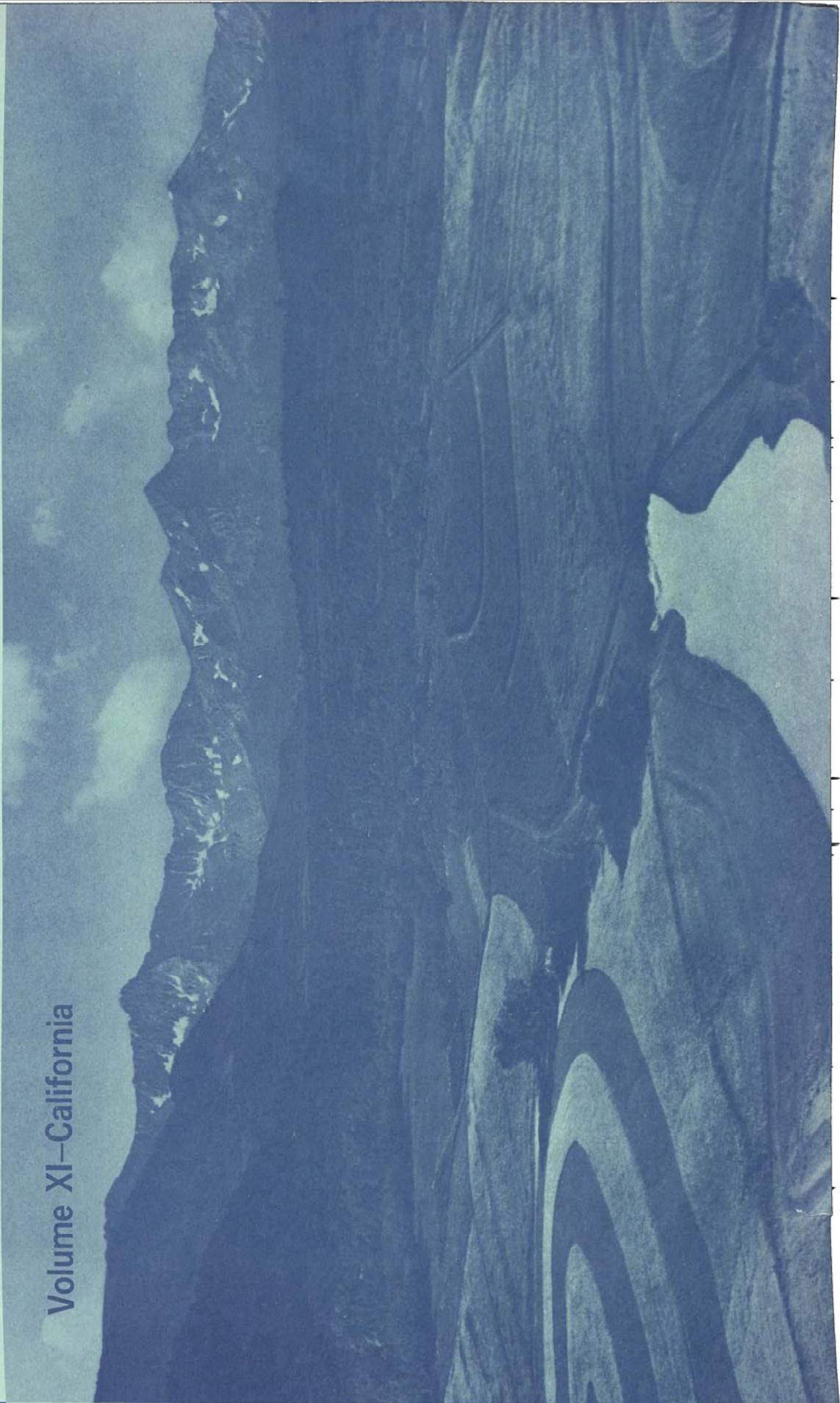


NOAA ATLAS 2

Precipitation-Frequency Atlas of the Western United States

J. F. Miller, R. H. Frederick, and R. J. Tracey

Volume XI—California



A UNITED STATES
DEPARTMENT OF
COMMERCE
PUBLICATION



U.S. DEPARTMENT
OF COMMERCE
National Oceanic
and Atmospheric
Administration
National Weather
Service
Silver Spring, Md.
1973

NOAA ATLAS 2

Precipitation-Frequency Atlas of the Western United States

J. F. Miller, R. H. Frederick, and R. J. Tracy

Volume XI—California



U.S. DEPARTMENT OF COMMERCE
Frederick B. Dent, Secretary

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
Robert M. White, Administrator

NATIONAL WEATHER SERVICE
George P. Cressman, Director
Silver Spring, Maryland—1973

Prepared for U.S. Department of Agriculture, Soil Conservation Service, Engineering Division

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20540 • Price \$10.00
Stock Number 017-09145

NOAA ATLAS 2

Precipitation Frequency Atlas of the
Western United States

- Volume I. Montana
- Volume II. Wyoming
- Volume III. Colorado
- Volume IV. New Mexico
- Volume V. Idaho
- Volume VI. Utah
- Volume VII. Nevada
- Volume VIII. Arizona
- Volume IX. Washington
- Volume X. Oregon
- Volume XI. California

UDC 551.377.36(084.4)(794)

