hour design storm).

Basis for Design Storm Distribution

The orographic effects of the Rocky Mountains and the high plains near the mountains as well as the semi-arid climate influence rainfall patterns in the Denver area. Rainstorms often have an “upslope” character where the easterly flow of moisture settles against the mountains. These types of rainstorms have durations that can exceed six hours and, although they may produce large amounts of total precipitation, they are rarely intense. Although upslope storms may cause local drainage problems or affect the flood levels of large watersheds, typically they are not the cause of 2- through 100-year type of flooding of small urban catchments in the Denver area.

Very intense rainfall in the Denver area typically results from convective storms or frontal stimulated convective storms. The most intense periods of rainfall for these types of storms often occur in periods that are less than one or two hours. These storms can produce brief periods of very high rainfall intensities. These short-duration, high-intensity rainstorms cause most of the flooding problems in the great majority of urban catchments.

Analysis of a 73-year record of rainfall at the Denver rain gage revealed that an overwhelming majority of the intense rainstorms produced their greatest intensities in the first hour of the storm. In fact, of the 73 most intense storms analyzed, 68 had the most intense period begin and end within the first hour of the storm, and 52 had the most intense period begin and end within the first half hour of the storm. These types of storms have been categorized as “leading intensity” storm events. The data clearly show that the “leading intensity” storms predominate among the “non-upslope” type storms in the Denver region.

The recommended design storm distribution takes into account the observed “leading intensity” nature of the convective storms. In addition, the temporal distributions for the recommended design storms were designed to be used with CUHP (1982 and later), the published NOAA 1-hour precipitation values (NOAA 1973) and Horton’s infiltration loss equation. They were developed to approximate the recurrence frequency of peak flows and runoff volumes (i.e., 2- through 100-years) that were found to exist for the watersheds for which rainfall-runoff data were collected. The procedure for the development of these design storm distributions and the preliminary results were reported in literature and UDFCD publications (Urbonas 1978; Urbonas 1979).

Table 5-2. Design storm distributions of 1-hour precipitation

Time	Percent of 1-hour precipitation depth (%)				
Minutes	2-Year	5-Year	10-Year	25- and 50-Year	100- and 500-Year
5	2.0	2.0	2.0	1.3	1.0
10	4.0	3.7	3.7	3.5	3.0
15	8.4	8.7	8.2	5.0	4.6
20	16.0	15.3	15.0	8.0	8.0
25	25.0	25.0	25.0	15.0	14.0
30	14.0	13.0	12.0	25.0	25.0
35	6.3	5.8	5.6	12.0	14.0
40	5.0	4.4	4.3	8.0	8.0
45	3.0	3.6	3.8	5.0	6.2
50	3.0	3.6	3.2	5.0	5.0
55	3.0	3.0	3.2	3.2	4.0
60	3.0	3.0	3.2	3.2	4.0
65	3.0	3.0	3.2	3.2	4.0
70	2.0	3.0	3.2	2.4	2.0
75	2.0	2.5	3.2	2.4	2.0
80	2.0	2.2	2.5	1.8	1.2
85	2.0	2.2	1.9	1.8	1.2
90	2.0	2.2	1.9	1.4	1.2
95	2.0	2.2	1.9	1.4	1.2
100	2.0	1.5	1.9	1.4	1.2
105	2.0	1.5	1.9	1.4	1.2
110	2.0	1.5	1.9	1.4	1.2
115	1.0	1.5	1.7	1.4	1.2
120	1.0	1.3	1.3	1.4	1.2
Totals	115.7%	115.7%	115.7%	115.6%	115.6%

3.2 Depth Reduction Factor (DRF) Adjustments

A Depth Reduction Factor (DRF) adjustment can be used when applying a point precipitation value to an entire watershed area for a given recurrence interval. Since average rainfall over a large watershed is generally lower than point rainfall, a DRF is applied to reduce point precipitation values to area-average precipitation values. The NOAA Atlas provides guidelines for adjusting the rainfall depths with increasing catchment area. These guidelines were provided in NOAA Altas 2, Volume III and did not change with the release of NOAA Atlas 14. Area-depth adjustments are given in the Atlas for durations of ½-, 1-, 3-, 6- and 24-hours. Figure 5-1 is based on the NOAA Atlas. The 15-minute curve was extrapolated by UDFCD from the information shown for other storm durations on Figure 5-1. The fast response times of urbanized watersheds and sharp rainstorm distribution gradients in the UDFCD region require adjustments of rainfall depths for storm durations that are less than ½-hour. Figure 5-1 provides DRF curves that can be applied to the 25-, 50-, 100- and 500-year events (NOAA 1973).

