2. Storm Type For the purpose of estimating the PMP for a specific basin, rainstorms can be classified as "general-storms" or "local-storms." For a project basin with a critical duration of 6 hours or less, a local-storm PMP generally would produce the PMF. For a critical duration of more than 24 hours, a general-storm PMP normally would be more critical. For a critical duration of 6 to 24 hours, a 6- or 12-hour local storm and a 24-hour general storm should be analyzed to determine whether the local- or general-storm PMP would be more critical.

3. Generalized Estimates For most of the United States, generalized PMP has been estimated and published by the NWS in collaboration with other agencies including the USACE, the USBR, the Tennessee Valley Authority (TVA), and the Soil Conservation Service (SCS), (NWS Hydrometeorological Reports No. 33–56, 1956–88). Fig. 8.7 shows the regions covered by these studies.

These publications describe in considerable detail how the generalized PMP estimates were made. The procedures used differ from region to region depending on the physiographic and meteorological characteristics of the region. The resulting Hydrometeorological Reports (HMRs) also differ in the sizes of drainage areas considered as well as the degree of detail given. In the studies for mountainous regions, topographic control sometimes cannot be shown in the detail required for some small drainage areas. For the region east of the 105th meridian, PMP can be estimated for a storm area of any size (HMR 51, 1978) and the spatial as well as temporal distributions can be determined (HMR 52, 1982). Studies for the other regions do not give this much detail.

Some judgment on the level of the generalized PMP estimates can be obtained by comparison with the greatest known rainfalls of record (Riedel and Schreiner, 1980). This study presents maps showing rainfall that is equal to or greater than 50% of the PMP. Fig. 8.8 is an example of the 30 maps, each for a different combination of area sizes (25.9 to 51,800 km^2) and durations (6 to 72 hours). This figure shows that for 25.9 km^2 (10 mi^2) and 24 hours there were 32 separate rainfalls greater than or equal to 50% of PMP east of the Continental Divide and 54 cases for west of the Divide. Some observations from the referenced study are:

a) For a given area and duration, some large regions east of the Continental Divide have no storms greater than or equal to 50% of PMP. However, within the same regions, there often are storms greater than or equal to 50% of PMP in adjacent area sizes and durations.
b) In western states, values greater than or equal to 50% are concentrated along the Sierra Nevada and Cascade Ranges. Storms approaching PMP can be expected more often in these wet regions than in dry regions.
c) The relative lack of storms greater than or equal to 50% of PMP in the east compared to the west is most likely due to a few very extreme storms in the east, which when transposed to compute PMP, far exceed most observed values.

The last observation is supported by the fact that there are 19 storms in the east and 13 storms in the west where the rains are greater than or equal to 70% of PMP for 25.9 km^2 and 24 hours. There are also other factors that enter into the comparisons, such as the number of major storms that have been studied in detail and the number of observation stations and the length of record.

4. Site-Specific Study There are basins of unique topographic characteristics where generalized PMP estimates cannot be properly applied. Under such conditions, or in areas where generalized PMP estimates are not available for the size of the drainage area, a site specific study may be needed (Wang, 1986).

The Hydrometeorological Reports are a good source for learning how such a study can be carried out. Further guidance can be obtained from a PMP manual (WMO, 1986). It has been shown that a meteorologist experienced in estimating extreme rainfall is required to properly make a PMP estimate. Major steps to be considered include:

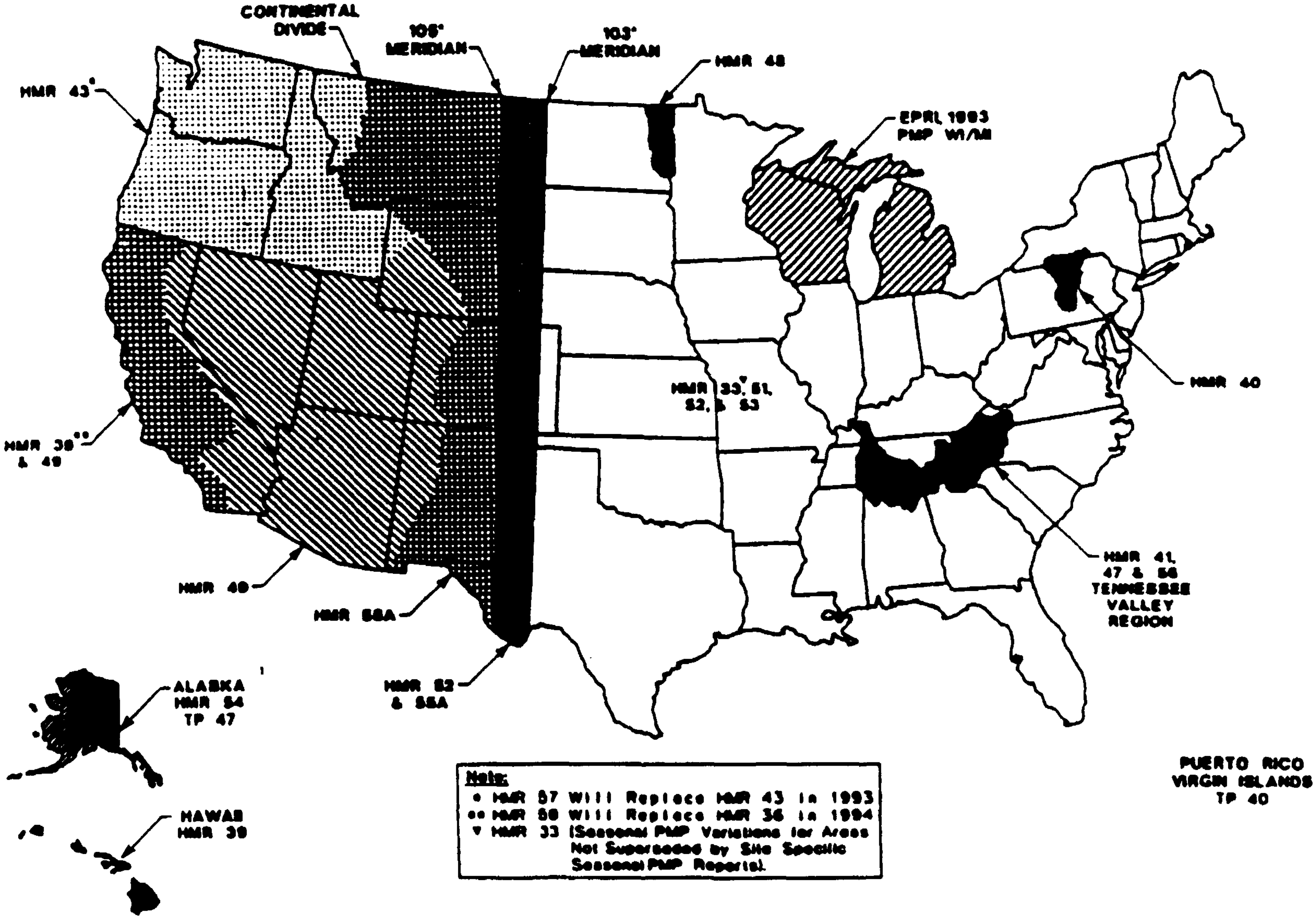

Figure 8.7—Regions Covered by Generalized PMP Studies.