551.5 Meteorology
.377 Precipitation
.36 Frequencies
(084.4) Atlas
(794) California

Contents

| List of Illustrations | | | |
|---|------|---|----|
| | Page | | |
| Abstract | iv | | |
| Preface | iv | | |
| Introduction | 1 | | |
| Objective | 1 | | |
| Historical review | 1 | | |
| Approach | 1 | | |
| Analysis | 1 | | |
| Basic data | 1 | | |
| Frequency analysis | 3 | | |
| Isoplival maps | 4 | | |
| Interpretation of results | 13 | | |
| Season of occurrence | 13 | | |
| Within versus among storms | 13 | | |
| Point probabilities | 13 | | |
| Area analysis | 13 | | |
| Importance of snow in estimating frequency values | 14 | | |
| Reliability of results | 14 | | |
| California | 15 | | |
| Discussion of maps | 15 | | |
| Procedures for estimating values for durations other than 6 and 24 hr | 15 | | |
| Illustration of use of precipitation-frequency maps, diagrams, and equations | 16 | | |
| References | 19 | | |
| Figure 1. Relation between 2-yr 1,440-min precipitation and 2-yr observation-day precipitation | 2 | Figure 16. Precipitation depth-duration diagram (6- to 24-hr) | 18 |
| Figure 2. Test of 2-yr 24-hr precipitation values from short- and long-record stations for the State of Washington | 2 | Figure 17. Illustration of use of precipitation-frequency diagrams using values from precipitation-frequency maps and relations | 18 |
| Figure 3. Geographic distribution of stations with recording gages. Symbols indicate total length of record available | 4 | Figure 18. Regions used to develop equations for 2- and 100-yr 1-hr values for northern half of California | 21 |
| Figure 4. Geographic distribution of stations with nonrecording gages. Symbols indicate total length of record available | 5 | Figure 19. Regions used to develop equations for 2- and 100-yr 1-hr values for southern half of California | 23 |
| Figure 5. Relation between annual and partial-duration series | 6 | Figure 20. 2-yr 6-hr precipitation for northern half of California | 25 |
| Figure 6. Precipitation depth versus return period for partial-duration series | 6 | Figure 21. 5-yr 6-hr precipitation for northern half of California | 27 |
| Figure 7. Principal paths of moisture inflow in the western United States for storms producing large precipitation amounts. Hatched areas are major orographic barriers | 6 | Figure 22. 10-yr 6-hr precipitation for northern half of California | 29 |
| Figure 8. Regions used to develop statistical parameters for interpolation of 2-yr 24-hr precipitation values | 7 | Figure 23. 25-yr 6-hr precipitation for northern half of California | 31 |
| Figure 9. Regions used to develop statistical parameters for interpolation of 100-yr 24-hr precipitation values | 10 | Figure 24. 30-yr 6-hr precipitation for northern half of California | 33 |
| Figure 10. Regions used to develop statistical parameters for interpolation of 2-yr and 100-yr 6-hr precipitation values | 11 | Figure 25. 100-yr 6-hr precipitation for northern half of California | 35 |
| Figure 11. Geographic distribution of errors for equation used to interpolate 2-yr 24-hr precipitation values for the Eel River Basin, Calif. | 12 | Figure 26. 2-yr 24-hr precipitation for northern half of California | 37 |
| Figure 12. Geographic distribution of errors for equation used to interpolate 2-yr 24-hr precipitation values for the Big Horn River Basin, Wyo. | 12 | Figure 27. 5-yr 24-hr precipitation for northern half of California | 39 |
| Figure 13. Examples of isohyetal patterns used to develop: (A) storm-centered depth-area curves and (B) geographically fixed depth-area curves | 13 | Figure 28. 10-yr 24-hr precipitation for northern half of California | 41 |
| Figure 14. Depth-area curves | 13 | Figure 29. 25-yr 24-hr precipitation for northern half of California | 43 |
| Figure 15. Precipitation depth-duration diagram (1- to 6-hr) | 17 | Figure 30. 30-yr 24-hr precipitation for northern half of California | 45 |
| | | Figure 31. 100-yr 24-hr precipitation for northern half of California | 47 |
| | | Figure 32. 2-yr 6-hr precipitation for southern half of California | 49 |
| | | Figure 33. 5-yr 6-hr precipitation for southern half of California | 51 |
| | | Figure 34. 10-yr 6-hr precipitation for southern half of California | 53 |
| | | Figure 35. 25-yr 6-hr precipitation for southern half of California | 55 |
| | | Figure 36. 50-yr 6-hr precipitation for southern half of California | 57 |
| | | Figure 37. 100-yr 6-hr precipitation for southern half of California | 59 |
| | | Figure 38. 2-yr 24-hr precipitation for southern half of California | 61 |
| | | Figure 39. 5-yr 24-hr precipitation for southern half of California | 63 |
| | | Figure 40. 10-yr 24-hr precipitation for southern half of California | 65 |
| | | Figure 41. 25-yr 24-hr precipitation for southern half of California | 67 |
| | | Figure 42. 50-yr 24-hr precipitation for southern half of California | 69 |
| | | Figure 43. 100-yr 24-hr precipitation for southern half of California | 71 |

Abstract

Preface

List of Tables

| | Page |
|--|------|
| Table 1. Number of precipitation stations by length and type of record in each Western State | 3 |
| Table 2. Empirical factors for converting partial-duration series to annual series | 3 |
| Table 3. Statistical parameters for relations used for interstation interpolation of 2-yr 24-hr precipitation values | 6 |
| Table 4. Factors most useful in relations for interstation interpolation for 2-yr 24-hr precipitation values | 8 |
| Table 5. Statistical parameters for relations used for interstation interpolation of 100-yr 24-hr precipitation values | 9 |
| Table 6. Factors most useful in relations for interstation interpolation for 100-yr 24-hr precipitation values | 9 |
| Table 7. Statistical parameters for relations used for interstation interpolation of 2-yr 6-hr precipitation values | 9 |
| Table 8. Statistical parameters for relations used for interstation interpolation of 100-yr 6-hr precipitation values | 12 |
| Table 9. Factors most useful in relations for interstation interpolation of 2-yr 6-hr precipitation values | 12 |
| Table 10. Factors most useful in relations for interstation interpolation for 100-yr 6-hr precipitation values | 12 |
| Table 11. Equations for estimating 1-hr values in California with statistical parameters for each equation | 16 |
| Table 12. Adjustment factors to obtain <i>p</i> -rain estimates from 1-hr values | 17 |
| Table 13. Precipitation data for depth-frequency atlas computation point 34°00' N., 117°00' W. | 17 |

Each volume of this Atlas contains precipitation-frequency maps for 6- and 24-hr durations for return periods from 2 to 100 yrs for one of the 11 western states (west of about 103° W.). Also included are methods and nomograms for estimating values for durations other than 6 and 24 hrs. This new series of maps differs from previous publications through greater attention to the relation between topography and precipitation-frequency values. This relation is studied objectively through the use of multiple regression screening techniques which develop equations used to assist in interpolating values between stations in regions of sparse data. The maps were drawn on a scale of 1:1,000,000 and reduced to 1:2,000,000 for publication.