For more-frequently occurring storm events, including the 2- through 10-year events, UDFCD analyzed results from a 2010 study conducted by Carlton Engineering, Inc. on behalf of the City of Colorado Springs *Fountain Creek Rainfall Characterization Study* (Carlton 2010). The Carlton study developed cell-centered DRFs[2] based on extensive analysis of radar data in the Fountain Creek watershed. UDFCD analyzed the data provided in this report to develop geographically-fixed DRF estimates for the 2- through 10-year events, by averaging recommended DRFs from the Carlton report and the NOAA Atlas. Figure 5-2 provides these curves.

The DRF adjustment factors are provided in Table 5-3 (2-, 5-, and 10-year design storms) and Table 5-4 (25-, 50-, 100, and 500-year design storms) to assist with DRF calculations.

[2] DRFs are commonly classified as “cell-centered” or “geographically-fixed” depending on how the factors were developed. Cell-centered DRFs are determined by analyzing gridded storm-cell data to determine the ratio of the average depth of rainfall produced by the overall storm cell (average of all grid point depths) to the maximum point rainfall depth (maximum grid point depth). A geographically-fixed DRF represents the ratio of average precipitation of a geographic area (watershed) to the maximum point rainfall depth occurring in the watershed. The difference between the two is the point of reference. For a cell-centered DRF, the point of reference is the storm cell itself, which may pass over many watersheds along the storm track. For a geographically-fixed DRF, the point of reference is the watershed, which receives precipitation as a storm cell passes over the watershed.

Table 5-3. DRFs for design rainfall distributions 2-, 5-, and 10-year design rainfall

Time (minutes)	Correction Factor by Watershed Area in Square Miles[1]								
	2	5	10	15	20	30	40	50	75
5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
15	1.00	0.97	0.94	0.91	0.90	0.85	0.75	0.65	0.56
20	1.00	0.86	0.75	0.68	0.61	0.55	0.48	0.42	0.35
25	1.00	0.86	0.75	0.68	0.61	0.55	0.48	0.42	0.35
30	1.00	0.86	0.75	0.68	0.61	0.55	0.48	0.42	0.42
35	1.00	0.97	0.94	0.91	0.90	0.90	0.90	0.90	0.89
40	1.00	0.97	0.94	0.91	0.90	0.90	0.90	0.90	0.89
45	1.00	1.00	1.00	1.02	1.02	1.01	1.01	1.01	1.00
50	1.00	1.00	1.00	1.02	1.02	1.01	1.01	1.01	1.00
55	1.00	1.00	1.00	1.02	1.02	1.01	1.01	1.01	1.00
60	1.00	1.00	1.00	1.02	1.02	1.01	1.01	1.01	1.00
65	1.00	1.00	1.00	1.02	1.02	1.01	1.01	1.01	1.00
70	1.00	1.00	1.00	1.02	1.02	1.01	1.01	1.01	1.00
75	1.00	1.00	1.00	1.02	1.02	1.01	1.01	1.01	1.00
80	1.00	1.00	1.00	1.02	1.02	1.01	1.01	1.01	1.00
85	1.00	1.00	1.00	1.02	1.02	1.01	1.01	1.01	1.00
90	1.00	1.00	1.00	1.02	1.02	1.01	1.01	1.01	1.00
95	1.00	1.00	1.00	1.02	1.02	1.01	1.01	1.01	1.00
100	1.00	1.00	1.00	1.02	1.02	1.01	1.01	1.01	1.00
105	1.00	1.00	1.00	1.02	1.02	1.01	1.01	1.01	1.00
110	1.00	1.00	1.00	1.02	1.02	1.01	1.01	1.01	1.00
115	1.00	1.00	1.00	1.02	1.02	1.01	1.01	1.01	1.00
120	1.00	1.00	1.00	1.02	1.02	1.01	1.01	1.01	1.00
125-180	N/A	N/A	N/A	1.00	1.00	1.00	1.00	1.00	1.00
185-360	N/A	N/A	N/A	1.23	1.28	1.30	1.32	1.33	1.33

[1]For areas between the values listed in the table, correction factors can be obtained through linear interpolation between columns.