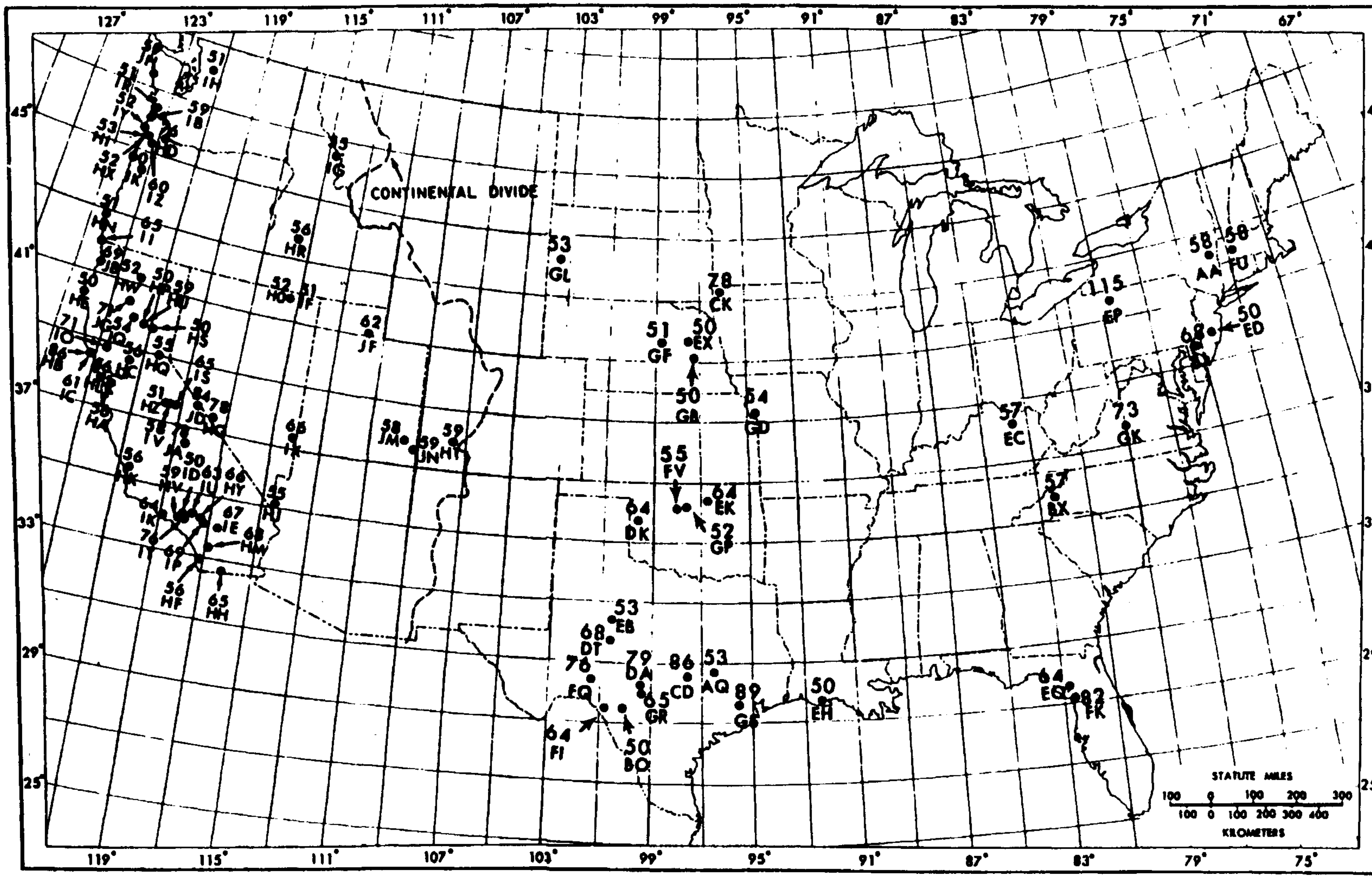

Figure 8.8—Observed 24–hour, 25.9 km^2*(10 sq. mi.) Rainfall Quantities Expressed as Percent of All-Season PMP Estimates.*

a) determination of critical storm duration for the site,
b) definition of a meteorologically homogeneous region surrounding the site,
c) identification of major storms that have occurred in the region,
d) determination if these storms could occur on the site,
e) preparation of isohyetal maps for the qualifying storms,
f) determination of moisture maximization factors for candidate storms (including elevation adjustments),
g) transposition of candidate storms adjusted for maximum moisture,
h) further adjustment of each storm for differences in topography between the storm location and the site,
i) determination of temporal distribution for critical storms, and
j) envelopment of the transposed and adjusted storm depths to obtain the estimate of PMP.

It should be noted that no two PMP studies have been carried out in exactly the same way. Topographic problems, availability of records on major historic storms and other meteorological data for a "sufficient" length of time are some reasons why each site-specific PMP study differs from others.

C. Transformation of PMP to PMF

Transformation of a PMP to the PMF is generally accomplished by the more conventional unit hydrograph method or the computer-based simulation model discussed earlier in this chapter. In applying either method, a careful reconnaissance of the project basin is needed. It is also important to divide the basin into a number of sub-basins so that the areal variation of rainfall and basin characteristics can be properly incorporated. The basin is divided so that areal variation in rainfall, soil, vegetative cover, and topography within each sub-basin would be as small as practicable. For most cases, five to fifteen sub-basins are required except for very small basins.

The consideration of antecedent and/or subsequent storms, snowmelt, and base flow are important in the transformation of a PMP to the PMF. These subjects are discussed earlier in this chapter.

D. Greatest Rainfalls and Floods of Record

Before a PMF estimate is adopted for design purposes, its reasonableness is often investigated further by comparing the PMP and PMF with greatest storms and floods of record.

Fig. 8.9 shows the world's greatest observed point rainfalls, while Table 8.2 gives the greatest observed rain depths in the United States for selected area sizes and durations. These data can be compared with PMP estimates to check their reasonableness; however, geographical, meteorological, and topographic similarities between the study areas and the record storms used for comparison should be carefully evaluated and taken into consideration. For example, the 2,590 km^2 (1,000 mi^2) 24-hour rainfall of 767 mm (30.2 in.) in the table recorded at Yankeetown, Florida potentially could occur at other locations in the southeastern United States, but not in the Rocky Mountain region of Colorado.

Table 8.3 (Riedel, 1990) is similar to Table 8.2 but also includes maximum values from Taiwan, India, and China, where extreme rainfalls are known to occur. This table also can be used as reference for comparison between PMP estimates and record rainfall.

Figs. 8.10 and 8.11 are plots of the data in Tables 8.2 and 8.3 for easier comparison with PMP determined for a specific area size. Bullard (1986) of the USBR has made a comparison of PMF peaks with historical floods for sites throughout the United States.

