

= 1,335,000 MW

This heat energy can be compared to large thermal power plants, which may have a capacity of 3000 MW. It can be seen that the energy released in thunderstorms is immense.

### Variability of Precipitation

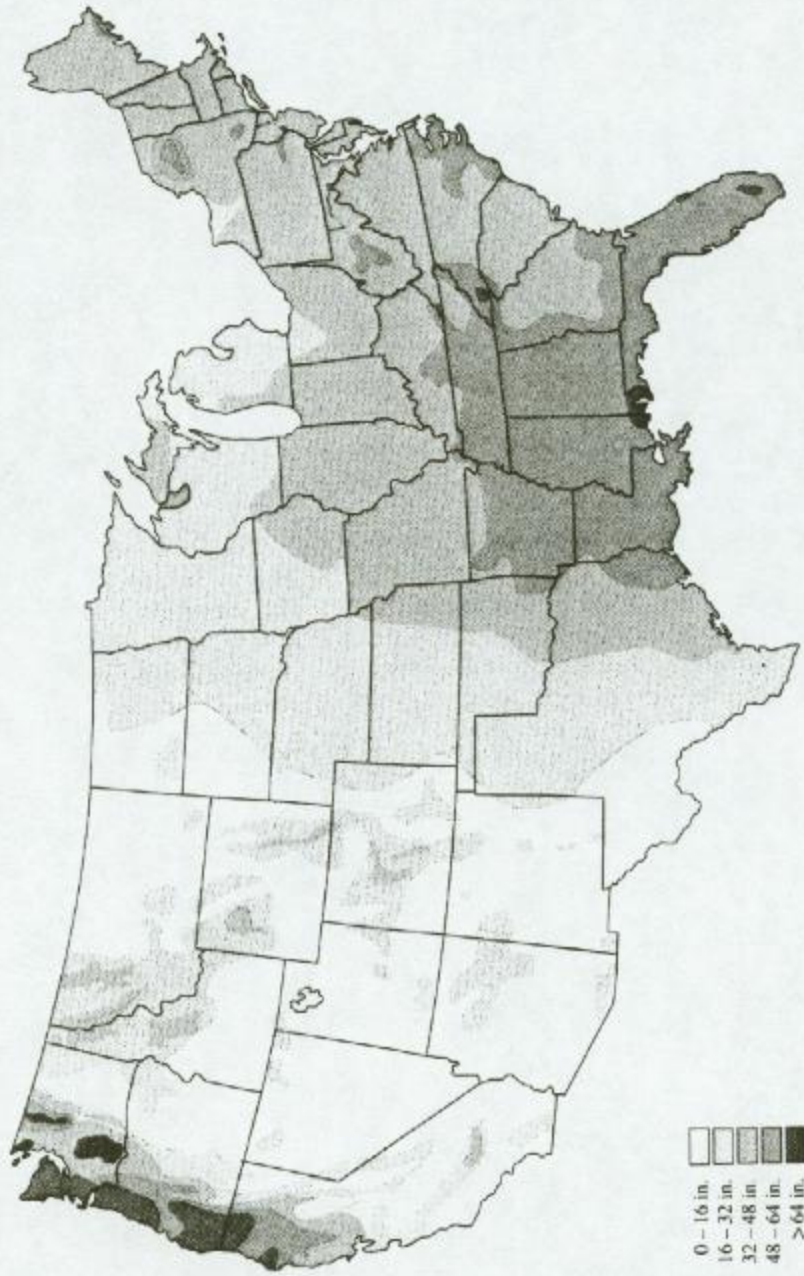
Precipitation varies in space and time according to the general pattern of atmospheric circulation and according to local factors. The average over a number of years of observations of a weather variable is called its *normal* value. Figure 3.3.5 shows the normal monthly precipitation for a number of locations in the United States. Higher precipitation occurs near the coasts than inland because the oceans supply the bulk of the atmospheric moisture for precipitation. Areas to the east of the Cascade mountains (e.g., Boise, Idaho) have lower precipitation than those to the west (e.g., Seattle, Washington) because much of the moisture in the predominantly westerly air flow in the mid-latitudes is extracted as the air rises over the mountains.

Pronounced seasonal variation in precipitation occurs where the annual oscillation in the atmospheric circulation changes the amount of moisture inflow over those regions (e.g., San Francisco and Miami). This pattern is illustrated in Fig. 3.3.6, which shows the normal monthly precipitation for various locations in the United States. Precipitation is very variable in the mountain states in the west where orographic effects influence precipitation. Precipitation increases going east across the great plains and is spatially more uniform in the east than in the west. Precipitation variability for the world is shown in Fig. 3.3.7. The average annual precipitation on the land surface of the earth is about 800 mm (32 in), but great variability exists, from Arica, Chile, with an annual average of 0.5 mm (0.02 in) to Mt. Waialeale, Hawaii, which receives 11,680 mm (460 in) per year on average.

