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TECHNICAL PAPER NO. 38

Generalized Estimates of Probable Maximum Precipitation for the United States West of the 105th Meridian

for Areas to 400 Square Miles and Durations to 24 Hours

Prepared by
Cooperative Studies Section
Hydrologic Services Division
U.S. Weather Bureau
for

Engineering Division
Soil Conservation Service
U.S. Department of Agriculture

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NOTE

The estimates of probable maximum precipitation presented herein have been superseded for some regions by the results of studies made since the first printing of Technical Paper No. 38 in 1960. Revised estimates have been published for California: "Interim Report, Probable Maximum Precipitation in California," Hydrometeorological Report No. 36, October 1961. Estimates for the United States portion of the Columbia River Basin have been revised but not yet published. Plans call for publication under the title, "Probable Maximum Precipitation, Northwest States," Hydrometeorological Report No. 43, which probably will not be available until late 1966.

Some of the maximum observed precipitation amounts reported in Chapters 2 and 4 of Technical Paper No. 38, have been exceeded since it was first issued. Since, in general, most of the information on precipitation contained herein is up to date, and much of it is not available elsewhere in published form, Technical Paper No. 38 is being reprinted without change.

Generalized Estimates of Probable Maximum Precipitation for the United States West of the 105th Meridian

for Areas to 400 Square Miles and Durations to 24 Hours

INTRODUCTION

Assignment. Generalized estimates of probable maximum precipitation have been available for the United States east of the 105th meridian for several years. [1]. The need for similar data for the planning and design requirements of the Soil Conservation Service in the region west of the 105th meridian led that agency to cooperate with the Weather Bureau in the preparation of like estimates for that area. This report presents generalized estimates of probable maximum precipitation for areas from a point to 400 square miles and for durations up to 24 hours.

Scope. The engineer who will be using the generalized estimates of probable maximum precipitation presented herein will naturally want to know what these values represent, how they were obtained, how they should be used, and how accurate they are. For these reasons, this report not only deals with the final results but goes into as much detail as appears necessary to provide the engineer with an adequate background for intelligent use of the results.

Accuracy of results. The generalized estimates of probable maximum precipitation presented in this report are the most accurate that can be derived on the basis of the available data and the current stage of meteorological knowledge, particularly concerning storm structure or mechanism. Both these factors will increase and improve with time. It should not be astonishing, therefore, if future data and developments in the field of meteorology should indicate a need for revision of the estimates.

Acknowledgments. The project was under the general supervision of W. T. Wilson, Chief of the Cooperative Studies Section of the Hydrologic Services Division, W. E. Hiatt, Chief. The project leader was J. F. Miller of the Cooperative Studies Section, who personally directed the studies related to the meteorological phase of the project. The statistical phase was developed and the related work conducted by D. M. Hershfield, L. L. Weiss, and W. T. Wilson, all of Cooperative Studies Section. Conferees included Dr. C. S. Gilman, V. A. Myers, and J. T. Riedel, all of the Hydrometeorological Section; M. A. Kohler, Chief Research Hydrologist; J. L. H. Paulhus, Division Staff Hydrologist; A. L. Shands, Assistant Chief of Division; and R. D. Tarble, Radar Hydrologist. Coordination with the Soil Conservation Service was maintained through H. O. Ogrosky, Chief, Hydrology Branch, Engineering Division. Collection and processing of data were performed by R. L. Birchfield, S. L. Briggs, M. R. Caspar, D. J. Foat, N. S. Foat, R. L. Gottschalk, R. B. Holleman, E. C. I'Anson, A. E. Larkin, W. E. Miller, C. Mundt, C. E. Noboa, S. Otlin, C. L. Smith, G. W. Sohns, J. B. Tucker, and A. J. Weinstein. Typing was done by L. L. Nelson and N. S. Foat; drafting by N. Calub, V. Campbell, and C. W. Gardner. The final draft of the text was written by J. L. H. Paulhus and edited by Mrs. L. K. Rubin of the Hydrometeorological Section.

Chapter 1

THE PRECIPITATION PROCESS

1.1 Steps in precipitation process

1.1.1 Knowledge of the process of precipitation formation is required for a thorough understanding of the definition and derivation of probable maximum precipitation (PMP) to be presented in subsequent chapters. The basic steps leading to precipitation are: (1) sufficient atmospheric moisture, (2) cooling of the air, (3) condensation of water vapor into liquid or solid form, and (4) growth of condensation products to precipitation size.

1.2 Atmospheric moisture

1.2.1 Water, in the form of vapor, is always present in the atmosphere. For convenience the amount of water vapor is often given in terms of inches of precipitable water (W_p), which is the depth of water that would be realized over a given area if all the water vapor in the air column above that area were to be condensed and precipitated on that area without loss. There is, of course, no natural precipitation process that will completely remove all water vapor from the atmosphere. Measurements of W_p, usually made by radiosonde, range from a small fraction of an inch to almost 3 inches, depending on the geographical location, meteorological situation, and depth of air column. A partial listing of maximum observed W_p values for several stations in the United States is contained in Weather Bureau *Technical Paper No. 10* [2].

1.2.2 Periods of no rain and clear skies are usually associated with relatively low values of W_p. Cloudiness is usually observed at relatively high values of W_p. When rain is falling, W_p values are usually relatively high, but some of the highest amounts of W_p ever recorded were measured when no rain was falling. It follows, therefore, that other factors must act to produce cloudiness and precipitation.

1.2.3 It is perhaps unfortunate that the term *moisture* has been so carelessly used in hydrometeorology. For some reason moisture is generally understood to refer to water vapor only. Most dictionaries, however, define moisture as applying to the liquid form. The terms "atmospheric moisture," "moisture content," "moisture charge," "moisture supply," etc., as used in hydrometeorological reports generally refer to water vapor only. They are so used in this report except where it is made clear that water in other forms than vapor is included. By definition W_p, of course, refers only to water vapor. Thus, water in the form of cloud droplets, raindrops, or ice crystals is not generally included in any evaluation of the above terms (never in W_p), although water in these forms is often present in the atmosphere in relatively large quantities (ch. 2).

1.3 Cooling of air

1.3.1 As stated in paragraph 1.2.1, there is always some water vapor, or W_p, in the atmosphere. Naturally, there is an upper limit to the amount of water vapor in a given mass or volume of air. This upper limit is a function of the air temperature. For practical purposes, the air may be considered to be saturated when it contains the maximum amount of water vapor, or W_p, for its temperature. Lowering the temperature of the air will reduce its capacity for water vapor. Consequently, air of a given temperature having less than the maximum amount of water vapor for that temperature (in other words, unsaturated air) can become saturated without the addition of moisture if it is cooled down to the temperature for which the actual amount of water vapor present would produce saturation. The temperature to which air must be cooled, at constant pressure and constant water-vapor content, to effect saturation is called the *dewpoint*. Condensation (sec. 1.4) usually occurs at or near the saturation point.

1.3.2 Air may be cooled by several processes, but adiabatic cooling by reduction of pressure through lifting is the only natural process by which large masses of air can be cooled rapidly enough to produce appreciable precipitation. The rate and amount of precipitation depend largely on the rate and amount of cooling and the rate of inflow of moisture into the precipitation-producing mechanism to replace the vapor that is condensed and precipitated.

1.3.3 The lifting required for the rapid cooling of large air masses can be produced either by (1) horizontal convergence of the atmosphere, (2) frontal lifting, (3) orographic lifting, and/or (4) atmospheric instability. More often than not, two or more of these processes are active in producing the lifting associated with the heavier rainfall intensities and amounts. All four act simultaneously in some situations.

1.3.4 *Horizontal convergence*, commonly referred to simply as *convergence*, occurs when the pressure and wind fields act to concentrate inflow of air into a particular area, for example, a low-pressure area. If this convergence takes place in the lowest layers of the atmosphere, the tendency to pile up forces the air upward, resulting in its cooling.

1.3.5 *Frontal lifting* takes place when relatively warm air flowing towards a colder, hence denser, air mass is forced upward as the cold air acts as a wedge. Cold air overtaking warmer air will produce the same result by "wedging" the latter aloft. The surface of separation (strictly speaking, a transition zone) between the two different air masses is called a *frontal surface.* A frontal surface always slopes upward toward the colder air mass, and the intersection of the surface with the ground is called a *front.* A warm frontal surface (between advancing warm air and retreating or stationary cold air) usually has a slope of 1:100 to 1:300. The cold frontal surface (between advancing cold air and retreating warm air) has a steeper slope, usually 1:25 to 1:100. Consequently, the upward velocity component of air forced upward by frontal surfaces alone is usually relatively small, even under strong wind conditions.

1.3.6 *Orographic lifting* occurs when air flowing toward an orographic barrier is forced to rise in order to pass over it. The slopes of orographic barriers are often appreciably steeper than the steepest slopes of frontal surfaces. Consequently, other conditions being equal, air may be cooled much more rapidly by orographic lifting than by frontal lifting.

1.3.7 *Atmospheric instability* may be defined, for the purposes of this report, as a state in which the vertical temperature and/or moisture distribution is such that if a quantity of air is given an initial upward impulse, it will tend to continue rising because of having a lower density than the surrounding air—in other words, buoyancy, Unsaturated air rising in the atmosphere cools practically adiabatically; that is, without heat being added or removed. The adiabatic lapse rate, or change of temperature with elevation, is about 5.4 F.° per 1,000 ft. Rising saturated air behaves in a similar manner except that, because of the latent heat released by condensation, it cools at a slower rate. For practical purposes, ascending saturated air is considered to cool pseudoadiabatically; i.e., the water is precipitated immediately upon condensation. The pseudoadiabatic lapse rate increases with elevation because the moisture content of saturated air (hence, amount of latent heat of condensation released) decreases with elevation. It averages about 3.3 F.° per 1,000 ft. in the lower layers of the atmosphere and approximates the dry-adiabatic lapse rate (5.4 F.°/1,000 ft.) at high altitudes. A layer of unsaturated or saturated air with a vertical temperature gradient tending to exceed the dry-adiabatic or pseudoadiabatic lapse rate, respectively, is thus unstable since the temperature of a lifted parcel of air is warmer than that of the surrounding air.

1.3.8 Instability may also be realized in an unsaturated air mass having a lapse rate between the dry-adiabatic and the pseudoadiabatic. If, within this air mass, a parcel of air having a relatively high moisture content is lifted high enough, it cools dry-adiabatically to the *condensation temperature* at what is called the *lifting condensation level.* Above that level the parcel cools at the much slower pseudoadiabatic rate. As the lapse rate of the air mass is greater than the pseudoadiabatic, there is a level, called the *level of free convection*, where the temperature of the lifted parcel is the same as that of the surrounding air. Above the level of free convection the ascending parcel is warmer, hence lighter, than the surrounding air and continues to rise through buoyancy even if no other lifting forces exist.

1.3.9 Instability may also result from the lifting of a layer of air having a relatively high vapor content at the bottom and being relatively dry at the top. When lifted, the lower part of the layer soon reaches the lifting condensation level, above which it cools at the pseudoadiabatic rate. The top part of the layer, being relatively dry, cools at the more rapid dry-adiabatic rate. Continued lifting results in an increase of the vertical temperature gradient of the layer until the instability of the layer is realized.

1.3.10 As discussed in paragraphs 1.3.7–1.3.9, the instability of an air mass is released when the lapse rate is increased until it reaches critical values. The increase may originate from: (1)

lifting associated with horizontal convergence, (2) frontal lifting, (3) orographic lifting, (4) heating of the base of an air column, and/or (5) radiational nighttime cooling of cloud tops. The lifting processes were explained in paragraphs 1.3.3.–1.3.6. The methods by which instability may be induced thermally are not difficult to understand. The heat supplied by the ground to the base of an air mass by conduction acts to produce steep lapse rates in the daytime. The steepest lapse rates from this source usually occur in the afternoon when the ground is warmest. The high incidence of afternoon thundershowers is an indication of the effectiveness of this source of instability. Nighttime thundershowers, on the other hand, often result from the steepening of the lapse rate in clouds by radiational cooling of the cloud tops while the bases are still receiving heat radiated from the ground.

1.4 Condensation of water vapor into liquid or solid form

1.4.1 One of the most important steps in the production of precipitation is the condensation process by which the water vapor in the atmosphere is converted into liquid droplets or, at low temperatures, into ice crystals. The results of the process are often, but not always, visible in the form of clouds, which are nothing more than airborne liquid water droplets or ice crystals, or a mixture of the two. In the United States the heavier intensities of rainfall have their origin in clouds composed of both water drops and ice crystals (par. 1.5.3).

1.4.2 Saturation does not necessarily result in condensation. Condensation nuclei are required for the conversion of water vapor into droplets. Among the more effective condensation nuclei are certain products of combustion and salt particles from evaporated sea spray. There are usually sufficient condensation nuclei in the air so that it is generally assumed that condensation of water vapor takes place when the air reaches the saturation point.

1.5 Growth of cloud droplets and ice crystals to precipitation size

1.5.1 When air is cooled to below its initial saturation or condensation temperature, and condensation continues, the liquid droplets or ice crystals tend to accumulate in the resulting cloud as the temperature is lowered. The rate at which this excess liquid and solid moisture is precipitated from the cloud depends on (1) the speed of the upward current producing the cooling, (2) the rate of growth of the cloud droplets into raindrops heavy enough to fall through the upward current, and (3) a sufficient inflow of water vapor into the precipitation-producing area to replace the precipitated moisture.

1.5.2 Water droplets in an average cloud usually average about 0.0004 in. in radius and weigh so little that an upward current of only 0.5 ft./min. is sufficient to keep them from falling. Although no definite drop size can be said to mark the boundary between cloud and raindrops, a radius of 0.004 in. has been generally accepted. The radius of most raindrops reaching the ground is usually much greater than 0.004 in. and may reach one-eighth in. Drops larger than this tend to break into smaller drops because the surface tension is insufficient to withstand the distortions the drop undergoes in falling through the air. Drops of one-eighth in. radius have a terminal velocity of about 30 ft./sec., or roughly 20 mi/hr., so that an unusually strong upward current would be required to keep a drop of that size from falling.

1.5.3 Various theories have been advanced in attempts to explain the growth of cloud elements to precipitation sizes. According to Houghton [3] the two principal processes in the formation of precipitation are the ice-crystal and accretion processes, which may operate separately or in combination. The ice-crystal process involves the presence of ice crystals in a supercooled (cooled to below freezing) water cloud. A vapor-pressure gradient from water drops to ice crystals exists because the saturation vapor pressure over water is greater than that over ice. Hence, the ice crystals grow at the expense of the water drops and, under favorable conditions, attain precipitation size. The ice-crystal process is operative only in supercooled water clouds and is most effective at about −15° C. (5° F.).

1.5.4 The accretion, or collision, process is based on the relative velocities of fall and the consequent collisions to be expected between cloud elements of different sizes. The rate of growth by accretion depends upon the initial range of particle sizes, the size of the largest drops, the drop concentration, and the sizes of the collecting and collected drops. Studies [4] suggest that the electric field and drop charge may affect collision efficiencies and may be important factors in the release of precipitation from clouds. The accretion process operates at any temperature, and its effectiveness is different for solid and liquid particles.

Chapter 2

PRECIPITATION RATES

2.1 Introduction

2.1.1 Precipitation rates are a function of (1) the availability of moisture, and (2) the rate at which the moisture can be converted into precipitation. Both these factors, hence precipitation rates, exhibit marked seasonal and geographic variations and are not completely independent of one another.

2.1.2 Gage measurements of precipitation rates may occasionally be very inaccurate. Although measurements, in general, tend to be too low, some of the higher rates measured are difficult to explain on the basis of current theories of precipitation formation. Areal measurements, which involve interpolation and extrapolation of gage measurements, are also subject to appreciable error.

2.1.3 Since the results of this report are to be used as design criteria for hydraulic structures controlling streamflow from watersheds not exceeding 400 sq. mi., the primary concern is with high rainfall rates for durations of no more than 24 hr. Rainfall for lower intensities and longer durations is given little consideration.

2.2 Availability of moisture

2.2.1 The rate at which moisture is made available to the precipitation-producing, or storm, mechanism is a very important factor in determining the precipitation rate. If it were not for the continuing moisture supply into a storm, the total amount of precipitation produced could not exceed the maximum amount of W_p plus liquid water in the air above the precipitation area, or a total of about 6 to 7 in. in southern United States. Storms producing more than 7 in. of precipitation are fairly common so there must be some replenishment of the atmospheric moisture precipitated when greater amounts of precipitation are observed. Actually, it is very likely the above extreme amount of water in the air has never been observed and since no natural precipitation process removes all water vapor from the air, replenishment is a very important factor even in storms producing much less than 7 in. of precipitation.

2.2.2 Inflow of air into a storm is a natural feature of any storm mechanism. Lifting of air, the prime cooling factor in the precipitation process (ch. 1), is associated with a horizontal inflow, or convergence, of the air into the space vacated by the ascending air. The inflowing air is in turn lifted, leaving space for a new inflow. The process is, of course, continuous during the storm. The amount of moisture in the inflowing air and the rate of inflow are the two most important factors in determining precipitation rates.

2.2.3 The amount of W_p in the atmosphere varies with (1) distance from the moisture source, (2) latitude, (3) season, and (4) elevation. These effects are clearly indicated in tables and charts of mean W_p over the United States [2]. The chief source of water vapor in the atmosphere is water evaporated from the seas. Consequently, other conditions being equal, air moving inland from the sea has a much higher water-vapor content than does air with a long trajectory over land. Furthermore, since the air temperature determines the upper limit of the water-vapor capacity of the air and since evaporation from a water surface tends to be greater with warmer water temperatures, warm air over a warm body of water has a tendency for higher W_p values. The Gulf of Mexico and Caribbean Sea, for instance, are the most favorable sources of moisture for precipitation in the United States.

2.2.4 W_p values tend to be higher at low latitudes than at high latitudes because the temperature, hence water-vapor capacity of the air, is, in general, higher at low latitudes. Similarly, W_p values tend to be higher in summer than in winter because of the warmer air temperatures.

2.2.5 Other conditions being equal, a thin layer of air naturally contains less W_p than does a thicker layer. Thus, for example, the atmosphere above a high plateau tends to have less W_p than does the atmosphere above low-lying plains. Since air temperatures are generally warmest at low elevations and much of the water vapor is in the lowest levels, W_p in the atmosphere above a high mountain barrier may be much less than that for a similar layer extending down to sea level. Cutting off about 7,000 feet from the bottom of a column of pseudoadiabatic saturated atmosphere reduces W_p by about one-half.

2.2.6 Ascending air may also carry a considerable amount of liquid water in addition to water vapor. Until recently observations of liquid water content of clouds consisted of drops in samples swept out by instruments in airplane probing flights. Using this method, Weickmann and aufm Kampe [5] and Draginis [6] showed that there is a great deal of scatter between the measurements of liquid water content and the amount computed on the basis of moist-adiabatic ascent. The maximum concentration of liquid water they observed was 10 gm./m.^{3} in a cumulonimbus cloud. Tolefson [7] reported a measurement of 9.25 gm./m.^{3} in a cumulonimbus cloud. Probably the highest liquid water content that could be inferred from the samples would be 3 to 4 inches. In more violent storms than can be sampled by airplane probes, where violent updrafts are able to keep large hailstones in suspension, the liquid water content may be higher, but data are lacking.

2.2.7 The liquid water content of clouds can also be measured by radar with varying degrees of precision, giving a three-dimensional integration through time of the water content. Ligda [8] gives an excellent description of the manner in which weather radar operates. Briefly, radio pulses are transmitted and their echoes received and portrayed on a scope. The strength of echo is a function of the mass of liquid water which intercepts and reflects the transmitted beam. Consideration is given to drop-size distribution, strength of beam, distance, attenuation, and other influences. Recent and continuing work with radar may provide much-needed information on the mechanism of condensation and growth of raindrops. Profiles of reflectivity given by Donaldson [9] and Chmela [10], when converted to amounts of liquid water, indicate that the 3 to 4 inches referred to previously is not an overestimate. Their observations represent a few samples of storms in northeastern United States. If more samples were available from other parts of the country, so as to include more storms and more violent storms, larger concentrations of liquid water aloft might be found.

2.2.8 Donaldson and Chmela both show that the maximum reflectivity occurs at approximately 20,000 feet. In the *Handbook of Geophysics for Air Force Designers* [11], Donaldson states that the maximum concentration is usually at an altitude corresponding to ½ to ⅞ of the cloud height. It is thus suggested that while the maximum condensation may occur at lower elevations, rising currents of air in the clouds carry the drops higher and tend to hold them in suspension. The maximum amount (and concentration) of liquid water that can be held aloft and the mechanism (and rate) of its release from the supporting updraft are still largely matters of conjecture, particularly for short durations and small areas.

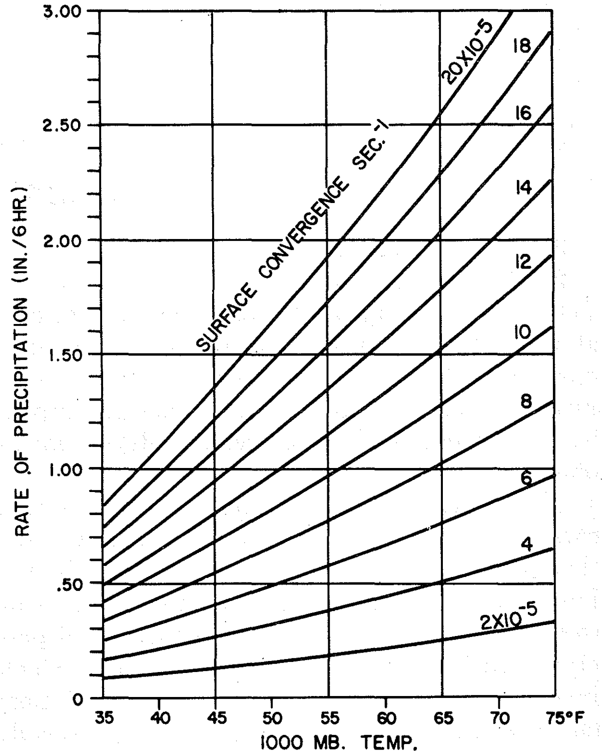


FIGURE 2-1.—Rates of precipitation from pseudoadiabatically ascending saturated air extending from sea level to 9 km., assuming a linear decrease of convergence with height to zero at 4.5 km. (about 15,000 ft.).

2.3 Rate of conversion of moisture into precipitation

2.3.1 The precipitation process was described in chapter 1. With sufficient moisture available, the precipitation rate then depends on how rapidly the moisture can be converted into precipitation. Since high precipitation rates depend chiefly on rapid cooling of adiabatically rising moist air necessarily associated with convergence and/or orographic lifting, precipitation rates from air containing a given amount of moisture may be related directly to convergence and/or orography.

2.3.2 Convergence is really a measure of inflow. It may also be visualized as the horizontal shrinking of a mass or column of air. Convergence is expressed in terms of shrinkage per unit time. Thus, for example, a convergence of 2×10^{-5} sec.$^{-1}$ would indicate that the horizontal cross-section area of a column of air was being reduced by 0.00002 per sec.

2.3.3 The convergence required to produce various precipitation rates from saturated air layers of various temperatures and thicknesses has been computed. The rate at which the amount of water vapor required for saturation decreases with lowering temperatures may be called the rate of production of moisture excess over saturation. Assuming that this moisture excess would all fall out as precipitation and convergence would decrease with height to zero at 4.5 km. (roughly 15,000 ft.) Peterson [12] constructed a graph (fig. 2–1) relating the 6-hr. precipitation to the temperature and convergence at the surface in a pseudoadiabatic saturated atmosphere. This graph demonstrates that if the assumptions are valid, considerable horizontal convergence must be associated with heavy rainfall rates. This appears to be true even with some allowance for horizontal convergence of the falling raindrops, which would cause the precipitation rate to be greater than the rate of production of moisture excess, and for some additional lift provided by orographic barriers.

2.3.4 Gilman and others [13] prepared schematic illustrations (fig. 2–2) of the change in shape of an initially cubic mass of saturated air with a surface temperature of 70° F. and a pseudoadiabatic lapse rate when sufficient horizontal convergence occurs to effect upward motion adequate to produce 1, 2, and 5 in. of rain. Diagrams B, C, and D are based on four assumptions: (1) convergence decreases linearly with pressure to zero at 600 mb., or roughly 14,000 ft., (2) winds at any given level are of uniform speed and radially directed, (3) rainfall intensity is uniform over area, and (4) the air is lifted pseudoadiabatically. Figure 2–2E is based on the same assumptions and in addition assumes that another wind component, constant in direction but with speed increasing from zero at 1,000 mb. to 50 knots at 200 mb., is superimposed on the radially-directed wind, or convergence, field of figure 2–2C. Figure 2–2 provides an indication of the degree of horizontal convergence required to produce large amounts of precipitation.

2.3.5 The effect of orographic lifting on precipitation intensity is a perplexing problem. It is difficult to determine within a particular storm how much of the variation in precipitation is related to changes in the storm mechanism and how much is related to orography. Also, the same orographic barrier that is a precipitation-producing factor on the windward slope acts as a precipitation-inhibiting agent on the lee slope. In rugged, irregular topography such as in western United States, most slopes will exhibit windward and lee characteristics at different times depending on the storm path and circulation. The amount of lift produced by a given flow with specific thermal and humidity characteristics across an orographic barrier is dependent, however, only on the height, slope, and other topographic characteristics of the barrier.

2.3.6 Lack of proper instrumentation precludes an accurate analysis of orographic effects on precipitation intensities in storms. However, computations based on reasonable assumptions of wind field, drop-size distribution, and precipitation-element trajectories over a generalized barrier indicate that storm precipitation may be distributed an appreciable distance downwind from the ridge. Moreover, precipitation profiles across an orographic barrier may vary widely from storm to storm. Figure 2–3 is a simplified schematic diagram illustrating some of the physical processes effecting these variations. It presents an idealized cross section of a barrier such as the Sierra Nevada, with a high plateau on the lee side.

2.3.7 The heavy lines (fig. 2–3) represent the streamlines of air flow across the barrier. On the left, or windward side of the ridge, points L and H represent the bottom and top, respectively, of the condensation or cloud layer. Precipitation-formation rates throughout the layer are indicated by the profile A. Dashed curves B_1 through B_6 represent trajectories of falling raindrops or snow crystals. Those formed at the higher elevations are carried farthest downwind and fall on the lee side. Those formed at lower altitudes fall on the windward slope. Curve C presents a rough indication of the precipitation distribution. Precipitation which is produced on the windward side of the barrier and falls on the lee side is called *spill-over.*

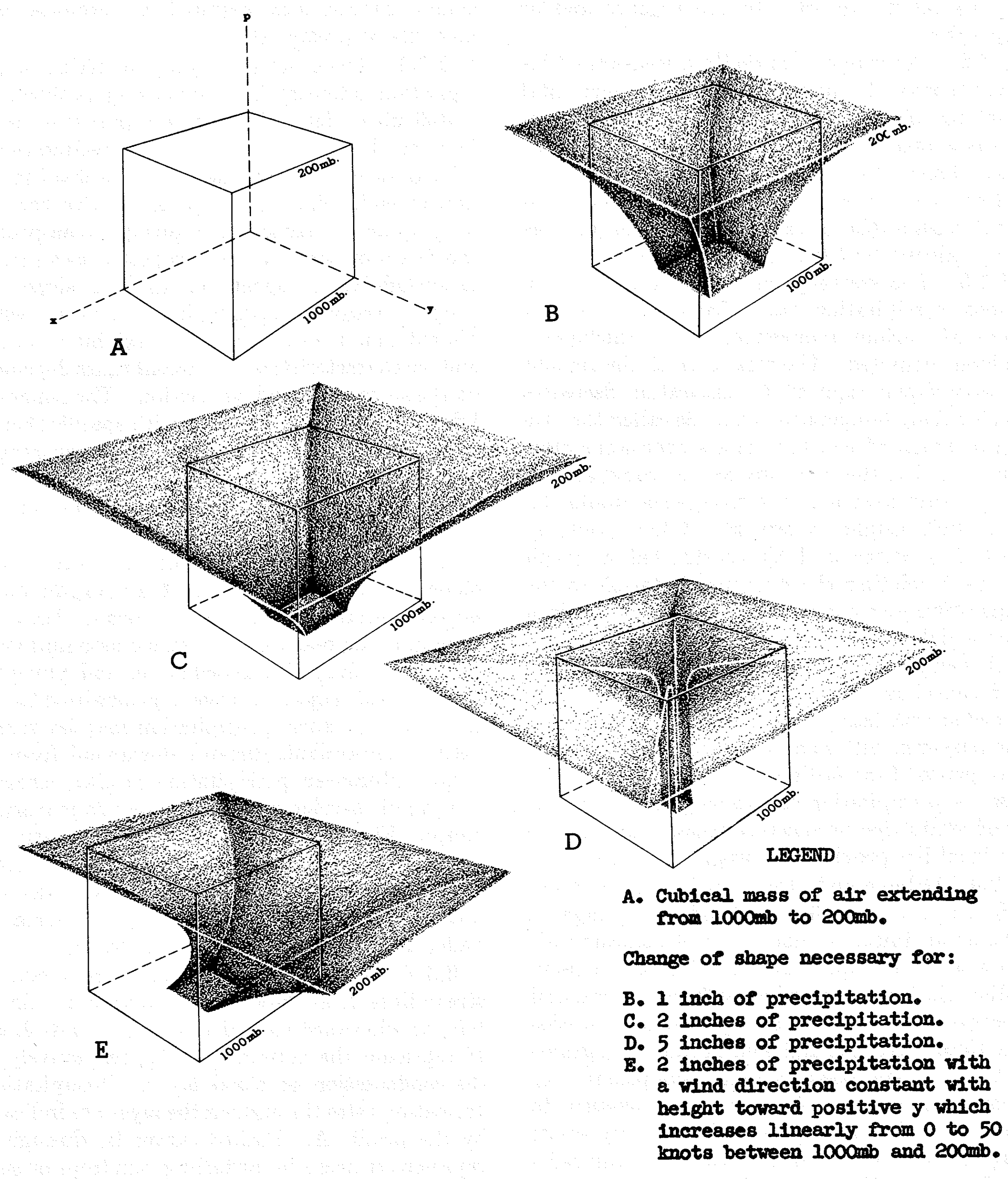


FIGURE 2–2.—Change in shape of a cubical mass of saturated air required to produce various rainfall amounts, assuming a 1,000-mb. temperature of 70° F. and a pseudoadiabatic lapse rate.

2.3.8 Other verticals such as HL could be selected, and A integrated both vertically and longitudinally. This procedure would provide additional profiles of C, or precipitation, which could be added. The composite shape of C would depict the precipitation profile over the barrier.

2.3.9 Wind vectors over the barrier would be required to evaluate the diagram (fig. 2–3). The precipitation-formation profile, A, would have to be integrated for different forms of water; i.e.,

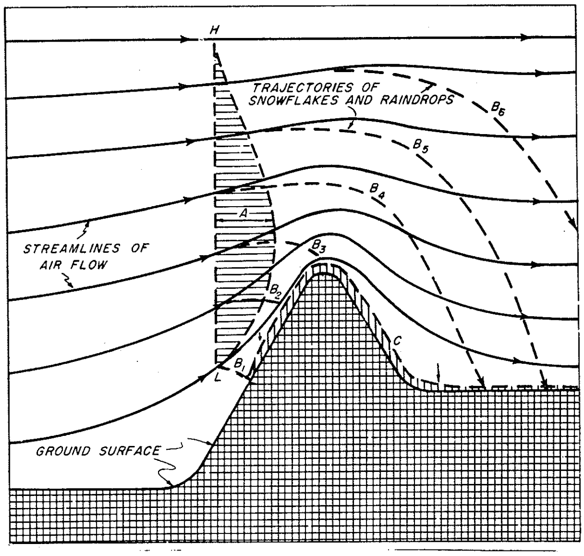


FIGURE 2–3.—Schematic illustration of spill-over.

liquid or solid. In addition, as snow formed at high altitudes, melted, and turned into rain, there would be a zone in which the trajectories would have a rather sharp change in shape. Falling rates of raindrops are fairly well known, and while little is known about those of snowflakes, they are undoubtedly much less. The actual wind flow over the usual orographic barrier would not be anywhere near as smooth or uniform as that depicted in figure 2–3. An actual profile across the Sierra Nevada (fig. 2–4) gives a good indication of the degree of generalization inherent in computations of orographic precipitation based on simplified wind-flow patterns.

2.3.10 The extreme distance for spill-over of heavy rainfall in the Sierra Nevada from orographic effects alone is estimated to be roughly 10 miles. The storm precipitation distribution across a barrier has never been measured accurately, but it probably varies widely from storm to storm, particularly for short durations and small areas.

2.3.11 In an attempt to determine the orographic effects on precipitation rates, the maximum observed clock-hour and 24-hr. precipitation for stations on the western slopes of the Sierra Nevada in California were plotted against the station elevation (figs. 2–5 and 2–6, respectively). The data are from recording-gage stations having at least 8 years of record between 1940 and 1951. Figure 2-5 shows that, within the range of observed data, maximum clock-hour precipitation is very poorly related to elevation. In other words, the plot suggests that it can rain as hard for one hour at a low elevation as it can at a high elevation. Figure 2–6, on the other hand, shows a slight tendency for maximum observed 24-hr. precipitation to be higher at the higher elevations, although the correlation is admittedly poor. A similar plot (fig. 2–7) of maximum observed observational-day precipitation for Colorado stations west of the Continental Divide also shows a slight tendency for higher values at higher elevations. Here again, however, the correlation is poor.

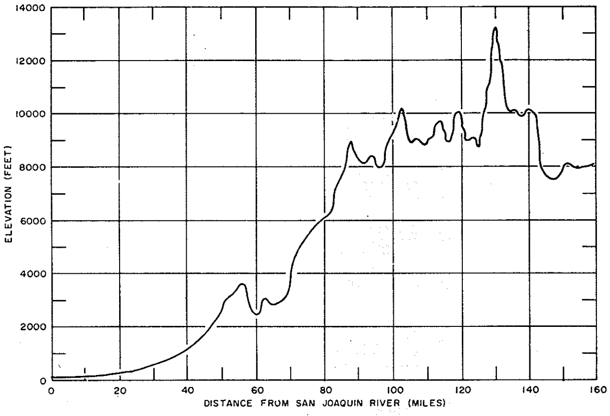


FIGURE 2–4.—Topographic profile across Sierra Nevada from 36°49′ N., 120°22′ W. to 38°22′ N., 118°15′ W.

2.3.12 Comparison of figures 2–6 and 2–7, which are for regions of comparable orography, reveals that the latter shows much lower precipitation values level-for-level than does the former. Obviously, other factors besides elevation and slope affect precipitation rates. The various factors governing availability of moisture were discussed in section 2.2. Distance from a moisture source was one of the factors mentioned. However, reduction of atmospheric water vapor with distance from the moisture source, as observed in the Plains Region, for example, is much too gradual to account for more than a small part of the difference between California and Colorado storm precipitation indicated by figures 2–6 and 2–7. Neither could the difference be explained on the basis of latitudinal or seasonal variations in atmospheric water-vapor content. Current knowledge of storm meteorology is admittedly limited, but what little is known suggests no great difference in the precipitation-producing efficiency of storms in these two regions.

2.3.13 It would appear from the preceding paragraph that there is no known explanation for

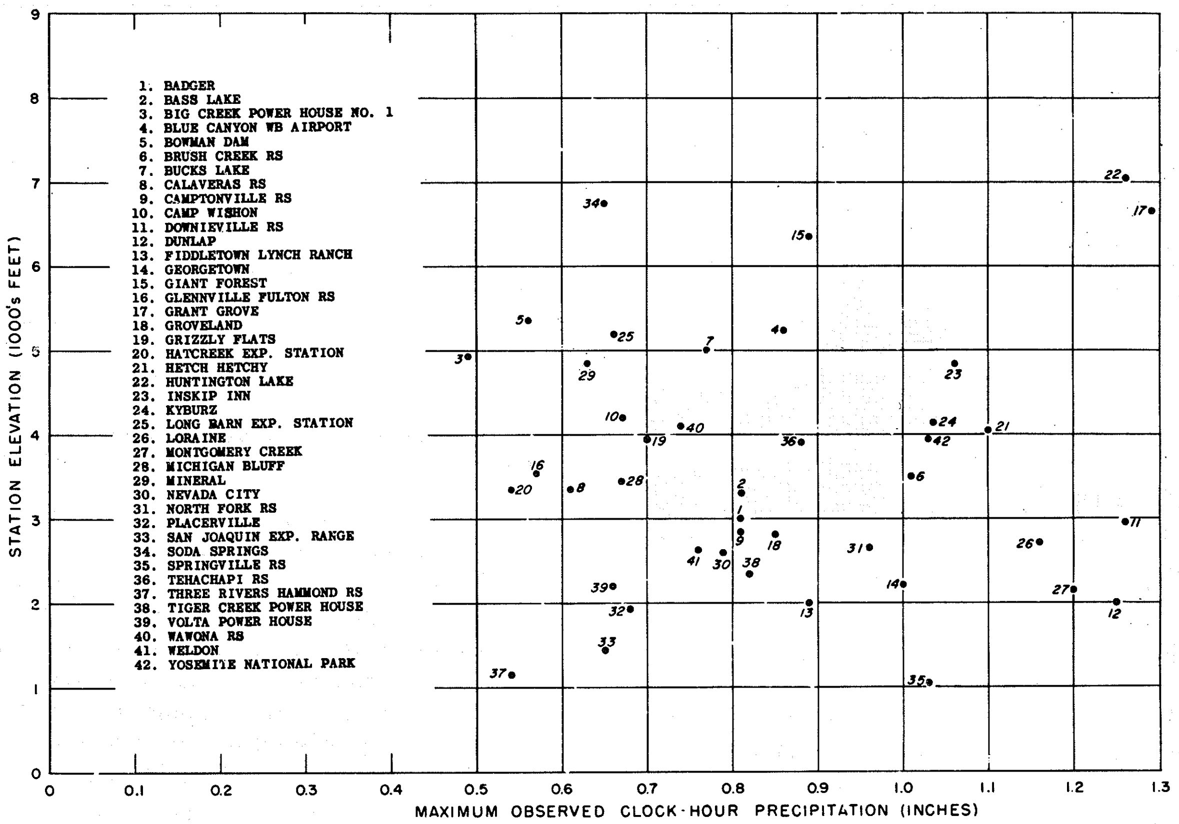


FIGURE 2–5.—Variation of maximum observed clock-hour precipitation with elevation for stations on the western slope of the Sierra Nevada in California.

the difference exhibited by figures 2–6 and 2–7. However, it is known that orographic barriers can effect great reductions in W_p within short distances and act to reduce precipitation downwind (pars. 2.2.5, 2.3.5, and fig. 2–3). Since storm precipitation shows such poor correlation with station elevation (figs. 2–6 and 2–7), the only conclusion readily apparent is that orographic barriers between the moisture source and the precipitation area comprise the most effective factor governing precipitation in mountainous regions. These barriers to moisture inflow are simply called *moisture barriers.*

2.3.14 The difference in elevation of the moisture barriers apparently provides the only logical explanation for the large difference in storm precipitation indicated by figures 2–6 and 2–7. Moist air from the Pacific reaches much of the western slope of the Sierra Nevada in California after crossing the coastal ranges at an average height of 1,000 to 2,000 feet. On the other hand, moist air from an even more favorable source region, i.e., a more southern and warmer region of the Pacific, is forced to cross moisture barriers averaging no less than 7,000 feet in order to reach western Colorado, where much lower 24-hr. precipitation maxima are observed.

2.3.15 Major storms occurring in the western United States as well as in other parts of the world have inflow winds of at least 25 m.p.h. Winds of this speed persisting for periods of 24 hours or longer bring air into the precipitation process from sources hundreds of miles way. This warm, moist air moving from the oceans must pass over orographic barriers before reaching many regions of the western United States. Figure 2–8 depicts these barriers to moist air inflow. The inflow direction of warm, moist air in extensive storms capable of producing probable maximum precipitation (PMP) for the longer durations was considered in the construction of this map. For instance, the map shows that the moist air reaching the region of the Great Salt Lake would be lifted to an elevation of 7,000 feet. A local storm of small areal extent could produce maximum point values of precipitation for short durations from a saturated air mass stagnant over the region at a lower elevation. However, the air flowing into a major large-area storm in this region would have to cross orographic barriers forcing it to rise to 7,000 feet. Thus the effective moisture-barrier elevation for this vicinity would be 7,000 feet although much of the terrain is at a lower elevation.