E. Conservatism of PMF Estimates

Attempts have been made by many researchers to assign a probability of exceedance to PMF. Many meteorological and hydrologic factors affect the estimate of a PMF. The basic approach is to determine

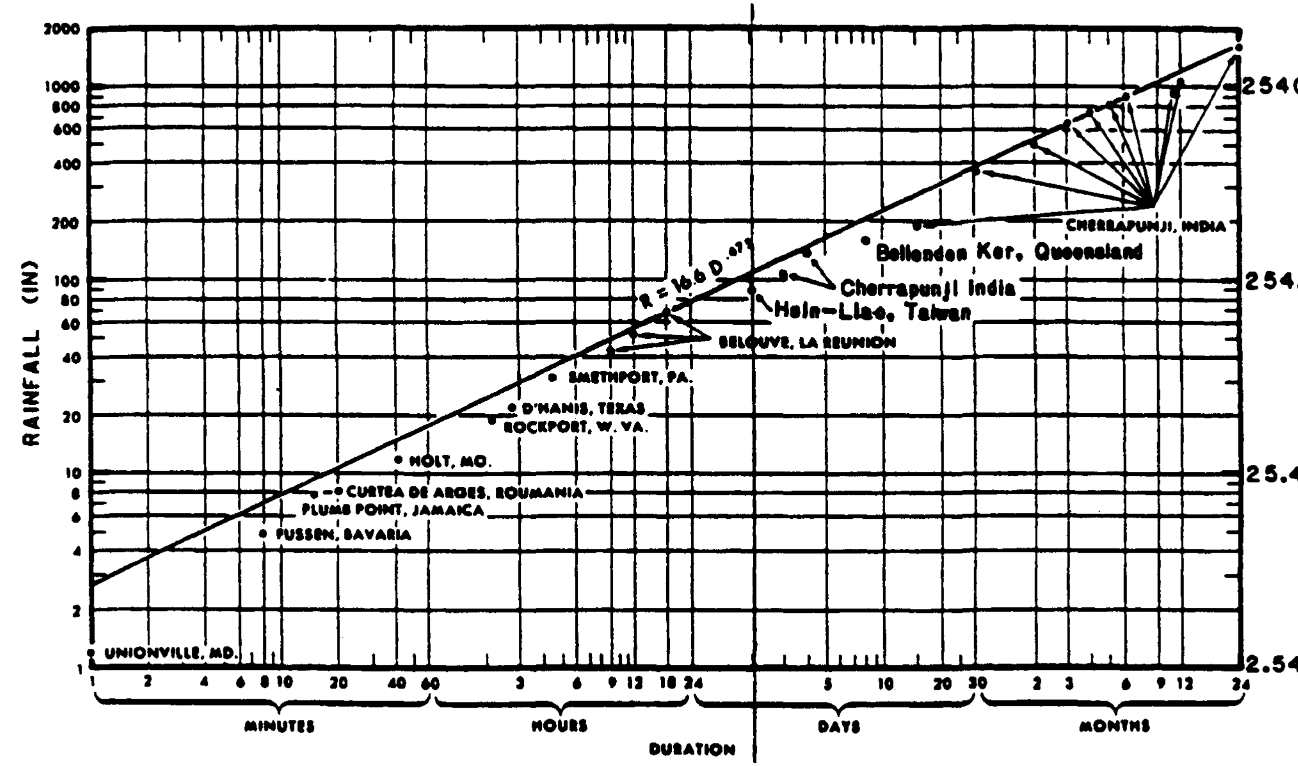

Figure 8.9—World's Greatest Observed Point Rainfalls (WMO, 1969).

TABLE 8.3. Maximum known observed depth–area–duration data for Taiwan, China, India, and the United States (average rainfall in millimetres (and inches).

Area	Duration (h) 6	12	18	24	36	48	72
25.9 km²	627a	757b	1036c	1232c	1488c	1585c	—
10 mi²	(24.7)	(29.8)	(40.8)	(48.5)	(58.6)	(62.4)	—
259 km²	526r	716s	950c	1166c	1405c	1473c	1680c
100 mi²	(20.7)	(28.2)	(37.4)	(45.9)	(55.3)	(58.0)	(66.1)
518 km²	500r	686r	925c	1120c	1354c	1412c	1565c
200 mi²	(19.7)	(27.0)	(36.4)	(44.1)	(53.3)	(55.6)	(61.6)
1295 km²	452d	625c	856c	1036c	1242c	1308c	1380c
500 mi²	(17.8)	(24.6)	(33.7)	(40.8)	(48.9)	(51.5)	(54.3)
2590 km²	381d	594c	744c	881c	1062c	1113c	1240c
1000 mi²	(15.0)	(23.4)	(29.3)	(34.7)	(41.8)	(43.8)	(48.8)
5180 km²	284b	450e	572e	630e	693e	859f	1095c
2000 mi²	(11.2)	(17.7)	(22.5)	(24.8)	(27.3)	(33.8)	(43.1)
12950 km²	206bh	282b	358b	472f	475f	734f	882t
5000 mi²	(8.1)	(11.1)	(14.1)	(18.6)	(18.7)	(28.9)	(34.7)
25900 km²	145h	201j	257k	371f	384i	587f	743t
10000 mi²	(5.7)	(7.9)	(10.1)	(14.6)	(15.1)	(23.1)	(29.2)
51800 km²	102h	152j	201k	264f	295i	424f	595t
20000 mi²	(4.0)	(6.0)	(7.9)	(10.4)	(11.6)	(16.7)	(23.4)
129000 km²	64km	107n	135k	160k	201k	279g	389g
50000 mi²	(2.5)	(4.2)	(5.3)	(6.3)	(7.9)	(11.0)	(15.3)
259000 km²	43m	64mo	89k	109k	152p	170p	226q
100000 mi²	(1.7)	(2.5)	(3.5)	(4.3)	(6.0)	(6.7)	(8.9)