### 3.4 RAINFALL

Rainstorms vary greatly in space and time. They can be represented by *isohyetal maps*; an *isohyet* is a contour of constant rainfall. Figure 3.4.1 shows an isohyetal map of total rainfall depth measured for two storms: one a storm of May 30–June 1, 1889, which caused about 2000 deaths in Johnstown, Pennsylvania, following a dam failure, and the other a storm of May 24–25, 1981, in Austin, Texas, which caused 13 deaths and \$35 million in property damage (Moore, et al., 1982). The Johnstown storm is plotted on a scale 50 times larger than the Austin storm. The maximum depth of precipitation in both storms is nearly the same ( $\approx 10$  in), but the Austin storm was briefer and more localized than the Johnstown storm. The Austin storm was caused by a convective cell thunderstorm of the type analyzed in Example 3.3.2.

Isohyetal maps are prepared by interpolating rainfall data recorded at gaged points. A rain gage record consists of a set of rainfall depths recorded for



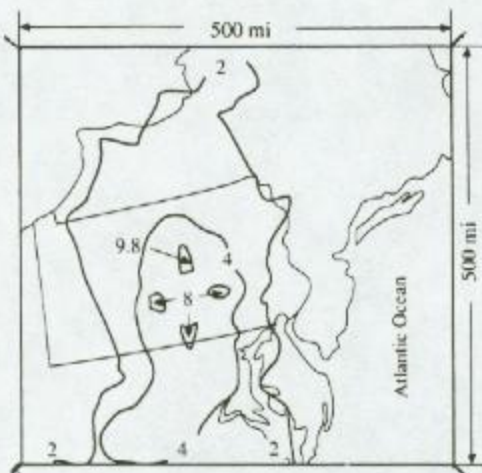
**FIGURE 3.3.5**  
 Mean annual precipitation in the U.S.A. in inches (1 in = 25.4 mm). (Adapted from *Climatic Atlas of the U.S.*, U.S. Environmental Data Service, U.S.G.P.O., pp. 43-44, June, 1968.)



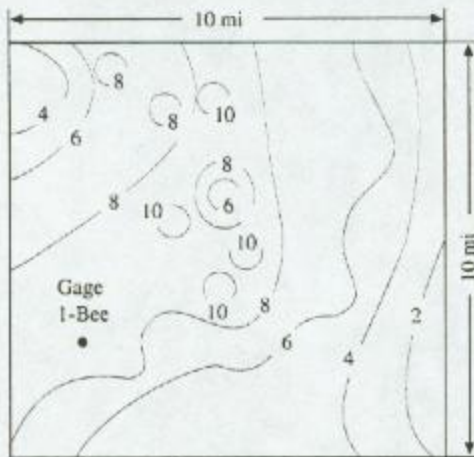
**FIGURE 3.3.6**  
 Normal monthly distribution of precipitation in the U. S. A. in inches (1 in = 25.4 mm). (Adapted from *Climatic Atlas of the U.S., U.S. Environmental Data Service, U.S.G.P.O., pp. 43-44, June, 1968.*)

A I T T A A A





(a) Storm of May 30—June 1, 1889, which produced the Johnstown flood in Pennsylvania. Maximum rainfall of 9.8 in. recorded over 18 hour period at Wellsboro, Pennsylvania. Isohyets are in inches depth of total rainfall in the storm. (Source: U.S. Army Corps of Engineers, 1943.)



(b) Storm of May 24—25, 1981, in Austin, Texas. Maximum rainfall of 11 in. recorded over 3 hours. Isohyets are in inches depth of total rainfall in the storm. (Source: Massey, Reeves, and Lear, 1982.)

**FIGURE 3.4.1**

Isohyetal maps for two storms. The storms have about the same maximum depth of point rainfall, but the Johnstown storm covered a much larger area and had a longer duration than did the Austin storm.

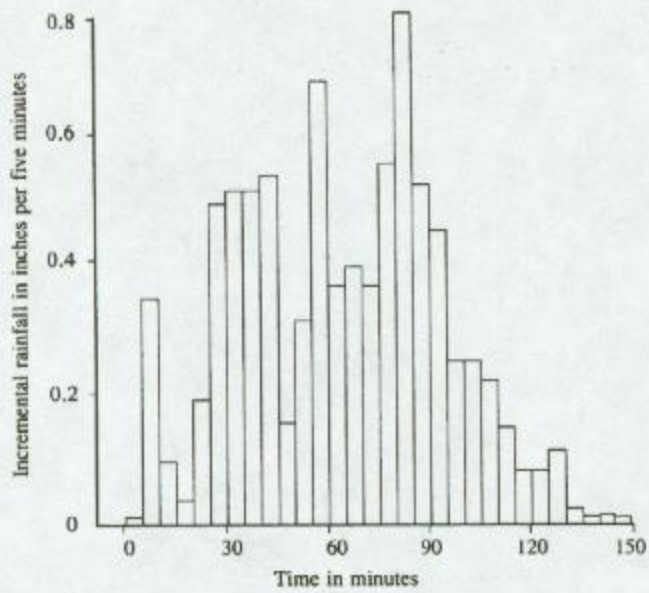
successive increments in time, as shown in Table 3.4.1 for the data in 5-minute increments from gage 1-Bee in the Austin storm. A *rainfall hyetograph* is a plot of rainfall depth or intensity as a function of time, shown in the form of a histogram in Fig. 3.4.2(a) for the 1-Bee data. By summing the rainfall increments through time, a *cumulative rainfall hyetograph*, or *rainfall mass curve*, is produced, as shown in Table 3.4.1 and Fig. 3.4.2(b).