2.3.16 The moisture-barrier effect is also evident in the Central Valley of California. A west wind will bring a deep layer of moist air directly across the valley to the Sierra Nevada, crossing San Francisco Bay and the relatively low hills surrounding it. A south wind will bring air northward into the northern part of the valley through this same gap. Thus moist air can reach large parts of the valley without crossing the higher barriers of the Coast Range. The southern part of the valley can be reached through this gap

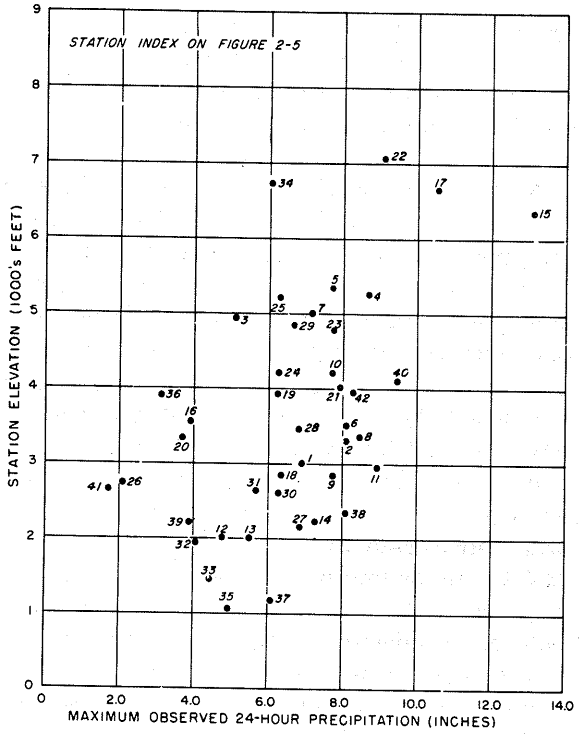


Figure 2–6.—Variation of maximum observed 24-hr. precipitation with elevation for stations on the western slope of the Sierra Nevada in California.

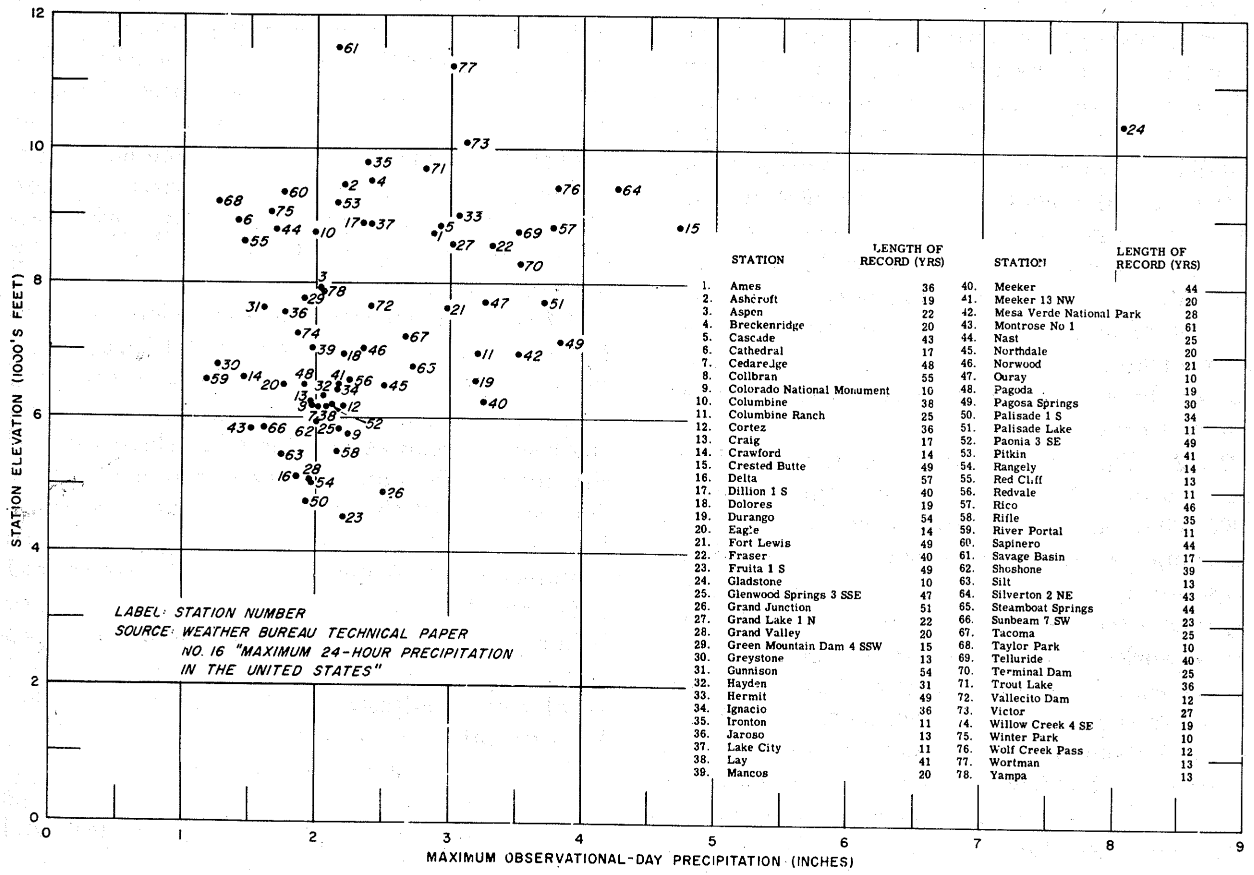


Figure 2–7.—Variation of maximum observational-day precipitation with elevation for stations west of the Continental Divide in Colorado.

STATION	LENGTH OF RECORD (YRS)	STATION	LENGTH OF RECORD (YRS)
1. Ames	36	40. Meeker	44
2. Ashcroft	19	41. Meeker 13 NW	20
3. Aspen	22	42. Mesa Verde National Park	28
4. Breckenridge	20	43. Montrose No 1	61
5. Cascade	43	44. Nast	25
6. Cathedral	17	45. Northdale	20
7. Cedaredge	48	46. Norwood	21
8. Collbran	55	47. Ouray	10
9. Colorado National Monument	10	48. Pagoda	19
10. Columbine	38	49. Pagosa Springs	30
11. Columbine Ranch	25	50. Palisade 1 S	34
12. Cortez	36	51. Palisade Lake	11
13. Craig	17	52. Paonia 3 SE	49
14. Crawford	14	53. Pitkin	41
15. Crested Butte	49	54. Rangely	14
16. Delta	57	55. Red Cliff	13
17. Dillion 1 S	40	56. Redvale	11
18. Dolores	19	57. Rico	46
19. Durango	54	58. Rifle	35
20. Eagle	14	59. River Portal	11
21. Fort Lewis	49	60. Sapinero	44
22. Fraser	40	61. Savage Basin	17
23. Fruita 1 S	49	62. Shoshone	39
24. Gladstone	10	63. Silt	13
25. Glenwood Springs 3 SSE	47	64. Silverton 2 NE	43
26. Grand Junction	51	65. Steamboat Springs	44
27. Grand Lake 1 N	22	66. Sunbeam 7 SW	23
28. Grand Valley	20	67. Tacoma	25
29. Green Mountain Dam 4 SSW	15	68. Taylor Park	10
30. Greystone	13	69. Telluride	40
31. Gunnison	54	70. Terminal Dam	25
32. Hayden	31	71. Trout Lake	36
33. Hermit	49	72. Vallecito Dam	12
34. Ignacio	36	73. Victor	27
35. Ironton	11	74. Willow Creek 4 SE	19
36. Jaroso	13	75. Winter Park	10
37. Lake City	11	76. Wolf Creek Pass	12
38. Lay	41	77. Wortman	13
39. Mancos	20	78. Yampa	13

only by northerly winds, which are relatively dry. The moist westerly and southwesterly winds must pass over the Coast Range or the Tehachapis. Thus these ranges determine the effective moisture barrier for the southern Central Valley.

2.3.17 The elevations indicated on the map of figure 2–8 are the lowest elevations to which warm, moist air with a trajectory directly from the source region would rise in reaching any particular point. In some regions moist air can come from other source regions but would encounter higher barriers. The arrows indicate the general directions of the moisture-bearing flow considered likely to prevail during major storms in the various sections of the West and do not show all directions from which warm, moist air can reach any region.

2.4 Measurement

2.4.1 In dealing with measured precipitation rates, the methods and errors of measurement should be considered. In the United States three types of gages are used in making official measurements of storm precipitation. These gages are: (1) the tipping-bucket recording rain gage, (2) the weighing-type recording gage, and (3) the standard 8-in. nonrecording gage. The last two will measure any form of precipitation whereas the first is limited to rainfall. Only the first two actually measure intensities; the nonrecording gage measures amounts only. Detailed descriptions of these gages are available in most textbooks on meteorology or hydrology and will not be given here. More important in evaluating the representativeness of maximum observed intensities, which are of primary interest in this study, is a knowledge of the gage-network density and the errors of measurement.

2.4.2 The United States, excluding Alaska and Hawaii, has an area of approximately 3,000,000 sq. mi. In this area there are about 3,500 recording gages, all but about 200 being of the weighing type, and about 9,500 nonrecording gages, or a total of about 13,000 gages. The average network density computes to be about one gage per 230 sq. mi., but many stations have two gages so the average station-network density probably averages about one station per 250 sq. mi. The countrywide distribution is not uniform, however, and the average network density in the West is appreciably less than that for the country as a whole. Prior to 1940 the network density in all parts of the country was a great deal less than it is now.

2.4.3 The opening through which precipitation enters the standard gage is roughly 1/80,000,000 of a square mile in area. If all 13,000 gages were concentrated in one group as close together as possible, the total catchment area would be no more than 1/6000 of a square mile—much less than the area of the standard baseball diamond!

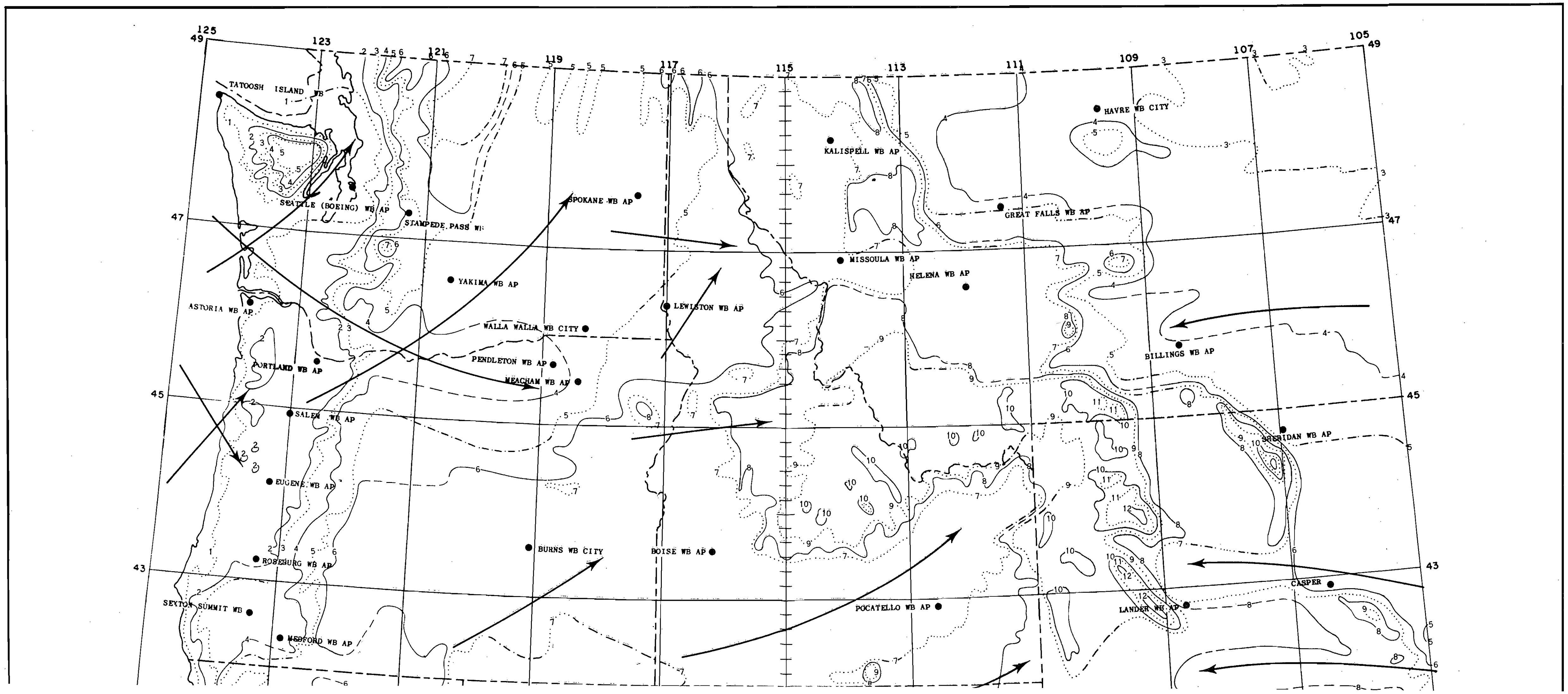
2.4.4 The recording gages are, of course, the only gages capable of measuring rainfall intensities with any degree of accuracy, particularly for durations under 24 hours. The average network density of the recording gages alone is slightly over one per 1,000 sq. mi. Their total catchment area is about 1,500 sq. ft. This lesser network density, hence fewer data on short-duration rainfall intensities, is the reason for basing the PMP estimates described in chapter 6 primarily on 24-hr. values.

2.4.5 Obviously, the rainfall rates measured by the existing network—let alone the much sparser network prior to 1940—are but a small sample of those that have occurred throughout the entire country. The sampling is particularly poor for local cloudbursts, which are restricted to a few square miles in area. The chance that the most intense rainfall in a cloudburst would center over a gage is extremely remote. The more uniform rainfall rates in large-area, or general, storms, often extending over tens of thousands of square miles, are naturally much better represented by the gage sampling.

2.4.6 Supplementary measurements of rainfall in severe storms are obtained through field surveys, colloquially called "bucket surveys". These surveys are made by meteorologists and engineers as soon as possible after the ending of the storm. The object of the survey is to gather data on rainfall that may have been collected in barrels, pails, bottles, etc. If the exposure of the container is satisfactory and it can be determined definitely that the container was either empty or held a known depth of liquid before the storm, the storm catch is then measured. The measurement is, of course, adjusted if the container does not have straight vertical sides.

2.5 Errors of measurement

2.5.1 There are several types of errors in gage measurements. Most of these errors are small and negligible, especially in connection with measurement of storm precipitation, and will not be discussed here. There are three types of errors of


125
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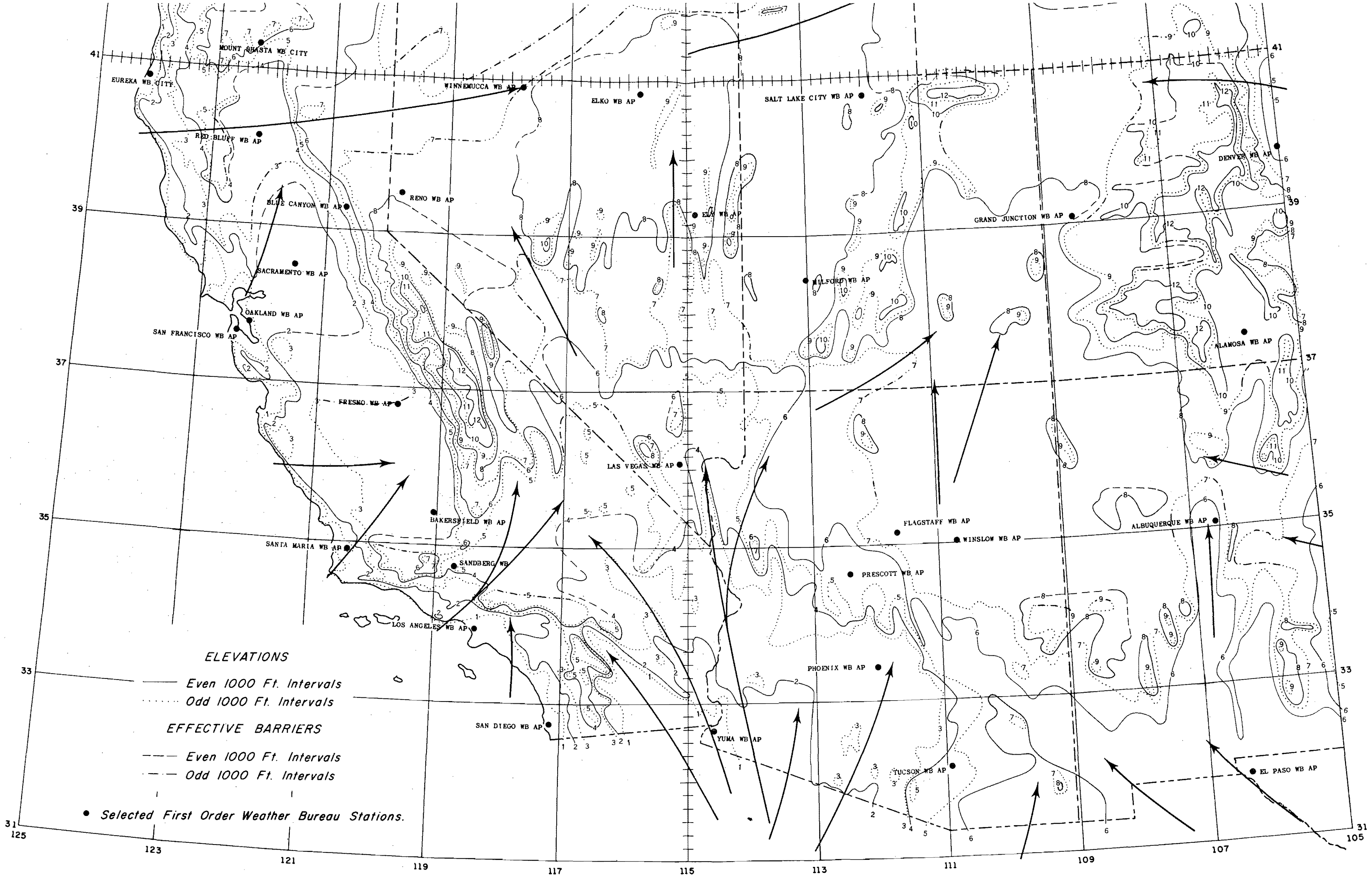
49
47
45
43
TATOOSH ISLAND WB
SEATTLE (BOEING) WB AP
STAMPEDE PASS WB
SPOKANE WB AP
KALISPELL WB AP
HAVRE WB CITY
GREAT FALLS WB AP
MISSOULA WB AP
HELENA WB AP
YAKIMA WB AP
LEWISTON WB AP
WALLA WALLA WB CITY
ASTORIA WB AP
PORTLAND WB AP
PENDLETON WB AP
MEACHAM WB AP
BILLINGS WB AP
SALEM WB AP
SHERIDAN WB AP
EUGENE WB AP
ROSEBURG WB AP
BURNS WB CITY
BOISE WB AP
CASPER
SEXTON SUMMIT WB
POCATELLO WB AP
LANDER WB AP
MEDFORD WB AP



ELEVATION OF BARRIERS TO MOISTURE INFLOW IN GENERAL STORMS

Prepared By
COOPERATIVE STUDIES SECTION
HYDROLOGIC SERVICES DIVISION
WEATHER BUREAU
WASHINGTON, D.C.
JULY, 1958

FIGURE 2-8.—Elevation of barriers to moisture inflow in general storms, in thousands of feet above mean sea level.

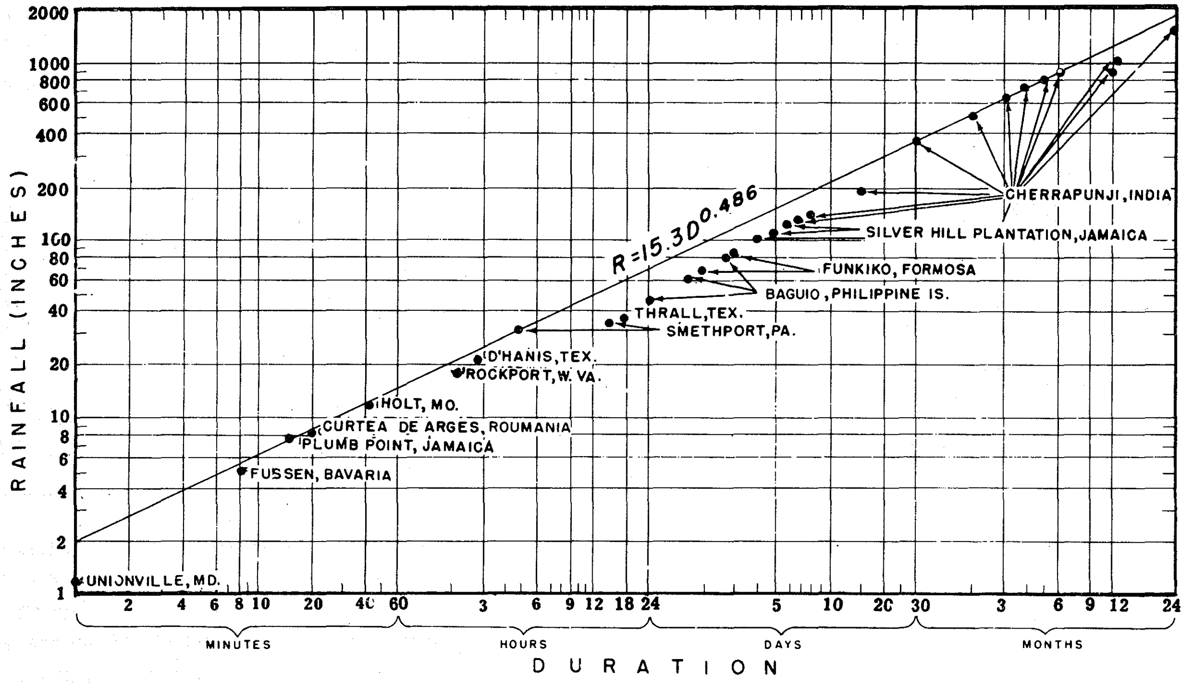


FIGURE 2-9.—Depth-duration relation of world's greatest rainfalls.

possible appreciable magnitude in measurements of high rainfall intensities. One is an observational error and the others are instrumental.

2.5.2 The most troublesome observational error may consist of (1) misreading the stick used for measuring the depth of water in the nonrecording gage, (2) immersing the wrong end of the stick, and (3) forgetting to apply the conversion factor (0.1) to the stick reading. The first two errors may result in indicated measurements that are either too high or too low. The third, however, yields measurements 10 times as high as they should be. Fortunately, the occurrence of observational errors like these is not common.

2.5.3 One type of instrumental error results from malfunctioning of a recording gage. For example, the linkage on a weighing-type gage may bind temporarily while rainwater keeps collecting in the bucket. After an interval, the weight of the water in the bucket may cause an instantaneous or rapid freeing of the binding mechanism. The resulting chart trace thus indicates what appears to be a sudden downpour into the gage, or an apparent intensity that could be much too high.

2.5.4 The tipping-bucket gage, on the other hand, tends to record intensities lower than the actual in heavy downpours. The deficiency results from the fact that rainwater continues to pour down the funnel of the receiver while the bucket is tipping and is therefore not measured. In intense rainfalls the indicated intensity may be about 5 percent too low. The water, however, is caught in a reservoir and measured independently of the recorder count. The difference is prorated throughout the indicated period of excessive rainfall.

2.5.5 The most serious error is that resulting from the gage effect on wind. The gage obstructs the horizontal flow of the air, which is forced around and over the gage. The upward component of the wind passing over the gage deflects precipitation that would otherwise fall into the gage, resulting in a deficient catch. The deficiency increases with the wind speed and is greater for snow than for rain [14]. Since most severe storms are accompanied by relatively strong winds, measurements of heavy rainfall and snowfall intensities are likely to be appreciably deficient unless other errors of opposite sign prevail.

2.6 Maximum observed rainfall rates

2.6.1 Considering the fact that there are many regions with few or no rain gages and that localized cloudbursts can take place without any official knowledge of their occurrence, there is very little likelihood that the greatest observed intensities are representative of the physical upper

TABLE 2–1.—*World's maximum observed point rainfalls*

Duration	Depth (in.)	Location	Date
1 min	1.23	Unionville, Md	July 4, 1956.
8 min	4.96	Fussen, Bavaria	May 25, 1920.
15 min	7.80	Plumb Point, Jamaica	May 12, 1916.
20 min	8.10	Curtea-de-Arges, Rumania	July 7, 1889.
42 min	12.00	Holt, Mo	June 22, 1947.
2 hr. 10 min	19.00	Rockport, W. Va	July 18, 1889.
2 hr. 45 min	22.00	D'Hanis, Tex. (17 mi. NNW).	May 31, 1935.
4 hr. 30 min	30.8+	Smethport, Pa	July 18, 1942.
15 hr	34.50	do	July 17–18, 1942.
18 hr	36.40	Thrall, Tex	Sept. 9, 1921.
24 hr	45.99	Baguio, Philippine Islands	July 14–15, 1911.
39 hr	62.39	do	July 14–16, 1911.
2 days	65.79	Funkiko, Formosa	July 18–20, 1913.
2 days 15 hr	79.12	Baguio, Philippine Islands	July 14–17, 1911.
3 days	81.54	Funkiko, Formosa	July 18–20, 1913.
4 days	101.84	Cherrapunji, India	June 12–15, 1876.
5 days	114.50	Silver Hill Plantation, Jamaica.	Nov. 5–9, 1909.
6 days	122.50	do	Nov. 5–10, 1909.
7 days	131.15	Cherrapunji, India	June 24–30, 1931.
8 days	135.05	do	June 24–July 1, 1931.
15 days	188.88	do	June 24–July 8, 1931.
31 days	366.14	do	July 1861.
2 mo	502.63	do	June–July 1861.
3 mo	644.44	do	May–July 1861.
4 mo	737.70	do	Apr.–July 1861.
5 mo	803.62	do	Apr.–Aug. 1861.
6 mo	884.03	do	Apr.–Sept. 1861.
11 mo	905.12	do	Jan.–Nov. 1861.
1 yr	1041.78	do	Aug. 1860–July 1861.
2 yr	1605.05	do	1860–1861.

TABLE 2–2.—*Maximum depth-area-duration data for the United States (Average precipitation in inches, storm indicated by letter)*

Area (sq. mi.)	Duration (hr.)						
	6	12	18	24	36	48	72
10	24.7a	29.8b	36.3c	38.7c	41.8c	43.1c	45.2c
100	19.6b	26.3c	32.5c	35.2c	37.9c	38.9c	40.6c
200	17.9b	25.6c	31.4c	34.2c	36.7c	37.7c	39.2c
500	15.4b	24.6c	29.7c	32.7c	35.0c	36.0c	37.3c
1,000	13.4b	22.6c	27.4c	30.2c	32.9c	33.7c	34.9c
2,000	11.2b	17.7c	22.5c	24.8c	27.3c	28.4c	29.7c
5,000	8.1bd	11.1b	14.1b	15.5c	18.7e	20.7e	24.4e

Storm	Date	Storm center
a	July 17–18, 1942	Smethport, Pa.
b	Sept. 8–10, 1921	Thrall, Tex.
c	Sept. 3–7, 1950	Yankeetown, Fla.
d	June 27–July 4, 1936	Bebe, Tex.
e	June 27–July 1, 1899	Hearne, Tex.

limits of rainfall rates. However, probable maximum precipitation, or PMP (par. 4.1.1) must at least equal or exceed the maximum observed values, which may then be looked upon as indicating the lower limit of PMP. As such, they are of considerable interest.

2.6.2 The world's maximum observed point rainfalls for durations up to 2 years are listed in table 2–1. When these data are plotted on logarithmic paper as in figure 2–9, they define the enveloping straight line $R=15.3D^{0.486}$ where R is rainfall in inches and D is duration in hours.

2.6.3 The depth-area-duration characteristics of several hundred major storms in the United States have been analyzed. The results can be found in *Storm Rainfall in the United States* [15]. This publication was the source of the maximum rainfalls for areas up to 5,000 sq. mi. and durations up to 48 hr. listed in table 2–2.

Chapter 3

METEOROLOGICAL ANALYSES OF MAJOR STORMS OF THE WEST

3.1 Introduction

3.1.1 As discussed in the preceding chapters, precipitation is a product of the moisture charge of the air and the storm mechanism; i.e., convergence, vertical motion, cooling, condensation, etc. In general, the maximum moisture charge occurs in summer. In much of the West the maximum convergence associated with large storms occurs in winter, that with smaller-scale thunderstorms usually in summer. The probable maximum precipitation should occur during the season when these influences have their optimum joint effect.

3.1.2 A study was made to determine the most favorable seasons for the occurrence of the larger amounts of storm precipitation in western United States. The month of occurrence for each of the five highest observed 1- and 24-hr. amounts at various stations west of the 105th meridian were plotted on a map. The 24-hr. data indicate that western United States can be divided into three regions; one from the Pacific Coast to the crest of the Cascade and Sierra Nevada Ranges, where the maximum amounts occur in the winter; another from this crest to the Continental Divide, where the maximum amounts occur during all seasons of the year; and the third, from the Continental Divide to the 105th meridian, where the maximum amounts occur during the summer months. Hourly data indicate that west of the crest of the Cascades and Sierra Nevada the maximum amounts could occur in any season. East of this crest, the maximum hourly amounts would occur during the summer.

3.2 Pacific Coast to the crest of the Cascade and the Sierra Nevada Ranges

3.2.1 Long-duration storm precipitation in this region is confined almost exclusively to the cold-season months, October to April. This seasonal precipitation regime can be explained by the seasonal variations of the large-scale circulation of the atmosphere. These variations are indicated by migrations of the Pacific High and Aleutian Low in the surface pressure pattern and of the jet stream of the upper atmosphere. The two surface pressure centers are a statistical average more than a permanent physical condition, but of the two the Pacific High is the more persistent. Its center is generally in the region between 140°–150° W. and 30–40° N. From a minimum in January, when the center is generally farthest to the southeast, there is a gradual increase in size and intensity and a northwestward displacement, with a maximum intensity and displacement in August. The development of the Aleutian Low is dependent on outbreaks of cold polar air. The Low then reaches its maximum expanse and intensity in January, with a decline in intensity and a northward displacement thereafter.

3.2.2 The jet stream, though its total effect on weather is not yet completely understood, exerts considerable influence on the development of cyclonic activity and the occurrence of precipitation [16, 17]. The jet stream, superimposed on the convergence fields associated with the pressure systems of the lower atmosphere, has a broad-scale effect on precipitation. The seasonal displacement of the jet stream is in phase with the seasonal variation of the Aleutian Low. It is farthest south in January, when its mean position is about 23° N. along the west coast of North America, and is farthest north in July, when it is at about 49° N. [18]. These positions of the jet stream are a result of averaging data from normal monthly pressure maps for the Northern Hemisphere. (This jet stream should not be confused with the meandering jet stream associated with the polar front which can exist far to the south at all seasons.) A somewhat different picture would result from a daily averaging of the latitude of the jet stream along the Pacific Coast. Nevertheless, approximately the same seasonal variation of the average location of the jet stream would be apparent from either method. In general, the latitudinal displacement of average features of the circulation accounts for the seasonal distribution of precipitation in the Far West.

3.2.3 In all major storms along the Pacific Coast of the United States, the sequence of events is similar. The air masses crossing this region have essentially the same source regions; i.e., warm Pacific Ocean areas where water evaporates into the air. The differences in the temperature, humidity, and stability characteristics of these air masses are minor and result primarily from differences in speed of movement and trajectory, which produce various degrees of modification. Most of the precipitation is released from moist, unstable air which acquires these characteristics over the Pacific Ocean and travels eastward across warm water from about the vicinity of the Hawaiian Islands onto the continent.

3.2.4 The meteorological situations associated with major storms can best be illustrated by describing pertinent features of several of the outstanding storms that have occurred along the Pacific Coast. One of these occurred January 20–25, 1935, in western Washington. Just prior to the beginning of this storm a large polar air mass moved southward from the Canadian interior. By evening of January 20, this air mass had spread out over the United States from the Mississippi Valley to the Pacific Coast. This was followed by the eastward displacement and deepening of the Aleutian Low centered off the Pacific Coast, near the latitude of the Canadian border. The gradient established by these pressure centers brought inland over the Washington coast, air from the southwest with a long over-water trajectory, hence, high moisture content. The conditions were maintained during the entire storm period by fresh southward outbreaks of polar continental air into western and central United States, preventing the eastward movement of the low-pressure system. The convergence of the moist air into the region, together with the overrunning of the shallow polar air, and the orographic lifting, produced almost continuous heavy precipitation over the region. The precipitation ended only after the northward retreat of the zone of maximum convergence with the center of low pressure.

3.2.5 The storm of December 9–11, 1937, was the result of a large low-pressure system which remained offshore for 3 days. The Pacific High was displaced southeastward, and the southwesterly circulation between these two systems fed a continual supply of warm, moist air over the California coast. This warm, moist air, being lifted by the rugged terrain and the convergence of the cyclonic system, produced an almost continuous rain until the passage of the polar front and the shift to a drier, more westerly wind. Passage of the polar front was delayed as it became nearly parallel to the isobars after leaving the main trough. The eastward movement of the Low may have been delayed by the blocking action in the central United States of a cold continental anticyclone extending from Alaska to the Gulf of Mexico.

3.2.6 The storms of January 19–24, 1943, consisted of a series of three low-pressure systems that moved inland across the Pacific Coast progressively farther south, causing a southward movement of the heavy rain centers and producing heavy rain along the entire coast southward from northern Oregon. At the beginning of the storm period, a cold high-pressure system extended from Alaska to Texas. The first of the low-pressure centers within the general field of low pressure covering the eastern part of the North Pacific approached the coast off British Columbia. This Low moved slowly southeastward and crossed the Washington coast on the 20th. Before the precipitation associated with this system had ended, a second low-pressure system approached the Oregon coast, resulting in additional precipitation. This second Low passed over Oregon early on the morning of the 22d. As before, while one Low moved inland, a succeeding, more intense Low approached the coast. This third Low moved farther south, crossed the coast of northern California and produced some of the heaviest rains ever measured in southern California.

3.2.7 During the period November 13–21, 1950, a storm similar to that of December 1937 occurred over California. In each case, the southerly displacement of the Pacific High and the Aleutian Low resulted in a protracted southwesterly flow over the Pacific Coast. The traveling disturbances in the 1950 storm were more pronounced and resulted in more definite bursts of precipitation followed by brief periods of no rain. In this storm the cold anticyclone present at the beginning of the previous storms did not start moving southward until the 17th.

3.2.8 One of the wettest storms of record along the Pacific Coast occurred over northern and central California during the period December 15–28, 1955. The record-breaking floods that resulted were caused by both the intensity and long duration of the storm. The general characteristics of this storm were similar to those of many other flood-producing storms along the west coast. On the 13th, the pattern for the production of heavy precipitation was beginning to form. A ridge was developing over western Canada and moving southward, blocking the eastward movement of low-pressure systems. At the same time, a low-pressure system formed about 800 miles off the Pacific Coast and moved slowly eastward. This low-pressure system became nearly stationary on the 18th in the southern Gulf of Alaska, about 500 miles off the coast. Cold air was pulled southward around the western side of the Low, and a line of discontinuity formed to the south of the low center. Surges of cold air moved southward from this low center and formed waves along the line of discontinuity. These waves moved eastward and caused bursts of rain over California. On the morning of the 23d, a deep Low formed off the northern California coast and intensified as it moved inland. With the passage of this intense storm center and the gradual southward spread of the warm, moist air being replaced over northern California with cooler air, the heaviest precipitation came to an end. The upper trough persisted offshore, however, and another low-pressure system formed on the 27th. This system moved eastward across California, causing additional substantial rainfall over northern California.

3.2.9 One of the most intense thunderstorms within this region occurred at Campo, Calif., on August 12, 1891, when 11.5 inches of rain fell in 80 minutes. The sparsity of data during this early period leaves some uncertainty concerning the small-scale synoptic features. The data indicate that there was a thermal Low east of the Coast Range extending from the Gulf of California northward to Nevada on the morning of the storm. The circulation, though light and variable, shows a southerly flow of moisture from the Gulf of California until evening of the 12th, the storm occurring from 11:40 a.m. until 1:00 p.m. Additional moisture could have come from the Pacific in a radial inflow pattern. The description of the storm by the cooperative weather observer indicates an unusually severe thunderstorm (pars. 6.4.4–6.4.11).

3.2.10 Without getting involved in the question of technical definition of tropical as distinguished from extratropical storms, it seems clear that the storms described in paragraphs 3.2.4.–3.2.9 were not of tropical origin. These storms are generally regarded as the ones to be extrapolated for synthesizing PMP. The storms of October 1911 and September 1939, cited in section 3.3, are both of tropical origin. The October 1911 storm missed California and went through Arizona into Colorado, where it produced heavy rain at Gladstone. The September 1939 storm hit southern California and produced heavy, but not record, rain. The storm is believed to have lost some of its intensity before reaching the coast.

3.2.11 Tropical storms combine an intense mechanism of convergent flow with high moisture supply, and while they are rare in western United States they cannot be dismissed without consideration as a possible prototype for PMP. How far north these storms can go and how intense they can be are problematic at present. None has occurred along the Pacific Coast since 1939, so there are few data to work with. They differ from Atlantic Coast hurricanes in several respects. The two most obvious are (1) the differing relationship of the counterclockwise circulation to the mountains along the two coasts and (2) the vastly greater moisture charge and accompanying energy of the Atlantic Coast storms. It is a matter of judgment where tropical storms might affect the Pacific Coast and what their effects might be. The consensus of several meteorological experts was the basis for some of the PMP values indicated on the maps in this report. Many authorities doubt that the ultimate tropical storm would exceed the PMP based on the more common winter-type storm.

3.3 Intermountain region

3.3.1 The region between the crest of the Cascades and Sierra Nevada and the Continental Divide is one of complex and varied topography. Except for a portion of the southern edge it is surrounded by high orographic barriers. These barriers exert a significant effect on the storms of the region, reducing the amount of moisture available and modifying the circulation of the storms as they move into the region. The large precipitation amounts for the longer durations are a result of general storms that move eastward across the region from the Pacific. In summer, circulation systems moving eastward from the Pacific encounter additional moisture from the Gulf of Mexico as it is carried around the western edge of a high pressure system centered east of the Divide. Also, tropical storms that form over the southeastern Pacific Ocean and move northward along the coast of Mexico can enter southwestern Arizona from the Gulf of California with little or no moisture diminution from orographic barriers. These storms have caused some of the heaviest precipitation in southeastern California and southwestern Arizona.

3.3.2 One of the outstanding storms of the intermountain region occurred November 18–23, 1909. Heavy rainfall from this storm was measured at Rattlesnake, Idaho. On the morning of the 18th, a High appeared over northern Alaska with one ridge extending southward over the Aleutians and another southeastward over central Canada. The Pacific High was centered just off the coast of California. A Low was observed off the coast of Washington, and another Low was centered over British Columbia, with a trough extending eastward along the Canadian border. The circulation around these pressure systems brought warm, moist air across the coast and over Washington, Oregon, and Idaho. Precipitation was fairly general in this region. The Low over Canada moved eastward along the Canadian border and by the morning of the 19th was well east of Idaho. The Low that was off the coast of Washington had by then moved inland over Canada just north of central Washington. Precipitation was continuing as a result of the lifting provided by the convergence mechanism associated with the pressure pattern and by the rugged topography of the area. The Low from western Canada moved slowly southeastward bringing continuing rain to southern Idaho until the middle of the 20th. After a brief period of clearing, a second Low moving eastward from the Pacific brought a fresh influx of warm, moist air and a renewal of the precipitation. This Low, moving inland from the Pacific across the Alaskan coast, continued in a southeasterly direction, moving across north of Idaho during the 23d. By morning of the 24th the Low was centered over northwestern Montana. The cold drier air that covered the region following the passage of the occlusion associated with this last system brought an end to further precipitation.