Storm	Date	Location of Center
a	17-18 July 1942	Smethport, PA, US
b	8-10 September 1921	Thrall, TX, US
c	11 September 1963	Peishih, Taiwan
d	7 August 1959	Tahushan, Taiwan
e	3-7 September 1950	Yankeetown, FL, US
f	17-18 September 1880	Uttar Pradish, India
g	26-28 July 1927	Gujarat, India
h	27 June–4 July 1936	Bebe, TX, US
i	27 June–1 July 1899	Hearne, TX, US
j	12-16 April 1927	Jefferson Parish, LA, US
k	13-15 March 1929	Elba, AL, US
m	22-26 May 1900	Chattanooga, OK, US
n	15-18 April 1900	Eutaw, AL, US
o	19-22 November 1934	Millry, AL, US
p	29 September–3 October 1929	Vernon, FL, US
q	5-10 July 1916	Bonifay, FL, US
r	7 August 1975	Linzhuanz, Henan, China
s	1 August 1977	Muduocaidang, NeiMongal, China
t	4 July 1935	Nishi, Hunan, China

Source: World Meteorological Organization, 1986 with addition of Chinese data.

the probability of exceedance of each maximized factor and compute the joint probability of these factors occurring simultaneously; however, this approach is practically impossible because:

1) the recurrence interval of any maximized individual factor that is much longer than the length of historical record is difficult to determine; and
2) the computation of joint probability from the exceedance probabilities of individual factors is difficult when the interactions between the factors are not completely known.

An alternative approach, though less rigorous and somewhat subjective, has been proposed (Wang and Revell, 1983) to measure the relative conservatism of a PMF estimate. By knowing how conservative the