The maximum rainfall depth, or intensity, (depth/time) recorded in a given time interval in a storm is found by computing a series of running totals of rainfall depth for that time interval starting at various points in the storm, then selecting the maximum value of this series. For example, for a 30-minute time interval, Table 3.4.1 shows running totals beginning with 1.17 inches recorded in the first

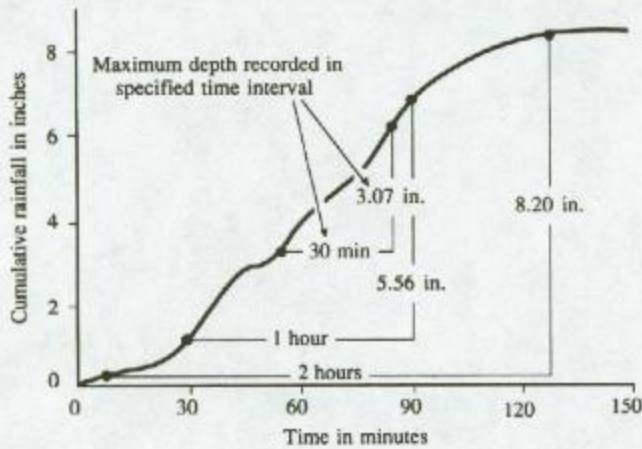
TABLE 3.4.1  
Computation of rainfall depth and intensity at a point

Time (min)	Rainfall (in)	Cumulative rainfall	Running Totals		
			30 min	1 h	2 h
0		0.00			
5	0.02	0.02			
10	0.34	0.36			
15	0.10	0.46			
20	0.04	0.50			
25	0.19	0.69			
30	0.48	1.17	1.17		
35	0.50	1.67	1.65		
40	0.50	2.17	1.81		
45	0.51	2.68	2.22		
50	0.16	2.84	2.34		
55	0.31	3.15	2.46		
60	0.66	3.81	2.64	3.81	
65	0.36	4.17	2.50	4.15	
70	0.39	4.56	2.39	4.20	
75	0.36	4.92	2.24	4.46	
80	0.54	5.46	2.62	4.96	
85	0.76	6.22	<b>3.07</b>	5.53	
90	0.51	6.73	2.92	<b>5.56</b>	
95	0.44	7.17	3.00	5.50	
100	0.25	7.42	2.86	5.25	
105	0.25	7.67	2.75	4.99	
110	0.22	7.89	2.43	5.05	
115	0.15	8.04	1.82	4.89	
120	0.09	8.13	1.40	4.32	8.13
125	0.09	8.22	1.05	4.05	<b>8.20</b>
130	0.12	8.34	0.92	3.78	7.98
135	0.03	8.37	0.70	3.45	7.91
140	0.01	8.38	0.49	2.92	7.88
145	0.02	8.40	0.36	2.18	7.71
150	0.01	8.41	0.28	1.68	7.24
Max. depth	0.76		3.07	5.56	8.20
Max. intensity (in/h)	9.12		6.14	5.56	4.10

30 minutes, 1.65 inches from 5 min to 35 min, 1.81 inches from 10 min to 40 min, and so on. The maximum 30 minute recorded depth is 3.07 inches recorded between 55 min and 85 min, corresponding to an average intensity of  $3.07 \text{ in}/0.5 \text{ h} = 6.14 \text{ in/h}$  over this interval. Table 3.4.1 shows similarly computed maximum depths and intensities for one and two-hour intervals. It can be seen that as the time period increases, the average intensity sustained by the storm decreases (5.56 in/h for one hour, 4.10 in/h for two hours), just as the average intensity over an area decreases as the area increases, as shown in Fig. 3.4.1. Computations



(a)



(b)

**FIGURE 3.4.2**

Incremental and cumulative rainfall hyetographs at gage 1-Bee for storm of May 24-25, 1981 in Austin, Texas.

of maximum rainfall depth and intensity performed in this way give an index of how severe a particular storm is, compared to other storms recorded at the same location, and they provide useful data for design of flow control structures. An important fact to be determined from historical rainfall records is the average depth of rainfall over an area such as a watershed.