3.3.3 A severe rainstorm occurred on October 4–6, 1911, when a wave on a cold front, moving in from the Pacific, met the warm, moist air of a tropical storm that had moved inland over southern Arizona. The hurricane had formed just off the west coast of Mexico on the 2d and had moved rapidly northward, crossing inland over Arizona on the 4th. The cold front came inland from the Pacific early on the 4th. The two systems met over Arizona, combined, and then moved rapidly northeastward. Orographic effects were important in the release of the precipitation from this storm, but the intensity of the circulation caused rain on both the leeward and windward slopes of the San Juan Mountains in southwestern Colorado.

3.3.4 The storm of September 3–8, 1939, also originated as a tropical disturbance that formed off the coast of Mexico. On the morning of the 4th, it was centered just west of the southern tip of Lower California. This system moved northward during the next three days, gradually losing its identity. Two other disturbances that were noted farther south on the morning of the 5th did not move far enough northward to be the direct cause of any precipitation, though they did maintain a continuous flow of moist, maritime tropical air into the region. The high moisture charge which resulted from this flow, together with the unusually strong southerly winds in advance of an upper trough over the Pacific Coast, furnished the high inflow rate of moisture necessary for heavy rainfall. Heavy showers began on the 4th over southeastern California and southern Arizona and continued until the 7th, when the filling of the upper trough and the surface Low caused the strong flow of moist air into the storm area to decrease sharply.

3.3.5 Storms associated with disturbances on the polar front are not restricted to the northern part of the intermountain region. On October 27–29, 1946, a storm occurred over parts of Nevada, Utah, and Arizona as a result of such a disturbance. On the morning of the 27th, a wave on the polar front was centered over the Nevada-Utah border, with the cold front extending southwestward across southern California and the warm front southeastward into New Mexico. Warm, moist air was being brought into the region from the Gulf of California and the southern Pacific Ocean. A High was located over the Great Lakes region with a ridge extending down along the Appalachians to the Gulf of Mexico. The Low stayed nearly stationary until the middle of the 28th when it started moving slowly northeastward. The High which was located over the Great Lakes had weakened and moved slowly southward. On the morning of the 29th, it was centered off the

Virginia coast. Although the moisture for this storm was primarily of Pacific origin, the circulation around the High over eastern United States did bring some moist air from the Gulf of Mexico into the intermountain region.

3.3.6 Discussion of storms in the intermountain region would not be complete without mention of two storms that occurred before 1900. One occurred on August 11, 1890, at Palmetto, Nev., where 8.80 in. was reported to have fallen in 1 hour. The other storm occurred on August 28, 1898, at Fort Mojave, Ariz., and produced 8.00 in. in 45 min. Both of these storms resulted from severe thunderstorms, the precipitation being restricted to a very small area. They were similar in many respects to the storm that occurred at Campo, Calif., in August 1891 (par. 3.2.9). The rainfall amount for the Palmetto storm is of doubtful reliability. Investigation of the original records and correspondence written by the observer shortly after the date of the observation indicate a possibility that the scale factor may not have been applied to the measurement of the precipitation. Thus the true value may have been 0.88 inches rather than 8.80. The observer's remarks, however, imply a cloudburst (pars. 6.4.17–6.4.18). Although the data at Palmetto may be in error, the more reliable observation at Fort Mojave (par. 6.4.14) in this same general location indicates that severe thunderstorms must be considered for the PMP for durations less than 6 hr. over small areas.

3.4 East slope of the Rockies

3.4.1 The principal moisture source for the region east of the Continental Divide is the Caribbean Sea and Gulf of Mexico. The moisture is brought to Wyoming and Montana around the western edge of high-pressure cells over the eastern United States and the eastern side of Lows located over or near the Rocky Mountains. This synoptic situation is typical of many of the largest storms for the region. Farther south, similar storms may occur with an additional source of heavy precipitation in the decadent tropical storms that originate in the Caribbean, cross the Gulf Coast, and move in a northwesterly direction.

3.4.2 The storms typical of Montana and northern Wyoming can be illustrated by describing four of them. The first was centered at Warrick, Mont., on June 6–8, 1906; the second, at Evans, Mont., on June 3–6, 1908; the third, at Springbrook, Mont., on June 17–21, 1921; and the fourth, at Savageton, Wyo., on September 27–October 1, 1923. In each case a low-pressure system centered over the Rockies and south of the area brought warm, moist air from the Gulf of Mexico over colder polar air at the surface. This Gulf air, moving northward and overruning the colder polar air at the surface and then curving westward around the northern edge of the Low, was lifted by the slope of the Rockies as well as by the denser polar air. The combination of lift produced by the cyclonic convergence, overrunning of the polar air, and the movement up the slopes of the Rockies produced sufficient cooling to release large amounts of precipitation.

3.4.3 On September 14, 1919, a hurricane, which originated over the Atlantic south of Puerto Rico and reached hurricane strength near eastern Cuba, crossed the Texas coast near Corpus Christi. This storm continued in a northwesterly direction up the Rio Grande Valley, slowly losing its identity. On the 17th a new Low was forming over northeastern New Mexico from the remnants of this tropical storm. The Low deepened, moved in a northeasterly direction, and was centered over Kansas on the morning of the 18th. Precipitation ended over New Mexico on the 19th as the Low continued moving northeastward and the tropical air was replaced by maritime polar air. The precipitation from this Low was centered at Meek, N. Mex., and was a result of the decadent tropical storm. The storm lost its tropical characteristics during the latter stages as it became enveloped in an extratropical cyclone.

3.4.4 A very outstanding east-slope storm occurred over eastern Colorado on May 30–31, 1935. There were two very intense centers in this storm, one occurring northeast of Colorado Springs and the other at Hale, Colo. The precipitation in this storm resulted from waves forming on a quasi-stationary front that extended in an east-west direction across central United States on the 29th. A ridge extending from a High over the Atlantic was bringing warm, maritime air from the Gulf of Mexico northward. A cold polar High, centered over central Canada and extending southward to Nebraska and Kansas, was forcing this warmer, tropical air aloft. On the 30th, a wave had formed on the quasi-stationary front and was centered over central Utah, moving slowly in an east-southeastward direction. Heavy precipitation was associated with this wave. On the 31st the Low was centered over the New Mexico-Texas border and was filling; i.e, the pressure in the Low was rising.

Chapter 4

EVALUATION OF PROBABLE MAXIMUM PRECIPITATION

4.1 Introduction

4.1.1 There is no doubt that there is a physical upper limit to the amount of precipitation that can fall over a specific area in a given time. Referring to floods, Horton [19] once wrote: "A small stream cannot produce a major Mississippi River flood for much the same reason that an ordinary barnyard fowl cannot lay an egg a yard in diameter; it would transcend nature's capabilities under the circumstances." The same reasoning applies to precipitation. The physical upper limit of precipitation has come to be known as *probable maximum precipitation*, or PMP.

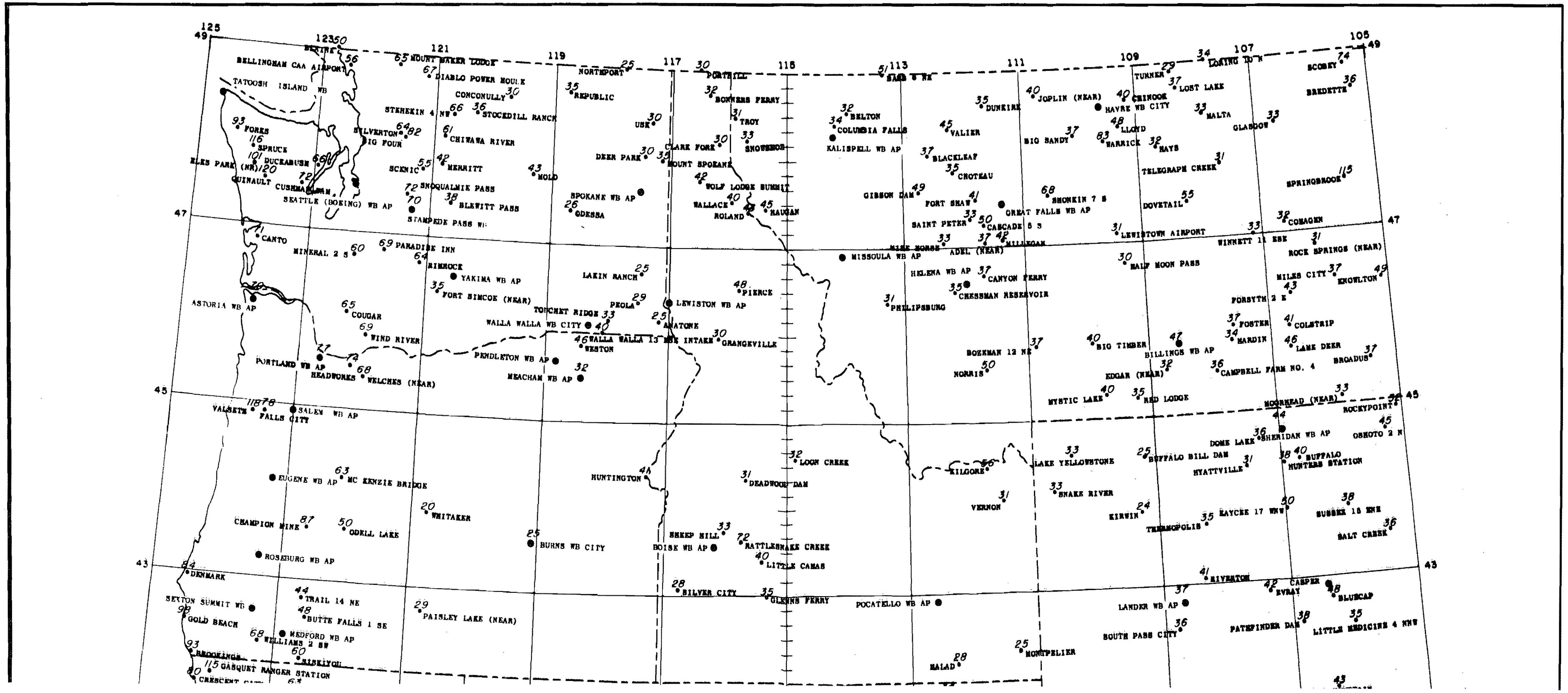
4.1.2 At one time the concept of PMP was expressed in terms of the words "maximum possible." However, in considering the limitations of data and understanding implicit in an estimate of "maximum possible" precipitation, it seemed that there was sufficient uncertainty to substitute for the expression "maximum possible" the more realistic one, "probable maximum." This was done with no intention or implication of making the values any different. "Probable maximum" simply seemed to be more descriptive and more realistic.

4.1.3 The use of meteorology for determining limiting precipitation values was initiated in the middle 1930's. The probable maximum, or maximum possible, storm evaluated in studies prior to about 1945 was understood to be a fictitious, or synthetic, storm that could produce the heaviest, meteorologically-possible precipitation over a specific area for all durations within a storm. A distinction between precipitation and storm is now generally recognized. The probable maximum precipitation, or PMP, as now generally known, for a specific area for various durations is usually determined by several types of storms. For example, the PMP for an area under 100 sq. mi. and for durations less than 6 hours is very likely to be realized from thunderstorms, but general storms are more likely to provide the limiting precipitation values for longer durations.

4.1.4 Basic to the determination of PMP is the assumption that it can be computed from the optimum combination of moisture charge and storm mechanism. There are two approaches in general use. The computation may be based on a storm model through which upper-limit values essentially of moisture and wind are processed. A more common approach, involving maximization of observed storm-precipitation data, is based on two assumptions: (1) precipitation can be expressed as the product of available moisture and the combined effect of storm efficiency and inflow wind, and (2) the most effective combination of storm efficiency and inflow wind has either occurred or has been closely approached in outstanding storms of record. The latter assumption usually necessitates *storm transposition;* i.e., the application of an outstanding storm from the area of its occurrence to a problem area within the same region of meteorological homogeneity. In the study described in this report, both approaches were investigated. For reasons given in paragraphs 4.4.1 and 4.4.2, the latter approach was used in deriving the basic PMP estimates for this report. Generalization of these basic estimates and the maintenance of consistency within the problem area and with the generalized estimates of PMP previously derived for the United States east of the 105th meridian [1] were accomplished by application of statistical procedures described in chapter 5.

4.2 Basic storm-precipitation data

4.2.1 Storm-precipitation data for this report were obtained from two sources: (1) storm studies by the Corps of Engineers and the Bureau of Reclamation, and (2) a survey of climatological data for large values of storm precipitation. The two major sources of storm studies were *Storm Rainfall in the United States* [15] and unpublished storm studies by the Bureau of Reclamation. Additional sources of storm-study data were *Cooperative Studies Report No. 11* [20] and unpublished studies done for *Cooperative Studies Report No. 12* [21]. The 10- and 500-sq.-mi. precipitation for the 6- and 24-hr. durations for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BELLINGHAM CAA AIRPORT
BLAINE
TATOOSH ISLAND WB
65 MOUNT BAKER LODGE
67 DIABLO POWER HOUSE
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CONCONULLY 30
STEHEKIN 4 NW 66
36 STOCKDILL RANCH
93 FORKS
116 SPRUCE
101 DUCKABUSH 66
ELKS PARK (NR) 120
QUINAULT
CUSHMAN DAM 72
SILVERTON 64
82
BIG FOUR
61 CHIWAWA RIVER
SCENIC 55
42 MERRITT
72 SNOQUALMIE PASS
70
38 BLEWITT PASS
SEATTLE (BOEING) WB AP
STAMPEDE PASS WB
43 MOLD
NORTHPORT
25
35 REPUBLIC
30 USK
DEER PARK 30
30 CLARK FORK
33 MOUNT SPOKANE
SPOKANE WB AP
26 ODESSA
42 WOLF LODGE SUMMIT
40 WALLACE
ROLAND 43
45 HAUGAN
30 PORTHILL
32 BONNERS FERRY
31 TROY
33 SNOWSHOE
71 CANTO
MINERAL 2 S 60
69 PARADISE INN
64 RIMROCK
YAKIMA WB AP
35 FORT SIMCOE (NEAR)
LAKIN RANCH 25
PEOLA 29
TOUCHET RIDGE 33
LEWISTON WB AP
25 ANATONE
48 PIERCE
30 GRANGEVILLE
WALLA WALLA WB CITY 40
46 WALLA WALLA 13 ESE INTAKE
WESTON
70
ASTORIA WB AP
65 COUGAR
69 WIND RIVER
77
PORTLAND WB AP
74 HEADWORKS
68 WELCHES (NEAR)
PENDLETON WB AP
MEACHAM WB AP 32
118 VALSETZ
78 FALLS CITY
SALEM WB AP
EUGENE WB AP
63 MC KENZIE BRIDGE
20 WHITAKER
CHAMPION MINE 87
50 ODELL LAKE
25 BURNS WB CITY
ROSEBURG WB AP
HUNTINGTON 44
31 DEADWOOD DAM
32 LOON CREEK
SHEEP HILL 33
BOISE WB AP
72 RATTLESNAKE CREEK
40 LITTLE CAMAS
84 DENMARK
SEXTON SUMMIT WB
98 GOLD BEACH
44 TRAIL 14 NE
48 BUTTE FALLS 1 SE
MEDFORD WB AP
68 WILLIAMS 2 SW
60 SISKIYOU
93 BROOKINGS
115 GASQUET RANGER STATION
40 CRESCENT CITY
63
29 PAISLEY LAKE (NEAR)
28 SILVER CITY
35 GLENNS FERRY
POCATELLO WB AP
28 MALAD
25 MONTPELIER
51 BABB 6 NE
32 BELTON
34 COLUMBIA FALLS
KALISPELL WB AP
35 DUNKIRK
45 VALIER
37 BLACKLEAF
35 CHOTEAU
GIBSON DAM 49
FORT SHAW 41
GREAT FALLS WB AP
SAINT PETER 33
50 CASCADE 5 S
MISSOULA WB AP
NINE MORSE 33
37 ADEL (NEAR)
48 MILLEGAN
HELENA WB AP 37 CANYON FERRY
35 CHESSMAN RESERVOIR
31 PHILIPSBURG
BOZEMAN 12 NE 37
NORRIS 50
40 JOPLIN (NEAR)
40 CHINOOK
HAVRE WB CITY
48 LLOYD
BIG SANDY 37
83 WARRICK
32 HAYS
68 SHONKIN 7 S
29 TURNER
37 LOST LAKE
34 LORING 10 N
33 MALTA
GLASGOW 33
74 SCOBEY
36 BREDETTE
TELEGRAPH CREEK 31
115 SPRINGBROOK
DOVETAIL 35
31 LEWISTOWN AIRPORT
WINNETT 11 SSE 33
32 COHAGEN
31 ROCK SPRINGS (NEAR)
30 HALF MOON PASS
MILES CITY 37
43
49 KNOWLTON
FORSYTH 2 E
37 FOSTER
41 COLSTRIP
34 HARDIN
46 LAME DEER
37 BROADUS
40 BIG TIMBER
47
BILLINGS WB AP
EDGAR (NEAR) 32
36 CAMPBELL FARM NO. 4
MYSTIC LAKE 40
35 RED LODGE
MOORHEAD (NEAR) 33
ROCKYPOINT
44
SHERIDAN WB AP
DOME LAKE 36
45 OSHOTO 2 N
33 LAKE YELLOWSTONE
KILGORE 56
25 BUFFALO BILL DAM
HYATTVILLE 31
38 40 BUFFALO
HUNTERS STATION
31 VERNON
33 SNAKE RIVER
KIRWIN 24
THERMOPOLIS 35
KAYCEE 17 WNW 50
38 SUSSEX 15 ENE
36 SALT CREEK
41 RIVERTON
LANDER WB AP 37
42 EVRAY
CASPER
48 BLUECAP
SOUTH PASS CITY 36
PATHFINDER DAM 38
35 LITTLE MEDICINE 4 NNW
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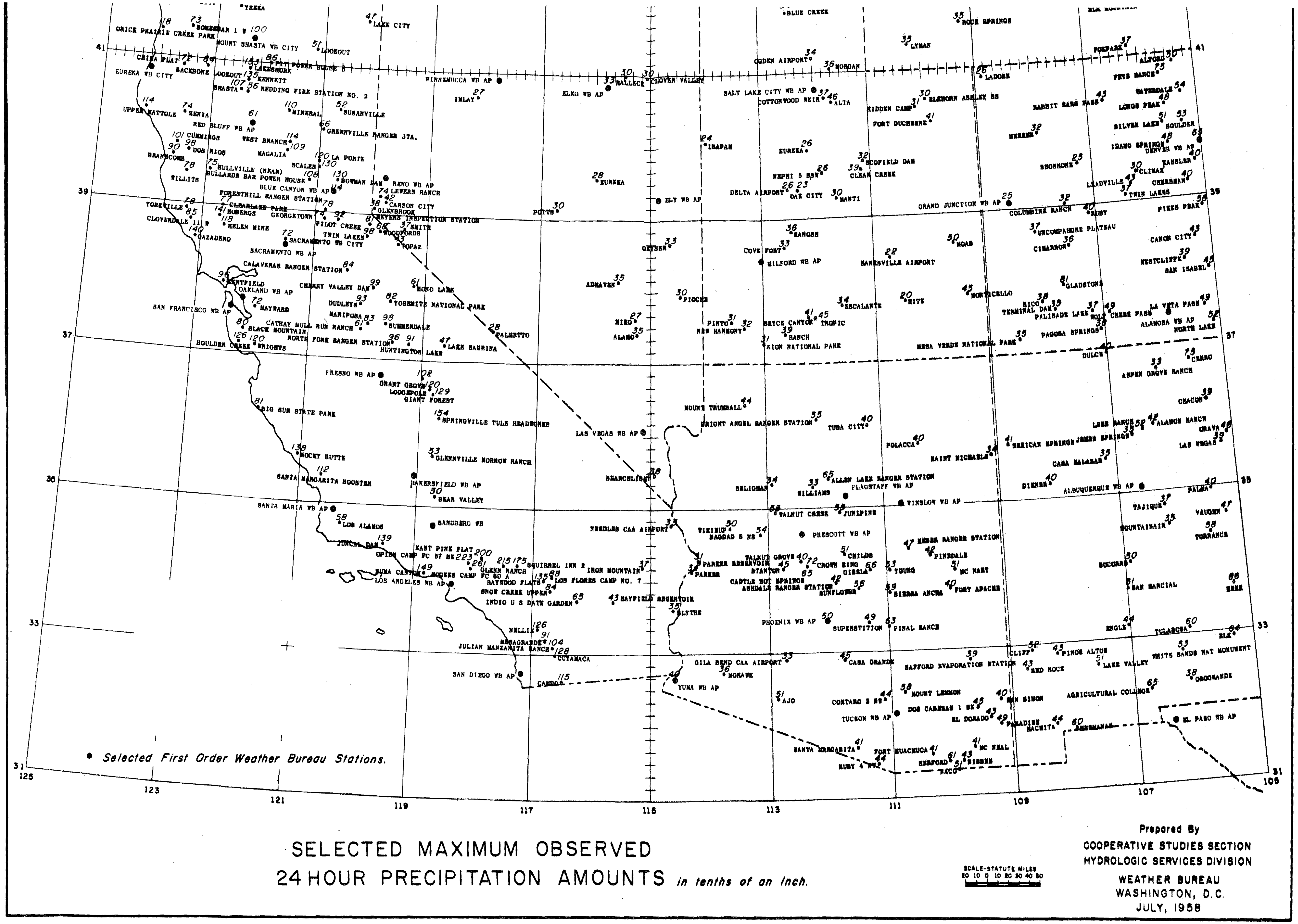
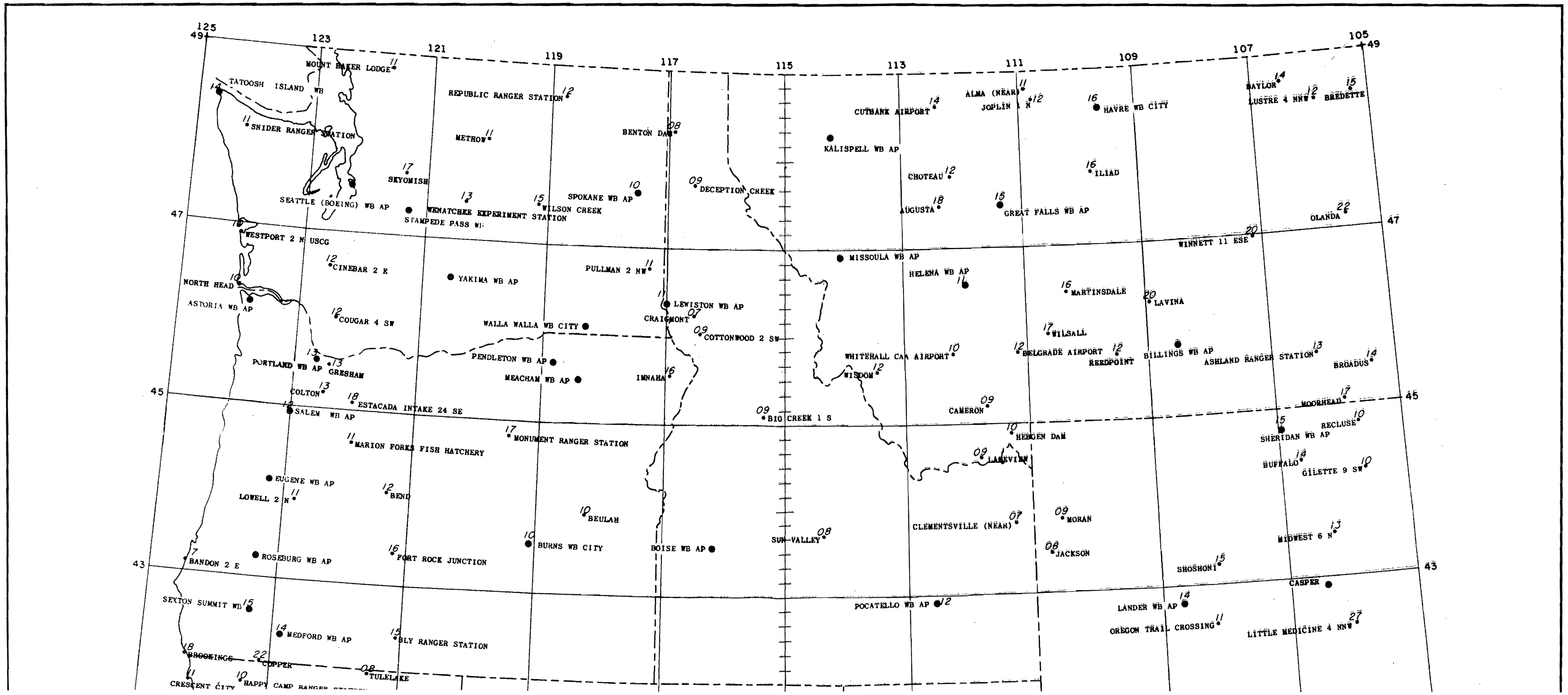


FIGURE 4-1.—Selected maximum observed 24-hr. precipitation amounts, in tenths of an inch.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MOUNT BAKER LODGE 11
TATOOSH ISLAND WB 14
SNIDER RANGER STATION 11
REPUBLIC RANGER STATION 12
METHOW 11
BENTON DAM 08
SKYOMISH 17
SEATTLE (BOEING) WB AP
WENATCHEE EXPERIMENT STATION 13
STAMPEDE PASS WB
WILSON CREEK 15
SPOKANE WB AP 10
DECEPTION CREEK 09
WESTPORT 2 N USCG 16
CINEBAR 2 E 12
YAKIMA WB AP
PULLMAN 2 NW 11
NORTH HEAD 10
ASTORIA WB AP
COUGAR 4 SW 12
LEWISTON WB AP 11
CRAIGMONT 07
WALLA WALLA WB CITY
COTTONWOOD 2 SW 09
PORTLAND WB AP 13
GRESHAM 13
PENDLETON WB AP
MEACHAM WB AP
IMNAHA 16
COLTON 13
ESTACADA INTAKE 24 SE 18
SALEM WB AP 13
MARION FORKS FISH HATCHERY 11
MONUMENT RANGER STATION 17
EUGENE WB AP
LOWELL 2 N 11
BEND 12
BEULAH 10
BURNS WB CITY 10
BOISE WB AP
BANDON 2 E 17
ROSEBURG WB AP
FORT ROCK JUNCTION 16
SEXTON SUMMIT WB 15
MEDFORD WB AP 14
BLY RANGER STATION 15
BROOKINGS 18
COPPER 22
TULELAKE 08
CRESCENT CITY 11
HAPPY CAMP RANGER STATION 10
KALISPELL WB AP
CUTBANK AIRPORT 14
ALMA (NEAR) 11
JOPLIN 1 N 12
HAVRE WB CITY 16
SAYLOR 14
LUSTRE 4 NNW 12
BREDETTE 15
CHOTEAU 12
ILIAD 16
AUGUSTA 18
GREAT FALLS WB AP 15
OLANDA 22
WINNETT 11 ESE 20
MISSOULA WB AP
HELENA WB AP 11
MARTINSDALE 16
LAVINA 20
WILSALL 17
WHITEHALL CAA AIRPORT 10
BELGRADE AIRPORT 12
REEDPOINT 12
BILLINGS WB AP
ASHLAND RANGER STATION 13
BROADUS 14
WISDOM 12
CAMERON 09
MOORHEAD 17
BIG CREEK 1 S 09
HEBGEN DAM 10
SHERIDAN WB AP 15
RECLUSE 10
LAKEVIEW 09
BUFFALO 14
GILETTE 9 SW 10
CLEMENTSVILLE (NEAR) 07
MORAN 09
JACKSON 08
MIDWEST 6 N 13
SUN VALLEY 08
SHOSHONI 15
CASPER
POCATELLO WB AP 12
LANDER WB AP 14
OREGON TRAIL CROSSING 11
LITTLE MEDICINE 4 NNW 27

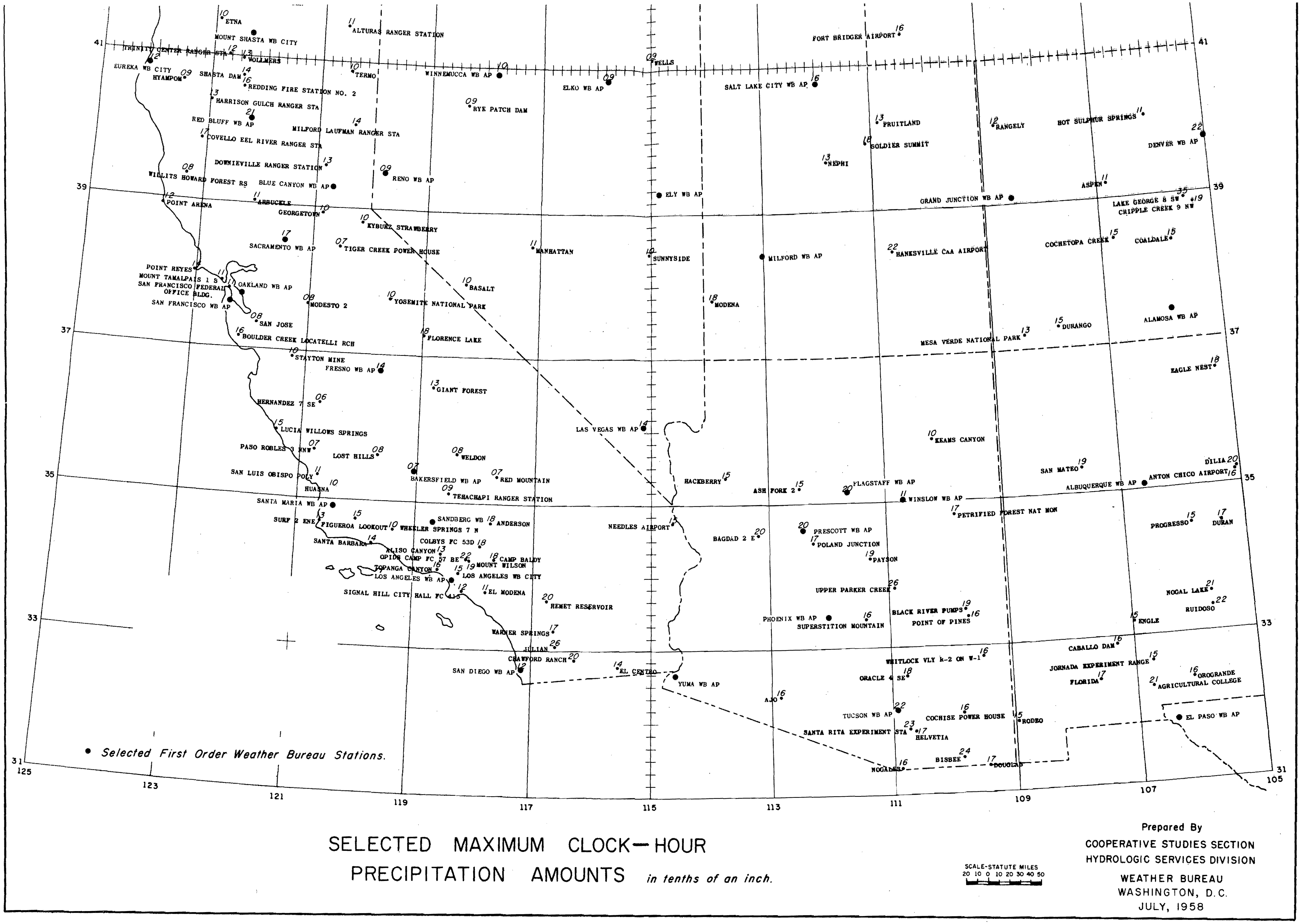


FIGURE 4-2.—Selected maximum clock-hour precipitation amounts, in tenths of an inch.

storms west of the 100th meridian are listed in appendix A. Of the 127 storms west of the 105th meridian, 72 had been analyzed for specific projects in California, Idaho, and Colorado. Vast areas of the West are not represented by storm-study data.

4.2.2 The uneven geographic distribution of the available storm-study data necessitated additional data for regions of sparse coverage. The large amount of work involved in storm studies precluded preparation of additional ones for this project. It was considered more feasible, because of the small areas being considered, to survey the climatological publications for large point values of precipitation.

4.2.3 Figure 4–1 shows the maximum observed 24-hr. precipitation amounts at selected stations in western United States. Only data for stations having the highest maximum in the immediate area surrounding the station are shown. The size of this area was subjectively determined and varies inversely with the station density and directly with the ruggedness of the terrain.

4.2.4 The values of figure 4–1 are only those that have been measured in official rain gages. The average density of rain gages in western United States is much less than ideal and differs even between adjoining States; e.g., California and Nevada. In some regions there are areas of several hundred square miles in which there have never been any rain gages. Stations have been established in those areas where the towns and ranches or farms were located along the river valleys and on the plains. The mountainous regions, where the variability of precipitation is the greatest, generally have the lowest station density.

4.2.5 In eastern United States official gage observations have been supplemented by "bucket surveys" (par. 2.4.6). Such surveys have not been made often in the West. The adequacy of these surveys depends upon the density of settlement. Where there are many small towns and villages and the farms are close together, there are many opportunities for obtaining reliable estimates of storm amounts from exposed containers other than official gages. In the West the majority of settlements are located in river valleys, which generally offer more favorable sites for farms and ranches. This uneven distribution of the relatively sparse population precludes "bucket surveys" in mountainous areas, where variability of precipitation is greatest.

4.2.6 Precipitation amounts from the cooperative stations, which largely comprise the precipitation-station network, are for the observational day. The cooperative observer usually measures the precipitation in the morning or evening and records the amount that fell in the 24 hr. preceding the observation time. There are no intervening measurements to determine whether the recorded amounts are from precipitation throughout the entire 24-hr. period or from precipitation for a few minutes or hours. The maximum 24-hr. rainfall obtained from the records of cooperative stations can vary from 50 to 100 percent of the true 24-hr. maximum amount. All previous attempts to estimate the true maximum 24-hr. values from the recorded amounts have been based on analyses of the accompanying synoptic situations and on comparison of the rainfall distribution at nearby recording-gage stations. This technique, described by Shands and Brancato [22], was applied to the outstanding values in this study.

4.2.7 Deficiencies also exist in observations of precipitation for durations shorter than 24 hr. Only about one-fourth of the gages are of the recording type (pars. 2.4.2 and 2.4.4), and their length of record is generally shorter than that of the nonrecorders. The records of recording-gage stations, except for Weather Bureau first-order stations, average approximately 18 yr. as compared to 50 to 60 yr. for the nonrecording stations. Moreover, the recording-gage charts are evaluated for 1-hr. intervals between full hours as indicated by the clock; e.g., from 3 to 4 p.m., 4 to 5 p.m., etc. Thus, any survey of hourly rainfall data for maximum values yields only the maximum "clock-hour" amount and not the true 1-hr. maximum. Figure 4–2 shows the maximum clock-hour amounts for selected stations in the West. The basis of selection was the same as that used for the 24-hr. amounts (par. 4.2.3).

4.2.8 The sparseness of the gage network (pars. 2.4.2–2.4.4) and the relative crudeness of isohyetal analyses used in storm studies makes any distinction between point and 10-sq.-mi. values impracticable. In most cases the central isohyet is drawn on the basis of the largest observed point value. The size of this isohyetal center is determined in a subjective manner from the station density, the ruggedness of the terrain, and the scale of the map. Within the limits of accuracy of the observation and the variability of the precipitation, the largest storm value observed in a gage is taken as the average depth over 10 sq. mi. and is considered applicable to all smaller areas within the 10 sq. mi.

4.3 Lower limits of PMP estimates

4.3.1 By definition (par. 4.1.1), PMP at any point must at least equal or exceed the maximum precipitation ever observed there. Considering the relatively short precipitation records and sparse gage networks, it is extremely unlikely that PMP has already been measured at any point. That PMP for a particular place must exceed maximum observed precipitation for that place is therefore a conservative statement. However, it stands to reason that maximum observed values provide some idea of the lower limits of PMP. If there are several precipitation stations within a relatively small area, a better estimate of the lower limit of PMP for a point in that area might be obtained by enveloping the maximum values of record for all the stations. In other words, the highest station amount observed would be assumed to be applicable to any point in the area. The lower limit of PMP will then exceed the maximum observed precipitation at most stations.

4.3.2 Figures 4–1 and 4–2 show the maximum observed 24-hr. and clock-hour rainfalls, respectively. Since these maps are based solely on official gage records, it is very likely that higher, but ungaged amounts have occurred (par. 2.6.1). Comparison indicates that maximum amounts observed at Weather Bureau first-order stations are about half those observed at cooperative stations, which have an average network density 30 to 40 times greater. Addition of "bucket survey" data indicates an even greater discrepancy.

4.4 Maximization by storm models

4.4.1 As stated in paragraph 4.1.4, storm models were investigated but the results were not satisfactory. Briefly, the use of storm models in determining PMP consists of (1) postulating a storm mechanism, or model, (2) testing it on observed storms to see if it will duplicate their precipitation values, and (3) introducing into the satisfactory models extreme values of moisture, wind, etc., to obtain PMP values. Various models [13, 23, 24] have been used in other studies for determining PMP over large areas and for quantitative precipitation forecasting. Attempts to apply storm models to areas as small as 400 sq. mi. have not been successful because the current observational network is not dense enough to measure in sufficient detail the localized moisture supply, wind, convergence, etc. Measurements of such parameters are only adequate for defining average conditions over large areas.

4.4.2 The inadequacy of storm models for determining PMP for small areas is well stated in the report of such a test in *Hydrometeorological Report No. 21B* [25]:

> The failure of the computation methods tested to reproduce the small-area rainfall must be charged to a combination of factors. The use of the same inflow-wind velocity for small areas as for 10,000 square miles was probably erroneous but the observations available did not permit a more detailed distribution across the area. It is also possible that the dewpoints used, representative for the 10,000-square-mile area, might need re-examination, although it is believed that any such error could not be of major importance. Omission of quantitative calculations of localized convergence effects is a recognized deficiency; that problem cannot be satisfactorily solved until adequate three-dimensional meteorological observations are available during storm periods.

4.5 Moisture adjustments

4.5.1 The maximization of observed storm precipitation for determining PMP involves moisture adjustment, the basic assumption being that the storm would have produced maximum precipitation had the maximum moisture supply been available. Briefly, the observed storm precipitation is increased by the ratio of the maximum W_p estimated as possible for the time of year of the storm occurrence to the W_p estimated as prevailing during the actual storm. The maximum W_p is estimated from the highest 12-hr. persisting dewpoint of record, and the W_p for the storm is estimated from the representative 12-hr. dewpoint for the storm. The manner in which these W_p estimates are obtained is described below.

4.5.2 The available moisture is a major factor in producing the precipitation of a particular storm. Until fairly recently the source and amount of moisture available could be estimated only from surface observations. The parameters of moisture needed, however, are the total amount available and its distribution through the atmosphere, rather than merely the surface moisture. Therefore, to study past storms, certain assumptions were necessary to relate the surface moisture to the W_p in the atmosphere. Studies of major storms have indicated that in most of them the air is saturated or nearly so. The moisture charge, or W_p, in any particular storm was therefore assumed to be equal to that of a saturated air mass with a surface dewpoint equal to that prevailing during the storm and a pseudoadiabatic lapse rate.

4.5.3 Although regular upper-air soundings had been made by the Weather Bureau at a few stations since the late 1920's, it was not until 1940 that a relatively adequate network of radiosonde stations was established. These stations release balloons, usually once or twice daily, with small boxes containing meteorological instruments and radio transmitters attached. As the balloons rise through the atmosphere, roughly to over 15 mi. above sea level, their transmitters send back the to the ground station an almost continuous record of pressure, temperature, and humidity. This sounding of the atmosphere is assumed to be made directly over the releasing station, even though the balloon may drift an appreciable distance during its ascent. About 30 min. are required for the balloon to reach an altitude of 5 mi. During this time, the balloon usually drifts from 15 to 30 mi. from the point of release.