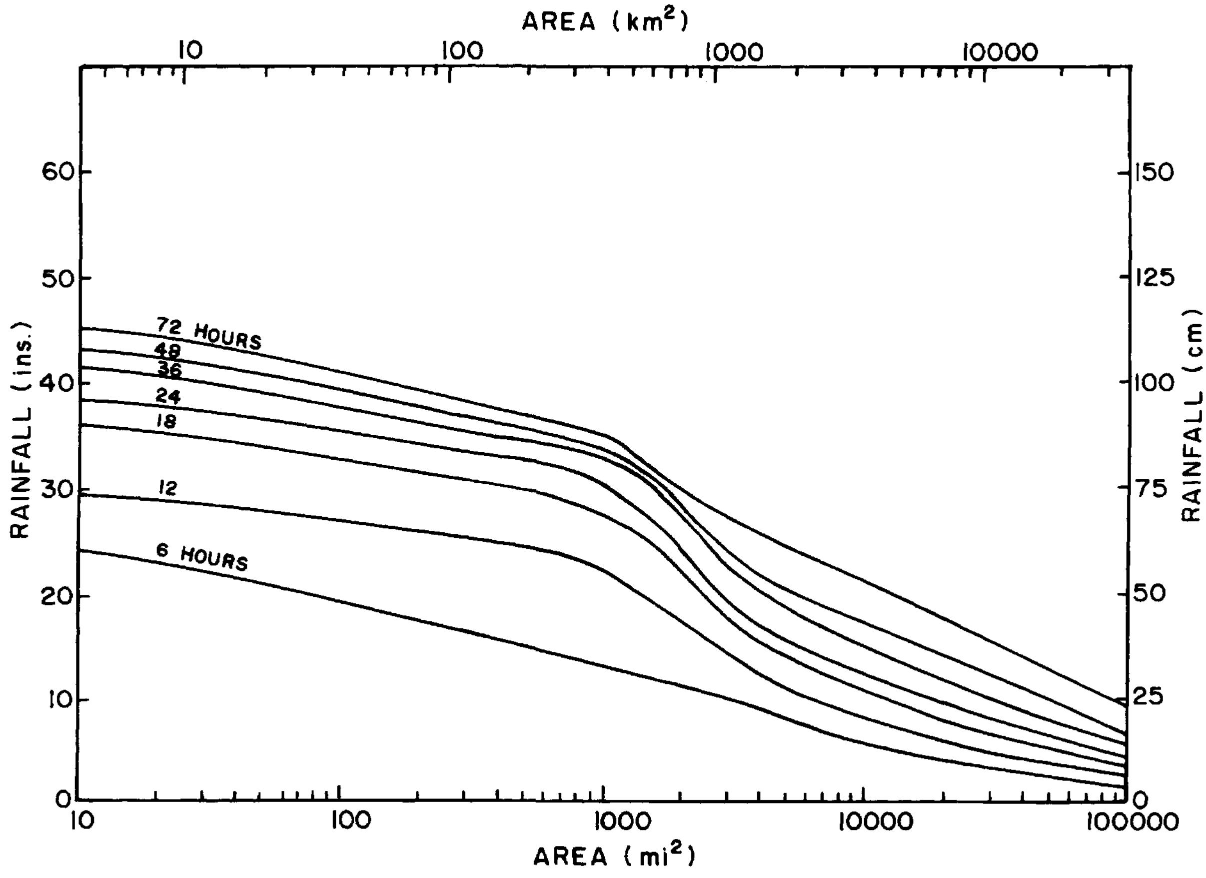

Figure 8.10—Maximum Known Observed Depth–Area–Duration Data for the U.S. (Table 8.2).

estimated PMF is, the engineer will be able to make a better decision as to how the estimate should be used in the design of the project. For example, a smaller or larger freeboard may be considered depending on whether the estimate is conservative or otherwise.

F. Standard Project Flood

The standard project flood (SPF) as defined by the USACE (1952) is a "hydrograph representing runoff from the Standard Project Storm (SPS)." As the PMF, it is a hypothetical flood, estimated by transforming the SPS. The SPS is the most severe storm that is considered "reasonably characteristic" of a region. It often undercuts storms of extraordinary severity and has been assumed to be approximately 40–60% of the PMP.

Estimation of the SPS can be best accomplished by following the procedures prescribed by the USACE (1952). Transformation of an SPS to the SPF can follow the procedure for transforming a PMP to the PMF. The SPF has been used to evaluate certain features of flood control projects and to identify flood plain, primarily by the USACE.

VI. FLOOD HAZARD AND FLOOD WARNING

As defined earlier in this chapter, a flood is an overflow on lands that are not ordinarily covered by water. When the land is in use by humans, the overflow causes damages to crops, property, and infrastructure and, at times, results in loss of human life.

