RAINFALL

CONTENTS

TABLES

FIGURES

1.0 OVERVIEW

The purpose of this chapter is to present the analytical methods used to develop the rainfall information needed in order to carry out the hydrological analyses described in the RUNOFF chapter of this *Manual*. Specifically, this chapter describes: (a) the development of point precipitation values for locations within the Urban Drainage and Flood Control District (District) (Section 2), (b) the temporal distribution of point rainfall to develop the hyetograph necessary for the Colorado Urban Hydrograph Procedure (CUHP) hydrological modeling (Section 3), and (c) preparation of intensity-duration-frequency graphs used in Rational Method hydrologic computations (Section 4). This chapter includes analysis of the 2-, 5-, 10-, 25-, 50-, and 100-year return storm events. If information is needed regarding other storm return periods or areas in Colorado but outside the District, the reader is directed to the *Precipitation-Frequency Atlas of the Western United States, Volume III-Colorado* (NOAA Atlas) published by the National Oceanic and Atmospheric Administration (NOAA) in 1973, which contains a more complete description of rainfall analysis in the State of Colorado.

The *Urban Storm Drainage Criteria Manual* that was originally published in 1969 contained rainfall depth-duration-frequency maps for the 2-, 10-, and 100-year recurrence frequencies. A detailed set of guidelines was given on how to use the depth-duration-frequency maps to develop design rainstorms and time-intensity-frequency curves for any location within the District. The NOAA Atlas published in 1973 was based on a longer period of record and a large number of gages within Colorado (NOAA 1973). Unfortunately the maps in the *Manual* and the NOAA Atlas did not agree with each other.

Since 1977 the District has studied the rainfall and runoff relationships in the Denver metropolitan area. As part of this effort, the rainfall depth-frequency distribution was investigated for a 73-year period at the Denver rain gage. Inconsistencies between the rainfall frequency distribution obtained using a long-term data record and the rainfall depth-frequency-duration maps in the *Manual* were discovered and reported (Urbonas 1978). Further investigations indicated that the NOAA Atlas maps, although not perfect, were more in line with the rainfall frequency distribution of the long-term record.

As the 1982 version of CUHP was being developed, it became apparent that the information in the NOAA Atlas could be converted to a family of design rainstorms by distributing these design storms in a manner that yielded reasonable peak runoff recurrence frequency distributions. 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 rainfall information should also be used within the District.

2.0 RAINFALL DEPTH-DURATION-FREQUENCY

In order to use CUHP or the Rational Method, it is necessary to find the 1-hour point rainfall for the area of interest. In order to use CUHP method for watersheds larger than 10 square miles in size, the 3-hour and 6-hour point rainfall depths are also required.

2.1 Rainfall Depth-Duration-Frequency Maps

Using the information contained in the NOAA Atlas, rainfall depth-duration-frequency maps were prepared for the Denver Region. Maps are presented for the 1-hour and 6-hour durations for the 2-, 5-, 10-, 25-, 50-, and 100-year recurrence frequencies as Figures RA-1 through RA-12.

2.2 Rainfall Depths For Durations Between 1- and 6-Hours

The 2-hour point rainfall depth can be determined using the nomograph presented in Figure RA-13 or the equation:

$$P_2 = P_1 + (P_6 - P_1)0.342 \qquad \text{(RA-1)}$$

Rainfall depths for the 3-hour storm can be determined using Figure RA-13 or the equation:

$$P_3 = P_1 + (P_6 - P_1)0.597 \qquad \text{(RA-2)}$$

in which:

P_1 = 1-hour point rainfall (inches)

P_2 = 2-hour point rainfall (inches)

P_3 = 3-hour point rainfall (inches)

P_6 = 6-hour point rainfall (inches)

In order to use Figure RA-13, the 1-hour and 6-hour point precipitation depths for any particular storm return period are determined using the maps in Figures RA-1 through RA-12. The two values are plotted on the vertical lines of Figure RA-13 labeled 1- and 6-hour duration. A straight line is drawn between the two points. The intersection with the 2-hour or the 3-hour line yields the point rainfall depth for that duration. See Section 7.1 for an example of the calculation of point rainfall depths.

3.0 DESIGN STORM DISTRIBUTION FOR CUHP

The 1-hour point precipitation value described in Section 2 is distributed into 5-minute increments for use with CUHP model (i.e., temporal distribution). This is described in Section 3.1 and summarized in Table RA-2. The rainfall duration used with CUHP varies with the size of the watershed being analyzed. Also, for watersheds 10 square miles or greater, there is an adjustment made to the incremental precipitation depths to take into account the greater watershed size (i.e., area adjustment). This is described in Section 3.2 and summarized in Table RA-3. A summary of the storm duration and whether area adjustments for different watershed sizes are needed is provided in Table RA-1.

Table RA-1—Storm Duration and Area Adjustment for CUHP Modeling

Watershed Area (square miles)	Suggested Minimum Storm Duration	Area Adjustment Required?
Less than 10.0	2 hours	No
10.0 to 20.0	3 hours	Yes
20.0 and larger	6 hours	Yes

3.1 Temporal Distribution

The current version of CUHP (see RUNOFF) was designed to be used with the NOAA 1-hour rainfall depths described in Section 2.1. The 1-hour rainfall depths for areas within the District are provided in Figures RA-1 through RA-6. To obtain a temporal distribution for a design storm for use in the Denver region, the 1-hour depth is transferred into a 2-hour design storm by multiplying the 1-hour depth(s) by the percentages for each time increment given in Table RA-2. The resultant design storm(s) may then be used with CUHP.

The total of all the incremental depths for the first hour of the design storm does not agree with the 1-hour depth used to develop the design storm. Do not be alarmed. The temporal distribution presented in Table RA-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 the District to provide, in conjunction with the use of CUHP, runoff flow peak rates and volumes of the same return period as the design storm. The NOAA Atlas values are “embedded” in the 2-hour and other duration design storms.

In order to develop the temporal distribution for the 3-hour design storm (for watersheds between 10.0 and 20.0 square miles in size), first prepare the first two hours of the storm using the 1-hour storm point precipitation and the temporal percentage distribution shown in Table RA-2. The difference between the 3-hour point precipitation from Equation RA-2 and the 2-hour point precipitation (Table RA-2) is then distributed evenly over the period of 125 minutes to 180 minutes. In order to develop the temporal distribution for the 6-hour design storm (watersheds greater than 20.0 square miles), first prepare the first three hours of the storm as described above. The difference between the 6-hour point precipitation from

Figures RA-1 through RA-12 and the 3-hour point precipitation is distributed evenly over the period of 185 minutes to 360 minutes.

Table RA-2—Design Storm Distributions of 1-Hour NOAA Atlas Depths

Time Minutes	Percent of 1-Hour NOAA Rainfall Atlas Depth				
	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 Adjustment to Rainfall Distribution for Watershed Size

The NOAA Atlas provides guidelines for adjusting the rainfall depths with increasing catchment area. Area-depth adjustments are given in the Atlas for durations of ½-, 1-, 3-, 6- and 24-hours. Figure RA-14 was based on a similar figure in the NOAA Atlas. The 15-minute curve was extrapolated by the District from the information shown for other storm durations on Figure RA-14. The fast response times of urbanized watersheds and sharp rainstorm distribution gradients in the Denver area require adjustments of rainfall depths for storm durations that are less than ½-hour.

The area adjustment procedure can be tedious and time consuming; therefore, Table RA-3 is provided to assist the engineer with the area-depth adjustment calculations. To adjust the design storm distribution to account for the averaging effects of larger watersheds, follow these three steps:

Step 1—Begin with the unadjusted design rainstorm for the needed storm duration (see Table RA-1) developed using the procedure described in Section 3.1.

Step 2—On the basis of total watershed size, select the appropriate column(s) of adjustment factors in Table RA-3.

Step 3—Multiply each incremental design storm depth by its respective adjustment factor for that time increment.

Table RA-3—Area Adjustment Factors for Design Rainfall Distributions

	2-, 5-, and 10-Year Design Rainfall Area—Square Miles				25-, 50-, 100-, and 500-Year Design Rainfall Area—Square Miles			
Time Minutes	10-20	20-30	30-50	50-75	10-20	20-30	30-50	50-75
5	1.00	1.00	1.10	1.10	1.00	1.00	1.05	1.10
10	1.00	1.00	1.05	1.10	1.00	1.00	1.05	1.10
15	1.00	1.00	1.05	1.00	1.00	1.00	1.05	1.10
20	0.90	0.81	0.74	0.62	1.00	1.00	1.05	1.00
25	0.90	0.81	0.74	0.62	0.90	0.81	0.74	0.60
30	0.90	0.81	0.74	0.62	0.90	0.81	0.74	0.60
35	1.00	1.00	1.05	1.00	0.90	0.81	0.74	0.70
40	1.00	1.00	1.05	1.10	1.00	1.00	1.05	1.00
45	1.00	1.00	1.05	1.10	1.00	1.00	1.05	1.10
50	1.00	1.00	1.05	1.10	1.00	1.00	1.05	1.10
55	1.00	1.00	1.05	1.10	1.00	1.00	1.05	1.10
60	1.00	1.00	1.05	1.10	1.00	1.00	1.05	1.10
65 - 120	1.00	1.00	1.05	1.10	1.00	1.00	1.05	1.10
125 - 180	1.00	1.15	1.20	1.40	1.00	1.15	1.20	1.40
185 - 360	N/A	1.15	1.20	1.20	N/A	1.15	1.20	1.20

See Section 7.2 for an example of the preparation of a design rainfall for use with CUHP.