4.5.4 Sufficient upper-air data are now available to permit tests of the assumption that the W_p in a storm can be satisfactorily approximated by W_p computed for a saturated pseudoadiabatic atmosphere having the same surface dewpoint as the storm. Comparisons between observed and estimated W_p values had been made [21] for 21 storms occurring between 1939 and 1952 over the Central Valley of California and the western slope of the Sierra Nevada. A dewpoint station was selected within the warm, moist air determined to be the moisture source for each storm. The highest dewpoint equalled or exceeded for a period of at least 12 hr. was selected as the representative dewpoint for the storm. The amount of W_p was then estimated for the layer from the surface to the 400-mb. level (about 23,000 ft. above sea level) on the basis of this representative dewpoint, assuming a saturated atmosphere and a pseudoadiabatic lapse rate. The actual, or observed, W_p for the same storm and the same layer of atmosphere was then computed from the upper-air soundings at stations in the same general area as the station providing the surface dewpoint. A relation developed between the observed and estimated W_p for the 21 storms yielded the regression equation: $W_p(\text{obs.}) = 0.02 + 0.99\ W_p\ (\text{est.})$ with a correlation coefficient of 0.92 and a standard error of estimate of 0.07 in.

4.5.5 Platzman [26], in a study of maximum rainfall in the Willamette Basin, Oreg., related the surface dewpoints at Sexton Summit with the moisture charge observed in soundings at Medford, Oreg. Forty-nine cases during January 1945 were selected from both storm and nonstorm situations. The W_p between 1,175 m. (about 3,800 ft., elevation of Sexton Summit) and 6 km. (about 20,000 ft.) was compared with the average of the two surface dewpoint observations made closest to the time of the sounding. The correlation coefficient was 0.89.

4.5.6 To determine if the assumption of a saturated air mass with a pseudoadiabatic lapse rate was applicable to other regions in western United States, several additional storms were studied. The W_p at many points in each of these storm situations was obtained from radiosonde observations and compared with that estimated from the surface dewpoint observed in the sounding, assuming saturation and pseudoadiabatic conditions. The scatter diagram showed good agreement with the results obtained in the previous studies. This suggests that the assumption may be considered applicable to all regions of the western United States.

4.5.7 The assumption that extremes of W_p would be approximated by values estimated from extreme surface dewpoints, assuming saturation and pseudoadiabatic conditions, was also investigated. Data from Oakland, Boise, and Denver were selected as representative of typical meteorological regions of western United States. Oakland data are considered representative of the regions where storms have their moisture supply from the Pacific without the interposition of any large orographic barriers; Boise, of the intermountain region where the moisture supply comes from either the Pacific or the Gulf of Mexico, passing over large orographic barriers; and Denver, of the eastern slope of the Rockies where moisture comes from the Gulf of Mexico without crossing any large orographic barriers. For the year 1950, W_p was computed from the surface to 400 mb. (about 23,000 ft.) in all soundings indicating W_p exceeding approximately 90 percent of that estimated from the surface dewpoint and pseudoadiabatic saturation conditions. The observed W_p was then compared with that estimated from the surface dewpoint in the sounding as shown in figure 4–3, which is based on 164 soundings for Oakland.

4.5.8 The large scatter in figure 4–3 is the result of deficiencies in both the method of obser-

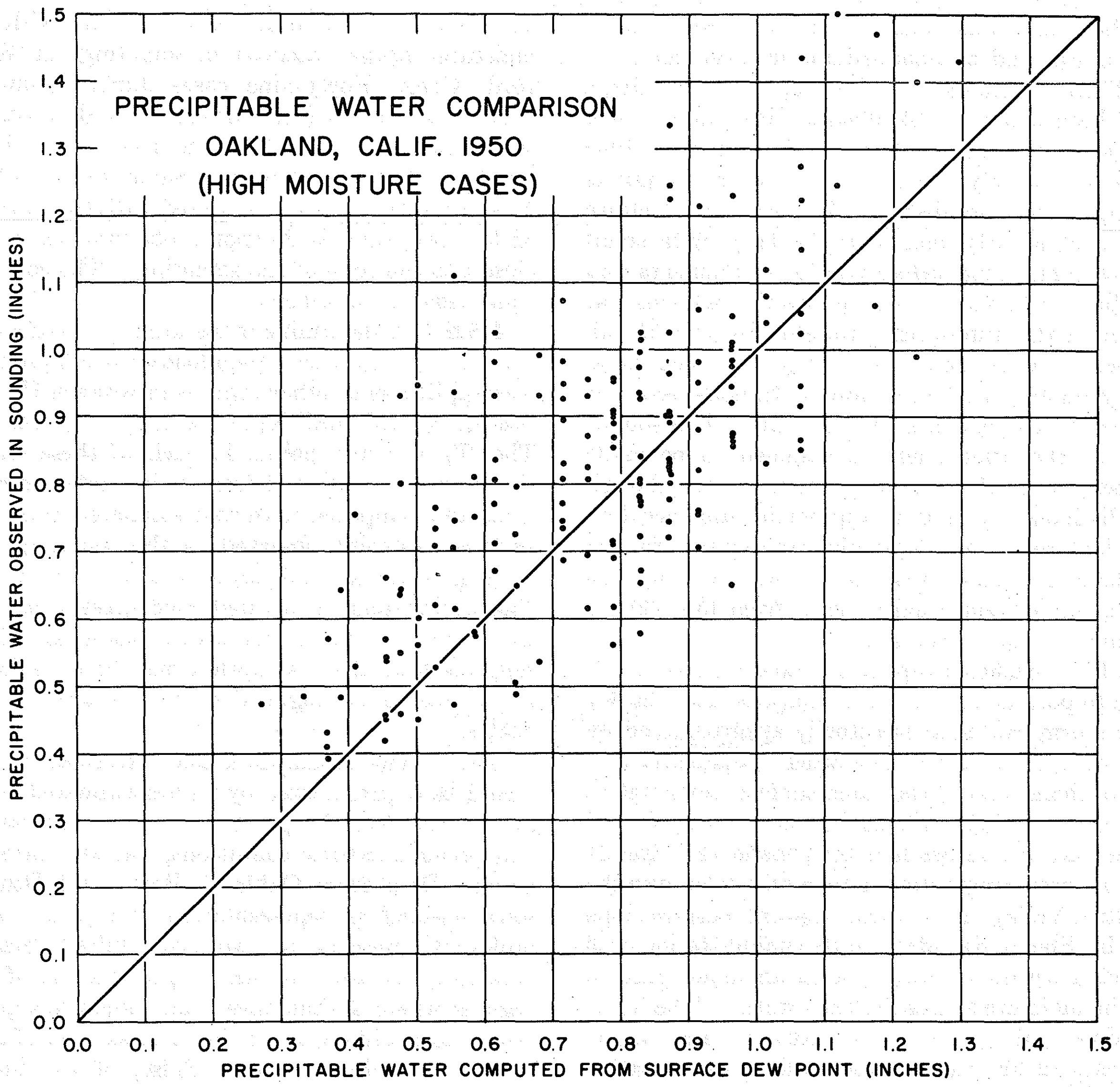


Figure 4-3.—Comparison of precipitable water observed in soundings at Oakland, Calif., in 1950, with that computed from the observed surface dewpoint and a saturated pseudoadiabatic atmosphere, using high moisture cases only.

vation and the method of selecting the soundings. Observational deficiencies may result from malfunctioning of the radiosonde equipment or from instrumental limitations, and probably result in a random error. There are meteorological conditions in which the surface dewpoint is not a good indication of the W_p in the atmosphere, and computed values may be either higher or lower than observed. Estimated W_p higher than observed could be the result of a moist air mass near the surface with a dry air mass above. Estimated W_p lower than observed could be the result of a dry air mass near the surface with a moist air mass above, or of a sounding through an unrepresentative part of the atmosphere, for example, through a thick isolated cloud. Though the scatter is large, the nearness of the data to a 45° line suggests that the assumption of pseudoadiabatic saturation conditions results in estimates of W_p that are a satisfactory approximation of the observed.

4.5.9 Similar plots were made by selecting the highest 20 percent of the dewpoints at 0300 GMT (7 p.m., PST) for each month for the year 1950. Figure 4-4 shows this comparison for Oakland. The open circles represent the summer months, May through September; and the solid symbols,

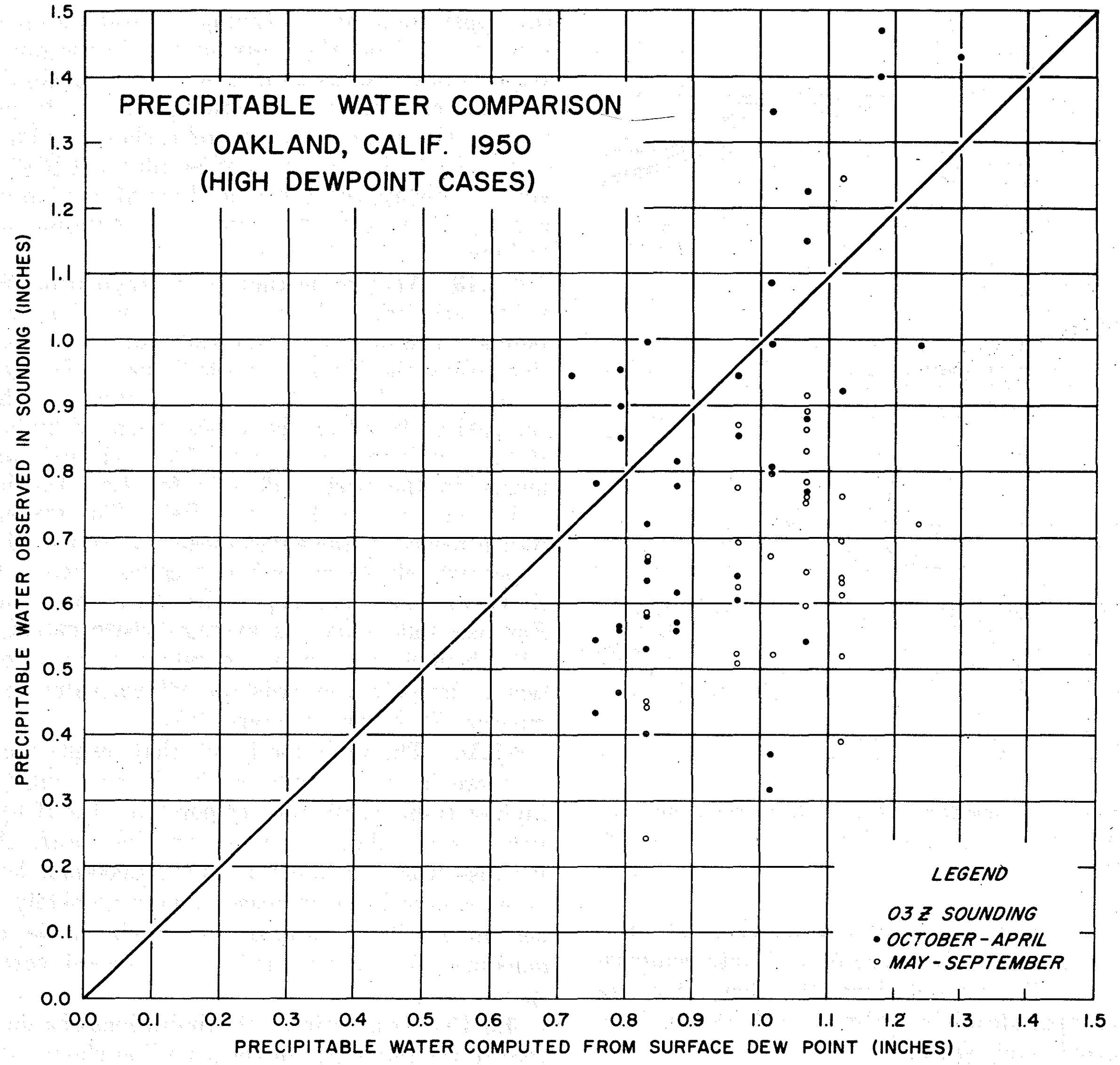


Figure 4–4.—Comparison of precipitable water observed in soundings at Oakland, Calif., in 1950, with that computed from the observed surface dewpoint and a saturated pseudoadiabatic atmosphere, using high dewpoint cases only.

the winter months, October through April. A line of best fit for all the data would show that the assumption of a pseudoadiabatic lapse rate results in an overestimate. If the data for only the winter months were considered, the line of best fit through the origin would then be within about 15 percent of a 45° line, with a standard error of about 25 percent of the mean. This suggests that in the winter, or storm, season, W_p associated with the highest dewpoints can be satisfactorily approximated by the assumption of a pseudoadiabatic saturated atmosphere. In general, the best fit between observed and estimated W_p occurred with storm events.

4.5.10 The highest 12-hr. persisting dewpoint is defined as the highest dewpoint that can be equalled or exceeded for 12 consecutive hours. It is considered to be the highest dewpoint that could persist for 12 hours. The highest 12-hr. persisting dewpoints of record had been obtained previously [27] as the result of a survey of dewpoint records for all Weather Bureau first-order stations having at least 40 yr. of record as of 1945. The highest 12-hr. persisting dewpoint for each month was plotted against date of occurrence, and a smooth enveloping curve was drawn. Several stations have observed higher 12-hr. persisting dewpoints since the original survey was completed,

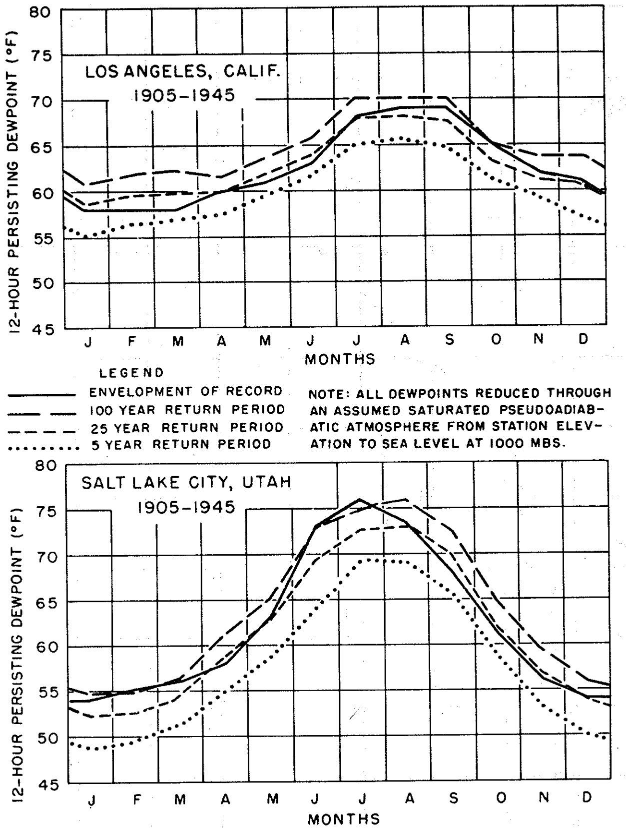


Figure 4–5.—Comparison of highest 12-hr. persisting dewpoints of record with those for selected return periods.

and the annual curves were adjusted to fit these additional data. In order to facilitate comparisons and W_p computations, the dewpoints are reduced pseudoadiabatically to the 1,000-mb. level (approximately sea level).

4.5.11 Consideration was also given to the need for extrapolating the above basic dewpoint data beyond the maximum observed. The Pacific Ocean west and southwest of California is the source region for warm, moist air for large parts of the West. The mean sea-surface temperature in January over the source areas is in excess of 60° F., while the average highest 12-hr. persisting 1,000-mb. dewpoint for stations along the California coast is 58° F. In July the mean sea-surface temperature is in excess of 65° F., while the highest 12-hr. persisting 1,000-mb. dewpoint along the California coast averages 64° F.

4.5.12 The higher sea-surface temperatures in the source regions suggest that the maximum land-surface dewpoints and associated W_p have not yet been observed. Determination of a physical upper limit of W_p through consideration of evaporation from the ocean surface in the source region would require assumptions about the initial moisture conditions of the atmosphere, the trajectory of the air, the amount of turbulent mixing along the trajectory, and other physical parameters. This approach has not been attempted because the requisite data and understanding are lacking.

4.5.13 Another method of extrapolating W_p is by statistical analysis of 12-hr. persisting dewpoints. The data were analyzed for several stations using the Fisher-Tippett Type 1 (Gumbel) distribution. Figure 4–5 shows the results of this comparison based on the annual series of highest 12-hr. persisting dewpoints for each calendar month in the period 1905–45 for Los Angeles, Calif., and Salt Lake City, Utah. The average return period of the envelopment of the record is approximately 25 yr. for Los Angeles, where only the October dewpoint approaches the 100-yr. value. For Salt Lake City, the average return period is still about 25 yr., but the envelope curve of observed dewpoints exceeds the 100-yr. value in 3 months: February, June, and July.

4.5.14 The variation in W_p that results from an increase in dewpoint can be shown using the highest 12-hr. persisting dewpoint and the 100-yr. value for mid-January at Los Angeles, Calif. An increase from 58° to 61° F. in the 1,000-mb. dewpoint results in an increase of approximately 16 percent in W_p. Estimates of PMP made by moisture adjustment would be increased correspondingly.

4.5.15 In addition to the limitations of a short record, the reliability of the sampling should also be considered. W_p is a continuous variable both in time and space. The methods for determining W_p in storms use observations at one point or the average of those at several points scattered over a small area, with the observations being taken 2 to 4 times daily. The choice of observational data is confined to the meteorological stations in operation at the time of the storm and to the times at which observations are taken. This sampling procedure is far from ideal but is the only practicable one at this time.

4.5.16 The W_p for individual storms was determined from the surface dewpoints during the storm period. Representative storm dewpoints were determined in accordance with the criteria described in *Hydrometeorological Report No. 25A* [28]. Two major criteria are quoted:

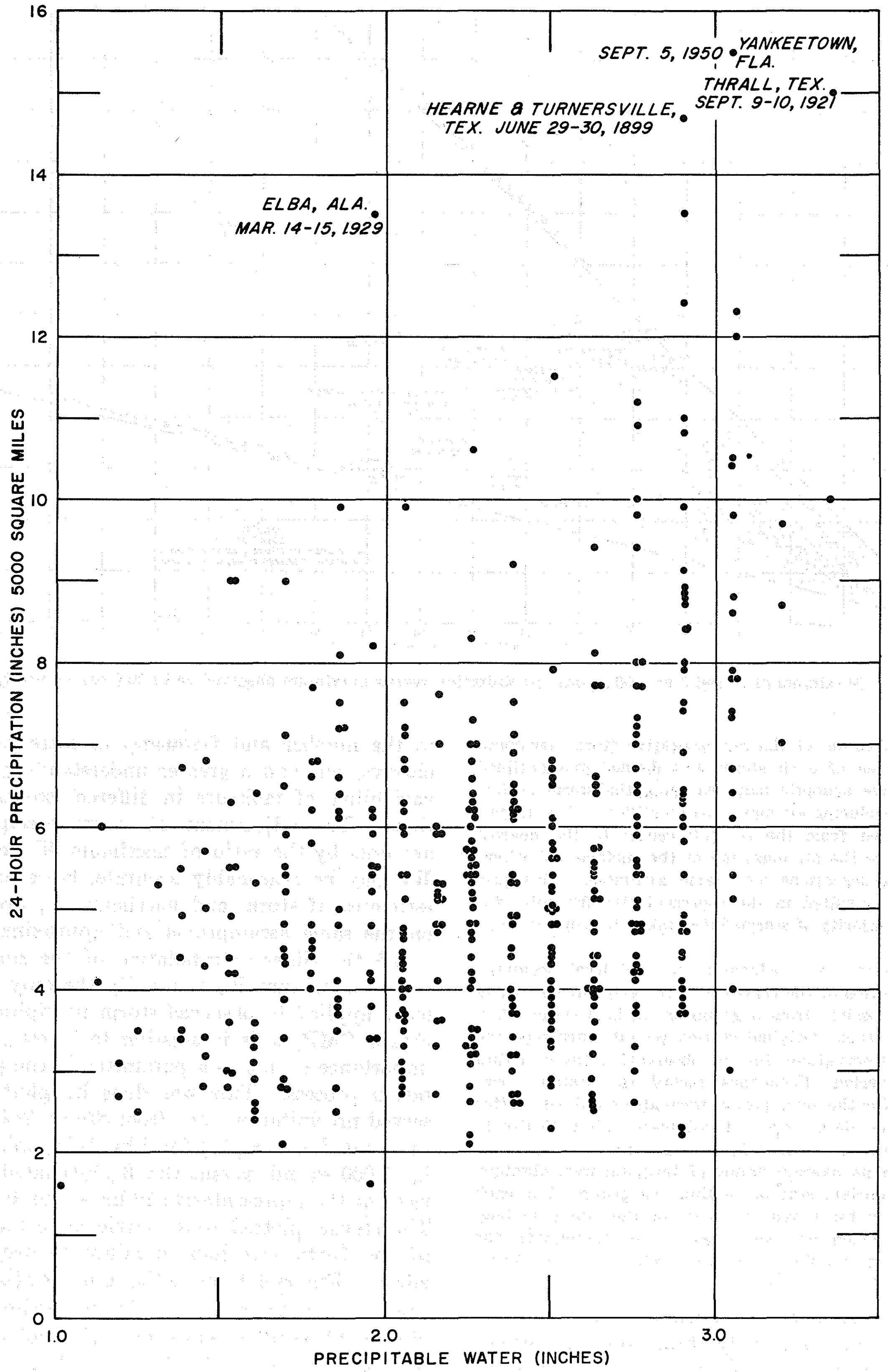


FIGURE 4-6.—Precipitable water versus maximum 24-hr. 5,000-sq.-mi. precipitation in selected major storms.

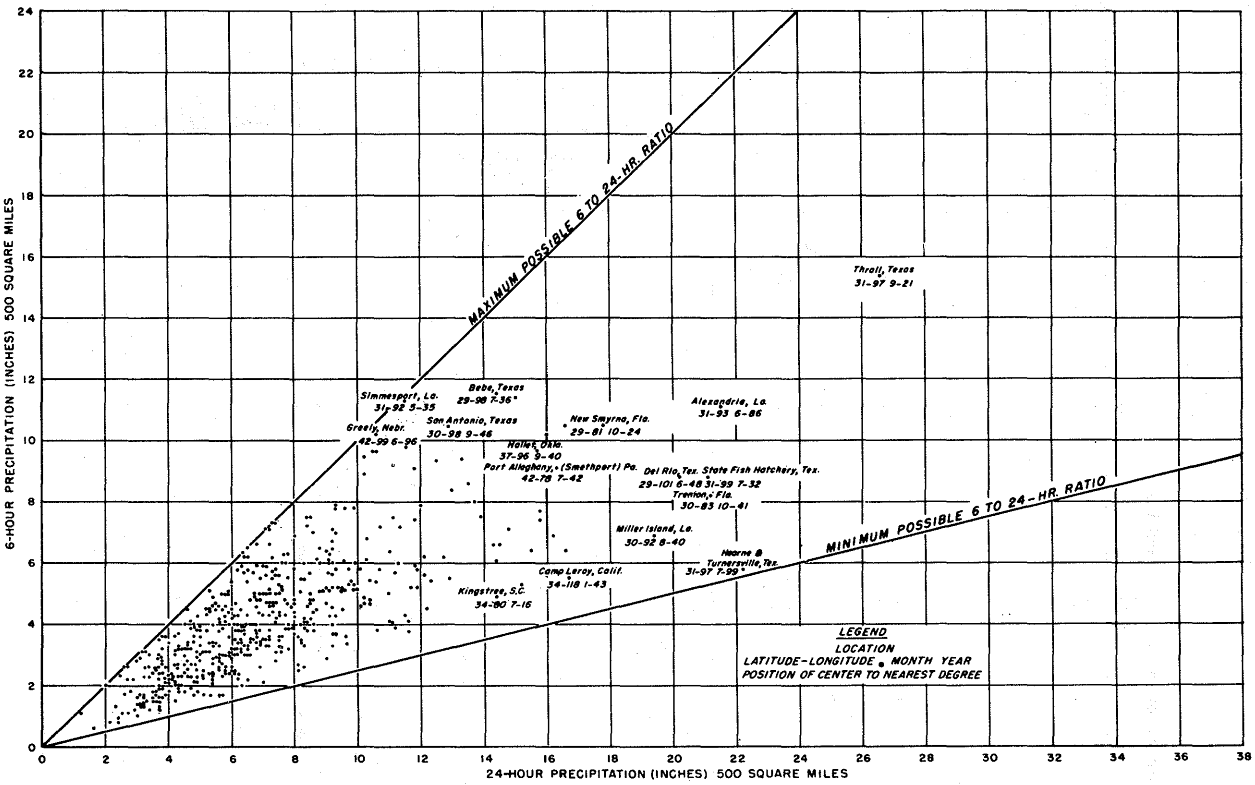


FIGURE 4–7.—Maximum observed 6-hr. 500-sq.-mi. precipitation versus maximum observed 24-hr. 500-sq.-mi. precipitation.

In the selection of the representative storm dewpoint, the rain area of each storm was defined and outlined on successive synoptic maps covering the storm period. The rain-producing air mass was identified and its trajectory retraced from the rainfall center to the nearest region where the air mass lay at the surface and where dewpoint observations were also available. This procedure has resulted in the representative dewpoint for the large majority of storms being taken in tropical maritime air.

To minimize observational errors and local peculiarities, a selection of the representative dewpoint was made wherever possible from a group of stations rather than a single station. Original station records furnished the dewpoint observations for all observation times within the storm period. From these records the minimum temperatures for the same period were also obtained. After the collected data were reduced pseudoadiabatically to 1,000 mb. to remove the effect of elevation difference between stations, average values of dewpoint were obtained from appropriate stations within the group. For each 12-hr. period the lowest dewpoint or the minimum temperature, whichever was lower, was tabulated; the highest value tabulated was then selected as the 12-hr. representative storm dewpoint.

4.5.17 Estimates of storm and maximum W_p can be considered only first approximations. More accurate values would require an increase in the number and frequency of meteorological observations and a greater understanding of the variability of moisture in different storm situations. The adjustment of storm precipitation amounts by the ratio of maximum W_p to storm W_p may be reasonably accurate, however, since estimates of storm and maximum W_p are based on the same assumptions and approximations.

4.5.18 Since extrapolation of the storm W_p to the maximum W_p is usually the only adjustment applied to observed storm precipitation to obtain PMP, it is interesting to investigate the importance of W_p as a parameter in the precipitation process. This was done by plotting observed precipitation data from *Storm Rainfall in the United States* [15] for 6 hr. 10 sq. mi. and 24 hr. 5,000 sq. mi. versus the W_p estimated on the basis of the representative 12-hr. storm dewpoint. The storms plotted were restricted to those east of the 105th meridian to minimize orographic effects. Figure 4–6 shows the result for the 24-hr. precipitation amounts. The lower portion of this plot could be filled completely with points. The storms in *Storm Rainfall in the United States*

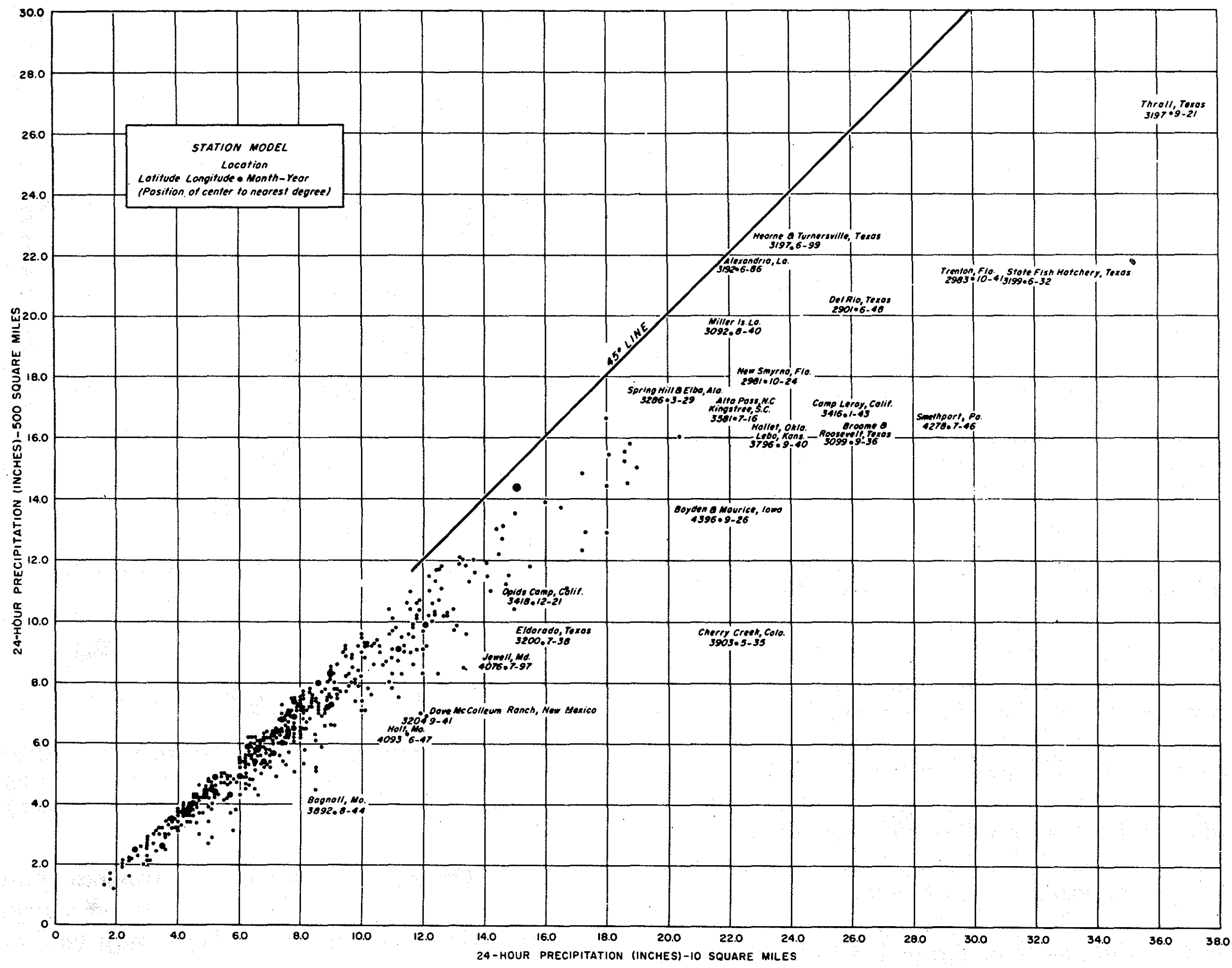


Figure 4–8.—Maximum observed 24-hr. 10-sq-mi. precipitation versus maximum observed 24-hr. 500-sq.-mi. precipitation.

are selected for analysis on the basis of their having produced large amounts of precipitation. There are many cases for each value of W_p where the precipitation is much smaller and even zero. The relation of figure 4–6 could be improved by continuing to eliminate the smaller values of precipitation for each dewpoint until there were only a few of the maximum values left. Diagrams have been plotted where the data were selected on the basis of W_p, say, for the highest persisting dewpoint for each year of record for a particular month at some station. The corresponding precipitation at the station or at some point upwind was plotted as the other parameter. In each case the resultant scatter was very nearly random.

4.5.19 A refinement that would be possible with more frequent and more closely spaced moisture data might result in recognition of considerable variation in the W_p of the inflowing air. Present practice attributes rainfall variations within a storm almost entirely to areal and time variations in the storm mechanism.

4.5.20 The moisture adjustment for storms ordinarily has been the same regardless of the duration of the precipitation or the size of area. Figure 4–7 shows the relation between maximum 6- and 24-hr. precipitation over 500 sq. mi. for the same storms. This data includes all the storms for which either preliminary or approved storm studies were available. A straight line that could be drawn through the data suggests that the practice of using one moisture adjustment for all durations in the same storm is acceptable. Similar plots were made with other sizes of area, and also by restricting the storms to those of the western United States, with the same result.

4.5.21 To test the effect of size of area on moisture adjustment, similar plots were made of the

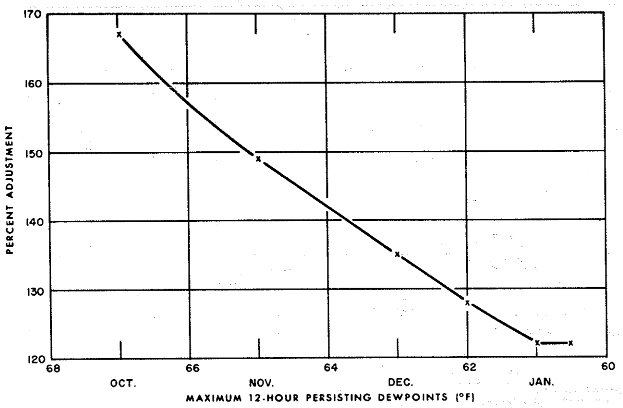


Figure 4–9.—Seasonal variation in moisture adjustment for storm of January 19–24, 1943, at Hoegee's Camp, Calif.

maximum 10-sq. mi. to the maximum 100-, 200-, 500-, and 10,000-sq.-mi. precipitation for the 6- and 24-hr. durations. Figure 4–8 shows this relationship for the 10-sq.-mi. versus the 500-sq.-mi. precipitation for the 24-hr. duration. The scatter about the line of best fit that could be drawn is relatively small. The small scatter and the nearness to a 45° line suggests that the high amounts of precipitation for small areas come from the same storms that produce the high amounts for larger areas and that the same moisture adjustment for all sizes of area in a storm is acceptable. The slight tendency of a line that might be drawn through the points of figure 4–8 to be convex up instead of straight is believed to be partly a product of bias in selecting the data. The data are from storms that covered fairly large areas. An attempt to correct for this inherent bias has been made by examining the areal distribution of rainfall that established maximum point values of record. The results tend to support a linear relationship between maximum rainfall over areas of 10 and 500 sq. mi.

4.6 Storm transposition

4.6.1 The maximum observed storm-precipitation data adjusted for maximum moisture charge (par. 4.5.1) were plotted on a map (not shown) and analyzed. The analysis allowed the largest moisture-maximized precipitation amounts to control the isolines within meteorologically homogeneous regions. This procedure implies transposition (par. 4.1.4) of the precipitation value and of the storm itself. The limits of transposition were determined by considerations of topography and of the regions in which similar storms have occurred.

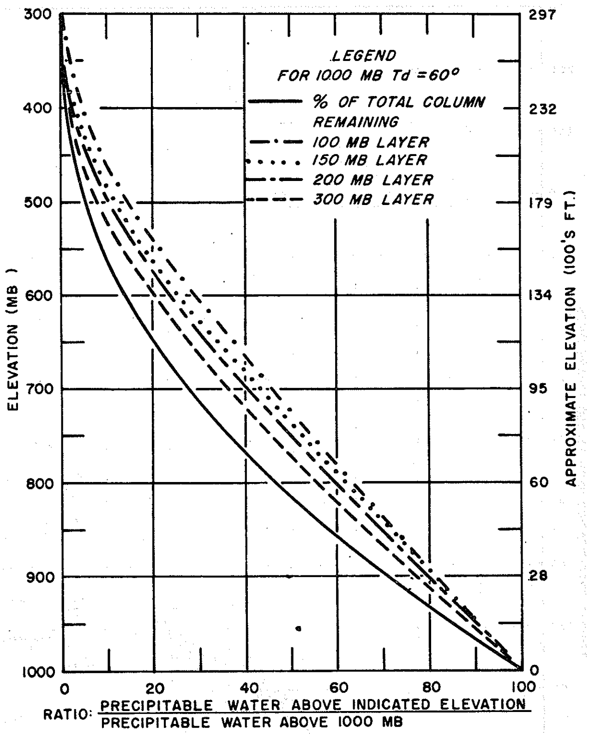


Figure 4–10.—Variation of precipitable water with elevation in a saturated pseudoadiabatic atmosphere having a 1,000-mb. temperature of 60° F. (Ratios in percent.)

4.6.2 Orographic influences are apparently an important component of the total storm efficiency. Transposition of storms in the West must be limited, therefore, to regions of similar orographic influences unless the various orographic effects can be evaluated. No completely satisfactory method of evaluating local effects resulting from differences in slope, orientation, exposure, etc., has been developed. Consequently, in this report only the broad-scale effects of topography were considered.

4.6.3 In this study each storm considered for transposition was examined individually and limits of transposition determined. In a general way the criteria considered consisted of the 2-yr. 24-hr. precipitation value, the moisture source, the barriers to moisture inflow, the broad-scale topography, and the history of the regions within which similar synoptic storms had occurred. In regions where data were sparse, the limits were more liberally determined. A list of all the storms considered is given in appendix A.

4.6.4 After the geographical limits of transposition for the outstanding storms had been determined, the observed precipitation amounts were adjusted to the maximum observed moisture charge (par. 4.5.1). Previous reports prepared for specific basins throughout the country and generalized estimates prepared for eastern United States [1, 24] and for part of California [21] assumed that a storm could occur 15 days earlier or later without any modification in the storm mechanism. In these studies the storms, therefore, have been adjusted to the maximum observed moisture charge within this 30-day period. One map (not shown) was prepared using moisture adjustments determined within this limitation.

4.6.5 An alternate procedure would be the examination of each storm and the determination of the maximum limits of seasonal transposition considered possible. Another map (not shown) was developed using this procedure. Each of the outstanding storms was examined and the transposition limits determined, using the criteria mentioned in paragraph 4.6.3. Figure 4–9 shows an example of the seasonal variation in adjustment for the January 19–24, 1943, storm at Hoegee's Camp, Calif. The representative storm dewpoint was 57° F. The maximum observed dewpoint on the date of occurrence was 61° F.; 15 days earlier it was 61.6°; and the maximum dewpoint observed within the winter season was 67°. The adjustment to maximum moisture charge on the date of occurrence is 123 percent; for the maximum moisture within 15 days, it is 125; and for the maxinum moisture charge within the "winter season," it is 167. Considering the inaccuracies involved in the measurement and the selection of the dewpoint, reduction to the 1,000-mb. level, and the assumptions concerning the moisture distribution through the atmosphere, it has been the practice to use the nearest whole degree in computing the moisture adjustment. Using this convention, the adjustment to maximum moisture within 15 days would be 128 percent. An increase of 1° in the maximum observed dewpoint results in a 5-percent increase in the moisture adjustment. The increase to the maximum winter-season moisture charge results in an increase of approximately 33 percent in the moisture adjustment. This variation in adjustment shows that significant differences can result if different limitations are placed on the seasonal transposition of storms.

4.6.6 For storm transposition in mountainous regions, assuming that the storm mechanism does not vary appreciably from one location to another, variations in precipitation must result chiefly from differences in available moisture. Figure 4–10 shows the percentage of moisture remaining in saturated layers of different thicknesses as the elevation increases. These different thicknesses of layers would produce different reductions in precipitation amounts as elevation increased.

4.6.7 That available moisture (as estimated by present methods) alone does not account entirely for precipitation differences in orographic regions is indicated by moisture adjustment of observed storms. For example, the storm of May 30–31, 1935, in eastern Colorado, had two centers. One center was at an elevation of 3,500 ft., and the other at about 6,000 ft. The 24-hr rainfall in each center was 24.0 in. With the information available, it is impossible to distinguish any difference in storm efficiency between the two centers. The moisture supply differs only by the depletion represented by the difference in elevations. Transposition of these two rainfall centers from one site to the other on the basis of moisture adjustment alone results in an increase of the high-elevation center and a reduction of the low-elevation center. The difference between adjusted and observed values suggests differences in storm mechanism or available moisture that cannot be evaluated on the basis of meteorological data and knowledge now available.