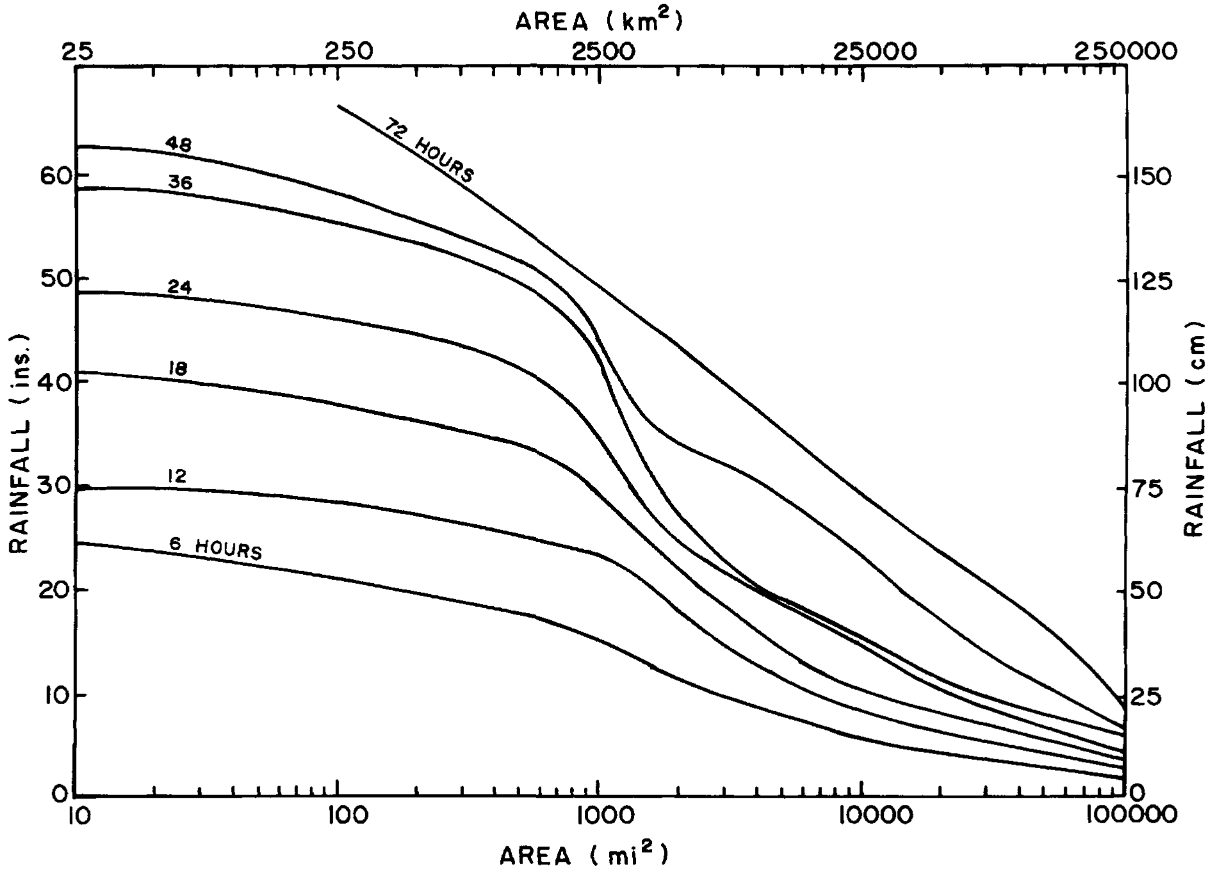

Figure 8.11—Plot of Maximum Known Observed Depth–Area–Duration Data for Taiwan, China, India, and the United States (Table 8.3).

Flood hazards are evaluated by the extent of inundation in the flood plains. The maximum depth and duration of inundation as well the rate of rise in flood level are the major factors that determine the flood severity; however, velocity of flow can be a factor. A slow rising flood may allow sufficient time to relocate the movable properties to safe places, resulting in minimum damages and no loss of life, but a fast rising flood can cause major damages and loss of life.

A series of land-use and flood-severity maps are generally available to assess potential damages due to flood. A real-time flood forecast and warning can predict the timing and extent of inundation prior to the occurrence of a flood and thus help to reduce the potential damages. Emergency action plans are available in many flood-prone communities to evacuate people to predesignated safe locations during catastrophic floods.

A. Evaluation of Potential Hazards

Total flood damage is one important indication of a potential flood hazard. The first step in estimating flood damages is to assess the severity of the flooding produced by a given flood event. The most important measures of flood severity are the areal extent of flooding, the depth of flooding at each selected location (buildings, warehouses, cropped land, etc.), and the duration of flooding. Other factors determining the severity are the time to reach the maximum depth, flow velocity, sediment concentration, and season of occurrence.

Generally, the flood damage potential at critical locations within the flood plain is determined by combining two types of maps (James and Lee, 1971):

1) A series of land-use maps, each indicating details of development including agricultural area (cropping pattern and seasonality), residential and industrial buildings, and other infrastructure. These maps are time-variant and are periodically updated.
2) A series of maps showing lines of equal inundation depth in the flood plain. These maps also are time-variant and should be updated depending upon the changes in the watershed land use and flood plain development. The maps are prepared for major historical floods and floods of various frequencies.

The areal extent and depth of inundation are best determined from historic flood data. These inundation depths and resulting damages can be used to develop depth-damage and depth-frequency data. Generally the historical flood damage data are not available for the full range of desired frequencies. Synthetic inundation boundaries and depths at selected structures are determined for flood peaks of various frequencies. These synthetic data are used to assess potential damages. Flood peaks and/or flood hydrographs are determined using the procedures discussed earlier in this chapter and Chapter 6 of the Handbook.

1. Backwater Computations With flood peak data for various exceedance probabilities available, the inundation boundaries, depths, and average flow velocities can be determined through backwater computations. The objective of these computations is to determine the shape of water surface profiles in the open channel and flood plain. Two widely used computer programs for computing water surface profiles are: WSP-2 (USDA, 1976) and HEC-2 (USACE, 1991).

The programs (described in the following section, Microcomputer Softwares for Flood Analysis) are used in flood plain management and flood insurance studies to delineate flood hazard zones and determine floodways. Fig. 8.12 shows typical results of program application—flood profiles for various frequencies (FEMA, 1983). Estimated water surface elevations at various locations are transferred from the profiles to topographic maps to define inundation boundaries for different levels of flooding. The difference between the ground elevation and the water surface elevation indicate the depth of inundation.

Because the water surface profiles correspond to flood peaks, the duration of inundation at a given structure cannot be determined through backwater computations; however, the duration of inundation at selected locations can be estimated from a flood hydrograph and a stage–discharge relationship. The stage causing inundation is used to estimate the corresponding discharge. The hydrograph is then used to determine the time between the rising and falling limb of the hydrograph that the discharge is greater than the critical value. This time duration would then be available for use with the land use maps to estimate the flood damages. Duration is most important when agricultural damages are to be estimated.