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 Figures RA-1 through RA-6 and multiply by the factors in Table RA-4 to determine rainfall depth and rainfall intensity at each duration. The intensity can then be plotted as illustrated in Figure RA-15.

TABLE RA-4—Factors for Preparation of Intensity-Duration Curves

Duration (minutes)	5	10	15	30	60
Rainfall Depth at Duration (inches)	$0.29P_1$	$0.45P_1$	$0.57P_1$	$0.79P_1$	$1.0P_1$
Intensity (inches per hour)	$3.48P_1$	$2.70P_1$	$2.28P_1$	$1.58P_1$	$1.0P_1$

Alternatively, the rainfall intensity for the area within the District can be approximated by the equation:

$$I = \frac{28.5\ P_1}{(10 + T_c)^{0.786}} \qquad \text{(RA-3)}$$

in which:

I = rainfall intensity (inches per hour)

P_1 = 1-hour point rainfall depth (inches)

T_c = time of concentration (minutes)

5.0 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 can 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, 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 results from convective storms or frontal stimulated convective storms. These types of storms often have their most intense periods that are less than one or two hours in duration. They can produce brief periods of high rainfall intensities. It is these short-duration, intense rainstorms that appear to 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. 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 the 1982 and later version of CUHP, 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 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 in District publications (Urbonas 1978; Urbonas 1979). The recommendations contained in this *Manual* are the result of refinements to the work originally reported in 1979.

6.0 SPREADSHEET DESIGN AIDS

Two spreadsheet design aids have been developed in order to facilitate computation of design rainfall.

The UD-Raincurve Spreadsheet computes the temporal distribution and area-adjusted design of rainfall for use with CUHP model. Input to the spreadsheet includes the 1-hour and 6-hour point rainfall amounts determined from Figures RA-1 through RA-12. The rainfall amount(s) should be entered into the page of the spreadsheet with the desired return period. The output is the rainfall distribution in 5-minute increments (including any required area adjustment) that may be used for CUHP modeling.

7.0 EXAMPLES

7.1 Example Computation of Point Rainfall

Find the 2-year and 100-year design storm point rainfall for Section 1, Township 1 South, Range 68 West.

Determine 1-hour and 6-hour point rainfall values from Figures RA-1, RA-6, RA-7, and RA-12.

Storm Event	Point Precipitation (Inches)	Map Reference
2-year, 1-hour	0.95	RA-1
2-year, 6-hour	1.46	RA-7
100-year, 1-hour	2.67	RA-6
100-year, 6-hour	3.67	RA-12

Determine 2-hour point precipitation values from Equation RA-1:

$$P_2 \text{ (2-year)} = \text{2-year, 2-hour} = 0.95 + (1.46 - 0.95)\ 0.342 = 1.12 \text{ inches}$$

$$P_2 \text{ (100-year)} = \text{100-year, 2-hour} = 2.67 + (3.67 - 2.67)\ 0.342 = 3.01 \text{ inches}$$

Determine 3-hour point precipitation values from Equation RA-2:

$$P_3 \text{ (2-year)} = \text{2-year, 3-hour} = 0.95 + (1.46 - 0.95)\ 0.597 = 1.25 \text{ inches}$$

$$P_3 \text{ (100-year)} = \text{100-year, 3-hour} = 2.67 + (3.67 - 2.67)\ 0.597 = 3.27 \text{ inches}$$

7.2 Example Distribution of Point Rainfall

Prepare a 100-year rainfall distribution to be used in CUHP computer model for a 15-square-mile catchment centered about Section 7, Township 4 South, Range 67 West.

As per Table RA-1, a 15.0-square-mile watershed requires a 3-hour storm with area adjustment.

Using Figures RA-6 and RA-12, the 100-year, 1-hour, and 6-hour point precipitation values are 2.60 inches and 3.50 inches respectively. The 3-hour point precipitation is calculated using Equation RA-2.

$$P_3 = 2.60 + (3.5 - 2.6)\ 0.597 = 3.14 \text{ inches}$$

Use the design storm distribution from Table RA-2 for 0 to 120 minutes. The period 125 to 180 minutes is calculated as the difference of P_3 from Equation RA-2 and P_2 from Table RA-2 evenly distributed over that time period. Area adjustment factors from Table RA-3 are applied. The results of the calculations are shown in Table RA-5.

Table RA-5—CUHP Rainfall Distribution for Example 7.2

Time (minutes)	Percentage of 1-Hour Rainfall[1]	Rainfall Without Area Adjustment (inches)[2]	Area Adjustment Factor[3]	Rainfall With Area Adjustment (inches)[4]
5	1.0%	0.026	1.0	0.026
10	3.0%	0.078	1.0	0.078
15	4.6%	0.120	1.0	0.120
20	8.0%	0.208	1.0	0.208
25	14.0%	0.364	0.9	0.328
30	25.0%	0.650	0.9	0.585
35	14.0%	0.364	0.9	0.328
40	8.0%	0.208	1.0	0.208
45	6.2%	0.161	1.0	0.161
50	5.0%	0.130	1.0	0.130
55	4.0%	0.104	1.0	0.104
60	4.0%	0.104	1.0	0.104
65	4.0%	0.104	1.0	0.104
70	2.0%	0.052	1.0	0.052
75	2.0%	0.052	1.0	0.052
80	1.2%	0.031	1.0	0.031
85	1.2%	0.031	1.0	0.031
90	1.2%	0.031	1.0	0.031
95	1.2%	0.031	1.0	0.031
100	1.2%	0.031	1.0	0.031
105	1.2%	0.031	1.0	0.031
110	1.2%	0.031	1.0	0.031
115	1.2%	0.031	1.0	0.031
120	1.2%	0.031	1.0	0.031
125-180		0.011[5]	1.0	0.011

Notes:

[1] From Table RA-2.

[2] Precipitation = 2.6 inches x Column 2.

[3] From Table RA-3.

[4] Column 3 x Column 4.

[5] (3.14 – (2.6 · 1.156))/12.

Alternatively, the 1-hour and 6-hour point precipitation values can be inserted into the spreadsheet to obtain CUHP rainfall distribution.

7.3 Example Preparation of Intensity-Duration-Frequency Curve

Prepare a rainfall intensity-duration curve for a 2.6-inch, 1-hour point precipitation.

Calculations are prepared using both Table RA-4 and Equation RA-3. They are summarized below in Table RA-6.

Table RA-6—Rainfall Intensity-Duration Values for a 2.6-inch, 1-Hour Point Precipitation

Duration (minutes)	Rainfall Intensity (inches/hour)	
	Table RA-4	Equation RA-3
5	$3.48 \cdot 2.6 = 9.05$	$28.5 \cdot 2.6/(10 + 5)^{0.786} = 8.82$
10	$2.70 \cdot 2.6 = 7.02$	$28.5 \cdot 2.6/(10 + 10)^{0.786} = 7.03$
15	$2.28 \cdot 2.6 = 5.93$	$28.5 \cdot 2.6/(10 + 15)^{0.786} = 5.90$
30	$1.58 \cdot 2.6 = 4.11$	$28.5 \cdot 2.6/(10 + 30)^{0.786} = 4.08$
60	$1.0 \cdot 2.6 = 2.60$	$28.5 \cdot 2.6/(10 + 60)^{0.786} = 2.63$

Using the two different methods (Table RA-4 and Equation RA-3) yields similar results. The values from Equation RA-3 are plotted in Figure RA-15.

8.0 REFERENCES

National Oceanic and Atmospheric Administration (NOAA). 1973. *Precipitation-Frequency Atlas of the Western United States, Volume III-Colorado*. Washington, D.C.: U.S. Department of Commerce, National Weather Service.

Urbonas, B. 1979. Reliability of Design Storms In Modeling. In *Proceedings International Symposium on Urban Storm Runoff*, 27-36. Lexington, KY: University of Kentucky.

Urbonas, B. 1988. Some Findings in the Rainfall-Runoff Data Collected in the Denver Area. *Flood Hazard News* 18(1):10.