Chapter 5

GENERALIZATION AND MAINTENANCE OF CONSISTENCY

5.1 Introduction

5.1.1 The objectives of this report are to present generalized estimates of PMP for the United States west of the 105th meridian consistent with those previously derived for the region east of that meridian [1]. Storm transposition is, of course, a generalizing procedure involving varying degrees of subjectivity (sec. 4.6). In this study generalization was based to a great extent on statistical procedures so that the opportunity for subjectivity was minimized. Statistical procedures were also used to check the consistency of the results of *Hydrometeorological Report No. 33* [1] and to insure consistency in the PMP estimates presented herein.

5.1.2 Statistical procedures cannot define a maximum value of rainfall. The concept of a fixed and definable upper limit of rainfall is based on a purely deterministic view of nature. The broad-view approach, which accommodates uncertainties, requires establishment of a conventional standard based on judgment. Statistical procedures, however, lend perspective to the whole problem of limit design, provide an objective and consistent basis for regional generalization once the level of PMP has been agreed upon, and have greatly influenced the results of this report.

5.1.3 In accepting the general level of the PMP estimates of *Hydrometeorological Report No. 33* for the estimates presented in this report, it was necessary to develop some parametric relationships. Testing of these relationships involved consistency tests not only between eastern and western United States but also within each region. In addition, it was pertinent to first appraise the estimates of *Hydrometeorological Report No. 33* on the basis of certain controlling basic storm data.

5.2 Appraisal of Hydrometeorological Report No. 33 estimates

5.2.1 Two storms have occurred which suggest that the general level of the estimates of *Hydrometeorological Report No. 33* is too low near the 105th meridian and along the Gulf Coast. These are the Cherry Creek storm of May 30–31, 1935, in eastern Colorado, and the Yankeetown, Fla., storm of September 1950.

5.2.2 There were two intense centers in the Cherry Creek storm which were the result of wave action along a quasi-stationary front (par. 3.4.4). Although there were no official rain gages in the major precipitation centers, a "bucket survey," conducted shortly after the storm by officials of the Engineering Department of the State of Colorado, provided many useful reports. There were several reports of 24 in. of precipitation within 24 hr. in both centers. Two measurements from this "bucket survey" are quoted to show the type of measurements of extreme amounts obtained:

> C. O. Peterson, residing 6 miles south of Elbert, in Sec. 34, T. 10 S., Range 64 West: Rain began at 5 A.M. on May 30th, with an extra hard rain at 12 noon. Ended at 6 P.M. Two distinct rain storms, the first lasting 2½ hours, and the second 5½ hours. The estimated depth of the first rain was 5 inches, total of 24 inches during the storm. Measured in a stock tank, 8 ft in diameter with 24-inch sides, which filled and overflowed.
>
> Lewis Shook and J. E. Mayer, of the Elbert County Bank, which is in Sec. 34, T. 9 S., R 64 W., measured the rain. Intense rain began at 1:30 P.M. May 30th, and ended at 4:30 P.M. There was a total of 24 inches of rain measured at Elbert. A standard rain gage with 4″ funnel on roof, connected by ⅛″ tube to graduated glass cylinder inside building overflowed. A bucket 12 inches deep set outside overflowed from rain which fell after the standard gage overflowed.

5.2.3 Because of the intense precipitation at the center of this storm and the many supplementary precipitation amounts from the "bucket survey", it was possible to estimate the average depth of precipitation over 10 sq. mi. in 24 hr. to be 22.2 in. The center was located at 39°36′ N., 102°8′ W. *Hydrometeorological Report No. 33* shows the PMP at this location to be about 28.2 in.

5.2.4 The representative 1,000-mb. dewpoint of 68°F. for this storm was selected at a point 325 mi. SSE of this center [28]. The moisture adjustment used for *Hydrometeorological Report No. 33* was the ratio of the W_p for the maximum observed dewpoint to the W_p for the representative storm dewpoint.

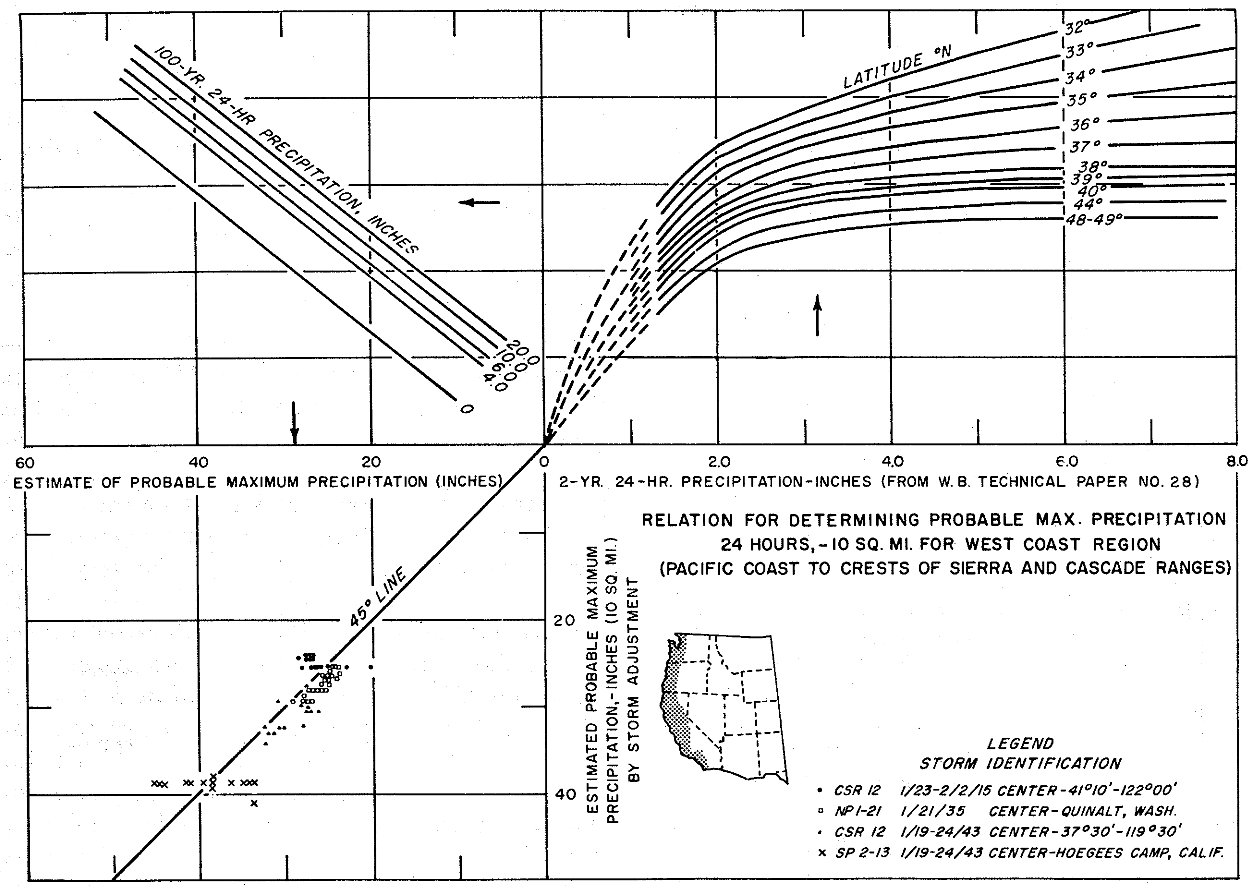


Figure 5–1.—Probable maximum 24-hr. 10-sq.-mi. precipitation for the west coast as a function of latitude and the 2-yr. and 100-yr. 24-hr. precipitation.

5.2.5 Selection of the maximum observed dewpoint requires a determination of the seasonal limitations on the adjustment of the storm. The assumption used in most previous estimates of PMP allowed an adjustment to the maximum dewpoint ever observed within 15 days of the date of occurrence. These maximum dewpoints are determined from the monthly maps of maximum observed dewpoints used in *Hydrometeorological Report No. 33.* If the moisture adjustment were computed for the maximum observed dewpoint within 15 days of the end of May, the adjustment factor would be 1.48. This would indicate an increase in the observed precipitation from 22.2 to 32.9 in. at the storm location. If a more restrictive limitation were placed on selection of the maximum observed dewpoint, the adjustment would be reduced. If the dewpoint for the date of occurrence were selected, then the adjustment factor would indicate an increase of 33 percent in the observed precipitation, or an increase from 22.2 to 29.6 in.

5.2.6 The Yankeetown storm of September 3–7, 1950, was centered at Yankeetown on the west coast of Florida. The maximum precipitation in this storm was determined from a "bucket survey" by the Corps of Engineers about 2½ months after the storm. This storm was a result of a hurricane that moved northward off the western coast of the Florida peninsula. The hurricane stalled in its forward movement just after crossing the coast of Florida, and then turned and moved southward. Its path formed a small loop, an unusual though not unprecedented occurrence, as the hurricane turned again and moved eastward, and then northward, passing east of Gainesville. For some 18 hr. the center of the hurricane was within 20 mi. of Yankeetown.

5.2.7 The heaviest precipitation was determined from the "bucket survey", to be 45.23 in. for 72 hr. at Yankeetown. This amount was determined from computation based on an observation of the amount of precipitation collected in a case of soft drink bottles exposed during the

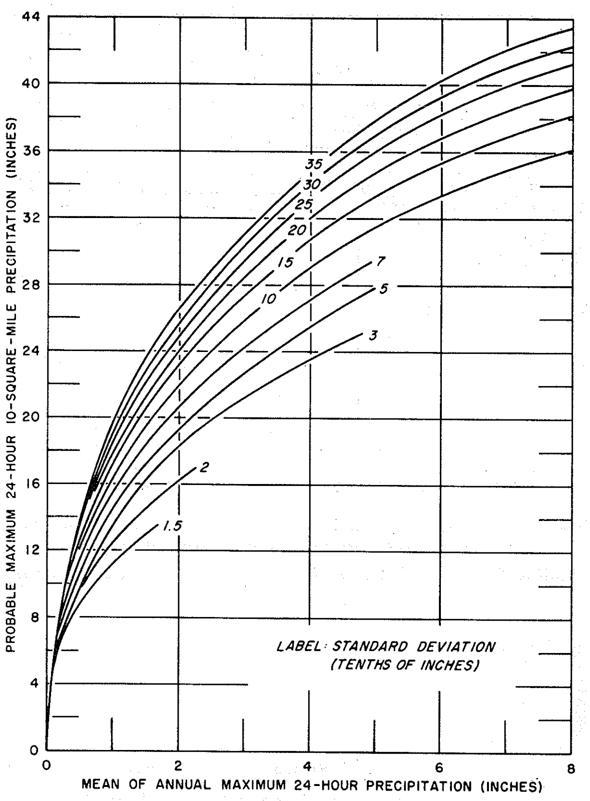


FIGURE 5–2.—Relation between probable maximum 24-hr. 10-sq.-mi. precipitation from *Hydrometeorological Report No. 33* and the mean and standard deviation of the annual maximum 24-hr. station precipitation.

storm. These bottles were reported to have filled and then overflowed. The estimated amount of precipitation is based only on the amount of precipitation caught in the bottles since no estimate could be obtained of the amount that overflowed. This amount could possibly be only a lower limit of the actual precipitation. Another source of error that cannot be measured is the amount of precipitation that would splash into the bottles from the ground and the sides of the case. This would have the effect of increasing the amount of water in the bottles (splash-in would exceed splash-out) and would be opposite in effect to the previous source of error. The assumption can be made that these two sources of error acting in opposite directions tend to cancel. The Hydrometeorological Section of the Weather Bureau investigated these reports and accepted the "bucket survey" values. The official gage at Cedar Key caught about 30 in. in 24 hr. There were other substantiating observations.

5.2.8 The Corps of Engineers completed a study of this storm and determined the 24-hr. 10-sq.-mi. precipitation to be 38.7 in. [15]. *Hydrometeorological Report No. 33* gives a PMP of 38.8 in. for this location. The representative dewpoint given for this storm is 76°F. [15]. The maximum dewpoint for this region at this season of the year is 78°F. The W_p-ratio for these dewpoints would indicate an increase in precipitation of 10 percent.

5.2.9 The Yankeetown storm would have little or no effect on estimates of PMP for western United States unless it were a basis for raising the general level of PMP. The Cherry Creek storm does raise the question of adjustment in a region pertinent to this report, and must be considered in that respect. These two storms suggest corrections of something like 10 percent for very short durations and very small areas. There is considerable uncertainty about the short-duration values for the Yankeetown and Cherry Creek storms. If the data published in *Storm Rainfall in the United States* [15] are accepted, then *Hydrometeorological Report No. 33* should be revised. If, on the contrary, it is believed that the reliability of these "bucket survey" measurements is subject to doubt, then *Hydrometeorological Report No. 33* can be defended on the basis of reluctance to rely on such data for the design of million-dollar structures.

5.3 Generalization procedures

5.3.1 PMP estimates based on traditional meteorological methods have been made for many places in the West. To meet the needs for generalization over the region, relations such as that of figure 5–1 were developed. Similar relations can be made to fit the PMP estimates of *Hydrometeorological Report No. 33* for eastern United States, as well as those for other regions. The results of *Hydrometeorological Report No. 33* can be understood from physical reasoning to be related to such parameters as mean annual precipitation, precipitable water, distance from the Gulf of Mexico (the main source of moisture for precipitation east of the Rockies), and others.

5.3.2 The parameters used for estimating PMP for the eastern United States, however, may not be sufficiently similar to those for PMP estimates in the West to insure a consistent, nationwide general level. Parameters are needed that can be transposed nationwide. For example, "distance from the Gulf" does not define a corresponding parameter for the West, although the

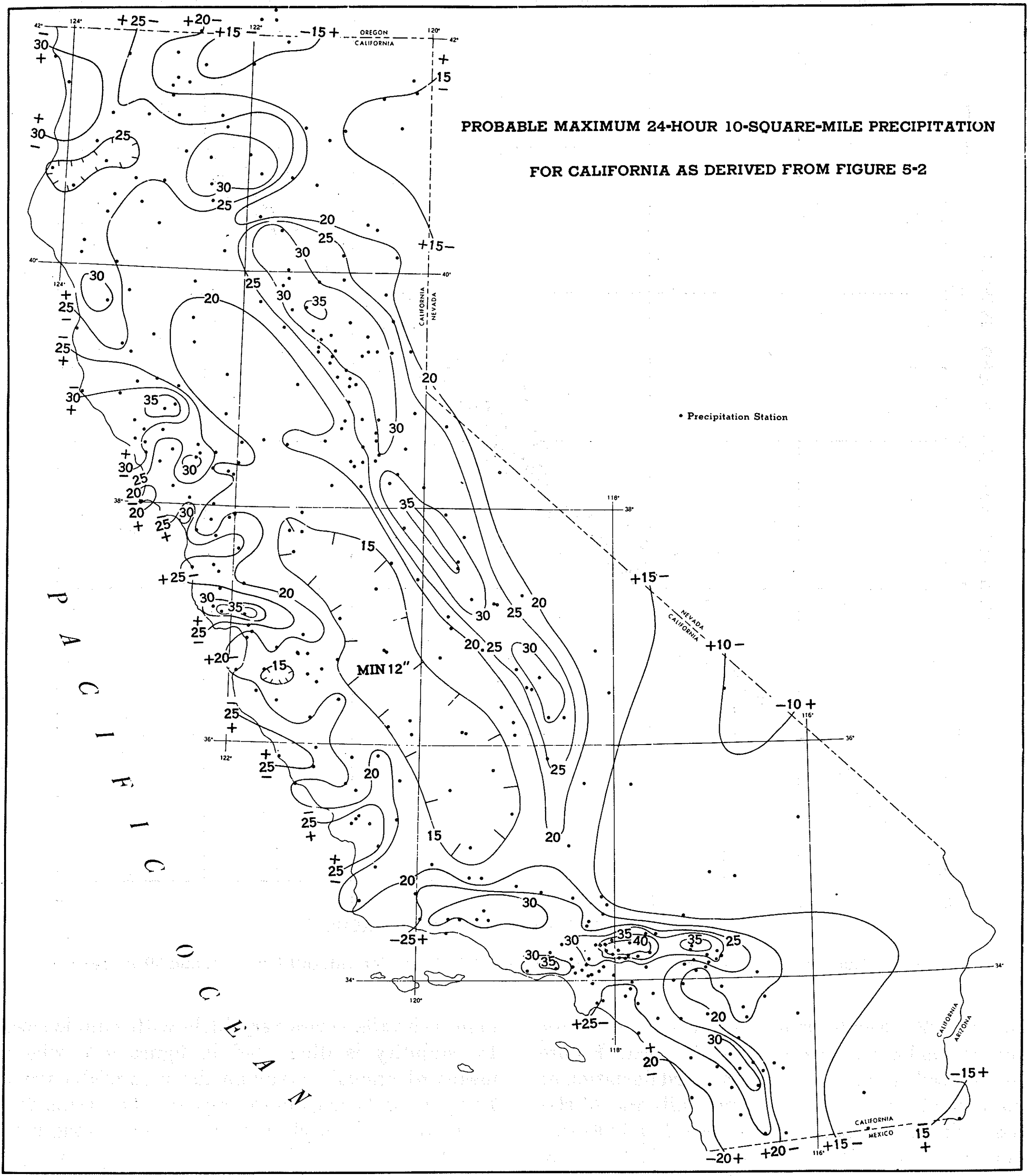


FIGURE 5-3.—Preliminary estimate of probable maximum 24-hr. 10-sq.-mi. precipitation (inches) for California as derived from the relation of figure 5-2.

physical concept of availability of moisture is valid for both regions. Also, relationships for the East would not indicate the latitudinal effect applicable to the West.

5.3.3 The mean and standard deviation of annual maximum rainfalls at individual stations are parameters that show a good relationship with the PMP estimates of *Hydrometeorological Re-*

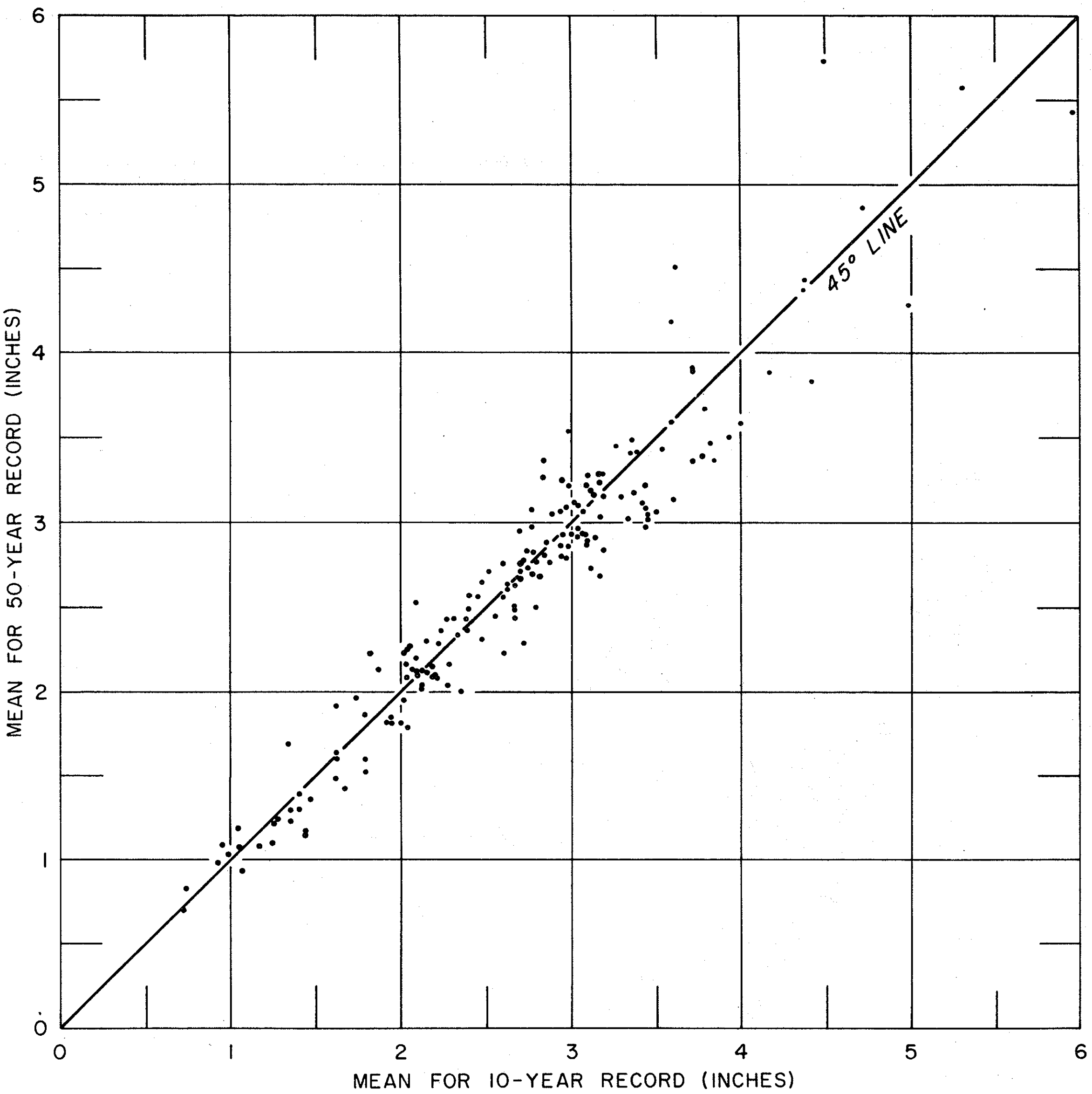


Figure 5–4.—Comparison of the mean of the annual series of daily station rainfall for 10-yr. and 50-yr. records.

port No. 33. Furthermore, they are available for any station having several years of record. Figure 5–2 is based on the mean and standard deviation of the annual maximum 24-hr. rainfalls for 73 stations with more than 20 yr. of record and 291 stations with 10 to 18 yr. of record, and PMP from *Hydrometeorological Report No. 33.* Use of figure 5–2 for estimating PMP in California yielded the results shown on the map of figure 5–3. This map may be compared with the final map of figure 6–1.

5.3.4 The mean of the series of annual maximum rainfalls varies very little with sample size. Its stability is illustrated in figure 5–4, where means of annual maximum daily rainfalls from 10-yr. records are plotted against the means for 50-yr. records. Each point represents a long-record station from which the 10-yr. and 50-yr. segments were taken at random. The small scatter indicates that the mean of the annual series is not appreciably affected by the addition of 40 yr. to a 10-yr. record nor by the elimination of 40 yr. from a 50-yr. record.

5.3.5 The standard deviation is more sensitive

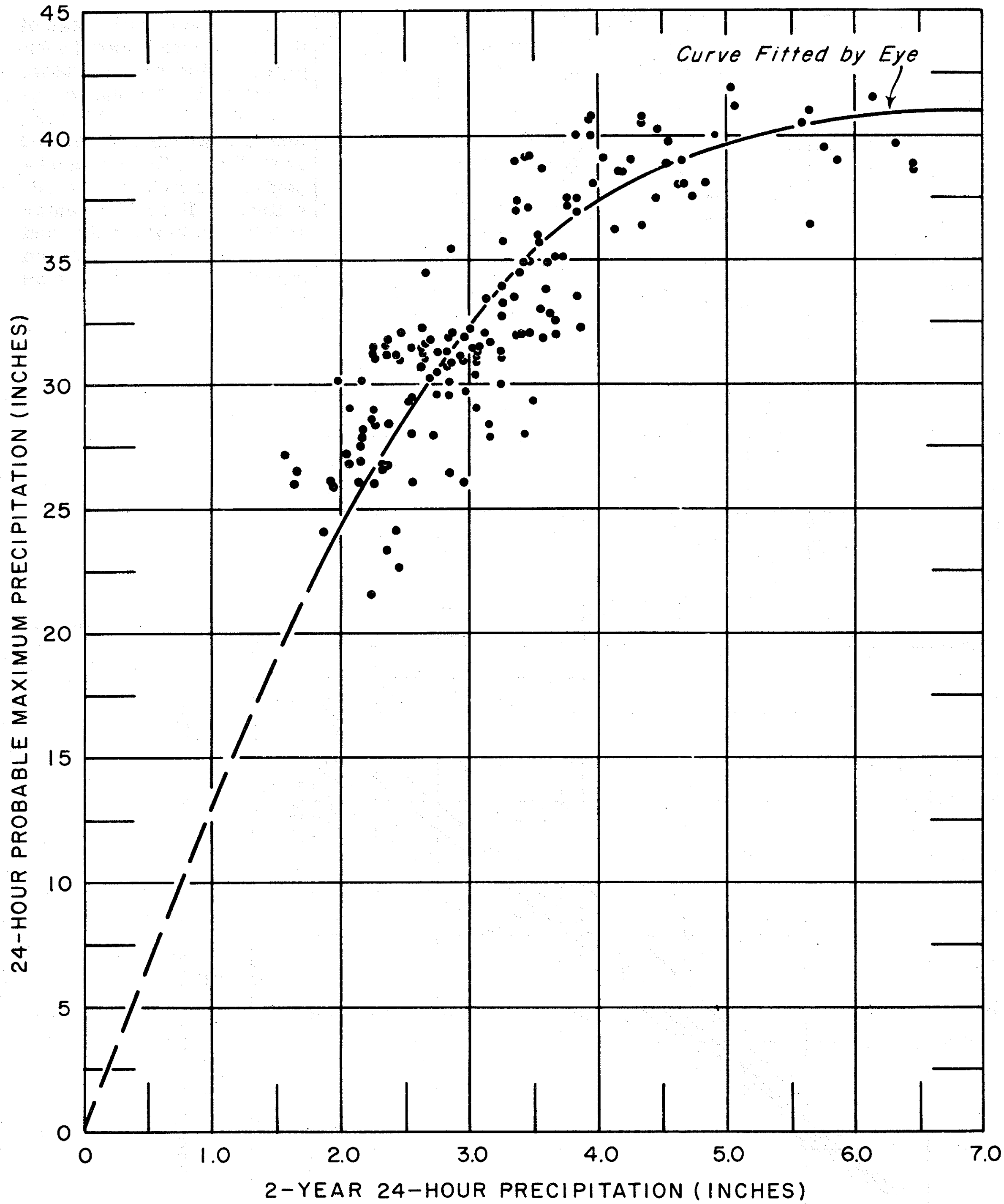
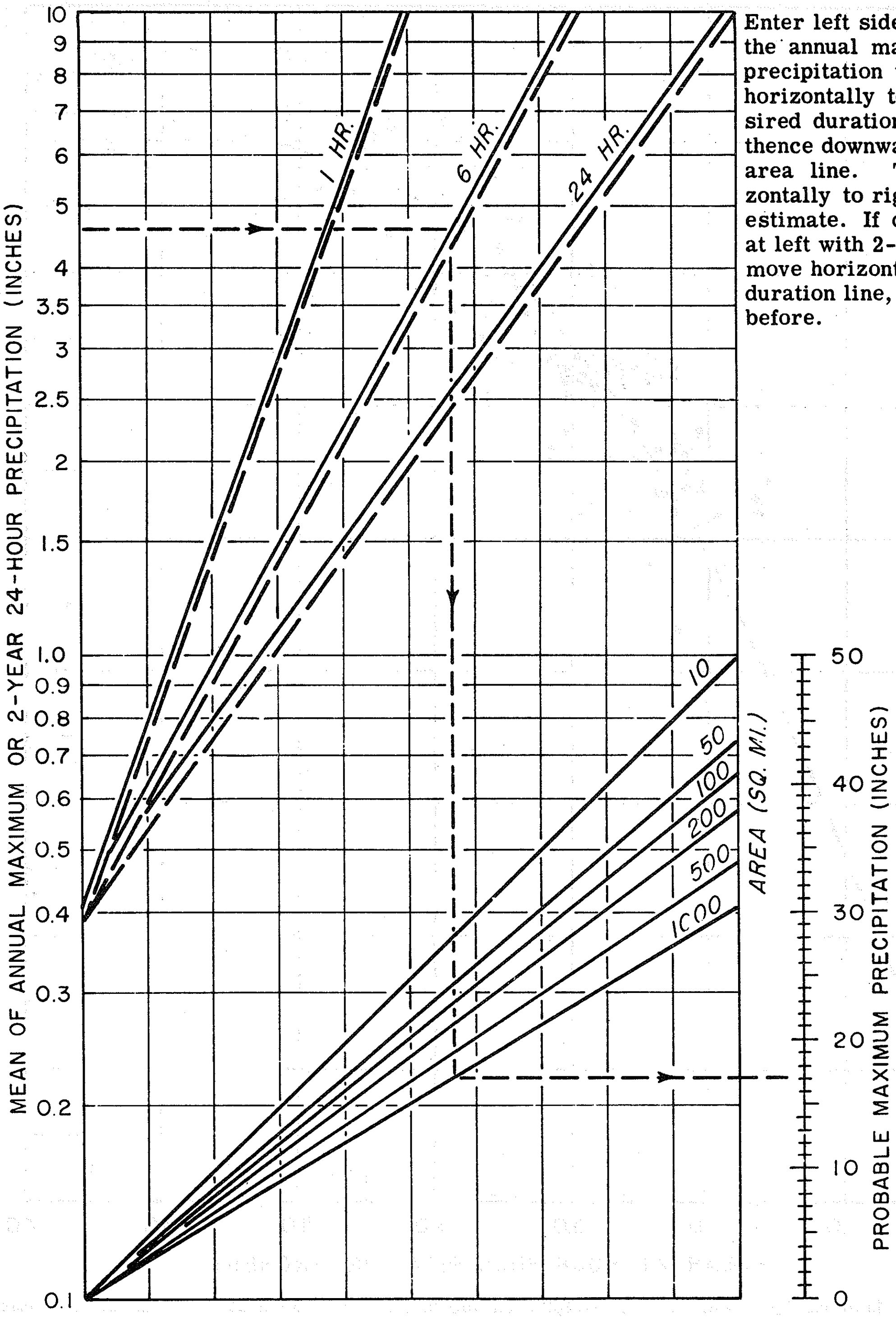


FIGURE 5-5.—Relation between 2-yr. 24-hr. station precipitation and probable maximum 24-hr. 10-sq.-mi. precipitation from *Hydrometeorological Report No. 33.*

to the effect of outstanding events than the mean is. However, in combination with the mean it may not be too sensitive as an estimator of PMP. For example, for a mean of 2.0 in. and standard deviations of 10 and 20 in., figure 5-2 yields respective PMP values of 22 and 24 in. Thus, in this instance, doubling the standard deviation increases the PMP only about 10 percent. Even without the



Enter left side with mean of the annual maximum 24-hr. precipitation values. Move horizontally to right to desired duration (solid line), thence downward to desired area line. Thence horizontally to right to P M P estimate. If desired, enter at left with 2-yr. value and move horizontally to broken duration line, — thence as before.

Figure 5-6.—Probable maximum precipitation as a function of the mean of annual maximum or 2-yr. 24-hr. precipitation, duration, and area, assuming an average coefficient of variation of 0.37. (Based on data from *Hydrometeorological Report No. 33.*)

standard-deviation parameter, there is still a good relationship between PMP and the mean of the annual maximum rainfalls.

5.3.6 Figure 5–5, based on the same data as figure 5–2 (par. 5.3.3), shows the relationship between 24-hr. PMP from *Hydrometeorological Report No. 33* and the 2-yr. 24-hr. rainfall for the same stations. This good relationship should be expected because the mean of the annual series, or the slightly lower 2-yr. value, is a measure of severe-storm experience, which is an integration of the occurrences of the combinations of parameters that, when extrapolated and combined more critically, are likely to produce PMP. Addition of the standard deviation improves the relationship because, in expressing the variability of the annual extremes, most weight is given to the events most closely approaching PMP.

5.3.7 If it is believed that regional variation in the coefficient of variation of annual maximum rainfall is largely a product of sampling vagaries, or if it is necessary to estimate PMP in some part of the world where the record is too short to give a good estimate of the coefficient of variation, an average value may be assumed. If average depth-area and average depth-duration relationships are also assumed, and the general level of the PMP estimates in *Hydrometeorological Report No. 33* is taken as a standard, then the relation of figure 5–6 may be used to approximate PMP.

5.4 Establishing consistency

5.4.1 In the physical storm model, the single observable result (rainfall) is a function of many variables having various and uncertain degrees of independence (moisture charge, season, wind profile, etc.). An ideal physical model would actually depict the functional relationship between rainfall and the factors that produce it, and its validity would be demonstrated in reproducing historical rainfall and in predicting rainfall. Aside from this, an extrapolation to PMP would require an extrapolation of many of these factors beyond the range of observation, plus some assumptions about the structure of their relationship. One assumption would be that the functional relationship occurring with observed rainfall would be preserved in the PMP. Another assumption would be that the structure itself is subject to variation, and that for PMP this structure or functional relationship might have a form, or combination of factors, that is more critical than has been observed.

TABLE 5–1.—*Ratio of maximum observed 24-hour rainfall to the mean of the annual extremes for selected stations*

Station	Max. obs. 24-hr. rainfall (in.)	Ratio
Elba, Ala	23. 70	6. 0
Brawley, Calif	5. 07	6. 8
Hoegee's Camp, Calif	26. 12	4. 1
Indio, Calif	6. 62	5. 8
Opid's Camp, Calif	22. 00	3. 2
Taylor, Tex	23. 11	5. 6
Opaeula, Hawaii	25. 95	6. 2
Hana, Hawaii	28. 20	4. 1
Hakalau Mauka, Hawaii	26. 40	2. 4
Papaikou, Hawaii	23. 00	2. 8
Cherrapunji (Police Sta.), India	39. 28	2. 1
Cherrapunji (Welsh Sta.), India	34. 50	1. 5

5.4.2 Obviously, a very complicated problem is presented by the suggestion that different combinations of factors (each extrapolated some way, and having various degrees of dependence with the others) be examined. A tremendous job of trial-and-error might be involved, because judgment would have to be applied to every plausible combination and degree of extrapolation before all but one PMP estimate could be rejected.

5.4.3 A simpler procedure would be to assemble the results of many combinations of factors that have produced extremely high values of rainfall (already combined by nature and known to be possible) and examine them. This was done by expressing the maximum observed 24-hr. rainfall in terms of the mean of the annual series for hundreds of stations; i.e., as a ratio. This ratio includes many of the contingencies and uncertainties discussed above, integrated as an expression of probability. Out of more than 1,000 station records, seventeen showed a ratio greater than 4, and five had a ratio higher than 5. The highest three ratios were 6.0, 6.2, and 6.8. Table 5–1 shows some of these high ratios, along with related data from stations having lower ratios but high annual extremes.

5.4.4 At this point it is pertinent to compare the highest ratios of maximum observed 24-hr. rainfall to the mean of the annual extremes (table 5–1) with ratios of 24-hr. PMP from *Hydrometeorological Report No. 33* to the mean of the annual extremes (fig. 5–7). The lowest ratio in figure 5–7 is 7, which safely envelops the highest observed. The ratio increases to about 13 in the north, and to about 18 in the vicinity of Pueblo, Colo. To give these ratios of 7, 13, and 18 some perspective, it is helpful to find a common denominator that will indicate their relative magnitudes

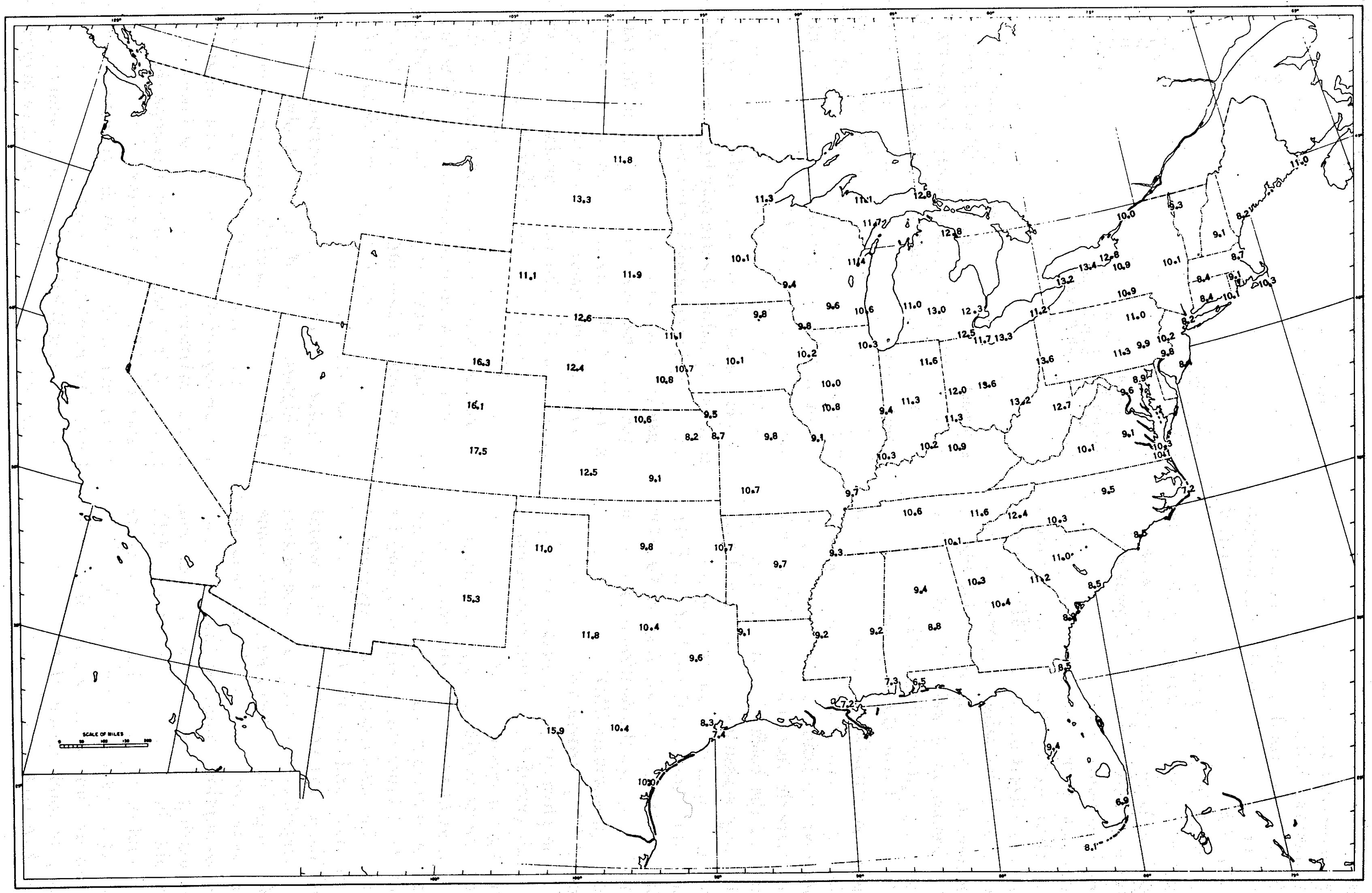


FIGURE 5-7.—Ratio of probable maximum 24-hr. 10-sq.-mi. precipitation from *Hydrometeorological Report No. 33* to mean of the annual maximum 24-hr. station precipitation.