In addition to the maps, each volume includes a historical review of precipitation-frequency studies, a discussion of the data handling and analysis methods, a section on the use and interpretation of the maps, and a section outlining information pertinent to the precipitation-frequency regime in the individual state. This state section includes a discussion of the importance of snow in the precipitation-frequency analysis and formulas and nomograms for obtaining values for 1-, 2-, 3-, and 12-hr durations.

Previous precipitation-frequency studies for the 11 western states have considered topography in only a general sense despite the numerous mountain ranges present. As a result, variation in precipitation-frequency values is greater than was portrayed in these studies. In this Atlas, the relation between precipitation-frequency values and topography has been considered both objectively and subjectively.

This work has been supported and financed by the Soil Conservation Service, Department of Agriculture, to provide material for use in developing planning and design criteria for the Watershed Protection and Flood Prevention program (P.L. 566, 83d Congress and as amended).

Each volume of the Atlas can be considered to consist of three parts. The first part contains several sections giving a historical review of the field, a discussion of the approach and methods used in the development of the precipitation-frequency maps, and a discussion of how to interpret and use the maps. This section outlines the general background information and is applicable to all states. The second part of the Atlas contains a discussion of items pertinent to the individual state. Included in this section are methods and nomograms designed to estimate precipitation-frequency values for durations other than 6 and 24 hrs. These procedures were developed for broad geographic regions; the ones applicable to a particular state are included in the appropriate volume. The last part contains the maps for the 6- and 24-hr durations for return periods of 2, 5, 10, 25, 50, and 100 yrs.

Coordination with the Soil Conservation Service was maintained through Kenneth M. Kent, Chief, Hydrology Branch, Engineering Division, and through his successor, Robert E. Ralston. The work was done in the Special Studies Branch, Water Management Information Division, Office of Hydrology, National Weather Service, Hugo V. Goodyear, Chief of the Branch (since retired) made many contributions to the preparation of the final manuscript. Overall direction and guidance was furnished by William E. Hiatt, Associate Director (Hydrology), National Weather Service, his successor, Max A. Kohler, and Joseph Paulhus, former Chief, Water Management Information Division. Data tabulations, computations and many other assisting duties were done by the Branch meteorological technicians.

Introduction

Objective

Although generalized maps of precipitation-frequency values have been available for many years, the construction of isopleth lines in mountainous regions has been done considering topography and its effect on precipitation in a general sense only. Investigations for this Atlas were undertaken to depict more accurately variations in the precipitation-frequency regime in mountainous regions of the 11 continental states west of approximately 103° W. These investigations are intended to provide material for use in developing planning and design criteria for the Watershed Protection and Flood Prevention programs.

Primary emphasis has been placed on developing generalized maps for precipitation of 6- and 24-hr duration and for return periods of 2 to 100 yrs. Procedures also have been developed to estimate values for 1-hr duration. Values for other durations can be estimated from the 1-, 6-, and 24-hr duration values.

Historical Review

The first generalized study of the precipitation-frequency regime for the United States was prepared in the early 1930's by David L. Yarnell (1935). Yarnell's publication contains a series of generalized rainfall maps for durations of 5 min to 24 hrs for return periods of 2 to 100 yrs. Yarnell's study served as a basic source of frequency data for economic and engineering design until the middle 1950's. The maps were based on data from about 200 first-order Weather Bureau stations equipped with recording precipitation gauges. In 1940, about 5 yrs after Yarnell's study was published, a hydrologic network of recording gauges, supported largely by the U.S. Army Corps of Engineers, was installed. This was done to supplement the Weather Bureau recording-gauge network and the network of a relatively large number of nonrecording gauges maintained by private individuals in cooperation with the Weather Bureau, for a long period of years. The additional recording gauges have subsequently increased the amount of short-duration (1- to 24-hr) precipitation data by a factor of about 20.

Weather Bureau Technical Paper No. 24, published in two parts (U.S. Weather Bureau 1953-54), was prepared for the Corps of Engineers, in connection with its military construction program. This Technical Paper contained the results of the first investigation of precipitation-frequency information for an extensive region of the increased hydrologic data network. The results showed the importance of the additional data for defining the short-duration rainfall-frequency regime in a mountainous region of the western United States. In many instances, the differences between the values given in *Technical Paper No. 24* and those given by Yarnell reach a factor of three, with Yarnell's figures generally higher. Results from these two studies in the United States were then used to prepare similar reports for the coastal regions of North Africa (U.S. Weather Bureau 1954b) and for several Arctic regions (U.S. Weather Bureau 1955a) where recording-gauge data were lacking. These reports were also prepared in cooperation with the Corps of Engineers to support its military construction program.

In 1955, the Weather Bureau and the Soil Conservation Service began a cooperative effort to define the depth-area-duration precipitation-frequency regime in the entire United States. *Weather Bureau Technical Paper No. 25* (U.S. Weather Bureau 1955b), partly a byproduct of previous work done for the Corps of Engi-

Approach

The approach used for this Atlas is basically the same as that used for *Technical Paper No. 40*, in which simplified relations between duration and return period were used to determine numerous combinations of return periods and durations from several generalized key maps. For this Atlas, relations from several general precipitation-frequency values and meteorologic and topographic factors at observing sites. These were used to aid in interpolating values between stations on the key maps.

The key maps developed in this study were for 2- and 100-yr return periods for 6- and 24-hr durations. The initial map developed was for the 2-yr return period for the 24-hr duration. This return period was selected because values for shorter return periods can be estimated with greater reliability than for longer return periods. The 24-hr duration was selected because this permitted use of data from both recording and nonrecording gauges. Also, because an extensive nonrecording-gauge network was established for many years before the recording-gauge network was established in 1940, the period of record available for 24-hr observations is much longer than that for the 6-hr duration. The second map developed was for the 100-yr return period for the 24-hr duration. In the development of this map the advantage of maximum sample size and length of record was retained at the expense of some decrease in reliability of computed values. The 6-hr maps for the 2- and 100-yr return periods followed. For the 6-hr duration, the sample size was materially smaller in both numbers and length of record because only recording-gauge data could be used. After these four maps were completed, values for intermediate return periods were computed for a grid of about 47,000 points, and appropriate maps were prepared.