2. Dam Break Analysis Dams are constructed to provide benefits such as water supply, irrigation, hydropower, flood control, and recreation; however, dam failure can cause catastrophic flooding in the downstream valley due to sudden release of impounded water. Depending upon the quantity of the stored water and the height of the dam, the flood peak can greatly exceed all known previous floods. The warning time available can also be much shorter compared to the time for a precipitation-induced flood.

The International Commission on Large Dams (ICOLD, 1973) and the United States Committee on Large Dams, in cooperation with the American Society of Civil Engineers (ASCE/USCOLD, 1975) have reported that about 38% of all dam failures are caused by inadequate spillway capacity with the dam subsequently being breached. About 33% of dam failures are caused by seepage or piping through the dam or along internal conduits, about 23% from foundation problems and about 6% by slope embankment slides, damage, or liquefaction of earthen dams from earthquakes, and landslide-generated waves within the reservoir. All these scenarios can result in dam failure and breaching. Johnson and Illes (1976) and Jansen (1988) have summarized major dam failures.

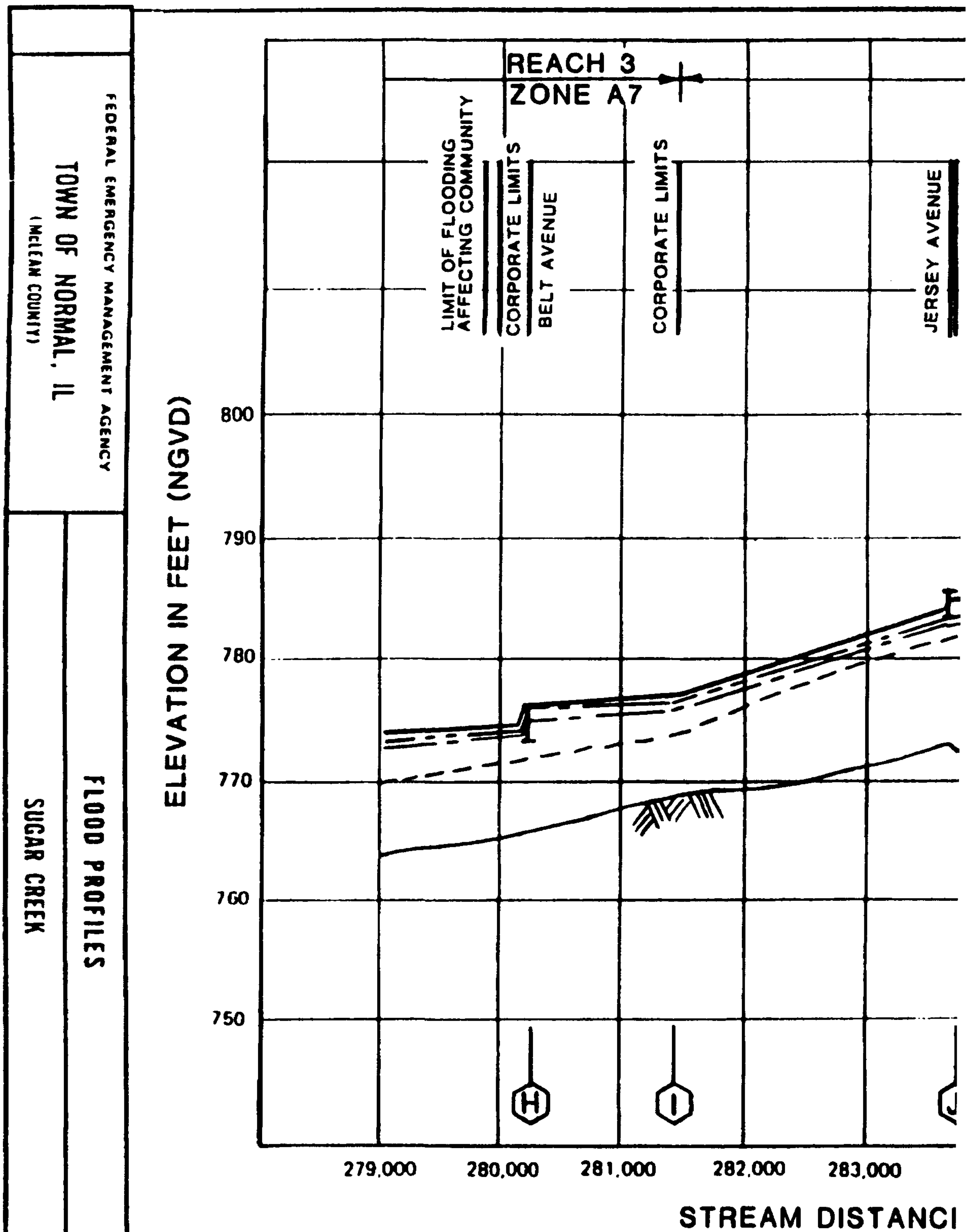

Figure 8.12—Flood Profiles for Various Return Periods.