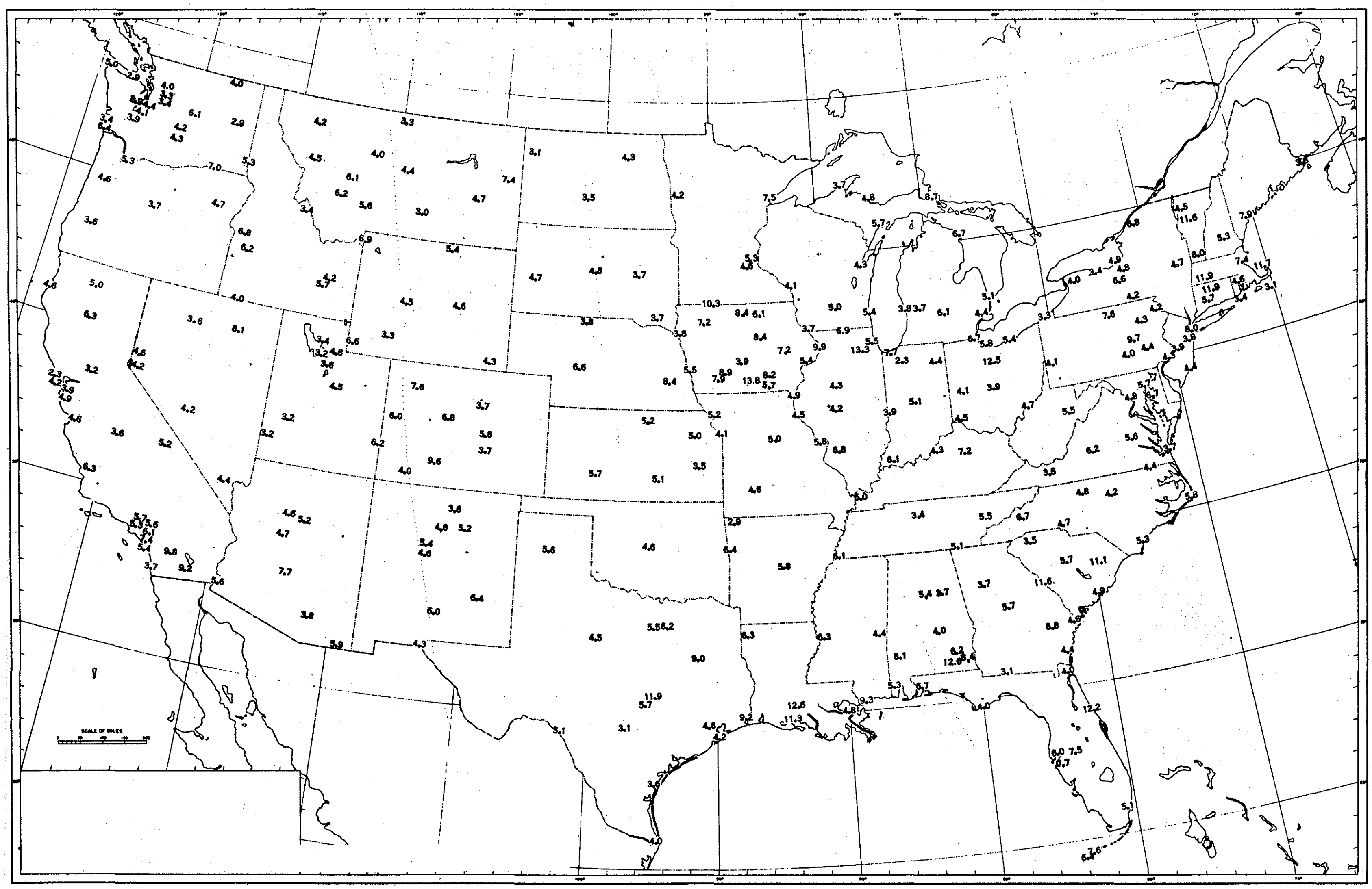


FIGURE 5-8.—Reduced variate of maximum observed 24-hr. precipitation.

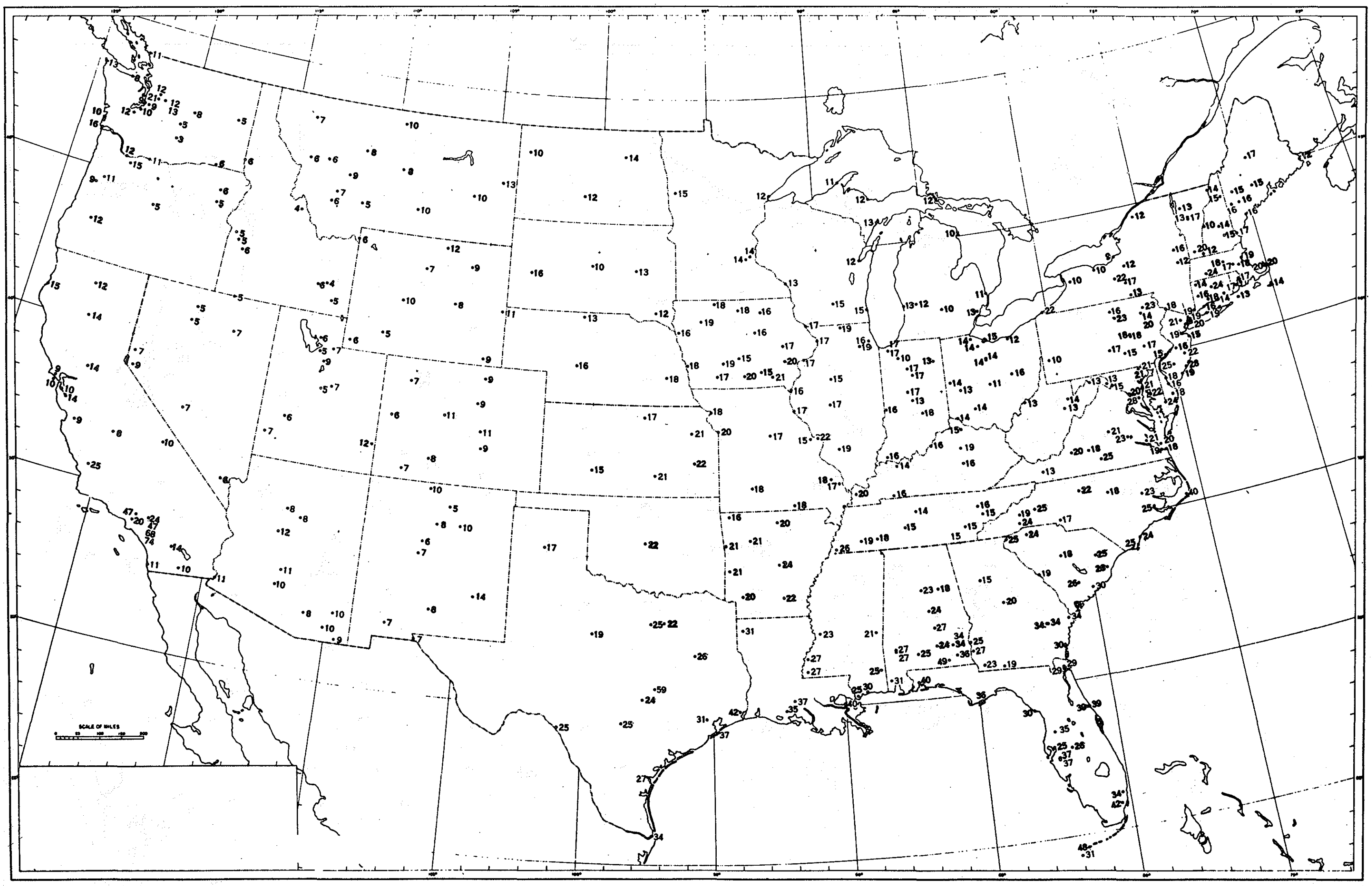


FIGURE 5–9.—Ten-million-year 24-hr. station precipitation, in inches.

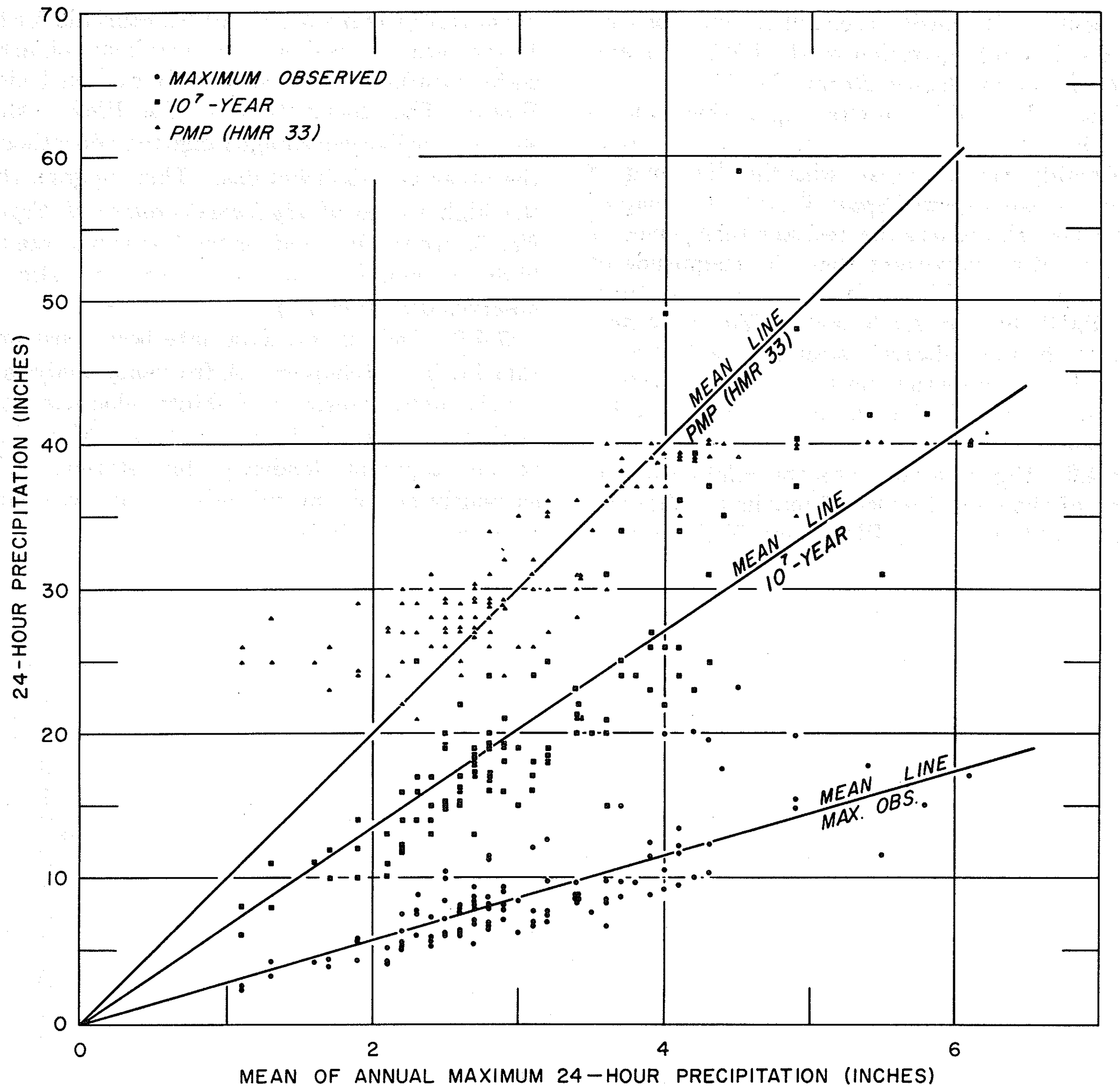


FIGURE 5-10.—Comparison of relations between (1) maximum observed, (2) 10^7-yr., (3) probable maximum 24-hr. precipitation and the mean of the annual maximum series.

and to consider the reason for the apparent regional variation of the ratio.

5.4.5 The *reduced variate* is a mathematical function of return period, corrected for length of record. Figure 5-8 shows the reduced variate of the maximum observed 24-hr. rainfall for Weather Bureau first-order and other selected stations with outstanding maxima. The maximum observed rainfalls were excluded from the theoretical computations but were placed on the extrapolated Gumbel curve to obtain an independent estimate of their reduced variates.

5.4.6 It is to be emphasized that the values of the reduced variate are not to be taken literally. The sampling error is large, and other distributions would yield different results. However, figure 5-8, based on a consistent and objective analysis, does show that there is no noticeable regional trend in the return period (or probability) of maximum observed 24-hr. rainfall. With this in mind, one can only conclude from the data of figure 5-7 that PMP from *Hydrometeorological Report No. 33* has much longer return periods (lower probability) in the north and west than in the south. Obviously, probability was not considered in the preparation of the PMP estimates of *Hydrometeorological Report No. 33.*

5.4.7 It would be interesting at this point to consider how a map of 24-hr. rainfall of equal probability would compare with the PMP map of *Hydrometeorological Report No. 33.* The map of figure 5–9 is based on a theoretical return period of 10^7-yr. More important than the magnitude of return period used is the fact that the map, unlike the PMP map of *Hydrometeorological Report No. 33*, shows a relatively steep gradient of rainfall values from south to north. Any other return period or distribution would show a similar gradient.

5.4.8 Figure 5–10 shows the relation of the mean of the annual series of maximum observed 24-hr. rainfalls to: (1) PMP from *Hydrometeorological Report No. 33*, (2) 24-hr. rainfalls for the 10^7-yr. return period, and (3) maximum observed 24-hr. rainfalls for 109 stations in eastern United States. The distribution of the PMP values shows a smaller percentage range than do either of the other two distributions. This suggests that the high values of *Hydrometeorological Report No. 33* are too low and/or the low values are too high—a suggestion possibly supported also by observed data (sec. 5.2).

5.4.9 Only 24-hr. data have been considered thus far in this chapter. A frequency analysis of hourly data showed probability characteristics similar to those of the 24-hr. data. Also, there is no apparent tendency for stations with extremely heavy 1-hr. rainfalls to have extremely heavy 24-hr. rainfalls.

Chapter 6

PROBABLE MAXIMUM PRECIPITATION WEST OF THE 105TH MERIDIAN

6.1 Basic precipitation data

6.1.1 Estimates of probable maximum precipitation (PMP) depend on the amount and quality of data available as well as the methods used in the maximizing process. The greatest mass of precipitation data available is for the calendar day or for the observational day (par. 4.2.6.) Large networks of cooperative stations have been taking daily observations for periods in excess of 50 years. Excepting about 200 Weather Bureau first-order stations, intensities of short-duration precipitation have been measured only since about 1940. Even the current network of precipitation stations provides considerably more measurements for the calendar day and observational day than for the shorter durations. For this reason the primary emphasis was placed on development of estimates of 24-hr. PMP for a point, or 10 sq. mi. Regional generalization, map smoothing, and the transposition of storms, mechanisms, or moisture were based on meteorological and statistical considerations (chs. 4 and 5, respectively).

6.2 PMP for 24 hr. and 10 sq. mi.

6.2.1 No distinction was made between point rainfall and the average depth over 10 sq. mi. (par. 4.2.8). Figure 6–1 shows the 24-hr. PMP over 10 sq. mi. for western United States. Intelligent use of the PMP map is facilitated by an understanding of the important features of the map and the consistency checks used. The map was developed on the basis of the results obtained by the methods discussed in chapters 4 and 5. The map of figure 6–1 is the result of group judgment on the general level and the geographic variation of PMP values presented. The more prominent features of the map are primarily a result of orography. PMP values are generally lower on the relatively flat regions at the base of most mountains than on the windward slopes. Although the western United States has many mountain ranges, the degree of generalization necessary in a project of this kind permitted showing the effects of only the more prominent ranges; i.e., the Sierra Nevada, Cascades, Big Horn Mountains, etc. There are undoubtedly other mountains, say, in northern Nevada, where the PMP could be higher for a few small individual basins than that shown on the map. Conversely, for lee slopes on these mountains and for the intervening valleys, the indicated PMP would be an overestimate. The regions showing minimum values of PMP conform to the large well-known valleys and desert regions; i.e., Death Valley, Snake River Valley, Great Salt Lake Basin, etc. As with the orographic barriers, it was impossible to give sufficient detail to show all valleys or lee slopes.

6.2.2 The methods used to develop the PMP map of figure 6–1 can be illustrated by considering two specific regions and examining some of the problems involved in developing the estimates for those regions. The Sierra Nevada slopes have been the subject of intensive study [21, 29, 30]. The orographic separation method used for maximizing is an evolution of the methods used in the Sacramento [29] and San Joaquin [30] studies. It consists of trying to evaluate separately the precipitation from convergence and that from orographic influences, to maximize each, and to recombine them for estimating PMP. The method is now under investigation by the Weather Bureau's Hydrometeorological Section, which is in the process of developing generalized estimates of PMP for California.

6.2.3 Another method used for maximizing involved the development of a relationship between PMP and 2-yr. 24-hr. precipitation, latitude, and 100-yr. 24-hr. precipitation (fig. 5–1). Other estimates were obtained by moisture adjustment and transposition of storms (chapter 4). Several estimates were made using different limitations on the seasonal transposition of storms (pars. 4.6.4 and 4.6.5).

6.2.4 The PMP estimates obtained by these different methods varied somewhat. The lowest estimates were generally provided by storm transposition limited to 15 days and by the orographic separation method. The highest estimates were obtained from adjustment of storms to the maximum moisture charge for the season of occurrence. Consistency checks were made of the estimates yielded by the various methods. The most acceptable values lay between the extremes.

6.2.5 Another interesting problem was the PMP for southern Arizona. Application of the usual 15-day limit to seasonal storm transposition resulted in PMP values that were too low with respect to other values in adjacent regions such as southern California, New Mexico, and to the north. The estimates were therefore increased to an acceptable general level on the basis of (1) a more liberal seasonal transposition of the storms originally considered transposable to this region, (2) transposition of additional storms to this region, and (3) the overenvelopment of the moisture adjustment and transposed storms to achieve results in better agreement with the general level. The possibility of hurricane rainfall also influenced the selection of the final PMP values.

6.2.6 The above examples are typical of the problems encountered and the procedures used in developing the PMP map of figure 6–1. The generalized estimates presented are intended to show the proper general level for large regions and to give reasonable envelopment for the majority of watersheds. In regions of complex orography such as the western United States, it is impossible to show exact answers for all watersheds. For some small watersheds more critically exposed than the average watershed, i.e., where there is a more critical orientation, steeper slopes, etc., the estimates of figure 6–1 tend to be too low. For watersheds more sheltered than the average watershed, i.e., less critically oriented, less slope, etc., the estimates of figure 6–1 tend to be too high.

6.2.7 Certain general consistency considerations should also be discussed to show regions where future investigation may indicate that changes should be made in the estimates provided in this report. Ratios of PMP to the mean, or 2-yr. frequency value were discussed in chapter 5. Similar ratios can be determined for the present map (fig. 6–1). These values range from a low of 4 in the Sierra Nevada and in the Coast Range near the Oregon-California border to a high of approximately 15 in the intermountain region. This variation is largely an expression of the effect of orographic barriers. Moisture coming from the Pacific Ocean must cross the Sierra Nevada or other barriers before reaching the intermountain region. The precipitation of moisture by orographic lifting of the moist air moving eastward, the increasing distance from the moisture source, and the lessening chance of encountering a storm mechanism, all act to decrease the frequency of severe storms in the region. This lower frequency will give a higher ratio (of extreme to the mean) since the ultimate storm potential does not decrease so rapidly as the mean. Since there are arguments for increasing the PMP, and thus the 7 to 1 ratio (fig. 5–7), along the Gulf Coast (sec. 5.2 and par. 5.4.8), a more nationwide uniformity would suggest that the lower ratios of the Far West should be considerably higher than 4. This would require an upward revision of PMP in the region west of the Cascade-Sierra crest beyond what current meteorological procedures indicate as reasonable.

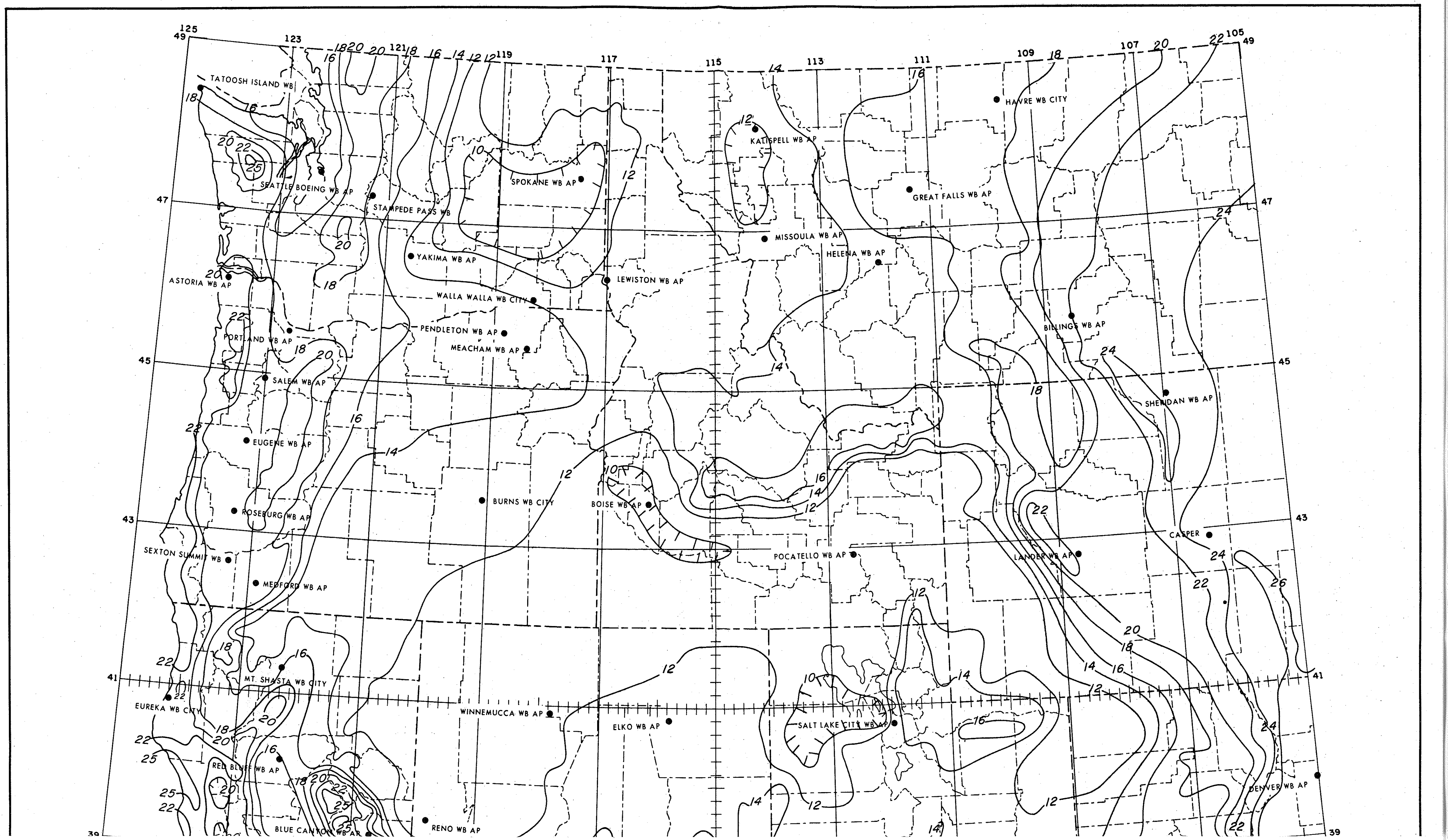
6.2.8 There is, however, no absolute measure of consistency. The ratio of PMP to the 2-yr. frequency value, as well as other measures of consistency, must be interpreted. It can be argued that the orographic influences on the precipitation over major orographic barriers produce heavy precipitation with greater frequency and that the maximum observed values probably come closer to the probable maximum than in nonorographic regions. This argument suggests that ratios as low as 4 along the west coast are not inappropriate.

6.2.9 As discussed earlier (par. 4.2.8), there is no valid basis for distinguishing within most storms between the maximum precipitation at a point and the average depth over 10 sq. mi. This limitation is equally applicable to the values of figure 6–1. These values can be applied to all sizes of area between a point and 10 sq. mi. For larger areas the appropriate reduction factor from figure 6–6 (sec. 6.7) should be applied.

6.2.10 There are no maximum or minimum values indicated in the centers of figure 6–1. The lowest value within a low center may be as much as an inch lower than the central isoline (sheltered valleys and lee slopes), but the safest practice would be to take no value lower than that given for the central isoline. The highest value within a high center may be as high as the next higher isoline would indicate if drawn, and would usually be on the very steepest windward slopes.

6.3 1- to 24-hr. and 6- to 24-hr. rainfall ratios.

6.3.1 The length of record and the density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SPOKANE WB AP
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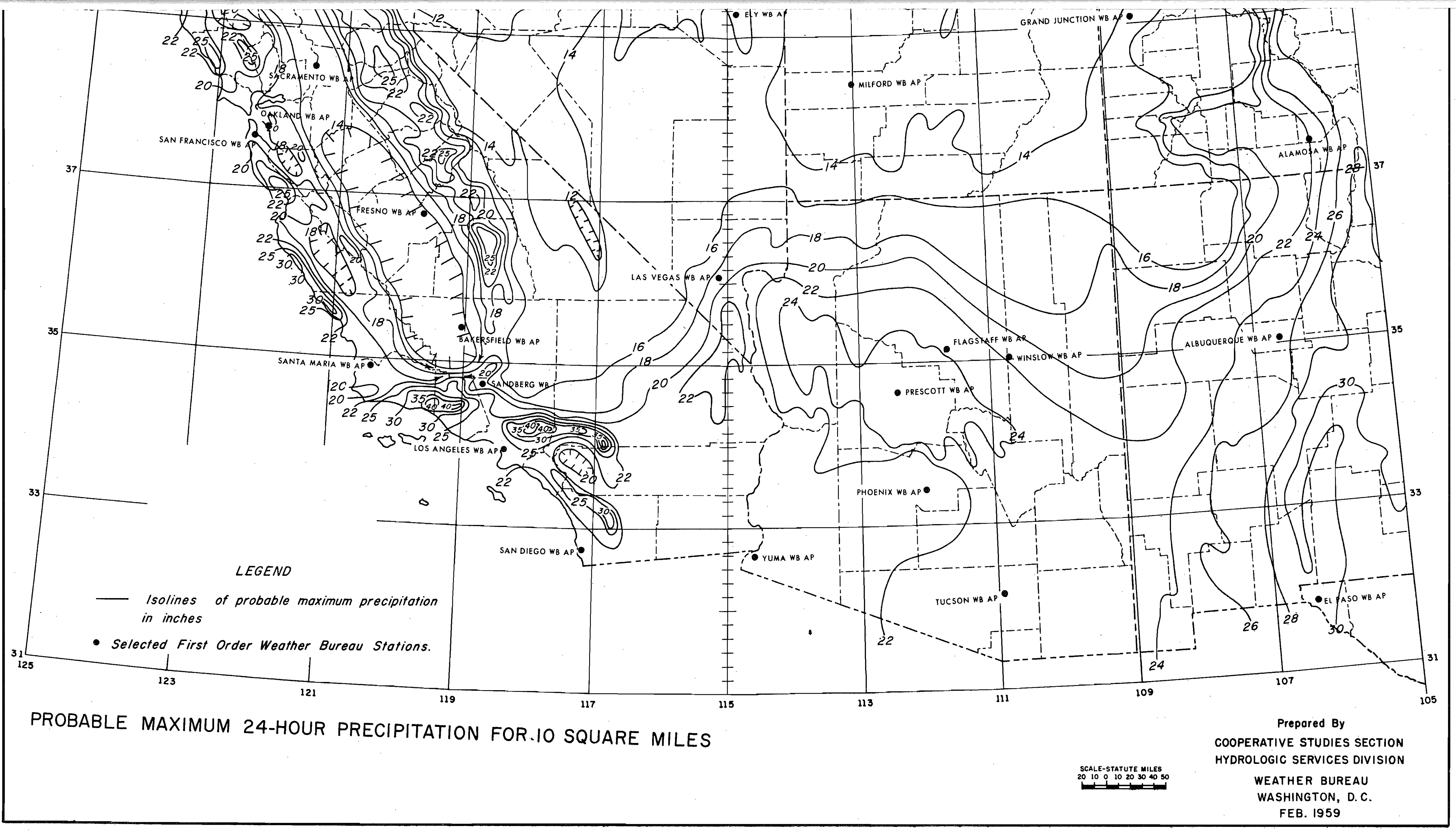


Figure 6–1.—Probable maximum 24-hr. 10-sq.-mi. precipitation, in inches.

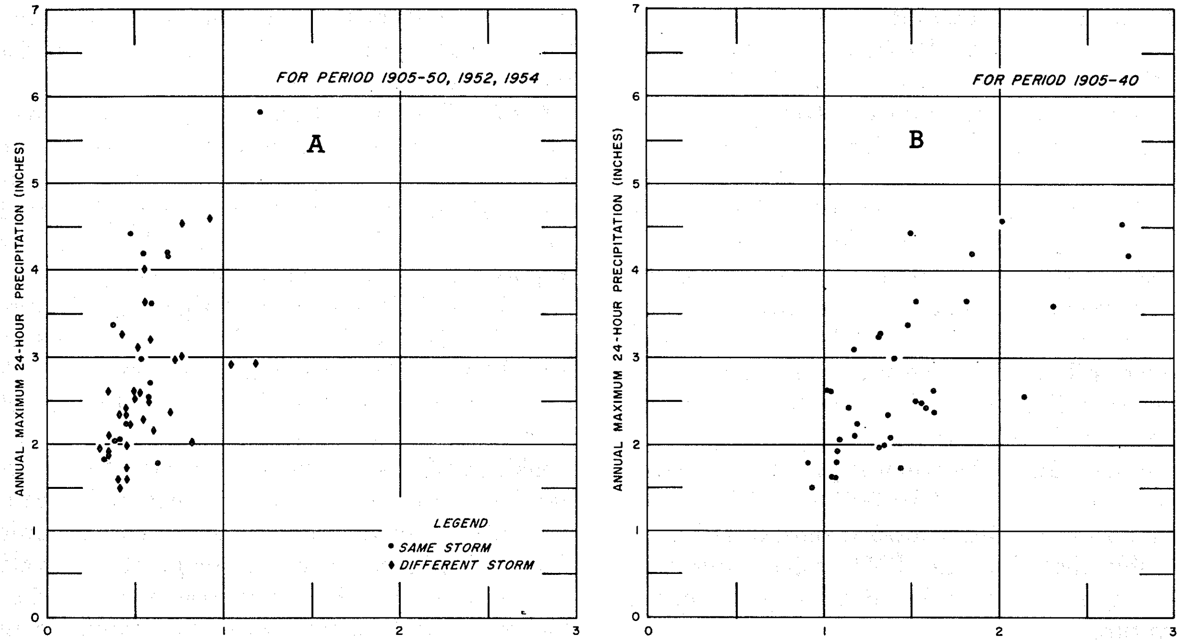


FIGURE 6–2.—Annual maximum 24-hr. precipitation versus annual maximum 1- and 6-hr. precipitation (Eureka, Calif.).

of precipitation data decrease sharply for durations less than 24 hr. For this reason, and because the processing of large masses of recorder data would be required to determine shorter-duration maximum observed rainfalls for many stations not already studied, amounts for shorter durations were determined partly from statistical relationships with the 24-hr. precipitation. Figure 6–2A shows the annual series for the 1-hr. vs. 24-hr. precipitation for Eureka, Calif. This diagram is representative of the scatter in the 1- to 24-hr. ratio for individual stations. Similar diagrams were plotted for several stations in western United States, with the scatter being sometimes worse and sometimes better than that of figure 6–2A. Figure 6–2B shows a similar scatter between the 6- and 24-hr. precipitation for the same station. In neither diagram is there any indication that the magnitude of the 24-hr. amounts has any effect on the ratios.

6.3.2 Weather Bureau *Technical Paper No. 28* [31] provides a convenient means for generalizing relations like those of figure 6–2. The 1- to 24-hr. and 6- to 24-hr. ratios were computed for both the 2-yr. and 100-yr. return period values and plotted on maps. Examination of these two sets of maps (not shown) showed no consistent bias indicating that magnitude had any effect on the ratio. Since the sampling error was smaller in the data used for the ratio map based on the 2-yr. return period than on the 100-yr., precipitation for the 2-yr. return period was used to develop the final ratio maps. In addition to the scatter that was apparent for individual stations, there was some random geographical variation, which was smoothed in analyzing the maps.

6.3.3 The ratios developed are based on between-storm relationship. Briefly, this means that the 2-yr. 1-hr. rainfall value does not necessarily come from the same storm that produced the 2-yr. 24-hr. amount. This is also true of the PMP. The short-duration amounts are often the result of short-duration small-area intense storms. The PMP for durations in excess of 6 hr. may usually be expected to come from a general storm producing large amounts over hundreds of square miles. Also, the ratios are between amounts of the same frequency. For PMP, the 1-, 6-, and 24-hr. amounts may have different frequencies. Although this introduces an error, the change in precipitation amount for a large increase in return period becomes increasingly smaller as the return period increases. There is no method for ascertaining the magnitude of this error since there is no way of ascertaining the frequency of the PMP, but it is believed to be negligible.

6.4 PMP for 1 hr. and 10 sq. mi.

6.4.1 Table 32 of *Hydrometeorological Report No. 5*, "Thunderstorm Rainfall" [32] gives 10 in. as the maximum observed 1-hr. point rainfall for the United States. This table antedated the Holt, Mo., storm of June 22, 1947, and was evidently compiled before investigation of the Campo, Calif., storm of August 12, 1891 (pars. 6.4.4–6.4.11) had been completed. In the discussion of maximum thunderstorm rainfall there are many references to limitations of knowledge, most of which still exist. The rather forthright admission that little could be done for estimating 1-hr. point PMP aside from enveloping the record still applies. In the less than 15 yr. since preparation of "Thunderstorm Rainfall" the 10-in. maximum for 1 hr. has been exceeded substantially. It is possible that the 1-hr. PMP values presented herein may also be exceeded at a few places in the near future.

6.4.2 The first approximation to PMP for 1 hr. was made by applying the 1- to 24-hr. ratio (sec. 6.3) to the 24-hr. PMP. The estimates prepared from this method were compared with the maximum amounts observed in western United States and other sections of the country. This comparison resulted in some modification of the estimates. The observed maxima having the greatest influence on the modification of the ratio-derived estimates are discussed below. The final estimates are shown in figure 6–3.

6.4.3 Some of the maximum rainfall intensities observed in the United States are: 1.23 in. in 1 min. at Unionville, Md., on July 4, 1956; 12.0 in. in 42 min. at Holt, Mo., on June 22, 1947; 11.50 in. in 80 min. at Campo, Calif., on August 12, 1891; and the 8.0 in. observed in 45 min. at Fort Mojave, Ariz., on August 28, 1898. These values are considered to approach the upper limit of precipitation for durations up to 1 hr. With these observed values as a base, the 1-hr. amounts of 16 to 17 in. resulting from application of the average 1- to 24-hr. ratio in southeastern New Mexico were considered excessive. These estimates were lowered to a maximum of slightly in excess of 14 in.

6.4.4 In southern California the maximum observed short-duration amount is the 11.50 in. in 80 min. at Campo. This value defines a lower limit of the PMP for 1 hr. The amount of precipitation in this storm is greater than the estimate obtained by applying the local 1- to 24-hr. ratio to the estimates of the 24-hr. PMP for 10 sq. mi. To envelop this storm and the 8.00 in. at Fort Mojave, the 1-hr. PMP over southern California and Arizona was increased to 12 in.

6.4.5 The magnitude of the 1-hr. 10-sq.-mi. PMP over the southern portion of western United States is greatly influenced by five storms: Campo, Calif., Holt, Mo., Fort Mojave, Calif., Chiatovich Flat, Calif., and Palmetto, Nev. Because of the importance of these storms, the validity of the reported rainfalls was re-investigated. Campo is near the Mexican border of California on a plateau ESE of San Diego at an elevation of 2,500 ft. There is no evidence of any local orographic influences. The observation was taken by S. E. Gaskill, a regular volunteer observer of the Signal Service (which preceded the Weather Bureau as the nation's meteorological service). Examination of a photocopy of the original observation form showed that the shower started at 11:40 a.m. and ended at 1:00 p.m. with the amount of precipitation recorded as 11.50 in.

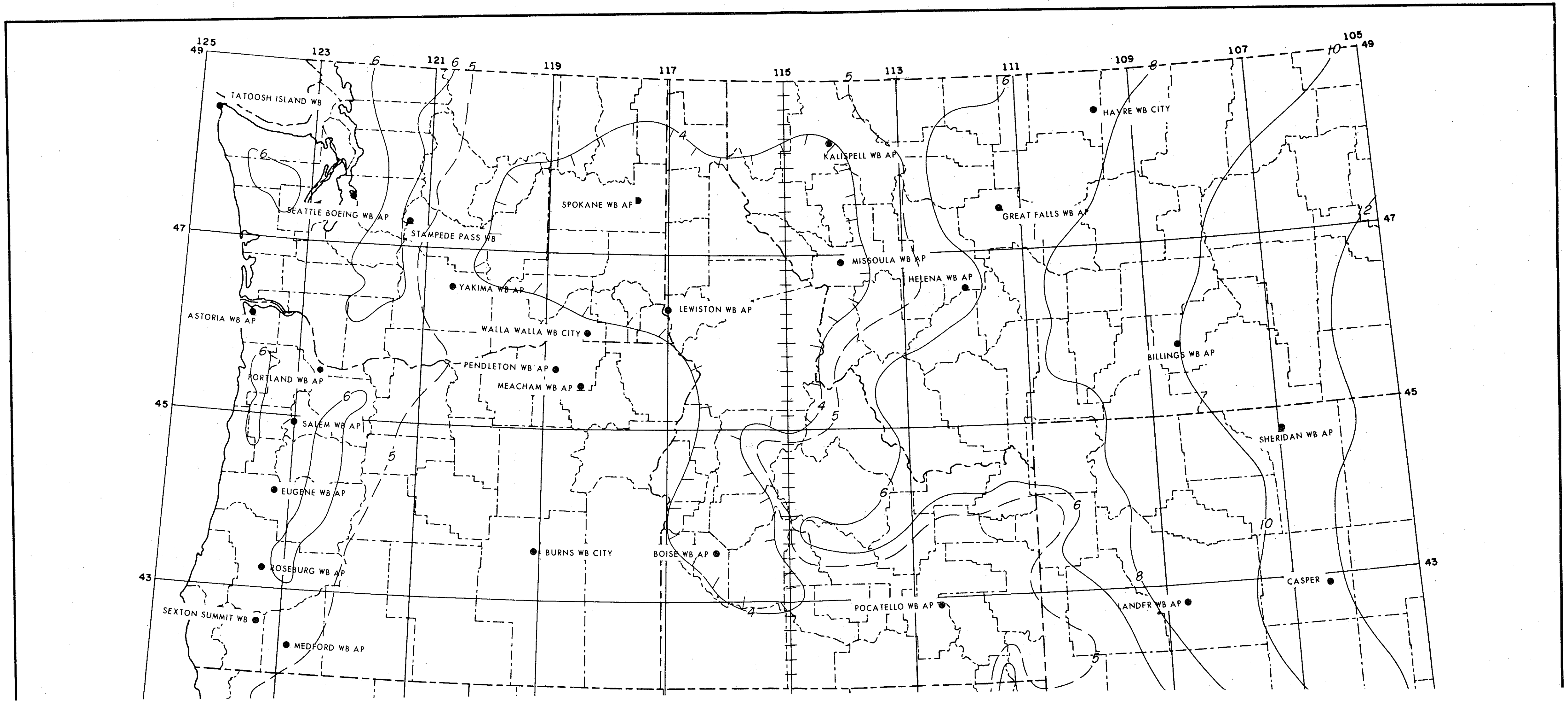
6.4.6 According to the observer's written notes the overflow cylinder of the gage overflowed twice, and an unknown portion of the precipitation was lost. In the observer's own words:

> On the 12th of August had a Cloud burst. One heavy thunder cloud came up and rained about 30 minutes verry hard raised the watters in the streams flood high by the gague. I could not tell it was running over. I emtied it and then another cloud came up and the one that had part pased over drew back and the two came together and it poured down whole watter nearly. I went to the gague again in 30 minutes and it was running over and the reservoir was nearly half full. I emtied it out of the gague and did not Stop to measure the reservoir and after the shower was over I went out to measure the watter and the gague was gone caried off by the flood. It was exciting times with us about that time.

A few days later, August 25, 1891, Mr. Gaskill wrote to Sacramento for a replacement rain gage.

> . . . the 12th of August when we had a watter spout and rained in 60 minutes the gague twice full and soon after I emptied the gague the second time the watter rose so rapidly that the gague was carried off in the great flood of watters we had all we could do to save our selves. I did not report to your before because I thought probably I might find the gague but I have made several diligent searches and connot fint it. After I emtied the gague the second time it rained about 30 minutes longer which I did not have any means of measuring as everything was afloat.