In previous studies, topography was considered only in a general sense and the isopleths were drawn by interpolating subjectively between the individual stations. In preparing this Atlas, multiple linear regression equations were developed for each of many regions of the western United States as an aid to estimating the precipitation-frequency values at each of about 47,000 grid points. These equations related topographic and climatic factors to the variations in the precipitation-frequency values. Isopleths were smoothed subjectively between values in adjoining regions. The subjective smoothing was based upon experience in analyzing precipitation-frequency maps; the amount of smoothing was rarely greater than the standard error of estimate for the equations in the adjoining regions.

Analysis

Basic Data

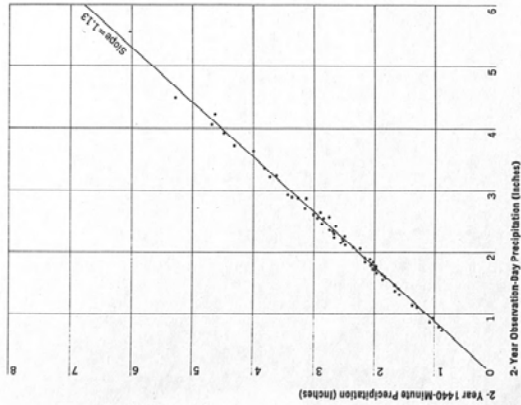
Station location. Frequency analysis of precipitation data requires a relatively long and stable station record. In analyzing a mean annual or a seasonal precipitation map, it is possible to use double-mass curve analysis to evaluate the effects of changes in station location or exposure. Within limits, the effects of differing locations on the annual precipitation values can be eliminated by use of relations determined from the double-mass curve analysis (Weiss and Wilson 1953). However, no technique for evaluation and modification of a series of extreme precipitation values has been developed. Therefore, it was necessary to ensure that the data used in this Atlas represented, as nearly as possible, observations taken from a single location.

Official records of station locations (latitude, longitude, and elevation) were examined to determine physical moves. The criterion used adopted that if a move at any station changed the elevation 100 ft or more or changed the horizontal location 5 mi or more, its data were treated as though they came from separate stations. In some cases, a station retained the same name but investigation indicated that it had been moved beyond acceptable limits. In such cases, the records for the station were terminated and new records were started. In other cases, published sources indicated location changes beyond acceptable limits, but subsequent inspection of records indicated these changes were corrections to reported values of elevation, latitude, or longitude rather than actual physical moves. Thus, the observations for the station actually were continuous at one location. Occasionally, a lesser move resulted in a significant difference in exposure, such as from the windward to the lee side of a mountain range. Data from stations such as these also were treated as data from separate stations.

Types of data. The primary data used in this Atlas can be divided into two categories. First, there are data from recording gauges; these data are published for clock-hour intervals. These data were processed to obtain maximum 6- and 24-consecutive clock-hour amounts for each month of record. The time interval selected did not have to start at a particular hour; for example, the 6-hr interval might be from 1 to 7 a.m. or from 3 to 9 p.m.; the 24-hr interval might be from 4 a.m. on one day to 4 a.m. on the next following day, or from 2 p.m. on one day to 2 p.m. on the next. Second, there is the large amount of data from nonrecording gauges. At these gauges, observations are usually made once each day at a given time for each station. At observation times, the amount of precipitation that fell in the preceding 24-hr interval is measured; this precipitation may have fallen during any part or all of the 24-hr period. These data are commonly referred to as observation-day amounts.

A subset of data in the first category is the recording-gauge data from the long-record first-order Weather Bureau (now National Weather Service) stations. There are approximately 200 such stations in the entire country (about 50 in the western United States). Maximum values for each year of record from these stations have been tabulated for the various durations to the nearest minute. The maximum 6-hr amount recorded each year is for a period of 360 consecutive minutes, regardless of the time beginning; for example, such a period might begin at 2:03 p.m. or at 3:59 p.m. Similarly, data for the 24-hr duration are for a 1,440-min period. These amounts are commonly referred to as 6-minute amounts.

Figure 1. Relation between 2-yr 1,440-min precipitation and 2-yr observation-day precipitation.



Fixed- versus true-interval precipitation values. The continuous clock-hour and observation-day data from most stations are available for intervals fixed by arbitrary clock intervals. Because the time of occurrence of precipitation is a random phenomenon, straddling often occurs; for example, part of the maximum precipitation may start in one time interval and end in the succeeding time interval. Skoldon does maximum precipitation for a specified duration occur within a mandatory measurement interval. For this reason, it was necessary to use relations between fixed-time intervals (or actual occurrence) and the 360- and 1,440-min periods to make maximum use of available data.

These relations have been investigated in previous studies (U.S. Weather Bureau 1954a, 1956, 1957-60). It was found that on the average 1.13 times a statistical value for a particular return period, based on a series of annual maximum observation-day (fixed-interval) amounts, was equivalent to a statistical value for the same return period obtained from a series of 1,440-min (true-interval) values. The ratio of statistical values computed from a series of six consecutive clock-hour measurements to those amounts to those from 1,440-min observations is 1.02; a similar ratio of statistical values computed from 24 consecutive clock-hour amounts to those from 1,440-min values is 1.01.

These ratios (for example, n -year 1,440-min precipitation equals 1.13 times n -year observation-day precipitation) are not built on a causal relation. They are average index ratios because the distributions of observation-day, n -hour, and n -minute precipitation are irregular and unpredictable. For example, the annual maxima of the two series for the same year do not necessarily come from the same storm. Graphical comparison of the values for the 2-yr return period based on observation-day and 1,440-min precipitation data is shown in figure 1.

The frequency and amount of straddling that occur can be investigated on probability considerations as well as empirically. The time axis can be represented by a straight line separated into uniform time intervals by an evenly spaced series of points. These intervals can represent individual hours, 6- or 24-hr periods, an observation day, and so forth. The maximum precipitation for any duration can be assumed to occur at a uniform time interval exactly equal to one of the fixed intervals, but without regard to the location of the fixed intervals. This time interval may fall at random with respect to the fixed intervals and will, in general, overlap two adjacent intervals. Using probability theory, Weils (1964) confirmed the empirical values used.