Table 5-4. DRFs for design rainfall distributions 25-, 50-, 100-, and 500-year design rainfall

Time (minutes)	Correction Factor by Watershed Area in Square Miles[1]					
	15	**20**	**30**	**40**	**50**	**75**
5	1.15	1.15	1.15	1.15	1.15	1.10
10	1.15	1.15	1.15	1.15	1.15	1.10
15	1.15	1.15	1.15	1.15	1.15	1.10
20	1.25	1.18	1.10	1.05	1.00	0.90
25	0.73	0.69	0.64	0.60	0.58	0.55
30	0.73	0.69	0.64	0.60	0.58	0.55
35	0.73	0.69	0.64	0.60	0.58	0.55
40	1.05	1.02	0.95	0.90	0.85	0.80
45	1.20	1.20	1.20	1.15	1.05	0.95
50	1.15	1.15	1.15	1.15	1.05	0.95
55	1.15	1.15	1.15	1.15	1.15	1.15
60	1.15	1.15	1.15	1.15	1.15	1.15
65	1.08	1.10	1.13	1.15	1.15	1.15
70	1.08	1.10	1.13	1.15	1.15	1.15
75	1.08	1.10	1.13	1.15	1.15	1.15
80	1.08	1.10	1.13	1.15	1.15	1.15
85	1.08	1.10	1.13	1.15	1.15	1.15
90	1.08	1.10	1.13	1.15	1.15	1.15
95	1.08	1.10	1.13	1.15	1.15	1.15
100	1.08	1.10	1.13	1.15	1.15	1.15
105	1.08	1.10	1.13	1.15	1.15	1.15
110	1.08	1.10	1.13	1.15	1.15	1.15
115	1.08	1.10	1.13	1.15	1.15	1.15
120	1.08	1.10	1.13	1.15	1.15	1.15
125-180	1.08	1.10	1.13	1.15	1.25	1.25
185-360	1.05	1.10	1.10	1.10	1.10	1.13

[1]For areas between the values listed in the table, correction factors can be obtained through linear interpolation between columns.

4.0 Intensity-Duration Curves for Rational Method

To develop depth-duration curves or intensity-duration curves for the Rational Method of runoff analysis take the 1-hour depth(s) obtained from NOAA Atlas 14 and apply Equation 5-1 for the duration (or durations) of interest:

$$I = \frac{28.5\, P_1}{\left(10 + T_d\right)^{0.786}}$$ Equation 5-1

Where:

I = rainfall intensity (inches per hour)

P_1 = 1-hour point rainfall depth (inches)

T_d = storm duration (minutes)