6.4.7 On September 27, 1923, a letter from a Mr. A. Campbell to the Weather Bureau Official in Charge at San Diego helped verify the Campo storm. In his letter Mr. Campbell, a resident of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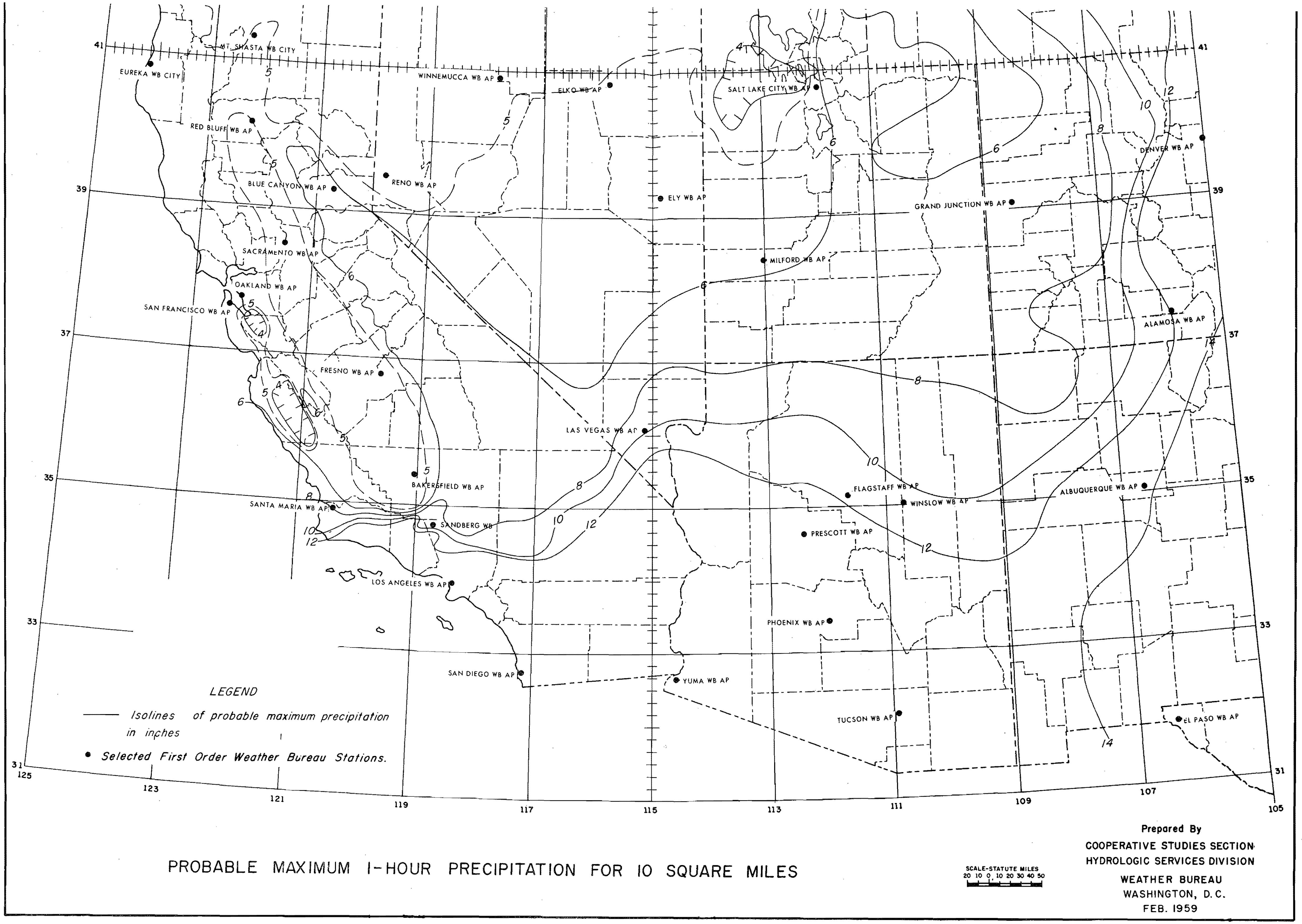


FIGURE 6-3.—Probable maximum 1-hr. 10-sq.-mi. precipitation, in inches.

Campo in 1891, who also observed this storm, testified as to the integrity and intelligence of the observer and as to the intensity of the storm. He described the storm as "deafening" with tremendous thunder and lightning, and over Campo (1½ miles from his house) it was black as midnight. (He observed only about 3 in. of rain at his station). He wrote:

> The center of the storm was the Campo Store and station and south to the Mexican line into Tecate Valley, a stretch of about 3 miles. They had a blacksmith and wagon repair shop in Campo and it carried wagon beds, old wheels, and old iron for miles down the Canyon below a clean sweep of everything loose around. I was in many, and many a thunderstorm on the desert and on the mountains around here but this beat everything. Two years ago we had one in Campo lasting 2 hours and measuring 7.10 inches.

6.4.8 There are other verifications of a storm of very heavy intensity occuring at Campo on this date. A search of old newspaper files disclosed reports of the occurrence of a very severe storm, in which even anvils were overturned and wrenched from their blocks in the flood. Roads were reported to be impassable for several days. In the 1908 *Monthly Weather Review*, page 259, Prof. McAdie, after a personal investigation, referred to the storm as "a well authenticated case of a cloudburst."

6.4.9 Few persons ever see two clouds come together as reported by the Campo observer. Those who scoff at such a statement are inclined to discredit other statements of the observer, including the amount of rain he reported. It is noteworthy that recent sferics and radar data confirm a number of instances of clouds coming together, particularly in connection with very heavy rains.

6.4.10 Early in the 1940's the Hydrometeorological Section conducted an investigation of the Campo storm. The considerable correspondence in their files indicates a truly exhaustive search for data. One of the uncertainties of the measurement is the size of the gage. The gage was an official gage probably very much like the current standard 8-in. gage but not necessarily identical. The gage diameter may have been 6 in. instead of 8. The Hydrometeorological Section study resulted in the conclusion that the events in the storm were as follows:

"Rained 30 minutes
"Collecting tube full and running over—Gaskill emptied it.
"Rained 30 minutes more
"Collecting tube full, reservoir half full.
"Gaskill emptied the collecting tube again.
"Rained 30 minutes more
"Gaskill went to the gage and found that it had disappeared, washed away by the flood.
"The reservoir was 'nearly half full', before he removed the gage to empty it."

6.4.11 The preponderance of evidence suggests that the amount of precipitation reported by the observer at Campo for August 12, 1891, is a valid observation of the precipitation. There are several things not mentioned that might indicate that the amount could be only a lower limit for the true maximum precipitation that fell in the storm. Thunderstorms which produce large amounts of precipitation are often accompanied by high winds. If this were the case during the Campo storm, the gage catch would certainly be deficient (par. 2.5.5). Furthermore, considering the random occurrence of the precipitation centers in thunderstorms, it would be purely by chance that the heaviest precipitation of the Campo storm occurred over the gage.

6.4.12 The other severe storm having a great influence in the evaluation of the 1-hr. PMP is the Holt, Mo., storm of June 22, 1947. The largest amounts in this storm were determined from a "bucket survey" conducted by the Corps of Engineers [33]. The central value of 12.0 in. in 42 min. was measured in a straight-sided bucket. There were two reports which gave the duration as exactly 42 min., and other reports indicated 40 to 45 min. At another location one-quarter mile away, another measurement in a paint can yielded approximately 12.12 in. between about 7:30 p.m. and about 8:25 p.m. Other observations taken at the same time confirm the severity and brief duration. A thorough analysis of the meteorological features of this storm has been published [34].

6.4.13 The report on the 12.0-in. 42-min. observation is quoted in part:

> . . . Heavy rain began between 7 P.M. and 7:35 P.M. on 22nd, ended about 8.20 P.M. on 22nd. Holt Creek was out of its bank in about 10 minutes after the storm started. It was 4 feet, or more, higher than it had ever been known before. On the west side of the town, there is a watershed which is about ¼ of a mile back to the ridge from the town. Between the railroad track and the watershed, a distance of about 400 feet, the water was in each house as much as 2 or 3 feet deep. Observer stated that the rain occurred in about 45 minutes. His wife has timed it and said it was exactly 42 minutes.

> Measurements were made in a bucket, 11 inches across and 14 inches deep, vertical side. Good exposure. Observer was positive that the bucket was empty before the storm on the 22nd.

6.4.14 Brief mention should also be made of the storm that occurred at Fort Mojave, Ariz., on August 28, 1898. A description of the storm written by the observer is published in the *Climate and Crop Service* for August 1898 [35]:

> On the 28th we had the biggest rain in 10 or 15 years, and to my regret, between the rain and furious wind, my rain gage was upset. To give an idea of the amount of rain that fell, and which lasted only 45 minutes, I had a wash tub set out on the mesa, clear of everything, and the water, after the rain, measured 8 inches.

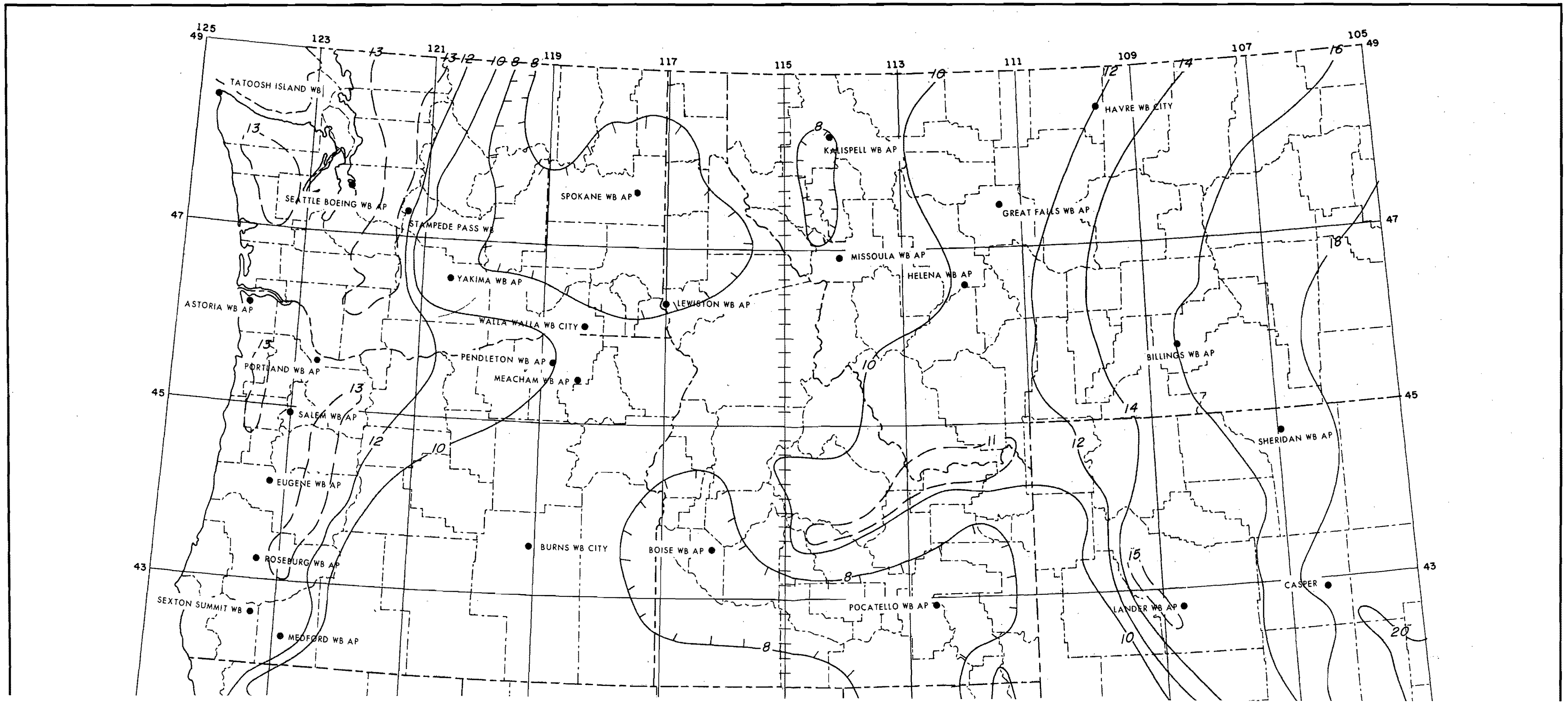
6.4.15 The occurrence of outstanding thunderstorm rainfall at Fort Mojave and of other severe storms throughout Arizona is believed to justify transposition of the Campo storm throughout the entire region south of the first major orographic barrier (par. 3.3.6). North of this barrier there is less chance of an adequate moisture supply for cloudbursts of the magnitude of the Campo storm. In some very rare instances, however, it might be possible for a temporary degree of stability to keep the storm mechanism from developing to release precipitation until a high moisture content had been built up. This is similar in concept to the moist air moving from the Gulf of Mexico northward to the Dakotas. The buildup of a high moisture content in the Great Basin, however, would be of rarer occurrence.

6.4.16 A relatively recent observation that greatly influenced the 1- and 6-hr. PMP isolines in the vicinity of the California-Nevada border was that reported in "Desert Flood Conditions in the White Mountains of California and Nevada" [36]. The measurement was made by Mr. D. Powell, a graduate student in geography at the University of California, on Chiatovich Flat (about 37°43′ N., 118°17′ W.) on the east slope of the White Mountains in California. The above publication reports the observation as follows:

> The heaviest precipitation accurately recorded anywhere in the general area occurred on 19 July 1955, when more than 8 inches of rain fell in slightly more than two hours on Chiatovich Flat, on the east flank of the northern White Mountains. The catch was made in a portable rain gage. It was purely accidental; the observer happened to be in the area, happened to have a portable rain gage, and carried it to the Flat on the chance that a heavy rain might fall.

6.4.17 The Palmetto, Nev., storm of August 11, 1890, (par. 3.3.6) provides additional evidence of cloudbursts in the vicinity of the lower California-Nevada border. The Palmetto station was then at a mining camp located about 37°27′ N., 117°42′ W. at an altitude of about 6,700 ft. in the Silver Peak Mountains. All available evidence appears to indicate that the reported 1-hr. 8.80-in. measurement on the 11th and another of 8.60 in. in $1\frac{1}{2}$ hr. on the 7th are greatly in error. The total rainfall reported for August was 24.00 in. Since the mean annual precipitation in the region is of the order of 5 in., there is a possibility that the substitute observer making the observations during that month was neglecting to apply the 0.1 reduction factor to the measuring stick readings. This possibility was mentioned in a letter written by the regular observer, Mr. William Oothout, Jr., on November 6, 1890, to Capt. James Allen, 3d Cavalry, U.S. Army, who was apparently in charge of the meteorological station network for that region. The letter, which also describes the storms of August 7th and 11th is quoted in part:

> Your favor of Sept. 26 relative to the excessive rainfall at Palmetto during August of this year reached me by today's mail.
>
> During the major part of August I was absent from Palmetto and the weather report for that month was made out by my bookkeeper, whom, I have no doubt made the mistake of not dividing his measurements by ten.
>
> The precipitation on the 7th and 11th came rather from a "waterspout" or "cloudburst" than from anything resembling a rainstorm. On the 11th two intensely black thunder clouds appeared over the crests of the surrounding mountains. One approaching from the North the other from the East. At a short distance from the camp these clouds seemed to join and rush with extraordinary swiftness towards Palmetto. The clouds, or better the resultant cloud, was riven with lightenings and the air became filled with a terrific roar above which the thunder seemed hardly audible. A steady column of water poured down, excavating a trench about 500 feet long and varying from zero to seven feet in depth and in place twenty feet in width. This "waterspout" passed almost directly over the little shelter where my thermometers stand and on the roof of which is fastened the rain guage. Before ten minutes had elapsed the entire lower part of the valley of Palmetto was 2 to 3 inches under water and the canon leading to Fish Lake Valley was a seething torrent from hill side to hill side. Every vestage of the stage road was completely obliterated for a distance of nine miles although the rain fall extended but little beyond Palmetto camp. Trees were rooted up and many holes and washes dug that measure over four feet in depth. The cloudburst on the 7th of August was very much the same as the one just described with the exception that it seemed to come from one cloud only. This cloud apparently touched the ground and rolled down the mountain side in a straight line from where my rain guage is situated. The rain seemed to cover more ground however and extended some what further to the West and N. West.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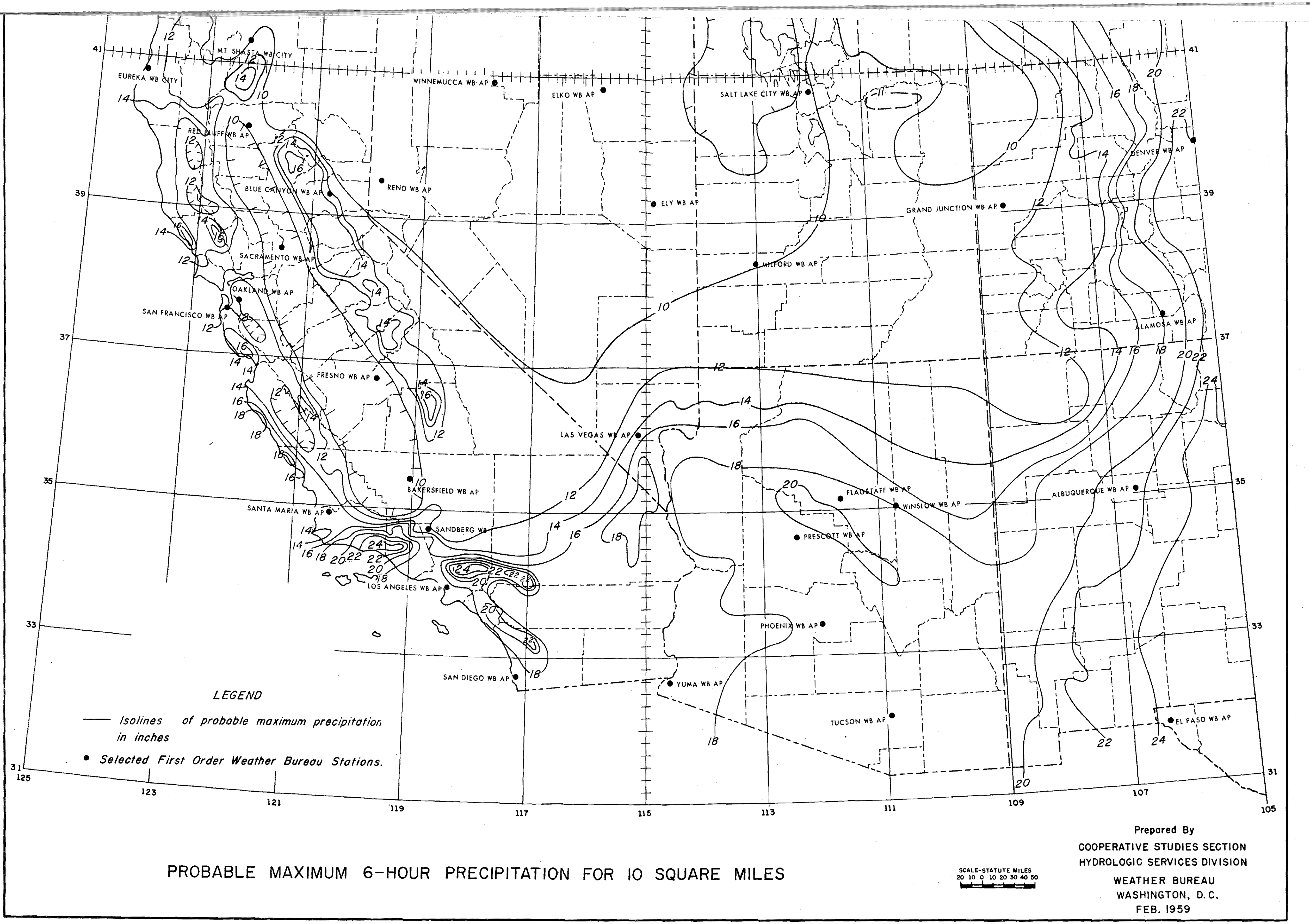

PROBABLE MAXIMUM 6-HOUR PRECIPITATION FOR 10 SQUARE MILES

Prepared By
COOPERATIVE STUDIES SECTION
HYDROLOGIC SERVICES DIVISION
WEATHER BUREAU
WASHINGTON, D.C.
FEB. 1959

FIGURE 6-4.—Probable maximum 6-hr. 10-sq.-mi. precipitation, in inches.

6.4.18 The description of the August 11 storm given in the letter quoted immediately above certainly indicates a cloudburst. Furthermore, the resultant flood and damage described could hardly be associated with a 1-hr. rainfall of 0.88 in., especially in this arid region. In his letter Mr. Oothout states that he was away for the major part of August. Although his letter contains no definite statement as to his presence or absence from the camp on the 11th, his very vivid description of that storm suggests that he may have been in camp on that date and may have made the observation himself. One cannot, of course, be certain that he did. Nevertheless, the description of the storm and the resultant flood and damage befits a rainfall intensity much closer to the reported 1-hr. amount of 8.80 in. than to the supposedly corrected value of 0.88 in. While the reported intensity was not used directly in deriving 1-hr. PMP, the observation did influence the construction of the 1-hr. PMP isolines of figure 6–3 in the vicinity of the lower California-Nevada border.

6.4.19 The low PMP center (fig. 6–3) west of Salt Lake City and covering the Salt Lake watershed is not a clearly defined center. In this entire intermountain region there are valleys and watersheds that are cut off from the usual sources of moisture. Some of them are so small that they are only identifiable on quadrangle maps, which are of relatively large scale. Others are larger and can be identified from the smaller-scale aeronautical charts. Even if it were possible to pinpoint all these valleys and watersheds, the knowledge and understanding of the processes that produce the 1-hr. PMP are so limited that applicable variations could not be defined adequately.

6.4.20 The low center west of Salt Lake City (fig. 6–3) is an example of one place where it is possible to indicate an isolated center. The fewness of isolated centers and the smoothness of the isolines on the 1-hr. PMP map may be reflections of presumed limited effect of orography on short-duration rainfall. They may also be interpreted as indications of willingness to admit lack of understanding of the causes of variations in 1-hr. precipitation.

6.5 PMP for 6 hr. and 10 sq. mi.

6.5.1 The 6-hr. PMP map (fig. 6–4) was developed mostly by applying the 6- to 24-hr. ratio to the 24-hr. PMP map (fig. 6–1) and comparing the results with appropriate averages of the 1- and 24-hr. amounts. The 6-hr. 10-sq.-mi. PMP was in part also derived by moisture adjustment and storm transposition; i.e., in the same manner 24-hr. PMP was obtained. Since many of the outstanding storms occurred before 1940, centers of heaviest precipitation were usually completely devoid of recording-gage data. The assignment of shorter durations to observational-day amounts was based on observers' remarks concerning the times of beginning and ending of the precipitation and on analyses of the associated meteorological situations. Moisture adjustment and transposition of storms increased the ratio-computed values in the region east of the Continental Divide.

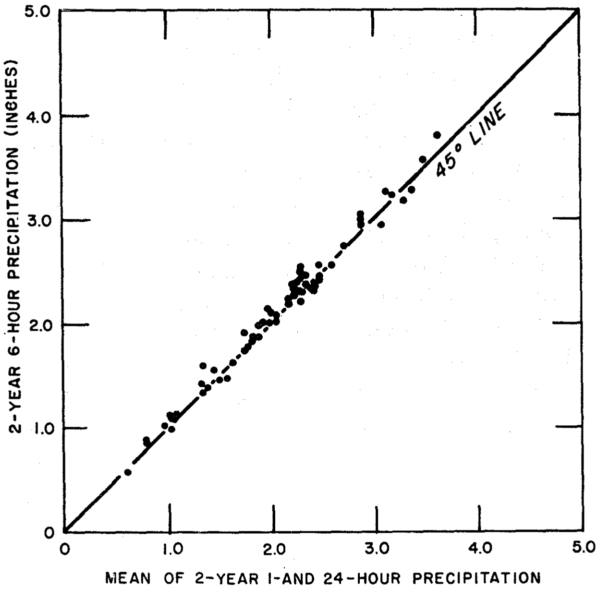

FIGURE 6–5.—Comparison of 2-yr. 6-hr. precipitation with mean of 2-yr. 1- and 24-hr. precipitation.

6.5.2 The 6- to 24-hr. ratio was discussed in section 6.3. The averaging of 1- and 24-hr. amounts to determine the 6-hr. value is the result of an investigation reported in Weather Bureau *Technical Paper No. 28* [31]. This investigation indicated a relationship between precipitation amounts for various durations. The equation, $(P_6)=A(P_{24})+B(P_1)$, was examined. In this equation, A and B are empirical constants, and P_{24}, P_6, and P_1 are the 24-, 6-, and 1-hr. precipitation amounts for a particular return period. The coefficients were determined to be: $A=\frac{1}{2}$, and $B=\frac{1}{2}$. This relationship was tested using data for 60 Weather Bureau first-order stations scattered throughout the United States. Figure 6–5 shows the results of this test for the 2-yr. return period. The same problems discussed in relation to the applicability of the 6- and 24-hr. ratio based on the 2-yr. return period are pertinent to the use of the mean of the 1- and 24-hr. amounts. Tests similar in nature to those described earlier have been applied with the same results.

6.5.3 Moisture adjustment of historical storms produced only one storm that had any effect on the magnitude of the 6-hr. PMP map derived from ratios. This was the Cherry Creek storm of May 30–31, 1935, discussed in paragraphs 5.2.1–5.2.5. Though that discussion was related solely to 24-hr. amounts, similar arguments apply to the 6-hr. values, though with less validity since the time distribution of the total storm precipitation is uncertain. The accepted value [15] for the maximum 6-hr. average depth over 10 sq. mi. is 20.6 in. Adjusting this value to the maximum observed moisture charge within 15 days of the storm date yields 30.5 in. Adjustment to maximum observed moisture charge for the date of occurrence results in a value of 27.4 in. The adopted PMP for 6 hr. and 10 sq. mi. at the storm site is 24.4 in.

6.5.4 The degree of smoothness for the 6-hr. map lies between the degrees of smoothness in the 1-hr. and 24-hr. maps. This is an expression of the increasing importance of orography as the duration increases from 1 to 6 hr. If there were no topography, the occurrence of precipitation centers would be random and their movement would depend only on the interactions of the atmosphere. As mentioned earlier, a 1-hr. thunderstorm can occur at any point with little regard to the local topography. As the duration increases, even though only from 1 to 6 hr., the persistence of a storm mechanism in one place, or the recurrence of a storm mechanism, becomes more dependent on topography.

6.5.5 An example illustrating the map-smoothing problem may help in applying the data on the PMP maps. The 6-hr. PMP map (fig. 6–4) is very flat over the vast plateau of northern Nevada and portions of adjoining States, showing values ranging from 8 to 10 in. The 10-in. values apply to windward slopes of mountains, such as the Warner Range in Modoc County in northeastern California. The 8-in. values apply to the flatter terrain typifying much of the region. While it would be possible to draw for prominent features such as the Warner Range, it would be impracticable to draw for lesser and more isolated mountains. Current knowledge of precipitation-producing processes (ch. 1) is too limited to justify the construction of exact and detailed isolines of PMP for each topographic feature.

6.5.6 It is known from observation and study of records that prominent mountains "set off," or "trigger," storms that produce precipitation several miles downwind from the crests (sec. 2.3). This may be more of an expression of frequency than of intensity. The air flow that carries rainfall centers downwind from the mountains tends to disperse the rain—both in time and in space.

6.6 Minimum recurrence interval.

6.6.1 Storage problems raise the question of how soon a major storm may be followed by another major storm. While durations exceeding 24 hr. are beyond the scope of this report, it was convenient, while collecting the necessary basic data, to compile a list of a few situations of heavy 24-hr. rainfalls followed in a few days by additional heavy falls. A few of these situations are listed in table 6–1.

6.6.2 One would naturally suspect that the greater the storm-rainfall intensity, the longer the time required to replenish the precipitated moisture and, hence, for a storm of comparable intensity to recur. While there is a tendency for persistence in weather, major storms are rare events that, in a sense, may be regarded as exceptions to persistence. Therefore, while it is physically possible for outstanding storms to repeat at intervals of something like 4 or 5 days, there is relatively little probability of the occurrence of such a series; and the longer the series, the smaller the probability. No attempt was made to solve this problem. Table 6–1 merely shows what has happened in various parts of the western United States. Its data suggests that the assumption of a minimum recurrence interval of 4 to 5 days for rainfall of PMP or approximate magnitude would be reasonable.

6.7 Depth-area relations

6.7.1 There are two basic types of depth-area relationships: (1) storm-centered relations, and (2) geographically fixed curves. The area reduction relation in this report (fig. 6–6) is storm-centered. The highest PMP values for any point, or 10 sq. mi., within a problem watershed should be used in applying the reduction from the depth-area curves. This is consistent with the method

TABLE 6-1.—*Time intervals between some closely spaced major storms (Daily precipitation in inches)*

Pacific Northwest	November 1909							
	17	18	19	20	21	22	23	24
Rattlesnake Creek, Idaho	-----	-----	3.20	1.80	1.10	3.90	7.00	-----
Grand Forks, Idaho	0	1.98	2.08	2.05	.05	2.22	.93	0.65
Snowshoe, Mont	.11	3.81	3.15	.09	.13	2.05	2.11	2.45
Quinault, Wasn	1.90	5.50	2.00	.61	.15	3.74	3.05	.49
Happy Home, Oreg	.34	1.72	1.60	2.18	.44	6.84	4.38	1.64

Idaho	February–March 1919						
	25	26	27	28	1	2	3
Soldier Creek	0.56	2.25	T	0.25	0.10	1.35	0.10
Sheep Hill	.67	1.80	.06	.53	.66	1.79	.17
Cottonwood Creek	1.19	1.30	T	.11	1.17	1.33	.25
Boulder Mine	.46	1.51	.15	.40	.58	1.52	.28

New Mexico	September 1941					
	21	22	23	24–27	28	29
Ancho	1.70	2.90	0.10	0	2.55	2.53
Arabela	2.40	4.74	0	0	2.41	1.55
Bell Ranch	.58	5.00	.62	0	1.70	2.00
White Sands	3.83	1.48	0	0	1.35	2.62

Oklahoma	May 1943								
	7	8	9	10	11	12–16	17	18	19
Miami	1.70	3.50	0	3.30	0.20	0	2.95	3.90	2.35
Vinita	0	1.24	.60	7.03	.68	0	3.68	3.26	2.49

California	November 1950					
	16	17	18	19	20	21
Blue Canyon	2.60	3.23	6.80	1.43	8.56	1.13
Deep Creek Power House	2.73	1.44	7.37	2.52	6.41	3.08
Highland	3.95	1.98	11.91	2.84	4.47	.15
Soda Springs	2.63	1.91	5.60	1.28	6.13	.60

California	December 1955							
	16	17	18	19	20	21	22	23
Blue Canyon	0.97	1.24	2.32	5.81	2.11	5.19	7.44	5.92
Brush Creek	.35	.66	1.69	4.44	4.33	.03	8.68	3.25
Cazadero	3.52	0	3.30	7.95	1.10	4.45	10.75	3.53
Wrights	.02	.30	.70	9.33	1.25	1.20	3.93	11.09
Strawberry Valley	1.13	.60	3.04	8.42	3.83	2.55	9.50	7.50

used in deriving the relation and with the practice of allowing the storm isohyetal pattern of the PMP to be oriented over the watershed in the most critical manner possible.

6.7.2 The frequency-derived, geographically-fixed, area-reduction curves of Weather Bureau *Technical Paper No. 29* [37] are based on different parts of different storms instead of on the highest amounts surrounding the storm centers. Since the area is geographically fixed, its precipitation stations measure rainfall sometimes near the storm center, sometimes on the outer edges, and sometimes in between the two. The averaging process results in their being typically flatter than the storm-centered curves of figure 6–6. This is understandable considering that such curves are steeper near the centers of storms. Each type of curve is appropriate for its respective application—one for design on a frequency basis, and the other for PMP.

6.7.3 One might expect the depth-area curves to vary with magnitude; i.e., to be steeper for the rarer and more outstanding storms. Although there is apparently theoretical justification for this, both from the statistical and meteorological views, empirical tests are not conclusive. In some tests there is a slight tendency in the direction expected, while others show no such tendency. The variation is well within the limits to be expected because of observational and processing errors. Accordingly, the depth-area curves of figure 6–6 are based on average depth-area data.

6.7.4 Except for very large areas and long durations, it has been the practice in using PMP data to assume that the depth-area, or storm, pattern would be oriented in the most critical manner over a watershed. This is a more conservative assumption than merely taking an observed storm pattern adjusted upward to PMP, but with no change in its orientation or configuration. Within the scope of this report, the former practice is recommended, even where orographic influences may be appreciable.

6.8 Depth-duration relations

6.8.1 Figure 6–7 shows a generalized duration-interpolation relationship for determining rainfall amounts for durations from 1 to 24 hr. when the values for 1, 6, and 24 hr. are known. This diagram was derived from large observed values as described in Weather Bureau *Technical Paper No. 28* [31] and *No. 29* [37]. While there may be regional variation in this type of relation as applied to PMP, it has not been possible to evaluate it. For the purpose of generalizing, the diagram of figure 6–7 is believed to be as good as any available for application to PMP.

6.8.2 It is pertinent to distinguish between the 6-hr. PMP and the maximum 6-hr. increment that would occur during, say, a 24-hr. PMP. The same idea applies, of course, to other durations. The 6-hr. PMP might occur at one time of year, and the maximum 6-hr. increment of the 24-hr. PMP might occur at a different time of year. To generalize on this problem would require a rather laborious study of seasonal varia-

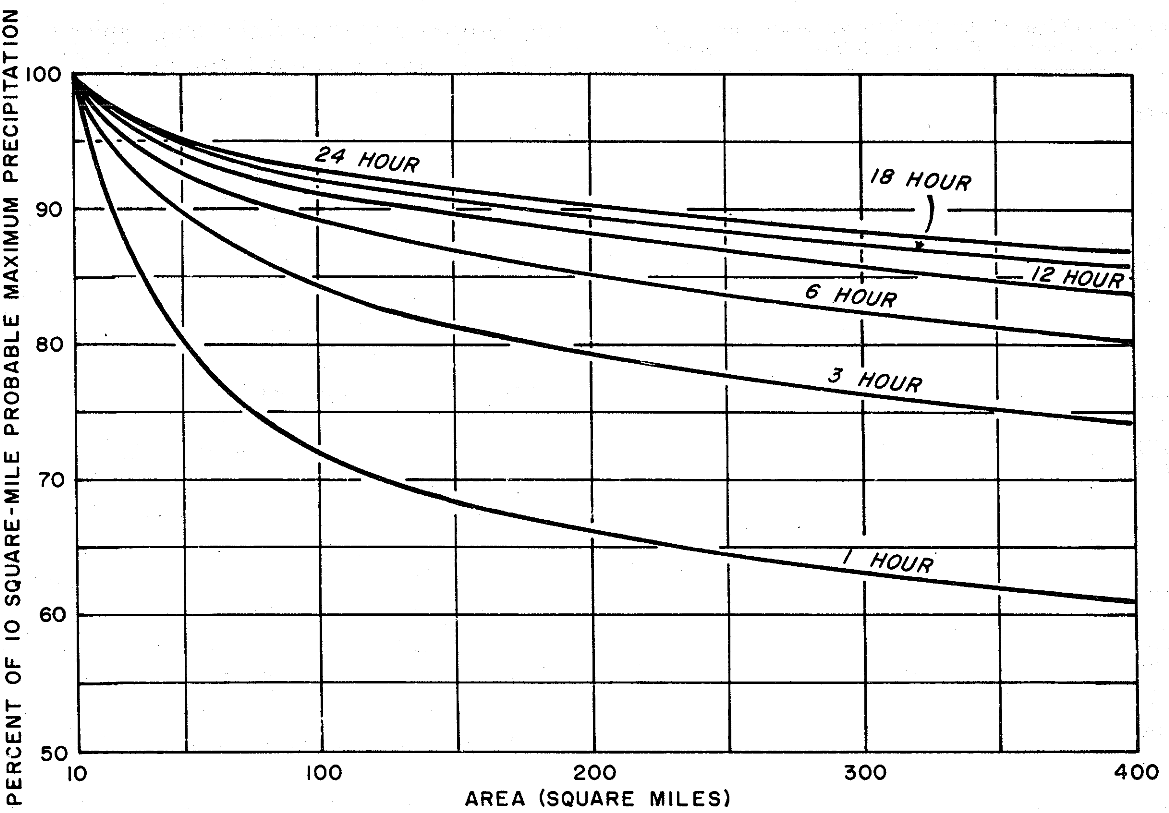

FIGURE 6–6.—Depth-area, or area-reduction, curves.

tion in PMP. Until this can be done, the distinction between the total-storm and partial-storm 6-hr. durations must be neglected.

6.8.3 For durations up to 24 hr., there is no consistent, or typical, chronological distribution of precipitation in outstanding storms. This is discussed in Weather Bureau *Technical Paper No. 29*, Part 3 [38]. Therefore, as with the areal pattern (par. 6.7.4), instead of distributing the increments of PMP according to an observed storm sequence, the use of the most critical sequence of PMP increments is recommended as being more conservative. With area, and with duration, in applying a synthetic storm to a watershed, it is important to make sure that none of the area or duration increments exceeds PMP for the area or duration concerned.

6.9 Evaluation of results

6.9.1 The maps and diagrams of this report are largely an expression of a consensus of meteorological and statistical judgment on the general level of PMP in western United States and on methods for regional generalization. The isolines of PMP shown in this report are based partly on computations of PMP at specific stations, storm centers, and coordinate intersections, and partly on methods of interpolation. These methods of interpolation included consideration of storm transposition, moisture sources, and major topographic features as influences on moisture movement and on storm mechanism. Greatest reliance probably was placed on an integration of these elements as expressed in the regional pattern of rainfall-intensity frequency. Accordingly, it is pertinent to consider the magnitude of statistical error inherent in rainfall-frequency analysis.

6.9.2 An illustration of the variability of precipitation and the uncertainty in evaluating the magnitude of error that is possible in estimates of extreme events is that mentioned by Hershfield and Wilson [39]. The 100-yr. 24-hr. values in Iowa, a plains area of 50,000 sq. mi., vary from less than 5 in. to nearly 8 in. among 70 stations having average record length of more than 50 yr. Except for a very slight general trend across the State, no reasonable causes could be assigned to this variation. There are no mountains or large bodies of water. The average value of 6.0 in. may

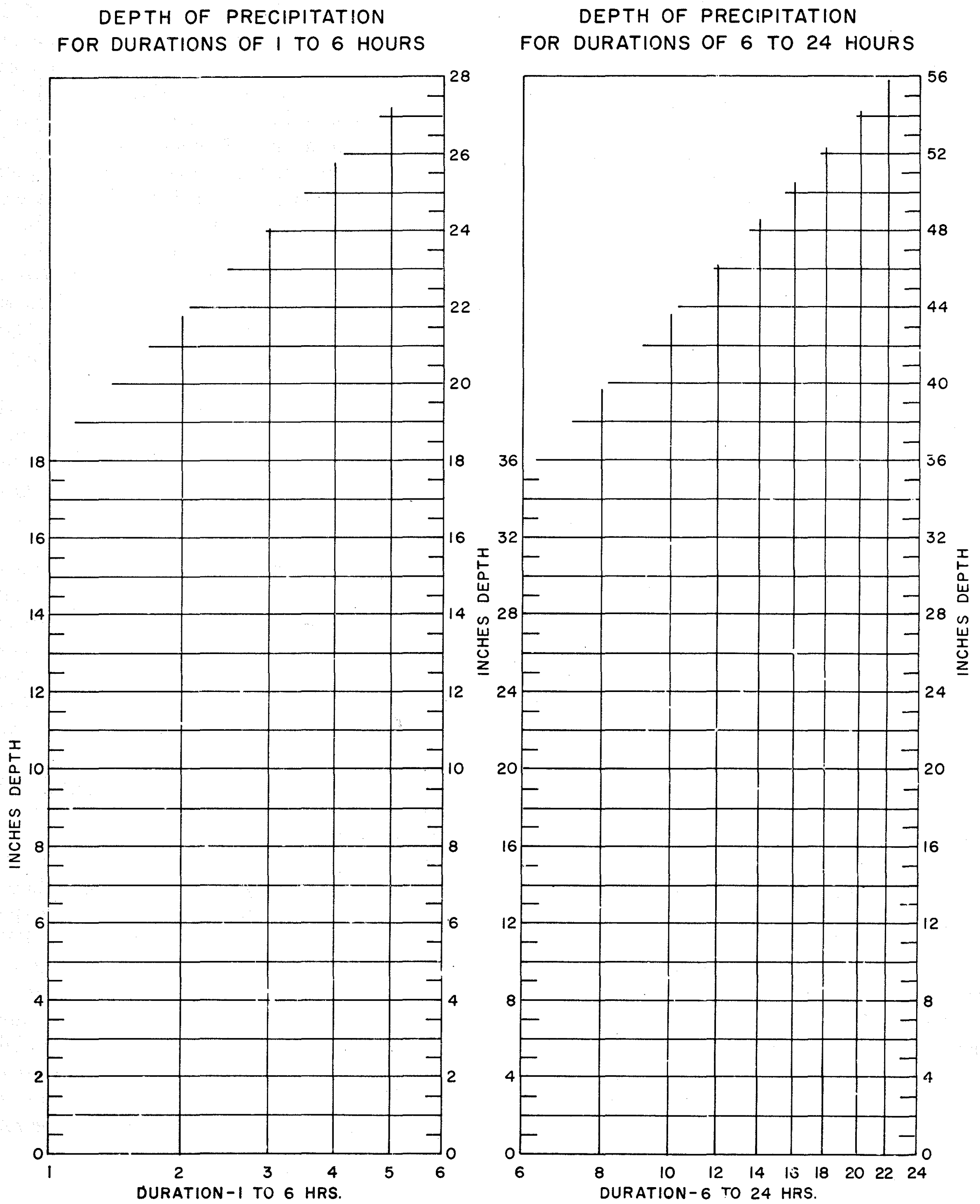

Figure 6-7.—Depth-duration diagrams.

be a better estimate for any place in the State than many of the individual station records would yield singly.