Data sources. The primary data sources used were *Climatological Data for the United States by Stations* (National Climatic Center 1897-1970) and *Hourly Precipitation Data* (National Climatic Center 1940-70). In California, it was possible to increase the data sample 15 to 20 percent by using unpublished data from gauges maintained by the State, local agencies, private corporations, individuals (California, Department of Water Resources 1906-69). Published data are usually of high quality because of periodic checks of observing sites and observation techniques and the quality-control procedures used in the publication process. The quality of unpublished data must be checked by a review of the inspection of unpublished data organization maintaining the gauges and by a careful screening of the data.

Length and period of record. In preparing generalized maps of precipitation-frequency values, a uniform period of record several times the length of the return period desired and computed at a relatively dense network of stations (or sampling all data and topographic extremes) is the ideal. In practical work, compromises are necessary.

The use of a nonuniform record period, especially when the period is short, may result in unrealistic relations between stations. For instance, if data taken during a short-record period at one station were taken during a relatively dry period, while data from the neighboring station were taken during a relatively wet period, the interstation relation would not be valid. Because the objective of this investigation is to define the geographic variation in mountainous regions, it is desirable to minimize other causes of variation. Use of a standard base period would minimize the above annual precipitation maps and also can be applied to the preparation of precipitation-frequency maps for shorter return periods.

Determination of precipitation-frequency values is usually based upon the longest record available. These values are assumed to be reasonably representative of the values that would be obtained if the entire record were known. The use of a short-record base period requires testing to determine if the data provide unbiased results representative of values that would be obtained from use of a long-record base period. For most regions covered in this study, the most recent 15-yr period immediately preceding the period when the maps for this Atlas were developed was used to compute precipitation values for the 2-yr return period. At locations with at least 30 years of data, the 2-yr values computed using the base period were compared with the 2-yr values computed using the total record. If the differences between the two series were small and randomly distributed, the 15-yr base period was adopted for all stations. Figure 2 shows the result of such a test for the

24-hr duration values for stations in Washington. The same test was made for the rest of the western states.

In most of California and Nevada, the values computed from the 15-yr base period data showed significant differences and some bias to values based upon the total record. In this region, it was necessary to use values based on the longest record possible for each station in preparation of the 2-yr maps. Stations without data during all or most of the more recent years were identified on the working maps.

To make use of data from the maximum number of stations, data from stations with 10 to 14 years of record were used in preparing the 2-yr maps. Such stations also were suitably identified on the working maps so that the analyst could use judgment in his interpretation of such values.

While a 15-yr record provides data several times the length of the return period for 2-yr maps, it provides only a small fraction of the length of the 100-yr return period. During a 15-yr period, some stations may experience precipitation amounts equivalent to a return period of 50, 100, or more years. However, the probability of having a 100-yr value in any prespecified 15-yr period is only 0.14. Similarly, the probability of not having a true 15-yr return in a given 15-yr period, the probability that a station has received its true 100-yr value is not greatly different from the probability that its neighboring station has not experienced its true 15-yr value. While, admittedly, this would be an extreme case, this example shows the importance of using as long a record as possible when preparing precipitation-frequency maps for long return periods. In this study, records for as long as possible for each station (without violating the 100-ft or 5-mi criterion) were used to compute the 100-yr return period values. The length of record and a confidence band to indicate the range of values likely to be expected at each station were included in the plotting model. With this information, the analyst could more effectively evaluate the reliability of each data point.

Published and unpublished data from approximately 3,300 stations were used in this study. The number of stations grouped by length of record and state are shown in table 1. Many recording gauges were established at sites where nonrecording gauges had been located for many years. In table 1, the first column for each state shows the number of stations with recording-gauge data. The second column for each state shows the total period of record for which observation-day data were available for each of these stations. The total record includes both recording and nonrecording data for the recording-gauge station. (Note: The total number of stations in columns 1 and 2 are equal.) The third column for each state shows the number of stations with nonrecording-gauge data only.

Figure 3 shows the location of the 1,030 recording stations used in this study. The length of record indicated is for the longest available record and includes the period where only a nonrecording gauge may have been located at the particular station. Figure 4 shows the location of the 2,292 nonrecording gauges that, together with the recording gauges, are used to provide data to define the 24-hr isohypetal pattern. A few additional stations with records of less than 10 yrs were used to provide guidance for estimating the precipitation pattern in extremely mountainous regions where no other data were available. Most of the data were for observation days. Empirical adjustments were used to convert statistical analyses of these data to the equivalent of 1,440-min data.

Figure 2. Test of 2-yr 24-hr precipitation values from short- and long-record stations for the State of Washington.

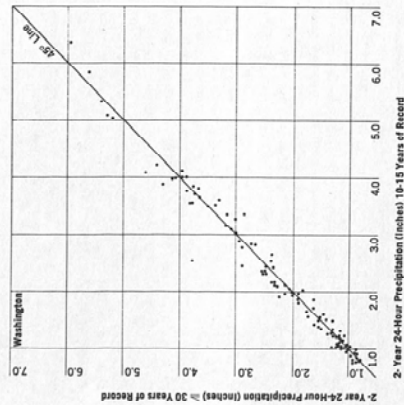


Table 1. Number of precipitation stations by length and type of record in each Western State