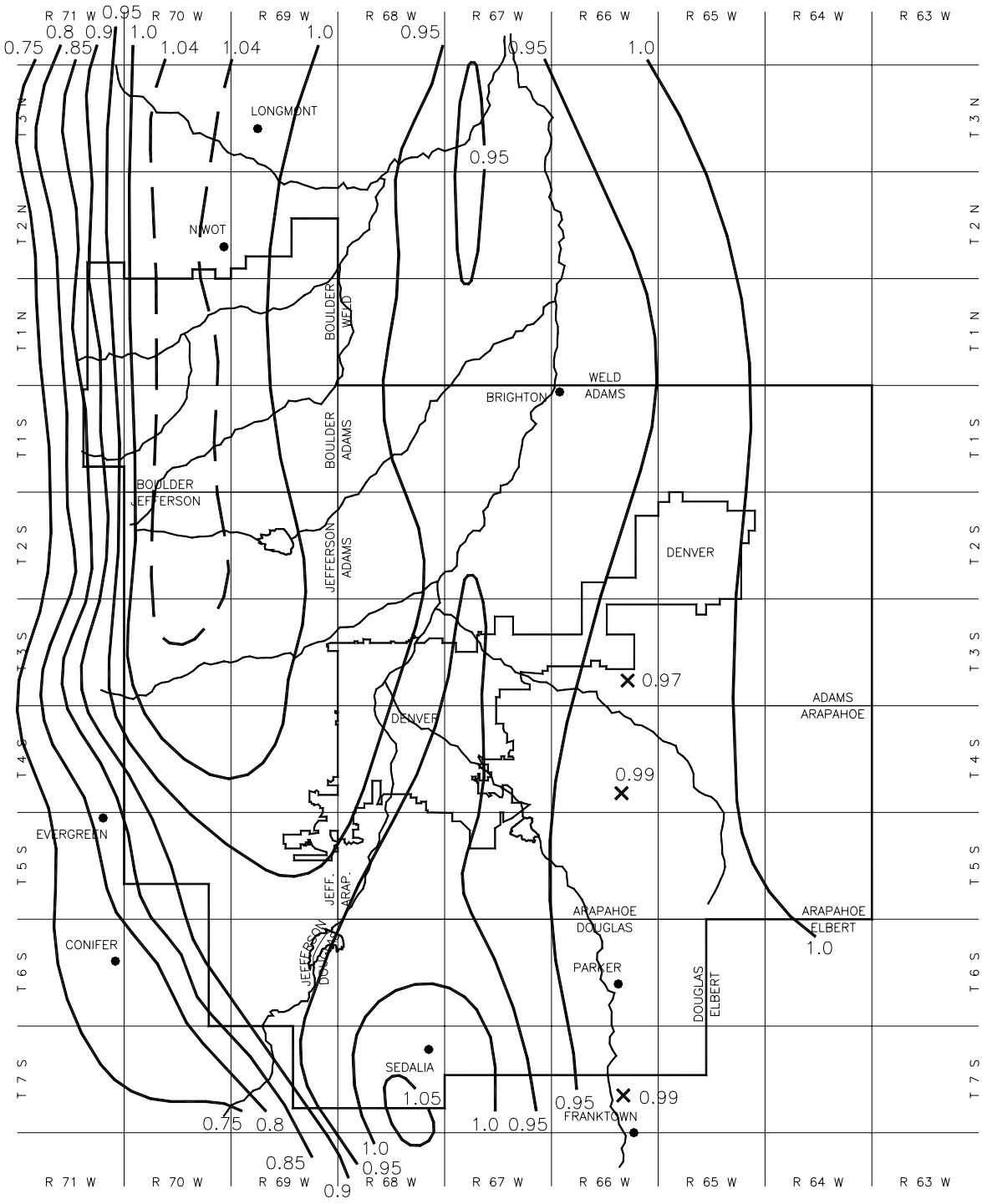

Figure RA-1—Rainfall Depth-Duration-Frequency: 2-Year, 1-Hour Rainfall

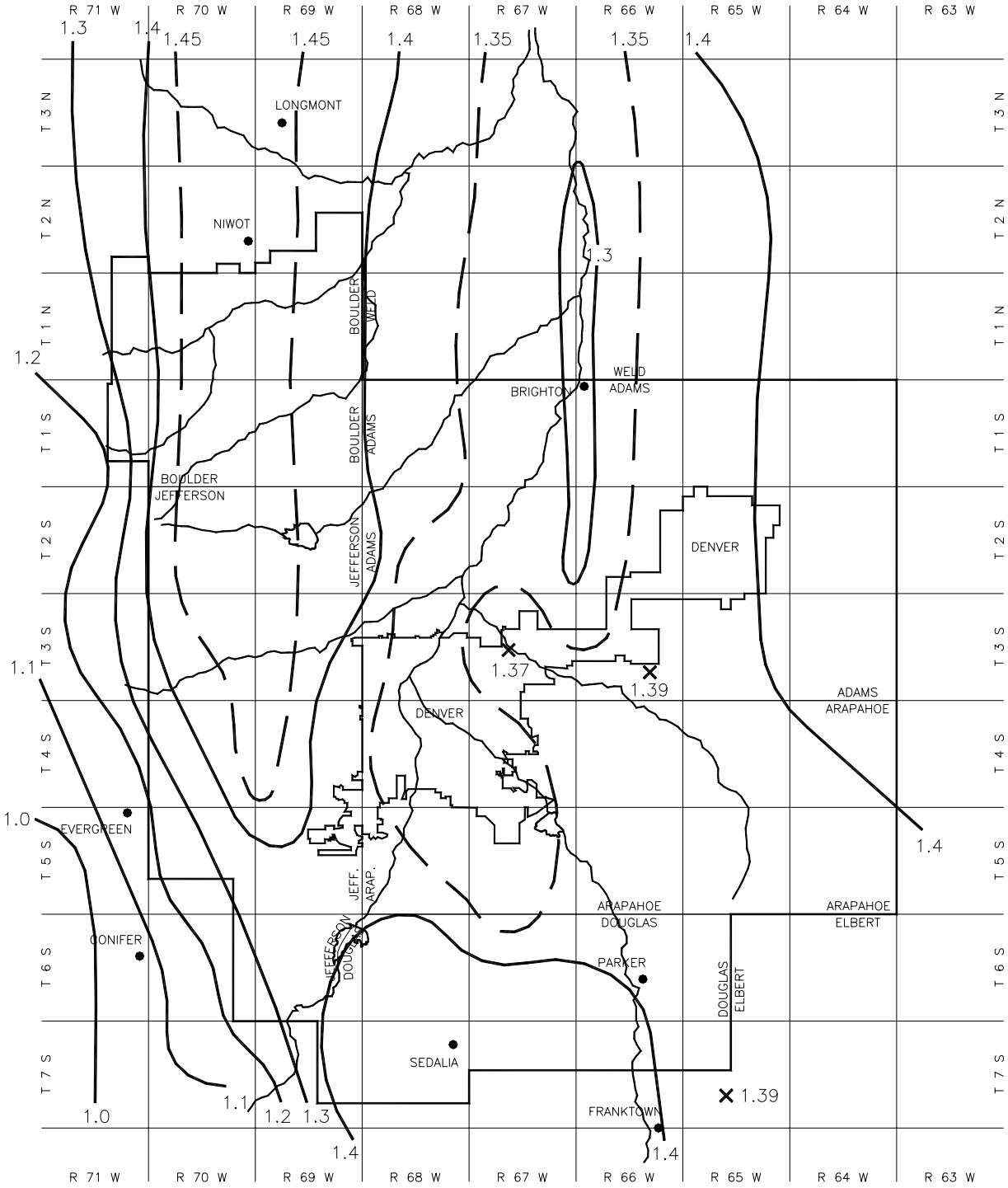

Figure RA-2—Rainfall Depth-Duration-Frequency: 5-Year, 1-Hour Rainfall

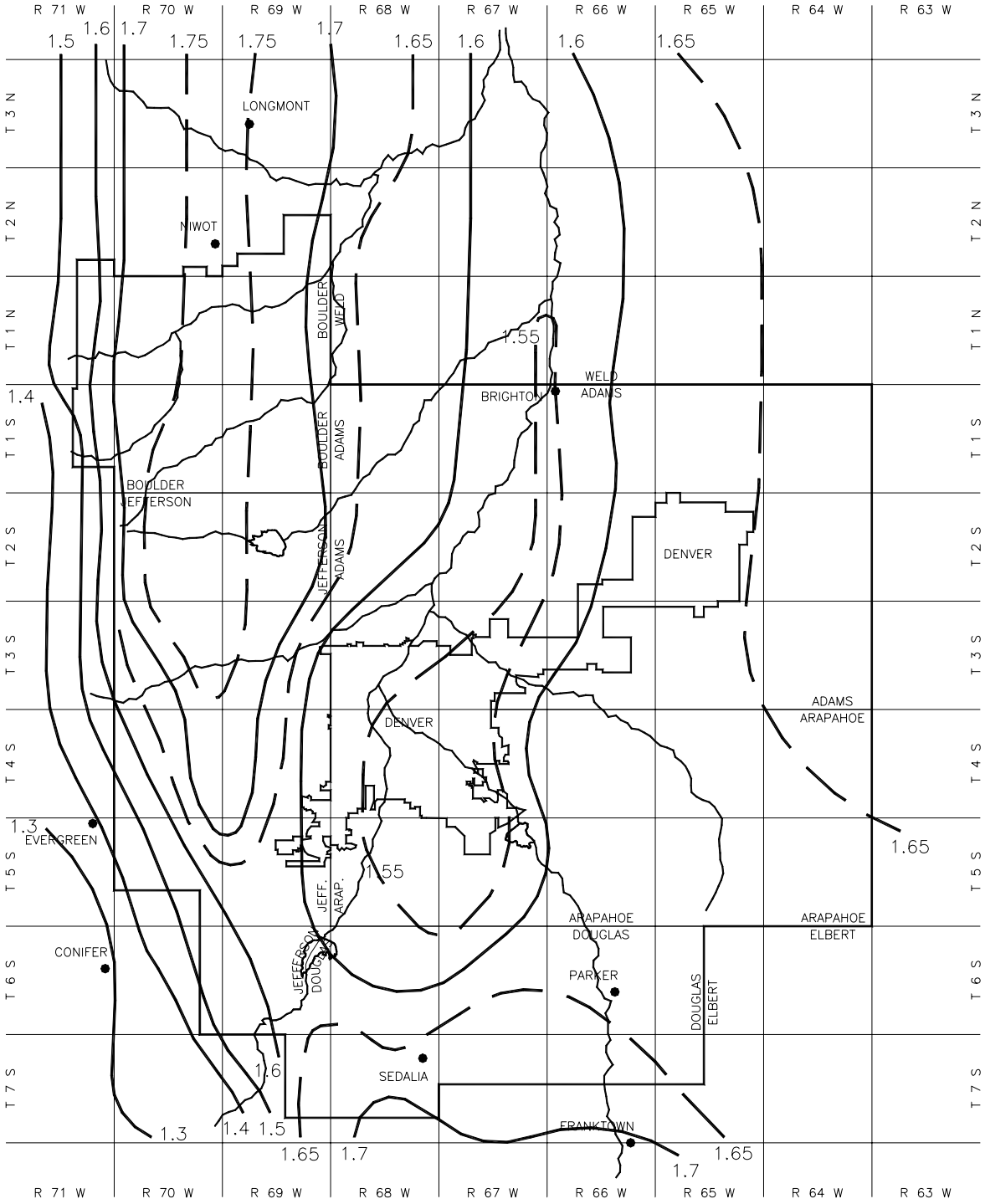