6.9.3 In regions of rugged topography, the estimates of even the more common frequencies are subject to considerable geographical sampling error. An example of this can be found in Los Angeles County, Calif., an area of 4,071 sq. mi.,

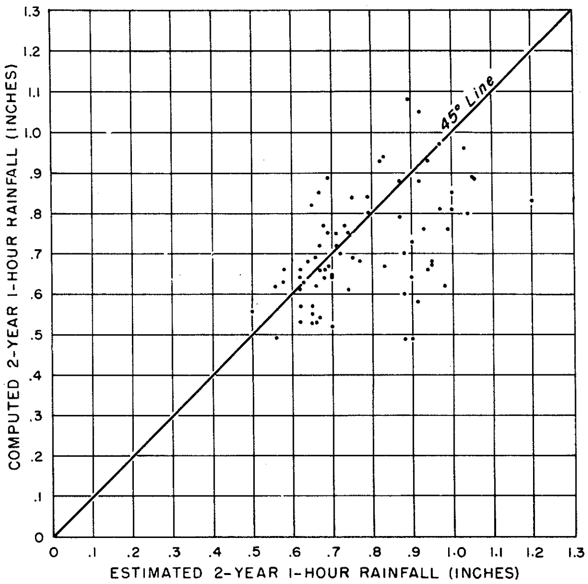

FIGURE 6–8.—Comparison of 2-yr. 1-hr. rainfalls computed from individual station records with those estimated from generalized map. (Los Angeles area.)

where the elevation varies from 1,000 ft. to more than 9,000 ft. within 15 mi. Generalized maps of the 2-yr. 1-hr. precipitation for this region were developed [31, 40] utilizing 30 stations in Los Angeles County. In 1958, data for 74 additional stations in this region were obtained. Figure 6–8 shows a comparison of the 2-yr. 1-hr. rainfalls computed from the records of these additional stations and the amounts estimated from the generalized maps. The scatter is the result of several factors. One is the sampling error in estimating the value over rugged topography with a limited length of record. Another is the error introduced by the smoothing process in developing generalized charts. The values obtained from each method, however, are still only estimates of the true value of the 2-yr. 1-hr. amount. This scatter, then, represents the discrepancy between two independent estimates, rather than an accurate measure of scatter.

6.9.4 The standard error of estimate of the frequency parameters used for regional generalization ranges from about 20 percent of the mean in plains regions to something like twice that amount in mountainous regions. To this fairly well-defined measure of uncertainty must be "added" the uncertainties inherent in the point PMP estimates discussed earlier. But the concept of standard error of estimate seems to be inappropriate in application to PMP, which is largely an envelopment instead of an estimate of central tendency. The envelopment process encompasses not only variability in the basic data and computations but much of the uncertainty in methods and judgment.

6.9.5 Evaluation of the uncertainty in the methods and judgment can be made only in a qualitative way, based largely on the reasonableness of the assumptions made and on the limits set for elements in the precipitation process. Additional uncertainty comes, of course, from the probability or reasonableness of combinations of the influences or processes that lead to heavy rainfall. Some of the uncertainty can be regarded as a random variable (statistical error) associated with results that do not exhibit any definite tendency to be either too high or too low. Other uncertainty can be recognized as a bias; i.e., a definite tendency to be too high or too low.

6.9.6 On lee slopes, in small sheltered valleys, and on plateaus, the isolines of PMP are likely to be too high (par. 6.2.6), and a method of compensating for some of this bias was discussed in paragraph 6.5.5. On average windward slopes there is believed to be no bias, and on a few unusually steep windward slopes the smoothed isolines of PMP presented herein may actually undercut the best estimates of PMP. For shorter durations the estimates are less reliable than for long durations. The single set of depth-area curves (fig. 6–6) is obviously an oversimplification and tends to give estimates that are too high for extremely rugged topography and possibly too low for relatively flat terrain.

Chapter 7

ESTIMATING PROBABLE MAXIMUM PRECIPITATION FOR SPECIFIC WATERSHEDS

7.1 Introduction

7.1.1 The purpose of this report is to provide generalized estimates of PMP for western United States for hydrologic design. The previous chapters discussed the precipitation process, the factors affecting precipitation intensities, the basic theory, data and methods for estimating PMP, and the degree of reliability of the final results. This chapter is intended to provide the user of the estimates presented in this report with some examples of how the various maps and diagrams should be used for obtaining estimates of PMP for specific watersheds.

7.2 Sand Creek Watershed (California)

7.2.1 Sand Creek Watershed, above the gaging station near Orange Cove, Calif., (36°38′ N., 119°18′ W.), is in the foothills of the Sierra Nevada, about 30 mi. ESE of Fresno, and covers an area of 32 sq. mi. in Fresno and Tulare counties. For the purpose of illustration, it is assumed that the hydrologic characteristics of the watershed are such that 1-hr. increments of 8-hr. PMP are required to determine design criteria for a hydraulic structure to control runoff from the entire watershed.

7.2.2 The 1-, 6-, and 24-hr. PMP values are first obtained from the maps of figures 6–1, 6–3, and 6–4. These values are found to be 5.5, 11.0, and 17.0 in., respectively. From these values and the duration diagrams of figure 6–7, the 3- and 8-hr. PMP are found to be 8.6 and 12.2 in., respectively. The 10-sq.-mi. PMP values for 1, 3, 6, and 8 hr. are thus 5.5, 8.6, 11.0, and 12.2 in., respectively. The reduction factors for adjusting these PMP values to the size of the watershed (32 sq. mi.) are obtained from figure 6–6, which yields 85, 92, 94, and 95 percent for the 1-, 3-, 6-, and 8-hr. durations, respectively.

7.2.3 Application of the above area-reduction factors to the 10-sq.-mi. PMP values yields 4.7, 7.9, 10.4, and 11.6 in., for the 1-, 3-, 6-, and 8-hr. watershed PMP. Plotting of these PMP values against their corresponding durations gives the probable maximum depth-duration curve for the Sand Creek Watershed (fig. 7–1). PMP values for 1 to 8 hr. as read from this curve are 4.7, 6.7, 7.9, 8.8, 9.6, 10.4, 11.1, and 11.6 in., respectively. The hourly increments of PMP are thus 4.7, 2.0, 1.2, 0.9, 0.8, 0.8, 0.7, and 0.5 in. The entire procedure is summarized in table 7–1.

7.2.4 Runoff is a function of, among other things, the time distribution of rainfall. Examination of many storms indicated only a slight central tendency of incremental rainfall amounts.

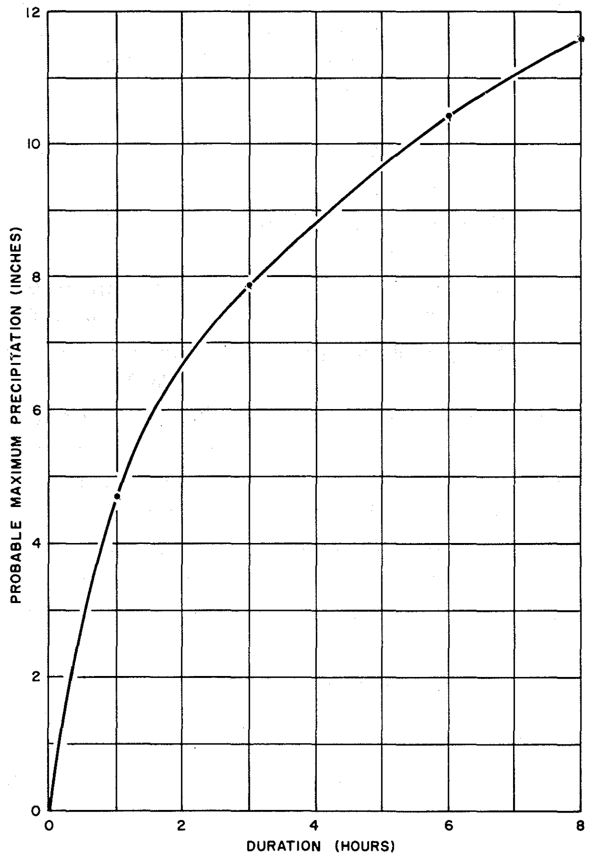

FIGURE 7–1.—Depth-duration curve of probable maximum precipitation for Sand Creek Watershed (Calif.).

TABLE 7–1.—*Probable maximum precipitation—Sand Creek Watershed*

Duration (hr.)	PMP[1] (in.)	PMP[2] (in.)	Area-red.[3] factor (%)	PMP[4] (in.)	PMP[5] (in.)	1-hr. incr.[6] (in.)
1	5.5		85	4.7	4.7	4.7
2					6.7	2.0
3		8.6	92	7.9	7.9	1.2
4					8.8	0.9
5					9.6	0.8
6	11.0		94	10.4	10.4	0.8
7					11.1	0.7
8		12.2	95	11.6	11.6	0.5
24	17.0					

1. PMP from maps of figs. 6–1, 6–3, and 6–4.
2. PMP estimated by means of fig. 6–7.
3. Area-reduction factors from fig. 6–6.
4. PMP reduced for size of watershed (32 sq. mi.) and used for plotting curve of fig. 7–1.
5. PMP as read from curve of fig. 7–1.
6. Hourly increments of PMP computed from preceding column.

The results were not sufficiently conclusive to define a typical chronological distribution of storm rainfall. The most critical distribution must be determined by the engineer, taking into consideration the rainfall and runoff characteristics of the problem watershed. While table 7–1 shows the hourly increments of the 8-hr. PMP in decreasing order, the engineer should feel free to rearrange these increments to obtain the most critical runoff values for design. The most critical rainfall distribution must be determined on the basis of hydrologic considerations and computations outside the scope of this report.

7.3 Bannock Creek Watershed (Idaho)

7.3.1 Bannock Creek, near Idaho City, Idaho (43°48′ N., 115°46′ W.), is in the mountains about 25 mi. NE of Boise. The design requirements for this small watershed (4.5 sq. mi.) are assumed to involve hourly increments of 4-hr. PMP.

7.3.2 The 1- and 6-hr. PMP values of 4 and 8 in., respectively, are first obtained from the maps of figures 6–3 and 6–4. No areal adjustment of these 10-sq.-mi. PMP values is required since the area of the watershed is less than 10 sq. mi. Paragraph 4.2.8 pointed out there is usually too little sampling within storm centers to permit the accurate delineation of the depth-area relation. Hence, the highest value observed is generally presumed to be applicable to areas as large as 10 sq. mi.

7.3.3 Since no area reduction is required and only four 1-hr. increments of PMP are needed, the construction of a probable maximum depth-duration curve is hardly necessary. It is perhaps more convenient to use the duration diagram of figure 6–7 to obtain directly the PMP values for 2, 3, and 4 hr. by interpolation between the 1- and 6-hr. values. The PMP values thus obtained for 1, 2, 3, and 4 hr. are 4.0, 5.3, 6.2, and 6.9 in., respectively, and the hourly increments are thus 4.0, 1.3, 0.9, and 0.7 in.

7.4 Willow Creek Watershed (California)

7.4.1 Willow Creek above the gaging station at the mouth, near Auberry, Calif. (37°9′ N., 119°28′ W.), is on the western slopes of the Sierra Nevada, about 30 to 40 mi. NNE of Fresno. Its drainage area is about 130 sq. mi. The maximum 1-hr. 10-sq.-mi. value is found from figure 6–3. The maximum point is well within the central 6-in. isoline. Accordingly, with the 1-in. isoline interval, the appropriate maximum point, or 10-sq.-mi., value is 7.0 in. Similarly, for 6 hr., the watershed extends well into the 14-in. center (fig. 6–4) and, with a 2-in. isoline interval, 16 in. should be used for the maximum point value. For 24 hr., the higher portions of the watershed extend into the 22-in. isoline (fig. 6–1), but do not quite reach the 25-in. center to the north. The maximum 10-sq.-mi. value for 24-hr. PMP is 24 in.

7.4.2 PMP values for whatever intermediate durations are required would be estimated by means of figure 6–7. After adjustment for the size of the watershed by application of area-reduction factors from figure 6–6, the adjusted PMP values would be used to derive the probable maximum depth-duration curve for the watershed. The curve would, in turn, be used to estimate increments of PMP for whatever durations are required to determine design criteria. The procedure is similar to that described in section 7.2.

7.5 Bear Creek Watershed (California)

7.5.1 Bear Creek near Vermilion Valley, Calif. (37°20′ N., 118°58′ W.), drains an area of about 54 sq. mi. in the Sierra Nevada, about 65 to 70 mi. NE of Fresno. The maximum 1-, 6-, and 24-hr. PMP point values (figs. 6–1, 6–3, and 6–4) for the watershed are about 7.0, 12.0, and 16.0 in., respectively. The relations of figures 6–6 and 6–7 are then used to obtain the increments and area-reduction factors required.

7.6 Lake Fork Watershed (Colorado)

7.6.1 Lake Fork above Sugarloaf Reservoir, Colo. (39°16′ N., 106°24′ W.), drains an area of about 18 sq. mi. and is located about 80 mi. WSW of Denver. The 1- and 6-hr. PMP values are indicated (figs. 6–3 and 6–4) to be 10.0 and 18.0 in. respectively.

7.7 East Fork of Carson River Watershed (Nevada)

7.7.1 East Fork of Carson River near Gardnerville, Nev. (38°52′ N., 119°42′ W.), has a drainage area of 344 sq. mi. This watershed lies on the east, or lee, side of the Sierra Nevada, and is about 50 to 80 mi. south of Reno, Nev. The highest point values taken for this watershed from the 1-, 6-, and 24-hr. PMP maps are 7.0, 12.0, and 17.0 in., respectively.

7.8 Crystal River Watershed (Colorado)

7.8.1 Crystal River near Redstone, Colo. (39°19′ N., 117°13′ W.), drains about 225 sq. mi. and is centered about 75 mi. east of Grand Junction. With topography as rugged as in this watershed, a 1-hr. PMP of 8.0 in. is just as likely to be correct as an interpolated value between the 6- and 8-in. isolines of figure 6–3. There is a good chance that at least one point in this watershed has a PMP value as great as average points along the 8-in. isoline only a few miles to the east. Similarly, the 6- and 24-hr. PMP point values should be rounded off to 14.0 and 18.0 in., respectively.

7.9 Humboldt River Tributary Watershed (Nevada)

7.9.1 At 41°29′ N. and 115°49′ W., 45 mi. north of Elko, Nev., there is a place called North Fork on one of the tributaries of the Humboldt River. The watershed area above North Fork is about 40 sq. mi. The stream flows from the east slope of the Independence Mountains. The 1- and 6-hr. PMP values obtained from the maps of figures 6–3 and 6–4 are 4.8 and 8.5 in., respectively. Ordinarily, values are rounded off to the closest, next-higher inch, which is a conservative approach. However, with values as low as those just above, rounding off can represent an appreciable increase, which might be undesirable in a location where PMP is about as low as anywhere in the West.

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APPENDIX A

BASIC STORM-STUDY DATA

(See paragraph 4.2.1 for definition and sources)

Storm dates	Storm center			Precipitation (in.)			
	Lat. (deg.)	Long. (deg.)	Elev. (ft.)	10 sq. mi.		500 sq. mi.	
				6 hr.	24 hr.	6 hr.	24 hr.
Colorado, Kansas, New Mexico, Oklahoma, and Texas							
5/29–6/1/94	40.1	105.5	9200	1.7	5.6	1.7	4.8
10/10–15/99	39.4	108.1	5500	1.0	1.8	0.9	1.7
5/1–3/04	41.0	105.2	7200	2.1	4.3	1.7	3.6
9/26–30/04	35.9	105.3	8200	3.8	6.6	2.6	5.8
7/21–25/05	32.9	105.3	5700	3.9	5.7	3.0	4.3
8/4–6/06	31.3	100.8	2100	7.8	8.6	7.2	8.4
10/18–19/08	38.5	102.8	4300	4.2	6.3	3.8	6.2
9/3–7/09	37.6	107.8	8900	1.6	2.9	1.5	2.8
10/4–6/11	37.8	107.7	10400	3.7	8.1	1.7	5.3
10/4–6/11	39.0	107.5	9500	1.0	2.2	0.9	2.1
3/19–21/12	39.0	107.5	9500	1.1	2.6	1.0	2.5
6/6–12/13	35.9	105.1	6800	4.3	5.1	3.0	4.5
4/29–5/2/14	36.3	103.1	5000	5.3	9.0	4.2	8.3
7/19–28/15	34.8	106.3	7100	4.6	5.2	4.1	4.6
9/15–17/19	33.7	105.2	6700	3.8	7.4	2.7	5.4
4/14–16/21	40.7	105.7	7500	2.2	7.3	1.7	5.6
6/2–6/21	38.4	105.1	5500	10.0	12.0	5.7	9.1
8/17–25/21	37.5	105.2	9200	2.9	3.0	1.7	2.3
7/27–8/3/22	39.8	105.6	7500	2.2	3.3	1.6	2.4
5/27–29/25	28.7	100.5	700	6.3	9.0	5.3	7.5
6/26–29/27	37.5	107.2	7700	1.3	2.8	1.1	2.6
9/6–10/27	37.6	107.8	8300	1.9	2.4	1.6	2.2
7/19–24/29	39.2	105.3	6900	3.0	3.0	1.1	2.1
7/27–8/7/29	37.6	107.8	8300	1.8	2.5	1.2	2.2
10/9–12/30	35.2	103.3	4100	5.7	9.9	4.6	7.9
6/2–6/32	38.5	101.8	3600	6.2	6.3	3.7	4.6
8/25–29/32	37.8	107.7	9400	0.9	2.2	0.8	1.9
4/19–22/33	38.1	105.5	7900	1.4	2.6	1.0	2.5
9/9–11/33	39.5	105.1	5500	3.9	4.2	3.4	3.7
5/30–31/35	39.6	102.1	3900	20.6	22.2	7.8	9.3
9/14–18/36	30.5	100.1	2100	16.0	26.0	7.7	15.8
5/26–30/37	34.8	103.7	5100	2.8	4.4	1.6	3.7
5/30–31/38	38.9	101.8	3400	10.0	10.0	7.1	7.1
6/20–23/38	38.9	107.0	9000	1.0	1.8	0.7	1.3
7/19–25/38	30.8	100.7	2800	11.5	15.9	7.0	9.3
8/30–9/4/38	40.4	105.1	5000	6.4	7.0	2.3	3.4
8/31–9/4/38	40.4	105.2	5200	5.8	8.5	3.7	6.3
6/19–20/39	32.7	100.9	2400	18.8	------	8.6	------
5/20–25/41	33.1	103.2	4000	3.8	6.5	2.3	5.4
9/18–23/41	37.7	108.0	9200	1.9	3.0	1.4	2.8
9/20–23/41	32.2	104.7	5100	10.1	12.1	4.4	6.9
4/17–21/42	36.9	103.0	4300	3.0	4.3	1.2	3.4
5/4–9/43	40.4	106.7	9700	1.0	1.8	0.8	1.5
6/1–3/43	39.6	107.3	5900	1.3	2.2	1.0	2.0
5/30/48	40.6	105.1	5000	7.8	------	------	------
6/23–24/48	29.4	100.6	1100	13.2	26.2	8.8	20.2
6/12–14/49	40.0	104.8	5000	8.5	9.1	------	------
6/23–28/54	30.2	101.6	1700	16.0	26.7	8.4	20.5
Wyoming, Montana, North Dakota, South Dakota, and Nebraska							
6/29–7/1/98	47.0	111.6	5200	1.2	2.6	1.1	2.5
4/22–24/00	45.8	110.0	4100	1.5	3.8	1.3	3.2
5/11–13/00	46.6	111.7	3500	2.5	3.8	1.6	3.5
5/19–20/02	48.5	112.8	4500	1.2	3.0	1.2	2.9
6/2–5/04	44.5	103.8	3900	1.7	4.2	1.3	3.7
6/6–8/06	48.1	109.6	5400	6.0	10.2	4.0	7.8
6/12–13/07	44.6	103.3	3600	6.6	------	5.0	------
6/21–23/07	47.8	112.2	3800	2.4	5.7	1.8	4.9
6/3–6/08	47.2	111.1	4800	1.9	6.5	1.7	[illegible]
6/7–8/10	46.6	109.3	5100	2.7	5.8	2.4	5.1
9/3–6/11	48.9	111.6	4400	1.9	3.7	1.5	3.3
4/11–14/12	47.8	103.5	2200	0.8	2.4	0.8	2.1
6/12–14/14	48.4	107.9	2300	2.8	3.6	2.6	3.4
6/25–28/14	46.5	100.3	2000	7.7	8.5	5.6	7.4
6/1–5/15	47.0	111.7	5200	1.3	3.6	1.0	3.0
6/19–22/16	47.5	111.7	3400	2.5	6.2	2.1	5.4
7/14–15/18	46.8	109.2	5000	2.0	4.4	1.5	3.6
9/27–28/19	48.6	113.0	4400	1.5	3.0	1.1	2.7
5/9–12/20	44.6	103.4	2800	4.0	5.2	1.5	4.2
6/17–21/21	47.3	105.6	2600	10.5	13.3	7.9	12.0
6/16–21/23	48.0	108.7	3500	2.0	3.3	1.7	3.1
7/22–26/23	44.8	106.9	3700	3.8	4.4	3.0	3.4
9/27–10/1/23	43.9	105.8	5100	6.0	9.5	4.3	7.7
5/5–9/27	43.8	101.2	2300	3.7	4.9	3.2	4.4
7/5–8/28	48.3	101.8	2100	4.2	6.9	3.7	6.4
5/25–30/29	47.0	103.8	2700	1.9	3.8	1.6	3.5
6/6–7/29	47.0	104.0	2800	3.0	4.9	2.5	4.6
3/15–19/32	44.2	110.9	6800	------	------	1.2	2.1
9/11–12/33	40.1	101.2	2800	3.5	5.6	2.4	4.7
6/11–13/37	47.5	105.6	2400	2.5	4.5	2.0	4.2
5/17–20/38	45.8	110.0	4100	2.3	4.2	2.0	3.7
9/6–8/41	45.4	107.9	3600	1.8	3.5	1.4	3.2
3/13–17/43	48.9	104.4	2200	0.8	2.4	0.6	1.6
6/2–5/44	44.9	104.2	3500	2.1	3.8	1.4	3.5
6/14–18/44	47.4	108.2	2700	4.0	4.4	3.6	4.0
6/26–27/44	49.0	102.6	2000	2.7	5.7	2.2	5.2
5/9–14/47	42.8	108.8	6300	1.3	2.5	1.0	2.1
6/13–16/47	42.2	100.0	2700	1.8	1.9	1.1	1.2
6/17–18/47	41.8	103.7	4100	9.4	------	------	------
8/10–13/47	48.8	104.6	2000	2.9	4.4	2.2	4.0
7/27–28/51	42.4	103.2	4100	6.3	------	3.3	------
Washington, Oregon, and Idaho							
5/26–30/06	45.8	118.4	1900	1.5	3.0	1.0	2.7
11/18–23/09	43.6	115.7	4000	3.7	7.2	2.5	4.9
11/18–23/09	43.6	115.8	4800	3.5	7.2	1.2	2.9
7/23–26/13	42.6	112.5	5800	------	------	2.7	3.2
2/23–25/17	43.9	114.3	8800	3.0	5.3	------	------
12/16–19/17	45.8	121.9	1200	2.7	5.9	1.9	4.8
2/28–3/3/19	44.2	115.9	5000	------	------	1.0	1.9
11/18–21/21	44.4	115.9	6500	------	------	1.0	2.4
2/17–21/27	45.1	117.2	7100	------	------	1.1	2.5
12/23–29/31	44.6	115.5	7000	1.5	3.2	1.1	2.3
12/17–19/33	47.4	115.7	4200	2.5	4.0	1.4	2.6
4/7–9/35	43.8	114.2	8700	1.8	3.9	------	------
3/25–4/1/40	43.1	116.8	6400	------	------	0.9	2.0
12/1–4/41	44.0	115.0	8800	2.0	5.4	1.7	3.9
1/19–23/43	44.2	115.7	4800	1.5	2.8	1.3	2.5
1/20–23/43	43.8	114.0	8700	1.7	4.4	0.7	2.0
6/7–12/44	43.7	113.6	6500	1.8	4.3	1.7	3.9
6/26–27/44	44.2	112.2	5700	2.2	4.2	1.7	3.3
11/17–20/46	44.2	115.2	6200	1.6	4.3	0.9	3.1
11/18–20/46	43.8	114.0	8100	1.4	5.0	0.7	2.4
9/16–18/47	42.4	112.1	4600	------	------	0.7	1.7
Arizona, California, Nevada, and Utah							
11/25–28/05	34.2	112.8	4700	3.5	4.4	2.8	3.9
12/1–4/06	31.9	109.9	6000	1.0	2.7	1.0	2.4
2/1–5/07	41.7	115.4	7900	2.0	5.7	1.4	3.6
3/15–27/07	39.9	121.4	5800	4.0	12.4	3.6	11.6
1/11–16/09	39.0	120.4	5600	4.6	11.6	4.0	10.2
1/23–31/11	39.9	121.4	4700	3.2	7.3	2.1	5.6
12/29/13–1/3/14	39.9	121.4	5200	6.5	14.0	5.6	12.2
2/17–22/14	34.3	118.1	3900	6.9	9.8	4.3	8.0
12/17–24/14	33.4	110.8	4500	2.2	3.1	1.2	2.6
1/23–2/2/15	41.2	122.0	4200	3.5	11.9	2.8	8.6
5/9–11/15	39.8	121.3	4500	2.4	6.8	1.7	5.2
1/1–4/16	39.8	121.6	2200	2.8	10.4	1.9	7.1
1/14–19/16	34.2	117.3	5700	6.3	17.6	3.9	11.2
2/19–24/36	40.6	111.6	8700	1.7	3.3	0.6	1.6
2/11–16/37	34.2	117.0	6800	3.2	7.8	2.3	5.7
9/4–7/39	34.7	113.6	2100	------	------	3.2	6.0
12/9–12/37	38.8	122.7	3000	5.7	14.8	4.3	11.5
12/9–12/37	37.6	119.5	9000	5.8	12.6	4.2	10.6
2/26–3/4/38	34.2	117.2	5200	9.2	18.0	5.5	12.9
2/27–3/4/38	37.6	115.2	4100	2.8	------	2.6	------
2/28–3/5/38	37.4	112.5	7000	1.5	3.8	1.4	3.6
2/24–29/40	39.5	121.4	4500	5.0	11.0	4.0	9.2
3/11–17/41	33.4	110.8	4500	1.5	3.3	0.9	2.4
5/11–14/41	39.5	121.0	4600	1.5	3.6	1.2	2.9
11/14–18/42	39.0	120.5	4000	2.8	8.8	2.3	7.5
1/19–24/43	34.2	118.0	2800	7.7	24.8	5.1	16.0
1/19–24/43	37.6	119.4	9500	5.6	16.2	4.2	11.6
5/31–6/5/43	40.6	111.6	8700	1.6	3.1	0.9	2.1
1/14–20/16	33.9	111.3	2400	1.6	2.7	1.3	2.3
1/24–29/16	33.1	116.7	3000	3.9	10.1	2.5	7.1
1/25–30/16	34.1	112.2	2000	1.9	4.0	1.3	3.1
2/20–25/17	37.6	119.6	7800	------	------	2.2	6.8
12/17–27/21	34.2	118.1	2300	5.6	15.6	3.8	10.6
4/5–6/25	41.8	115.4	10200	2.1	4.3	1.1	2.4
10/3–6/25	33.3	116.9	2700	2.2	5.4	1.6	4.7
4/4–9/26	34.2	118.0	2800	5.4	11.9	2.1	7.0
4/5–10/26	34.0	111.8	3300	3.2	4.0	2.2	3.7
2/10–22/27	34.0	116.8	7200	5.8	14.1	------	------
2/10–22/27	34.3	111.4	4600	2.0	4.3	------	------
12/8–13/29	41.1	122.2	3000	5.3	11.2	3.7	8.9
11/12–17/30	41.7	115.4	8600	2.1	5.6	1.2	3.1
12/29–1/1/34	34.2	118.0	2800	6.0	14.7	3.8	11.6
2/1–3/36	40.6	111.6	8700	1.7	2.9	0.9	1.8
6/10–13/43	41.7	115.4	8000	------	------	1.2	1.3
1/30–2/3/45	37.6	119.5	9100	5.8	14.6	4.2	11.4
10/27–29/46	37.4	114.1	2100	3.0	7.5	2.1	5.5
11/18–20/46	36.6	118.6	9900	3.7	9.3	------	------
6/4–5/47	40.5	122.2	700	3.0	3.5	------	------
6/8–12/47	41.2	111.9	4800	0.9	1.8	0.8	1.6
10/10–15/47	34.3	110.2	6500	2.4	4.1	2.0	3.6
11/13–21/50	36.5	118.5	9500	5.5	16.3	3.9	12.9
8/19–20/54	33.4	111.4	2600	5.0	5.3	4.0	4.1

APPENDIX B

GLOSSARY

adiabatic—Applies to changes of air temperature resulting only from compression or expansion accompanying an increase or decrease of atmospheric pressure.

annual series—A series made up of the annual maximum events for a particular duration. For example, the annual maximum daily rainfall is the largest of the 365 observations of daily rainfall.

anticyclone (or High)—An area of relatively high atmospheric pressure with closed isobars, the pressure gradient being directed from the center so that the wind blows spirally outward in a clockwise direction in the Northern Hemisphere.

bucket survey—A popular colloquial name given to surveys by meteorologists and engineers for supplementing official rain-gage data on severe storms. So named because many of the measurements obtained by the survey crews are of rainfall caught in exposed buckets.

cold front—The line of discontinuity at the earth's surface, or a horizontal plane aloft, where the forward edge of an advancing current of cold air is displacing a warmer air mass.

condensation—The process by which vapor becomes a liquid or a solid.

condensation level—Properly, the lifting condensation level; i.e., the level at which air becomes saturated when lifted adiabatically.

condensation nuclei—Particles upon which condensation of water begins in the free atmosphere.

condensation temperature—The temperature at which saturation would be reached if the air were cooled adiabatically without the removal or addition of moisture. Assuming the presence of sufficient condensation nuclei, condensation in the air will begin at this temperature.

conduction—The transfer of heat within and through a substance by means of internal molecular activity without any motion of the substance.

convection—The process whereby a circulation is created and maintained within a layer of the atmosphere, due either to surface heating of the bottom of the layer or to cooling at its top, and consisting in the sinking of relatively heavy air and forcing up of relatively light air.

convective condensation level—The level to which air, if heated sufficiently from below, will adiabatically rise before it becomes saturated.

convective instability—The condition of an unsaturated layer of air having a stratification of moisture such that, upon being lifted, the lower part of the layer becomes saturated first, and hence cools thereafter at a slower rate than does the upper, drier portion, until the lapse rate become equal to the pseudoadiabatic, and any further lifting results in instability.

convective thunderstorms—Thunderstorms caused by the adiabatic cooling of moist air which rises by reason of the vertical thermal or convective instability of the atmosphere.

convergence—A net horizontal inflow of air into a given space. The resulting accumulation of mass is limited by vertical motion. Hence, if there is convergent flow at the ground, there must be an upward vertical motion. If there is horizontal convergence in any upper layer, there must be upward and/or downward motion.

correlation coefficient—A number, between the limiting values of +1 and —1, which expresses the degree of linear relationship between two variables. A value near zero indicates very little relationship.

cyclone (or Low)—A circular or nearly circular area of relatively low atmospheric pressure with closed isobars, the pressure gradient being directed toward the center so that the wind blows spirally inward in a counterclockwise direction in the Northern Hemisphere.

dewpoint—The temperature to which air must be cooled, at constant pressure and constant water-vapor content, in order for saturation to occur.

dry adiabatic lapse rate—The rate at which dry air warms or cools during adiabatic descent and ascent, respectively; i.e., about 5.4 F° per 1,000 ft.

extratropical cyclone, Low, or storm—A low-pressure area of middle and higher latitudes born of the conflict in the middle latitudes between southward-flowing polar air and northward-moving tropical air.

front—The line of intersection of a frontal surface with a more or less horizontal surface; e.g., the earth's surface.

frontal surface—The surface of separation between two different and adjacent air masses.

frontal zone—The region of transition between two air masses.

general circulation—The average or prevailing large-scale movements of the atmosphere as represented by the yearly means of long records of surface and upper-air wind velocities, which fit into the average annual pressure patterns.

gradient—The rate of decrease in the value of any quantity with distance in any given direction.

Gumbel method—A method of analyzing extreme values applied to hydrologic data by Gumbel. The probability of occurrence of a value in the annual series equal to or less than x is given by $F(x)=\exp(-e^{-y})$, where $y=a(x-u)$. For a long record, a and u may be estimated by $1/a=0.779697s$ and $u=\bar{x}-0.45005s$, $\bar{x}$ being the sample mean and s, the standard deviation.

Gumbel paper—Special probability paper constructed for the analysis of extreme values. If the data plot close to a straight line, the Gumbel theoretical solution is considered applicable.

heat of condensation (or of vaporization)—The amount of heat given up by a unit mass of a substance when passing from the vapor to the liquid state; or, the amount of heat absorbed by a unit mass of a substance when passing from the liquid to the vapor state; both at constant temperature.

heat of fusion (or of freezing)—The amount of heat required to convert a unit mass of a solid to its liquid state, at constant temperature; or, the amount of heat given up by a unit mass of a liquid to the solid state, at constant temperature.

High (or high pressure area)—(See "anticyclone").

hurricane—A cyclone, or Low, of tropical origin with winds exceeding 74 m.p.h.

insolation—Solar radiation received, as by the earth.

instability—A state in which the vertical distribution of temperature is such that a particle, if given either an upward or downward impulse, will tend to move away with increasing speed from its original level.

isobar—A line connecting points having the same barometric pressure.

isoline—A line connecting points having the same value of a given element.

isotherm—A line connecting points having the same temperature.

jet (or jet stream)—A relatively narrow high-speed wind current found at high altitudes.

lapse (or lapse rate)—The rate of change of any meteorological element with height in the free atmosphere, but usually referring to temperature.

latent heat—The heat absorbed by a substance, without change in temperature, while passing from a liquid to a vapor state, or from a solid to a liquid, and released in the reverse change of state.

lifting condensation level—(See "condensation level").

Low (or low pressure area)—(See "cyclone").

mean (or average)—The sum of a set of individual values of any quantity divided by the number of values in the set.

median—The value of the middle term of a series if the number of terms is odd, or the average of the two middle terms if the number of terms is even.

millibar—A subunit of pressure equal to a force of 1000 dynes/cm.^{2}.
(A dyne is a unit of force which, acting upon a free mass of 1 gm., would impart to it an acceleration of 1 cm./sec.^{2}). The mean sea level pressure for the standard atmosphere is 1013 mb.

moisture charge (or moisture supply)—The water-vapor content of a column or layer of air.

occlusion—The overtaking of the warm front by the cold front in a low-pressure system and the resultant front.

orographic precipitation—Precipitation resulting when moist air is forced to rise by mountain ranges or other land formations lying across the path of the wind.

polar continental air—An air mass formed in the northern regions of North America and characterized by: (1) relatively low surface temperature, (2) stability in the lower layers, (3) low moisture content, and (4) shallow vertical extent.

polar maritime air—An air mass originating over polar seas which, while moving equatorward over warmer waters, undergoes increasing temperature, moisture content, and instability.

precipitable water—The total amount of water vapor in a layer of air expressed in terms of the depth of liquid water if all the vapor were liquefied. The term is a misnomer since no natural process removes all moisture from any layer of air.

precipitation—A general term for all forms of falling moisture, liquid or solid. In hydrology, precipitation refers only to that moisture actually reaching the ground.

precipitation area—A region over which precipitation is falling or has fallen.

probable maximum precipitation—The highest rainfall intensity meteorologically possible for a given duration over a specific area.

pseudoadiabatic lapse rate—The rate at which saturated air cools during adiabatic ascent if its moisture is precipitated immediately upon condensation.

quasi-stationary—Almost or appearing stationary (applied to fronts).

radiation—The process by which energy is transferred through space or through a material medium from one place to another in the form of electromagnetic waves.

radiosonde—A balloon-carried instrument with elements for determining the pressure, temperature, and relative humidity of the upper air, and with radio units for automatically transmitting the measurements to ground stations.

reduced variate—A mathematical function of the return period, corrected for length of record.

relative humidity—The ratio of the amount of water vapor in a given space to the amount which that volume would contain if it were in a state of saturation.

return period—The average number of years within which the magnitude of a given event will be equaled or exceeded.

ridge (of high pressure)—An elongated extension of a high-pressure center.

saturation—The condition in which the pressure exerted by water vapor is equal to the maximum vapor pressure possible at the prevailing temperature.

solar radiation—Radiation received directly from the sun.

spill-over—Precipitation formed over the windward side of a mountain range but falling to the ground on the lee side.

standard deviation—A measure of the extent of the dispersion of the values of a series about their average value. It is computed by taking the square root of the arithmetic mean of the squares of all the individual deviations from the arithmetic mean of the group.

standard error of estimate (or standard error)—The error that would be exceeded about one-third of the time.

surface tension—A phenomenon peculiar to the surface of liquids, in which the surface molecules seem to have a greater cohesion for one another than do the molecules in the body of the liquid, so that the surface acts like a stretched elastic film.

synoptic—Designating or pertaining to the branch of meteorology which deals with the analysis of observations taken at various points in a relatively large region at or near the same time.

thermal Low—A low-pressure center resulting from pronounced heating of the soil surface.

tropical continental air—An air mass originating over a land area in low latitudes and characterized by extreme dryness and warmth and instability.

tropical cyclone—A nearly circular, relatively intense, low-pressure area of tropical origin having closed isobars. (See "hurricane").

tropical disturbance—A relatively weak low-pressure area of tropical origin.

tropical maritime air—An air mass which originates over the relatively warm tropical seas and is therefore warm and moist.

trough (of low pressure)—An elongated extension of relatively low pressure extending from a Low center.

vapor pressure—The partial pressure of the water vapor in the atmosphere.

warm front—The line of discontinuity along the earth's surface, or a horizontal plane aloft, where the forward edge of an advancing current of relatively warm air is replacing a retreating colder air mass.

wave—A propagated disturbance in the form of a localized deformation of a front.

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