| Years of record | State | | | | | | | | | | Total | | | Percent | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|-----------------|---------|----|------------|----|----------|----|------|----|---------|----|---------|----|-------|---------|------------|----|--------|----|--------|----|------------|----|-------|----|---------|----|-----|----|-----|----|-----|-----|------|-----|-------|-----|-------|------|-------|------|-------|---|
| | Arizona | | New Mexico | | Colorado | | Utah | | Wyoming | | Montana | | Idaho | | Washington | | Oregon | | Nevada | | California | | Total | | Percent | | | | | | | | | | | | | | | | | |
| | RGR | TR | RGR | TR | RGR | TR | RGR | TR | RGR | TR | RGR | TR | RGR | TR | RGR | TR | RGR | TR | RGR | TR | RGR | TR | RGR | TR | RGR | TR | NR | TR | NR | TR | NR | TR | | | | | | | | | | |
| 10-14 | 6 | 5 | 38 | 29 | 10 | 33 | 18 | 16 | 28 | 13 | 8 | 20 | 23 | 16 | 31 | 29 | 22 | 78 | 19 | 18 | 10 | 31 | 20 | 19 | 26 | 19 | 33 | 11 | 6 | 10 | 98 | 95 | 209 | 303 | 237 | 509 | 812 | 29.4 | 23.0 | 22.2 | 24.4 | |
| 15-19 | 9 | 8 | 28 | 15 | 11 | 29 | 14 | 11 | 29 | 5 | 3 | 13 | 2 | 1 | 7 | 5 | 3 | 19 | 2 | 1 | 7 | 4 | 2 | 13 | 3 | 3 | 13 | 6 | 5 | 5 | 37 | 35 | 92 | 92 | 85 | 262 | 354 | 8.9 | 8.3 | 11.4 | 10.5 | |
| 20-24 | 23 | 12 | 36 | 34 | 12 | 36 | 52 | 36 | 31 | 18 | 9 | 16 | 31 | 20 | 14 | 59 | 50 | 23 | 3 | 2 | 5 | 15 | 14 | 21 | 15 | 19 | 29 | 6 | 7 | 6 | 47 | 42 | 132 | 363 | 219 | 343 | 646 | 29.4 | 21.3 | 15.0 | 19.4 | |
| 25-29 | 7 | 15 | 15 | 3 | 15 | 3 | 15 | 7 | 7 | 2 | 7 | 2 | 7 | 3 | 8 | 7 | 2 | 14 | 1 | 1 | 11 | 37 | 25 | 8 | 50 | 36 | 30 | 15 | 5 | 4 | 140 | 154 | 224 | 283 | 208 | 224 | 462 | 29.0 | 20.2 | 9.8 | 14.3 | |
| 30-34 | 1 | 19 | 3 | 11 | 3 | 11 | 3 | 7 | 4 | 4 | 4 | 4 | 2 | 1 | 8 | 2 | 9 | 2 | 8 | 0 | 6 | 1 | 19 | 4 | 11 | 4 | 11 | 3 | 3 | 53 | 18 | 43 | 43 | 41 | 173 | 226 | 5.1 | 7.2 | 4.6 | 6.3 | | |
| 35-39 | 2 | 10 | 6 | 11 | 2 | 10 | 2 | 10 | 6 | 2 | 9 | 1 | 6 | 2 | 6 | 2 | 9 | 2 | 9 | 1 | 4 | 4 | 19 | 4 | 11 | 4 | 11 | 1 | 3 | 15 | 18 | 43 | 43 | 41 | 173 | 226 | 5.1 | 7.2 | 4.6 | 6.3 | | |
| 40-44 | 6 | 53 | 4 | 16 | 2 | 16 | 2 | 10 | 6 | 1 | 6 | 1 | 6 | 1 | 8 | 1 | 8 | 1 | 8 | 1 | 4 | 4 | 12 | 4 | 11 | 2 | 10 | 2 | 4 | 0 | 2 | 16 | 0 | 15 | 91 | 212 | 0.0 | 0.3 | 3.1 | 4.0 | | |
| 45-49 | 0 | 1 | 4 | 16 | 4 | 16 | 2 | 10 | 6 | 1 | 6 | 1 | 6 | 1 | 8 | 1 | 8 | 1 | 8 | 1 | 4 | 4 | 12 | 4 | 11 | 2 | 10 | 2 | 4 | 0 | 2 | 16 | 0 | 15 | 91 | 212 | 0.0 | 0.3 | 3.1 | 4.0 | | |
| 50-54 | 1 | 1 | 5 | 13 | 3 | 13 | 4 | 12 | 2 | 13 | 2 | 13 | 2 | 5 | 8 | 1 | 11 | 1 | 11 | 1 | 5 | 1 | 15 | 2 | 10 | 4 | 12 | 2 | 4 | 0 | 3 | 13 | 0 | 29 | 112 | 112 | 0.0 | 0.0 | 28 | 4.9 | | |
| 55-59 | 1 | 4 | 3 | 14 | 2 | 14 | 2 | 7 | 1 | 3 | 5 | 8 | 1 | 3 | 5 | 1 | 11 | 1 | 11 | 1 | 5 | 1 | 15 | 2 | 10 | 4 | 12 | 2 | 4 | 0 | 3 | 13 | 0 | 29 | 112 | 112 | 0.0 | 0.0 | 28 | 4.9 | | |
| 60-64 | 0 | 1 | 3 | 14 | 2 | 14 | 2 | 7 | 1 | 3 | 5 | 8 | 1 | 3 | 5 | 1 | 11 | 1 | 11 | 1 | 5 | 1 | 15 | 2 | 10 | 4 | 12 | 2 | 4 | 0 | 3 | 13 | 0 | 29 | 112 | 112 | 0.0 | 0.0 | 28 | 4.9 | | |
| 65-69 | 0 | 1 | 3 | 14 | 2 | 14 | 2 | 7 | 1 | 3 | 5 | 8 | 1 | 3 | 5 | 1 | 11 | 1 | 11 | 1 | 5 | 1 | 15 | 2 | 10 | 4 | 12 | 2 | 4 | 0 | 3 | 13 | 0 | 29 | 112 | 112 | 0.0 | 0.0 | 28 | 4.9 | | |
| 70-74 | 1 | 1 | 1 | 0 | 4 | 4 | 6 | 3 | 4 | 0 | 5 | 4 | 2 | 2 | 2 | 0 | 5 | 0 | 1 | 0 | 6 | 0 | 1 | 3 | 7 | 8 | 3 | 1 | 3 | 2 | 0 | 8 | 21 | 0 | 15 | 29 | 29 | 0.0 | 15 | 1.3 | 0.9 | |
| 75-79 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | |
| 80-84 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 85-89 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 90-94 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Number: | 38 | | 191 | | 84 | | 178 | | 55 | | 114 | | 93 | | 288 | | 195 | | 40 | | 100 | | 87 | | 156 | | 94 | | 274 | | 180 | | 396 | | 1,030 | | 2,292 | | 3,322 | | 3,322 | |
| Total stns | 225 | | 281 | | 262 | | 346 | | 170 | | 114 | | 288 | | 195 | | 288 | | 140 | | 100 | | 243 | | 243 | | 274 | | 180 | | 87 | | 49 | | 1,202 | | 806 | | 3,322 | | 3,322 | |
| Percent: | 3.7 | | 8.3 | | 8.2 | | 4.9 | | 5.4 | | 5.0 | | 9.0 | | 8.5 | | 8.5 | | 3.9 | | 4.4 | | 8.4 | | 6.8 | | 9.1 | | 8.2 | | 2.6 | | 36.1 | | 35.1 | | 35.1 | | 35.1 | | | |
| By type | 6.9 | | 8.4 | | 7.9 | | 4.4 | | 5.1 | | 5.0 | | 8.6 | | 8.6 | | 8.6 | | 4.2 | | 4.4 | | 7.3 | | 6.8 | | 8.2 | | 2.6 | | 2.6 | | 36.1 | | 35.1 | | 35.1 | | 35.1 | | | |