Figure RA-3—Rainfall Depth-Duration-Frequency: 10-Year, 1-Hour Rainfall

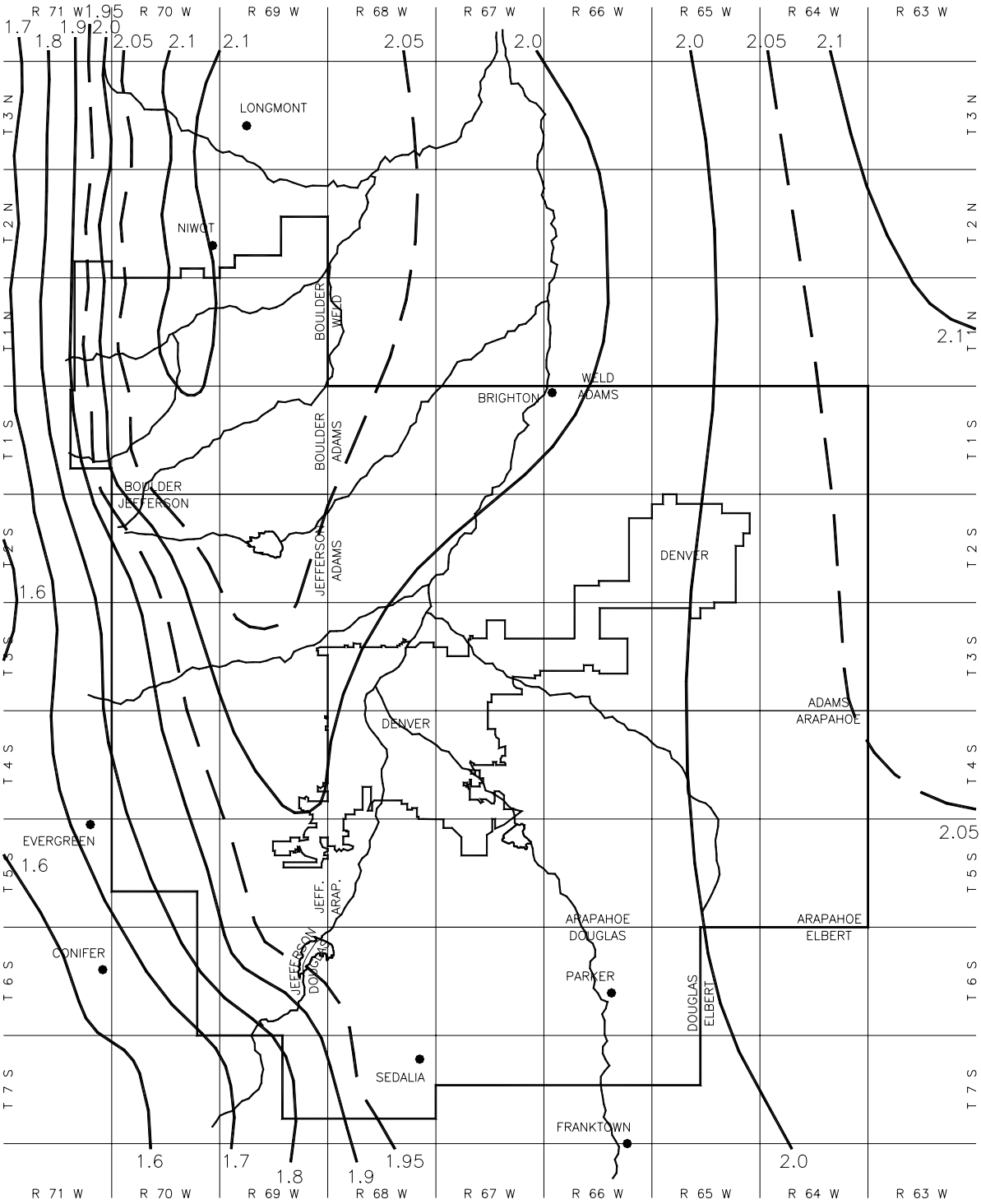

Figure RA-4—Rainfall Depth-Duration-Frequency: 25-Year, 1-Hour Rainfall

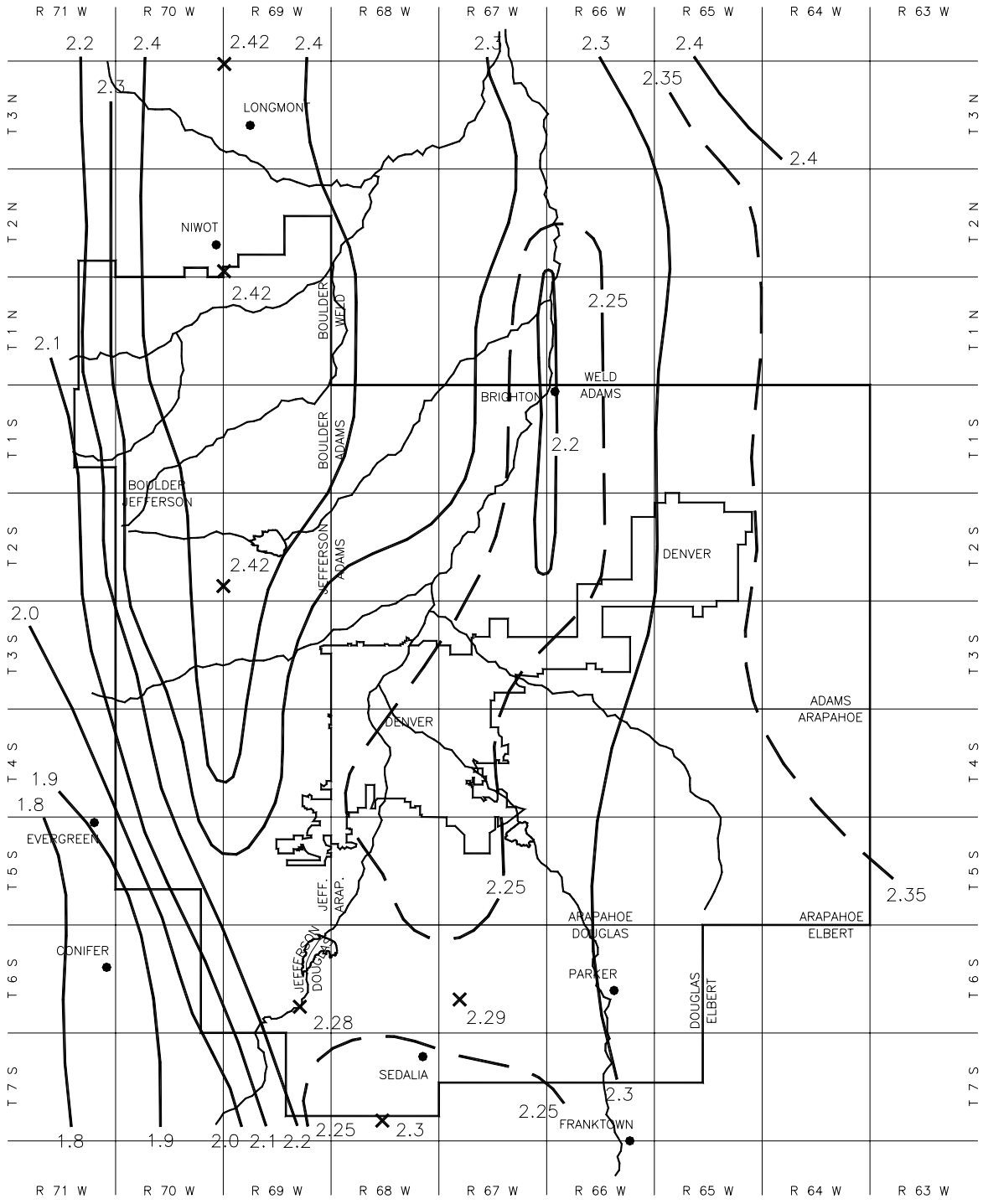

Figure RA-5—Rainfall Depth-Duration-Frequency: 50-Year, 1-Hour Rainfall