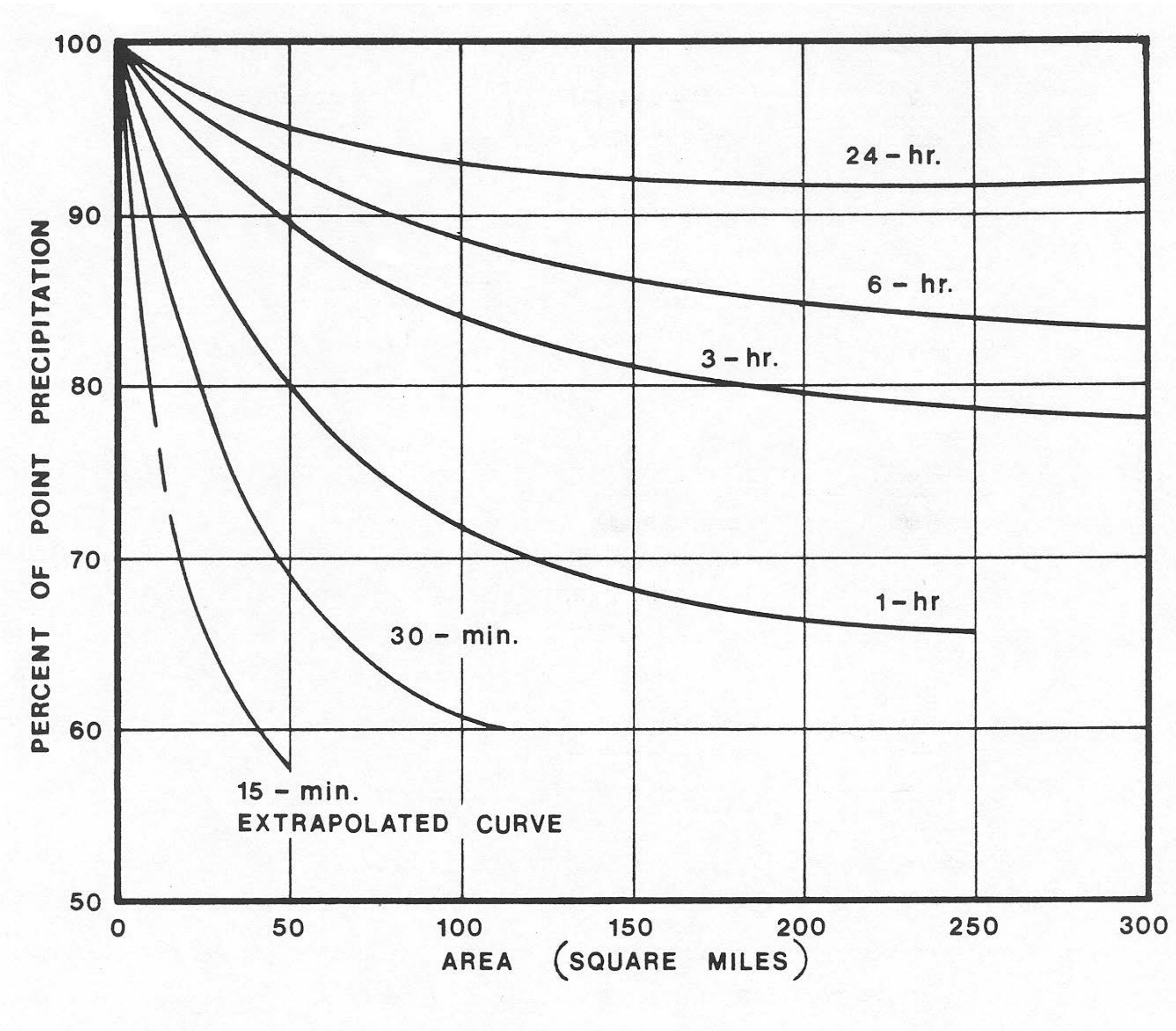

Figure 5-1. Depth reduction factor (DRF) curves for infrequent storm events

(25-, 50-, 100- and 500-year events) (NOAA Atlas 2, Volume III 1973 with extrapolation for 15-minute curve)