Note: RGR = stations having recording-gage record; TR = stations having recording-gage for part of the record; total record includes both recording- and nonrecording-gage record. NR = stations having only nonrecording-gage record.

Data tabulations. The maximum observed 24-hr (and 1- and 6-hr for recording gages) precipitation amount for each month was tabulated for each station. The maximum amount for each year of record was determined from these maximum monthly amounts. In the tabulations, data for some stations were missing or of questionable reliability for all or part of one or more years. For each such case, the data were evaluated individually to obtain the maximum length of record for the station. For instance, if data for a few months were missing, the maximum amount recorded for the remainder of the year was used to determine the maximum yearly amount if it appeared reasonable when compared with other years and with the maxima for that year at surrounding stations. This could result in an underestimation of the accepted amount, but it is felt that such errors are small and of little consequence.

Every effort was made to keep spurious data to a minimum. Reports of unusually large amounts at a station, or of large amounts at one station surrounded by stations reporting little or no precipitation, were examined to determine whether these large amounts were meteorologically reasonable. Cool season data were examined to ascertain if unusually large amounts were depth of snow rather than its water equivalent. However, not all large amounts were examined, nor could conclusive determinations be made regarding all of the large amounts that were examined. It is believed that most of the spurious data have been corrected.

Frequency Analysis

Two types of series. There are two methods of selecting data for analysis of extreme values. The first method produces the annual series. This method selects the largest single event that occurred within each year of record. In the annual series, year may be calendar year, water year, or any other consecutive 12-month period. The limiting factor is that one, and only one, piece of datum is accepted for each year. The second method of selecting data produces the partial-duration series. This method recognizes that large amounts are not calendar-bound and that more than one large event may occur in the time unit used as a year. In a partial-duration series, the largest *N* events are used regardless of how many occur in the same year; the only restriction is that independence of individual events be maintained. The number of events used is at least equal to the number of years of record.

One requirement in the preparation of this Atlas is that the results be expressed in terms of partial-duration frequencies. To avoid the laborious processing of partial-duration data, the annual series data were collected and analyzed and the resulting statistics were transformed to partial-duration statistics.

Conversion factors between annual and partial-duration series. Table 2 gives the empirical factors used to multiply partial-duration series analysis values to obtain the equivalent annual series analysis values. It is based on a sample of about 200 widely scattered first-order Weather Bureau stations. Only about one-fourth of these stations are in the western United States. The factors used in table 2 were taken from *Weather Bureau Technical Paper No. 40*. Reciprocals of these factors were used to convert the statistics of the annual series to those of the partial-duration series.

These relations have also been investigated by Langbein (1949) and Chow (1950) with equivalent results. The quality of the relation between the mean of the partial-duration series and that of the annual series data for 6- and 24-hr durations is shown in figure 5. The means for both series are equivalent to the 2.3-yr return period. Tests for samples of from 10 to 50 yrs of record length indicate that the factors of table 2 are independent of the record length.

| Return period | Conversion factor |
|---------------|-------------------|
| 2-yr | 0.88 |
| 5-yr | 0.96 |
| 10-yr | 0.99 |

Table 2. Empirical factors for converting partial-duration series to annual series

Frequency distribution. The frequency distribution used was the Fisher-Tippett Type I distribution; the fitting procedure was that developed by Gumbel (1958). This distribution and fitting procedure were used by the National Weather Service in previous studies of short-duration precipitation values (U.S. Weather Bureau 1953, 1954a, 1954b, 1955a, 1955b, 1957-60, and 1961). Studies by Hershfield and Kohler (1960) and Hershfield (1962) have demonstrated the applicability of this distribution to precipitation extremes. The distribution was fitted by the method of moments. The 2-yr value measures the first moment, the central tendency of the distribution. The relation of the 2-yr to the 100-yr value is a measure of the second moment, the dispersion of the distribution. The 2-yr and 100-yr precipitation can be used for estimating values for other return periods.

The return-period diagram, figure 5, taken from *Weather Bureau Technical Paper No. 40*, is based on data from National Weather Service stations having long records. The spacing of the vertical lines on the diagram is partly empirical and partly theoretical. From 1- to 10-yr return periods, it is entirely empirical, based on frequency curves drawn through plottings of partial-duration series data. For 20-yr and longer return periods, reliance was placed on the Gumbel procedure for fitting annual series data to the Fisher-Tippett Type I distribution. The transition was smoothed subjectively between the 10- and 20-yr return periods. If

precipitation values for return periods between 2 and 100 yrs are desired. It is necessary to obtain the 2- and 100-yr values from this series of generalized precipitation-frequency maps. These values are then plotted on the appropriate verticals and connected with a straight line. The precipitation values for the intermediate return periods are determined by reading values where the straight line intersects the appropriate verticals. If the rainfall values are then converted to the annual series by applying the factors of table 2 and placed on either Gumbel or log-normal graph paper, the points will very nearly approximate a straight line.