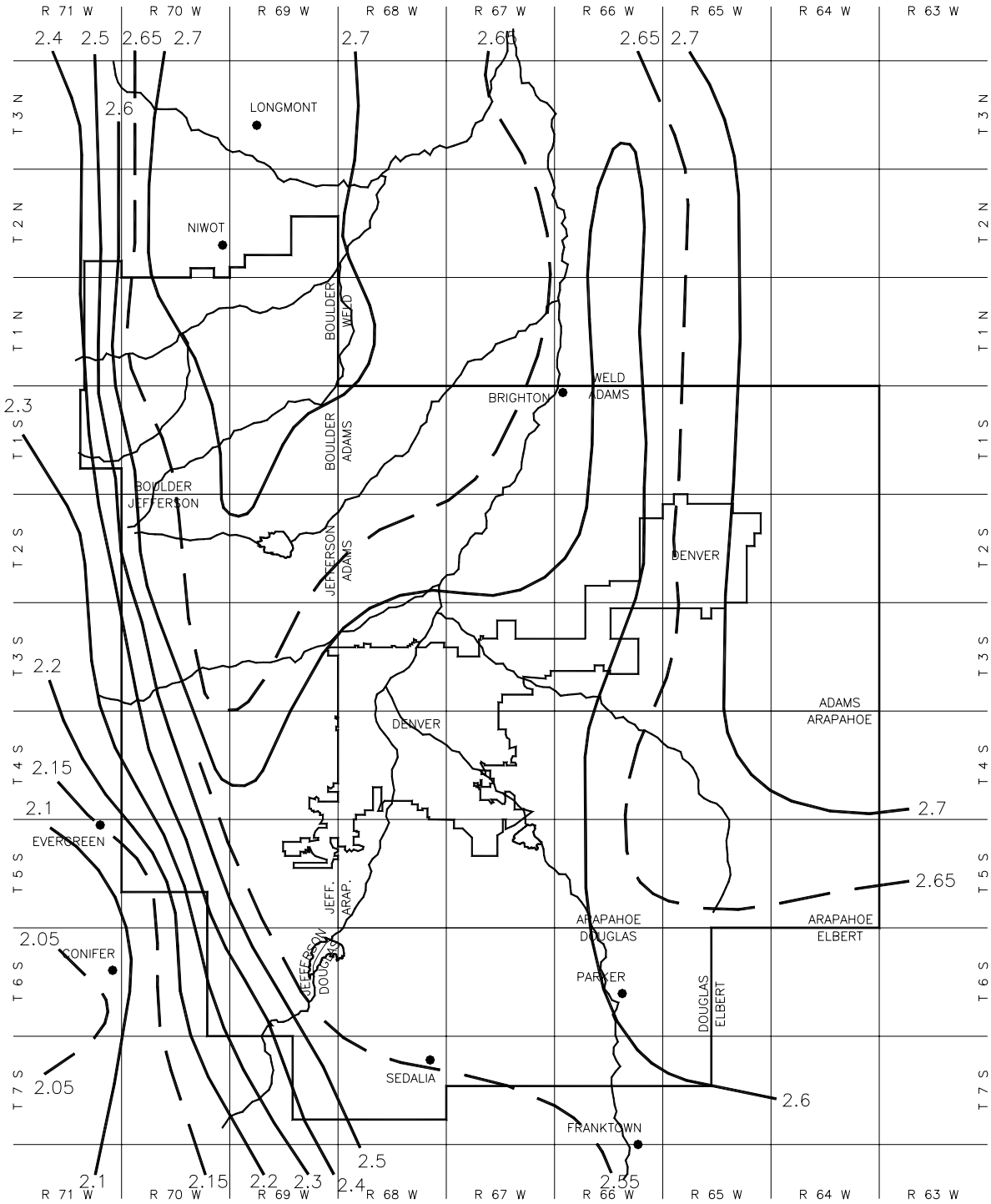

Figure RA-6—Rainfall Depth-Duration-Frequency: 100-Year, 1-Hour Rainfall

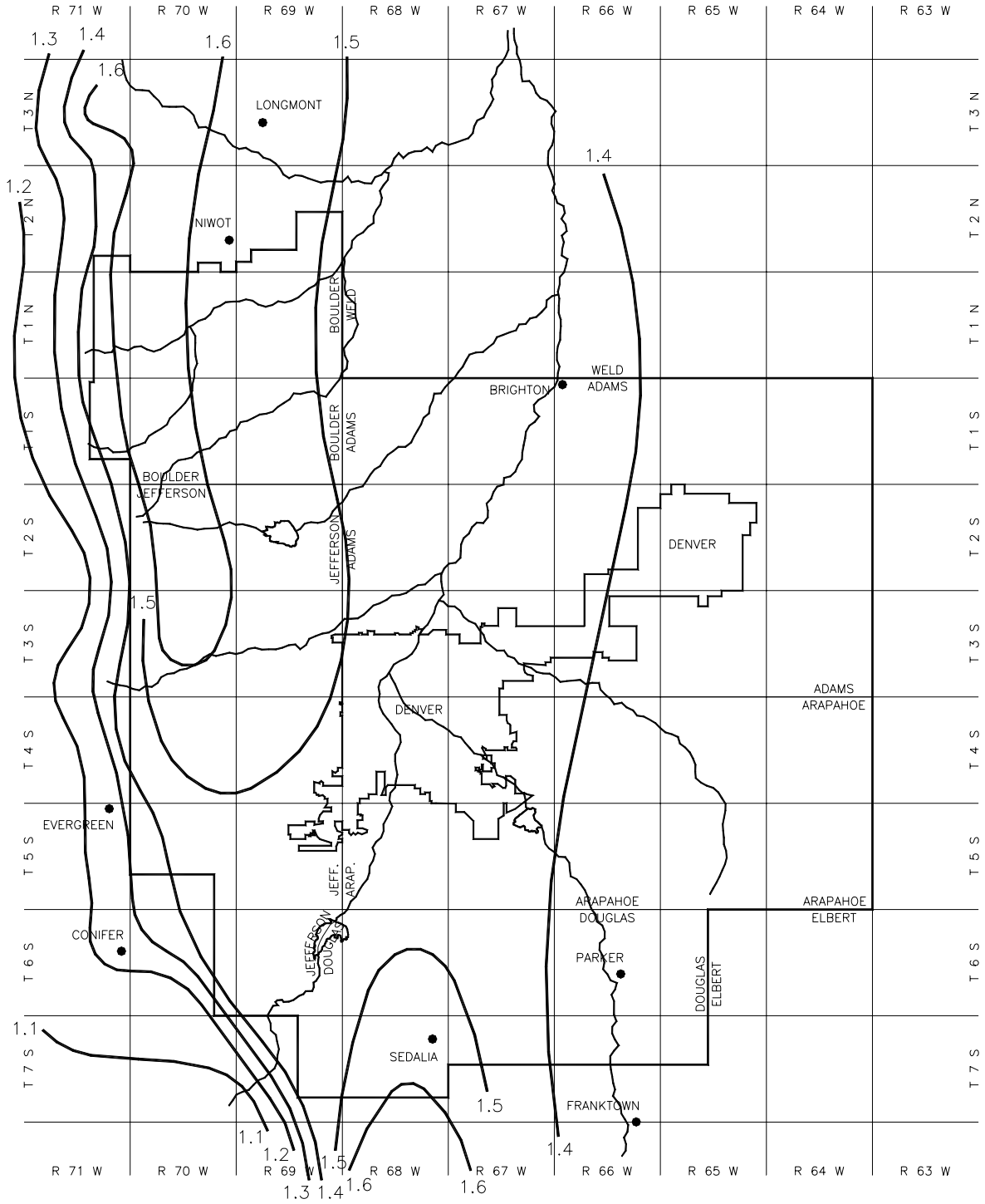

Figure RA-7—Rainfall Depth-Duration-Frequency: 2-Year, 6-Hour Rainfall

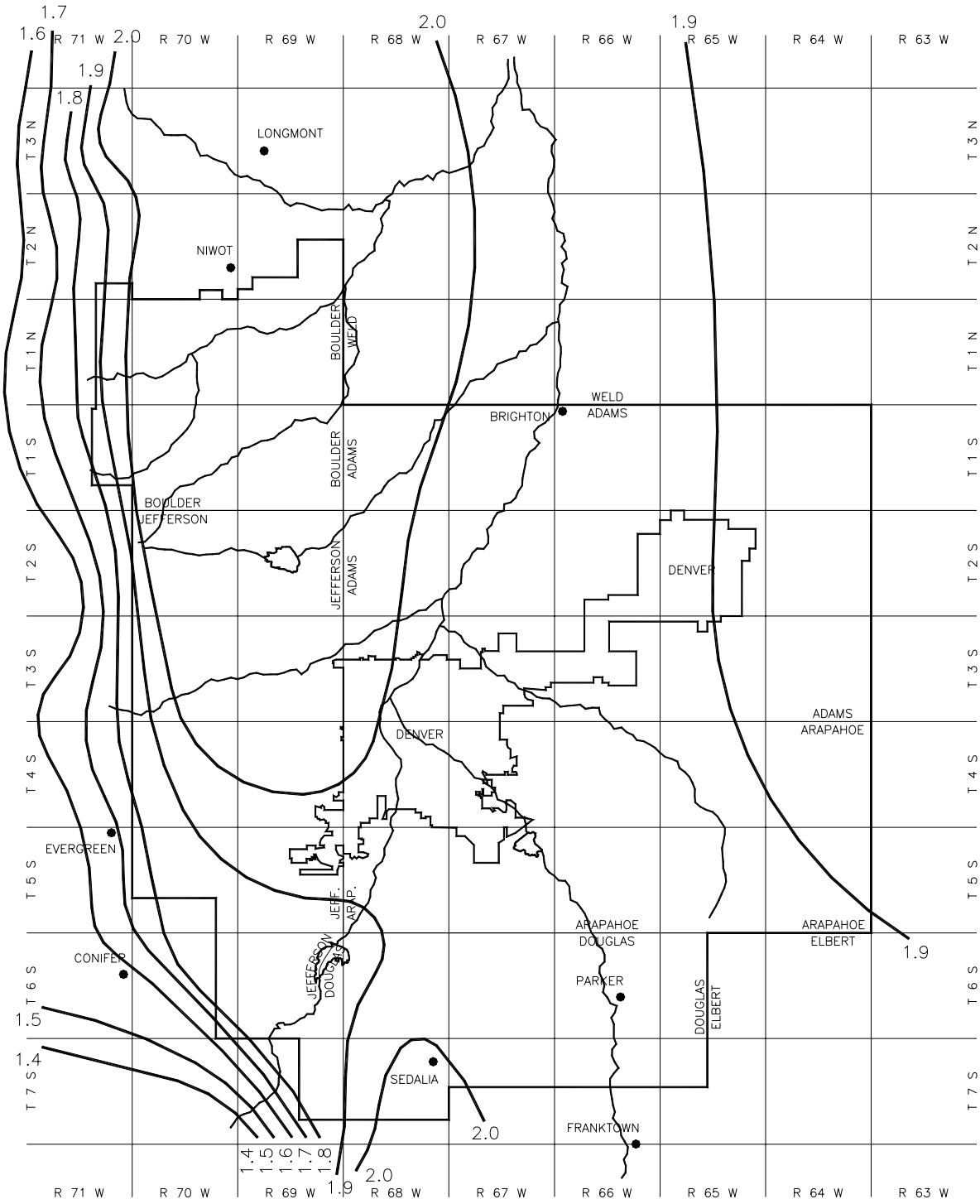