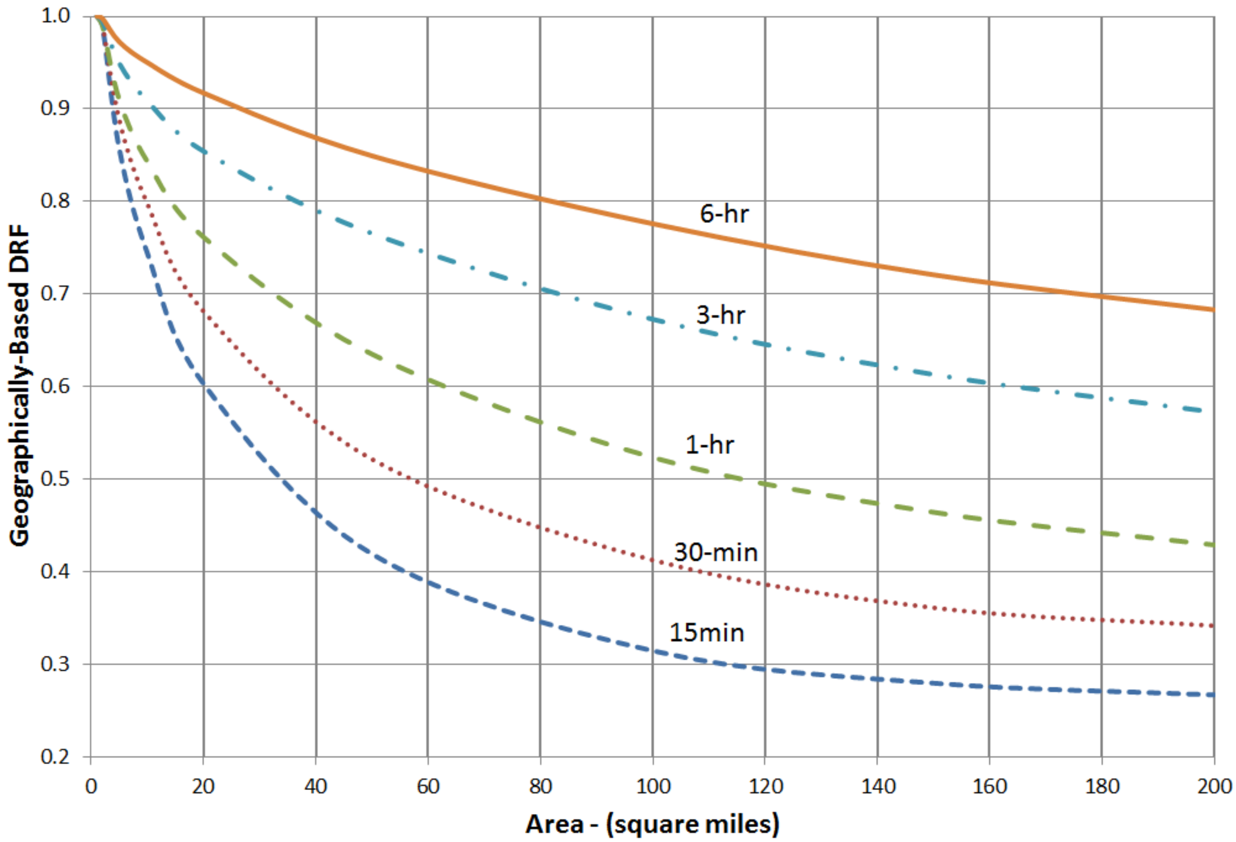

Figure 5-2. Depth reduction factor (DRF) curves for minor storm events (2-, 5-, and 10-year events)

(Carlton 2010)

5.0 Examples

5.1 Example preparation of intensity-duration-frequency curve

Use Equation 5-1 to plot rainfall intensity-duration curves for the 500-year, 100-year, 10-year, 5-year, and 2-year precipitation events in Denver. One-hour point precipitation values in Denver are as follows: 500-year (3.14), 100-year (2.31-inch), 10-year (1.33-inch), 5-year (1.09 inches), and 2-year (0.83-inches).

Calculations are prepared using Equation 5-1.

Duration (minutes)	**Rainfall Intensity (inches/hour)**	
5	$28 \times 3.14/(10+5)^{0.786}=$	10.46
10	$28 \times 3.14/(10+10)^{0.786}=$	8.35
15	$28 \times 3.14/(10+15)^{0.786}=$	7.00
30	$28 \times 3.14/(10+30)^{0.786}=$	4.84
60	$28 \times 3.14/(10+60)^{0.786}=$	3.12

Repeat this exercise for each return period.

Duration	**P_1**	**5**	**10**	**15**	**30**	**60**
2-year	0.83	2.77	2.21	1.85	1.28	0.82
5-year	1.09	3.63	2.90	2.43	1.68	1.08
10-year	1.33	4.43	3.54	2.97	2.05	1.32
25-year	1.69	5.63	4.49	3.77	2.61	1.68
50-year	1.99	6.63	5.29	4.44	3.07	1.98
100-year	2.31	7.70	6.14	5.15	3.56	2.29
500-year	3.14	10.46	8.35	7.00	4.84	3.12

The values from Equation 5-1 are plotted in Figure 5-15.