Figure RA-8—Rainfall Depth-Duration-Frequency: 5-Year, 6-Hour Rainfall

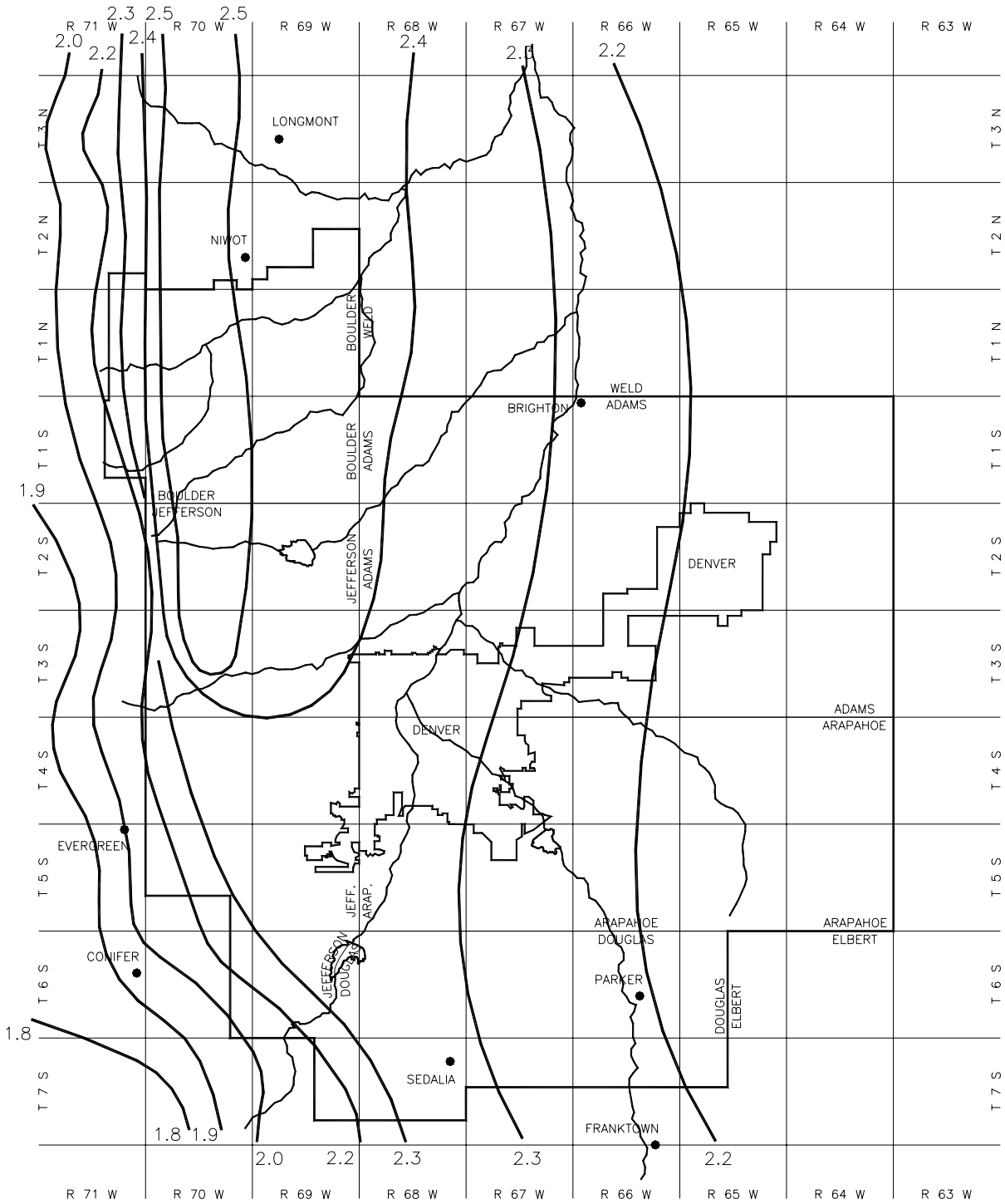

Figure RA-9—Rainfall Depth-Duration-Frequency: 10-Year, 6-Hour Rainfall

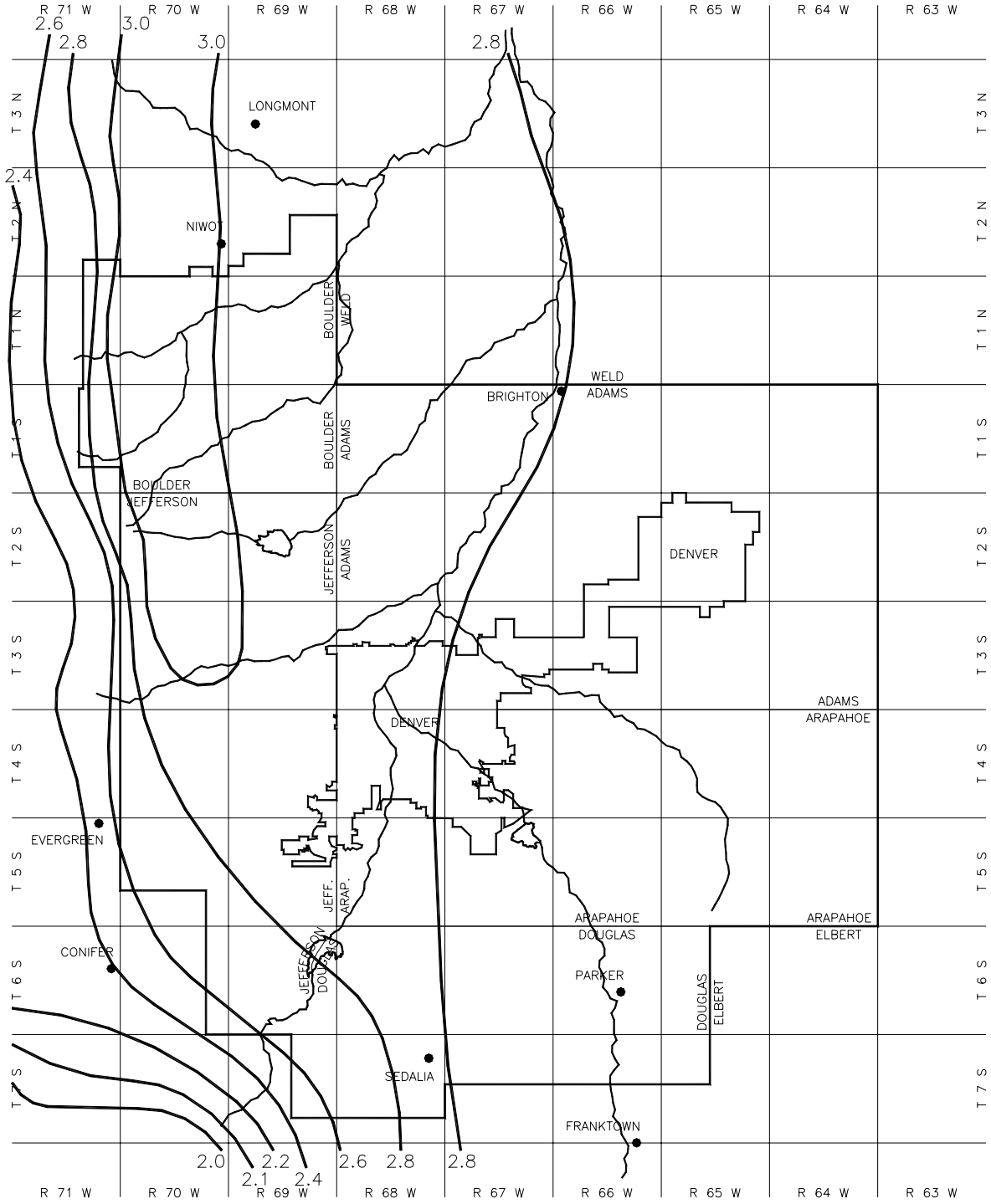

Figure RA-10—Rainfall Depth-Duration-Frequency: 25-Year, 6-Hour Rainfall

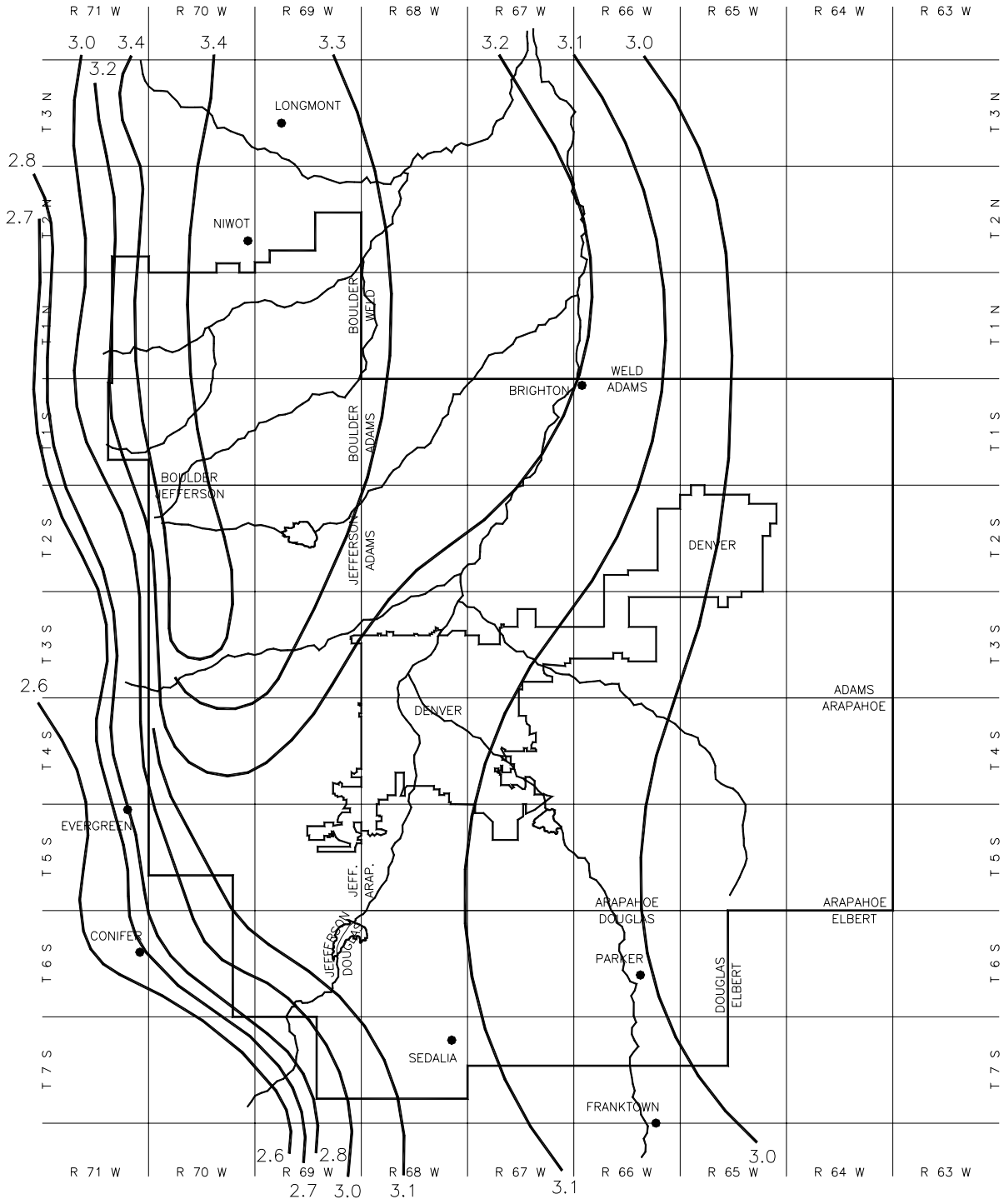

Figure RA-11—Rainfall Depth-Duration-Frequency: 50-Year, 6-Hour Rainfall

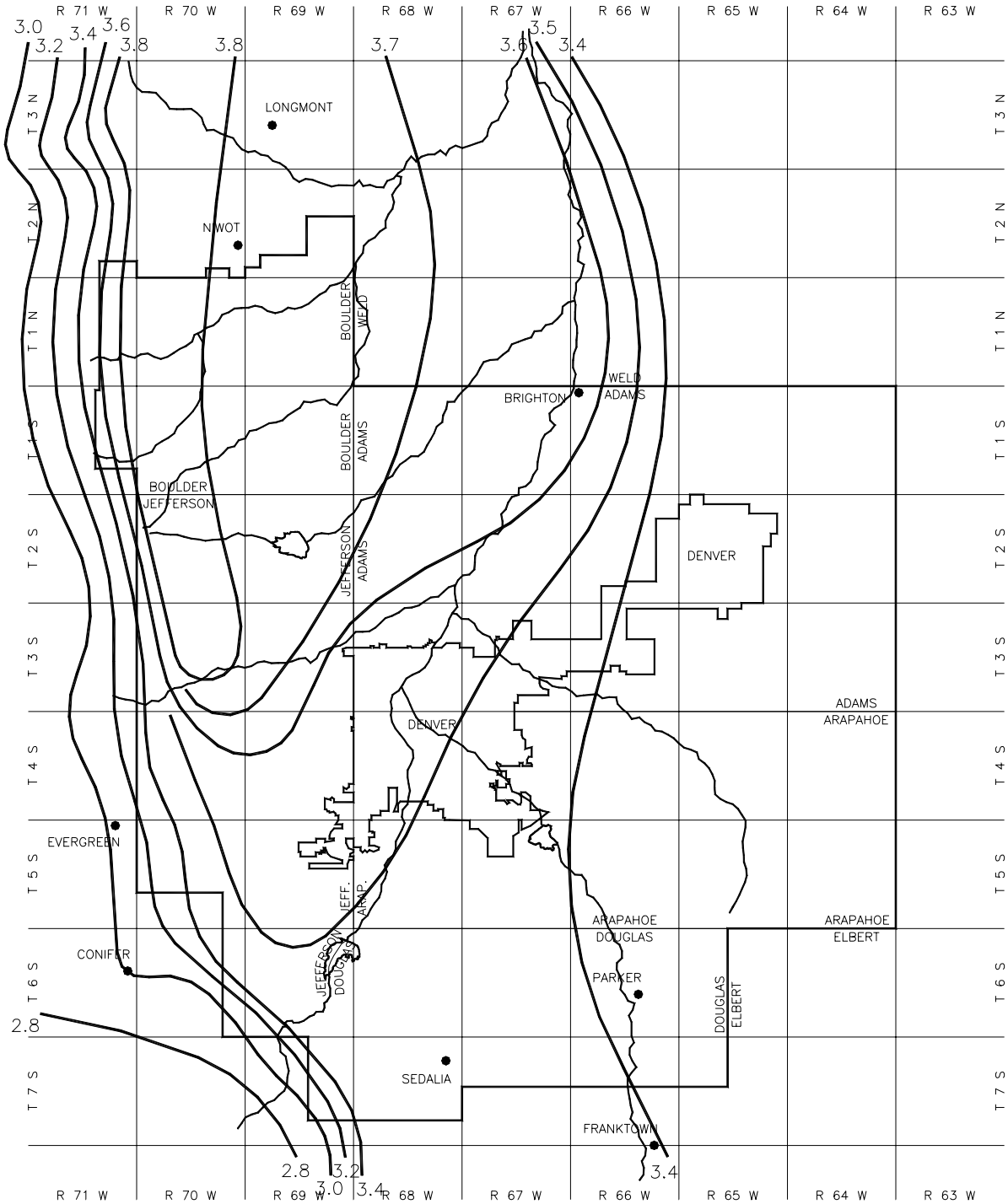

Figure RA-12—Rainfall Depth-Duration-Frequency: 100-Year, 6-Hour Rainfall

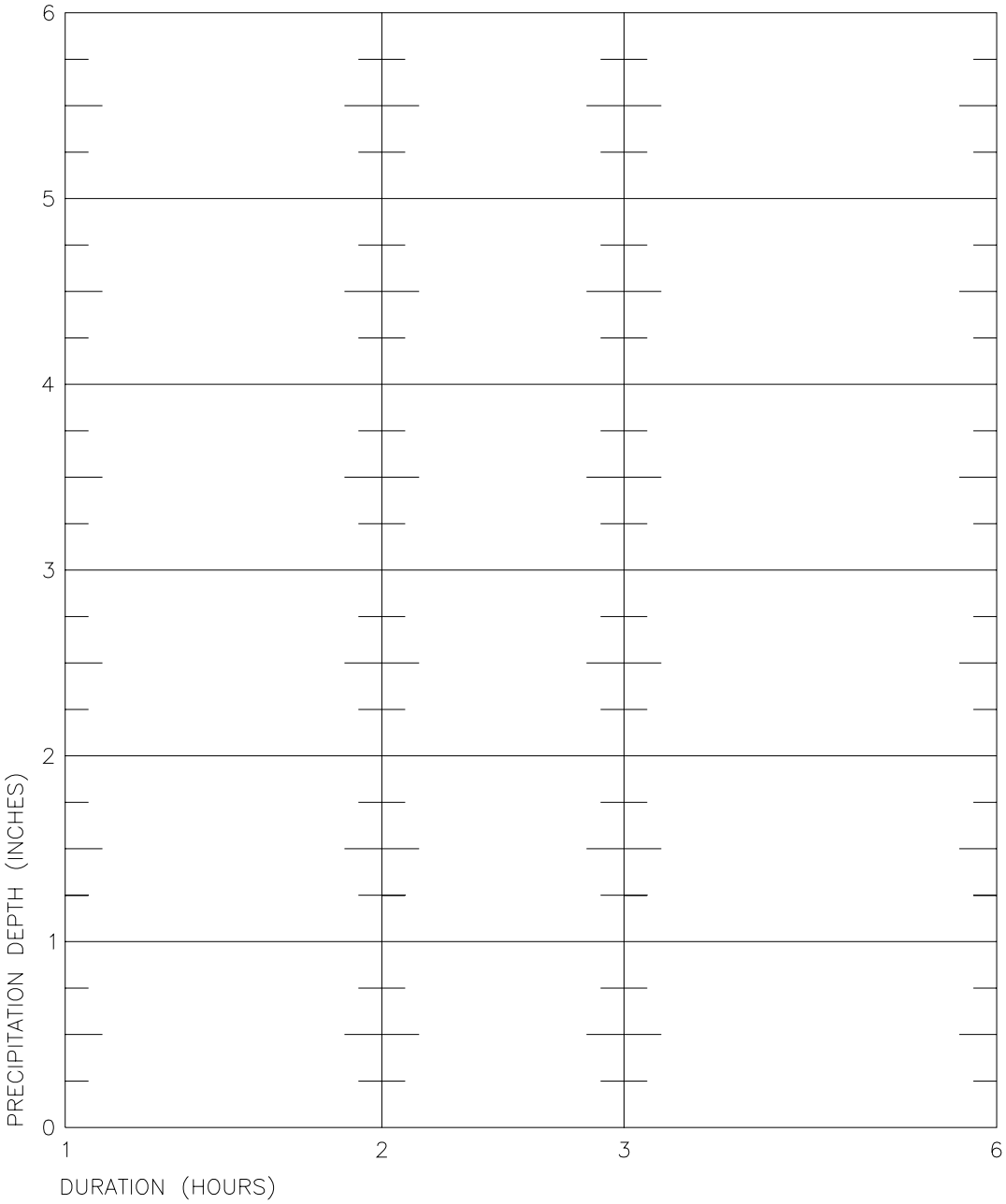