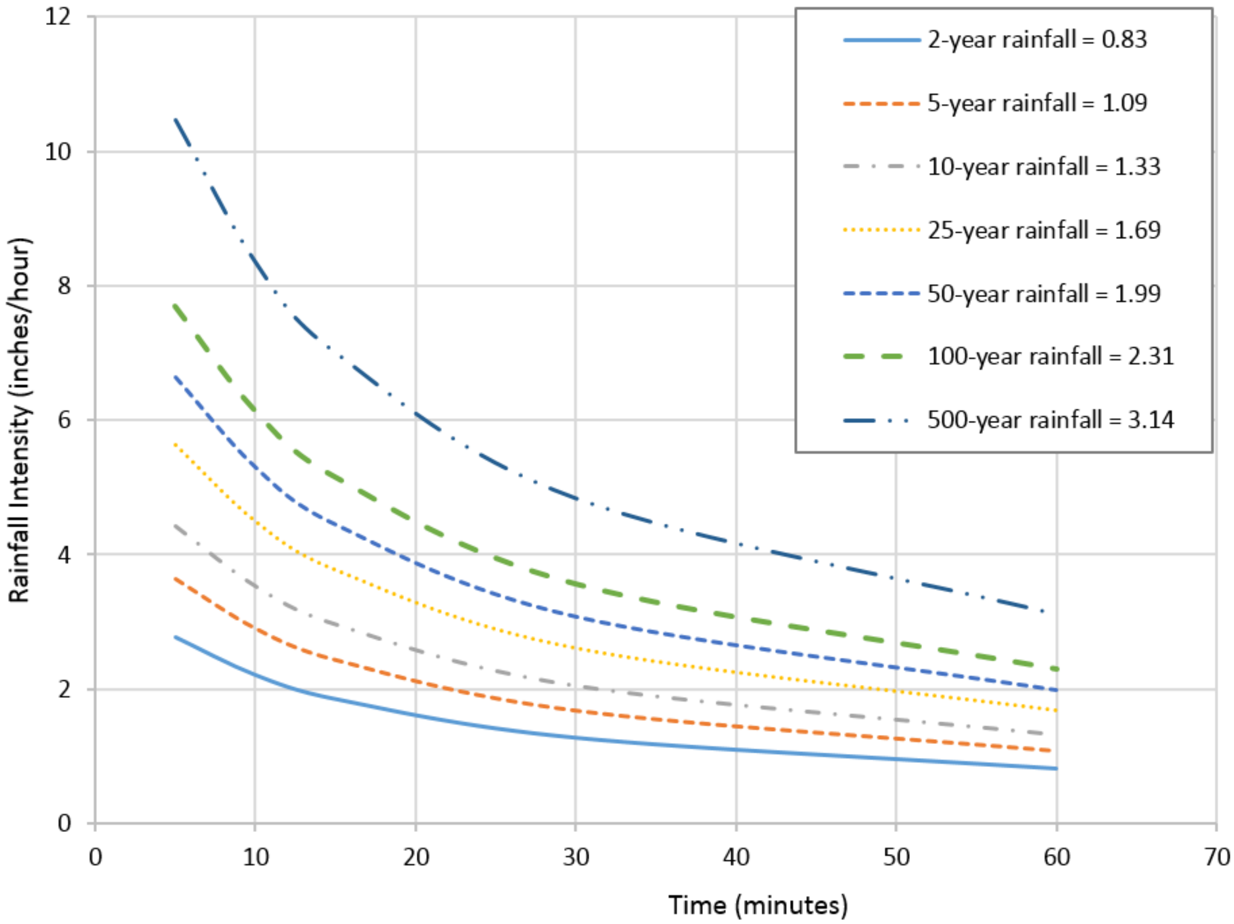

Figure 5-15. Example rainfall intensity-duration curves

6.0 References

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