Figure RA-13—Rainfall Depth-Duration-Frequency: Precipitation Depth-Duration Nomograph For Use East of Continental Divide

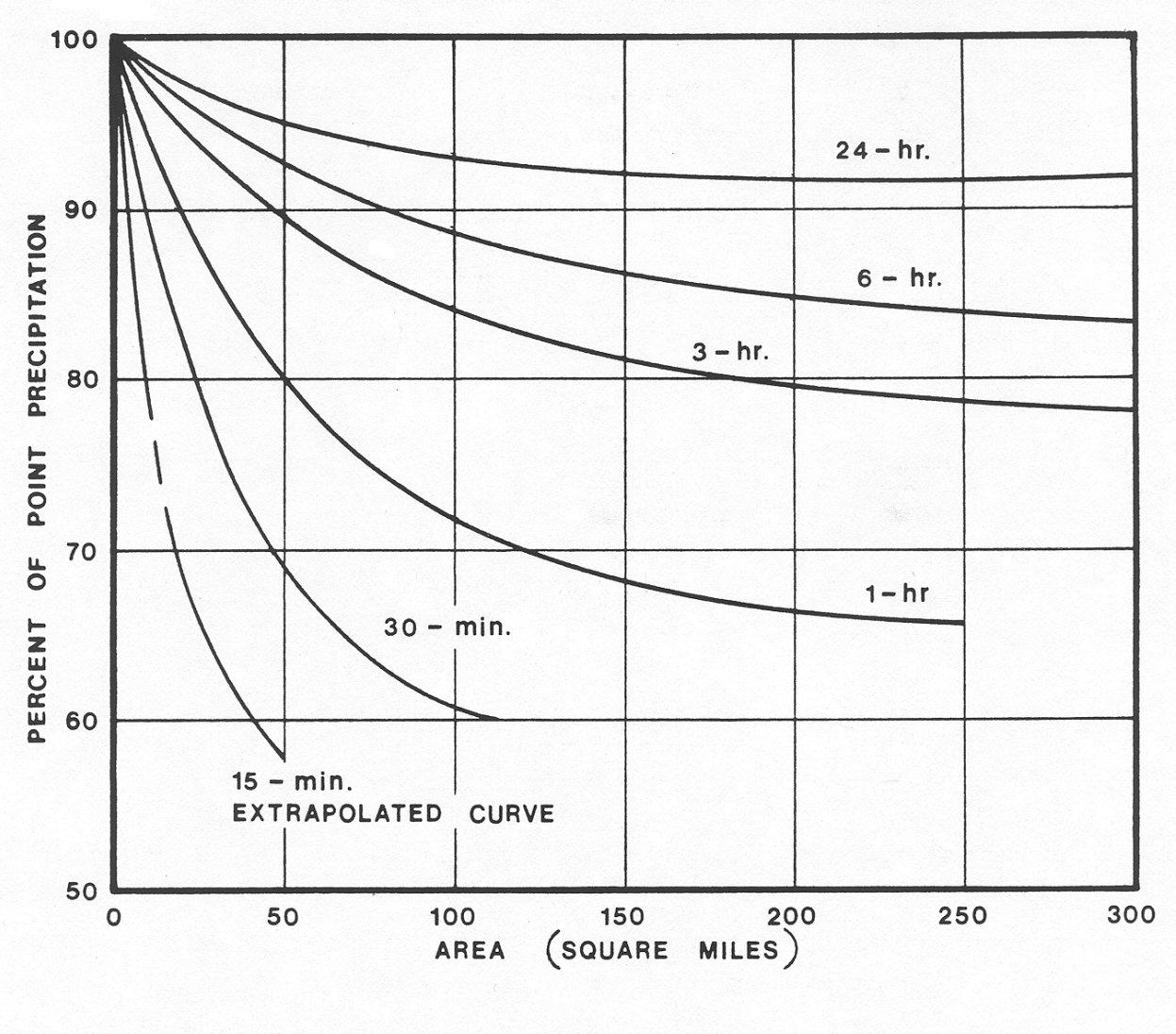

Figure RA-14—Depth-Area Adjustment Curves

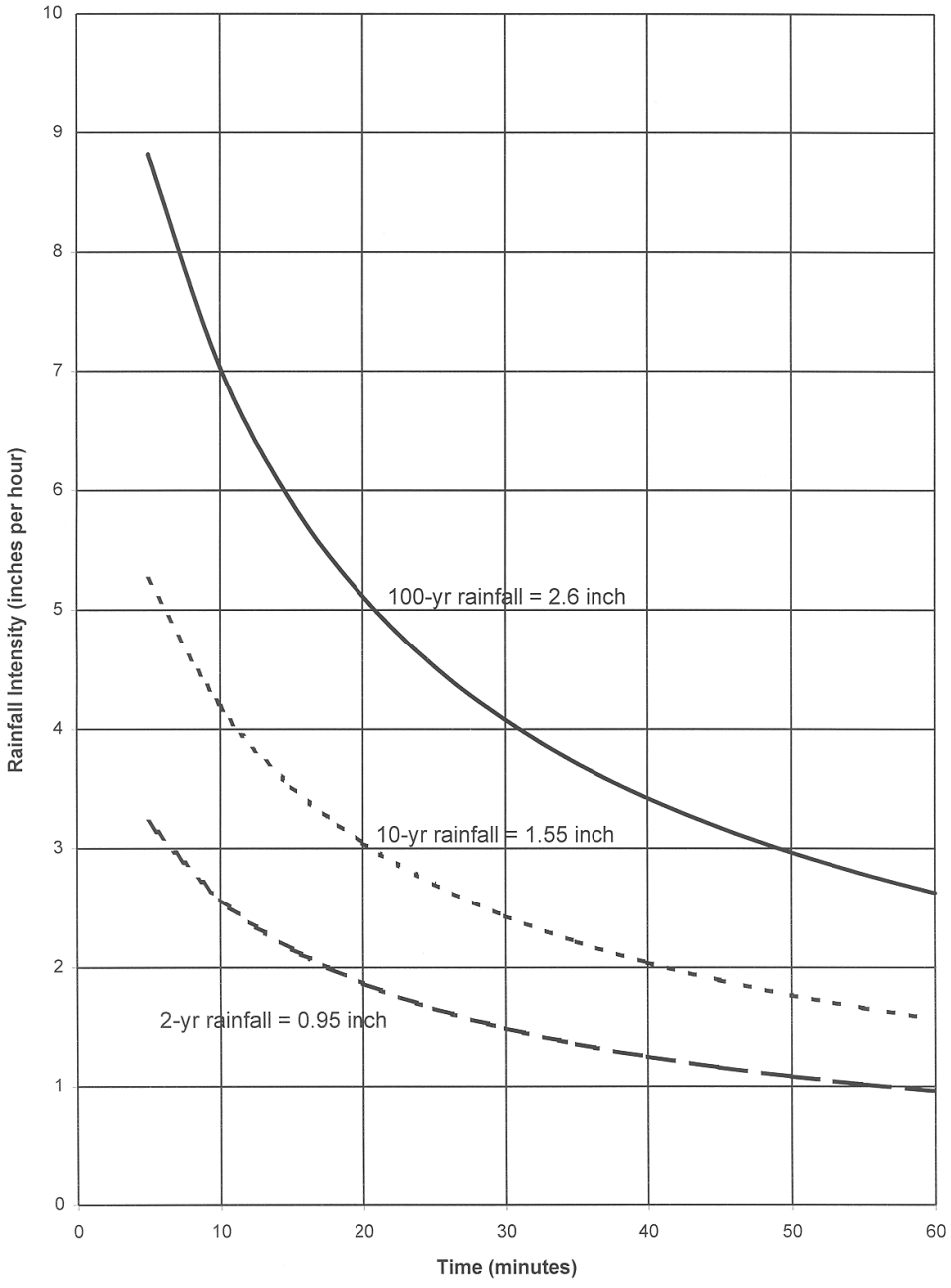

Figure RA-15—Rainfall Intensity-Duration Curves