Isopluvial Maps

Methodology. The factors considered to determine the sequence of preparation of the basic isopluvial maps for this series of generalized precipitation-frequency maps were (1) availability of data, (2) reliability of estimates for the return period, and (3) range of durations and return periods. Because of the large amount of data for the 24-hr duration and the relatively small standard error associated with the 2-yr values, a map showing such data was selected for preparation as the basic map for this series. The longest return period of interest, Next, the 2-yr 6-hr and the 100-yr 6-hr precipitation maps were prepared. These four key maps envelop the range of durations and return periods required and provide the data to be used for obtaining values for four intermediate return period maps at each duration.

Development of relations for interpolating precipitation-frequency values. The adequacy of the basic data network for determining precipitation-frequency values varies from place to place within the western United States. The greatest station density occurs along the Pacific coast west of the Cascade and Sierra Nevada Ranges (figs. 3 and 4). The lowest densities are in the intermountain plateau—between the Cascade-Sierra Nevada ranges and the Continental Divide—particularly in Nevada and in the Salmon River Mountains of Idaho. Even within particular regions, the stations are not evenly distributed. Most of the stations are located in the coastal plains, the river valleys, the western portion of the Great Plains, and the lower foothills of the mountains. Relatively few stations are located on steep slopes or on crests of mountains, in sparsely populated areas, or in areas where access is difficult.

It is desirable, therefore, to develop relations that can be used in interpolating precipitation-frequency values between stations in regions where data are relatively scarce. A preferred method is to relate variations in precipitation-frequency directly to variations in topographic factors; this is done when an adequate relation can be developed. The primary advantage of this procedure is that topographic factors can be determined at any point in a region. Topographic maps can be prepared from aerial photographs or surveys, or by other methods that do not require observations taken at a fixed point over a period of time. Among topographic factors frequently considered are: (1) elevation of the station, either the actual elevation or some effective elevation (an average elevation determined along a circle of a given radius around the station); (2) slope of the terrain near the station, both in the small and large scales; (3) distances from both major and minor barriers; (4) distances and directions from moisture sources; and (5) roughness of the terrain in the vicinity of the station.

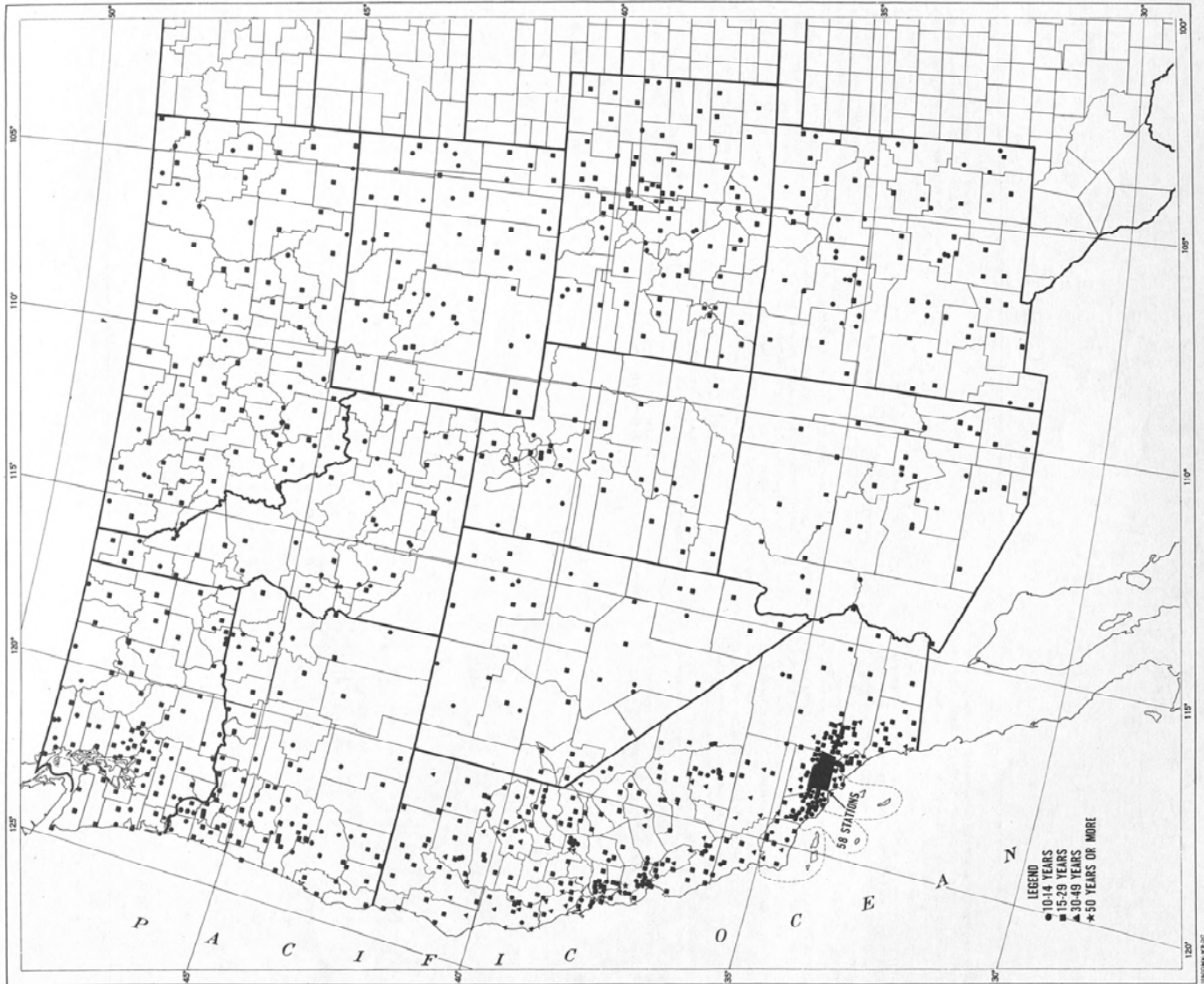


Figure 3. Geographic distribution of stations with recording gages. Symbols indicate road length of record available.

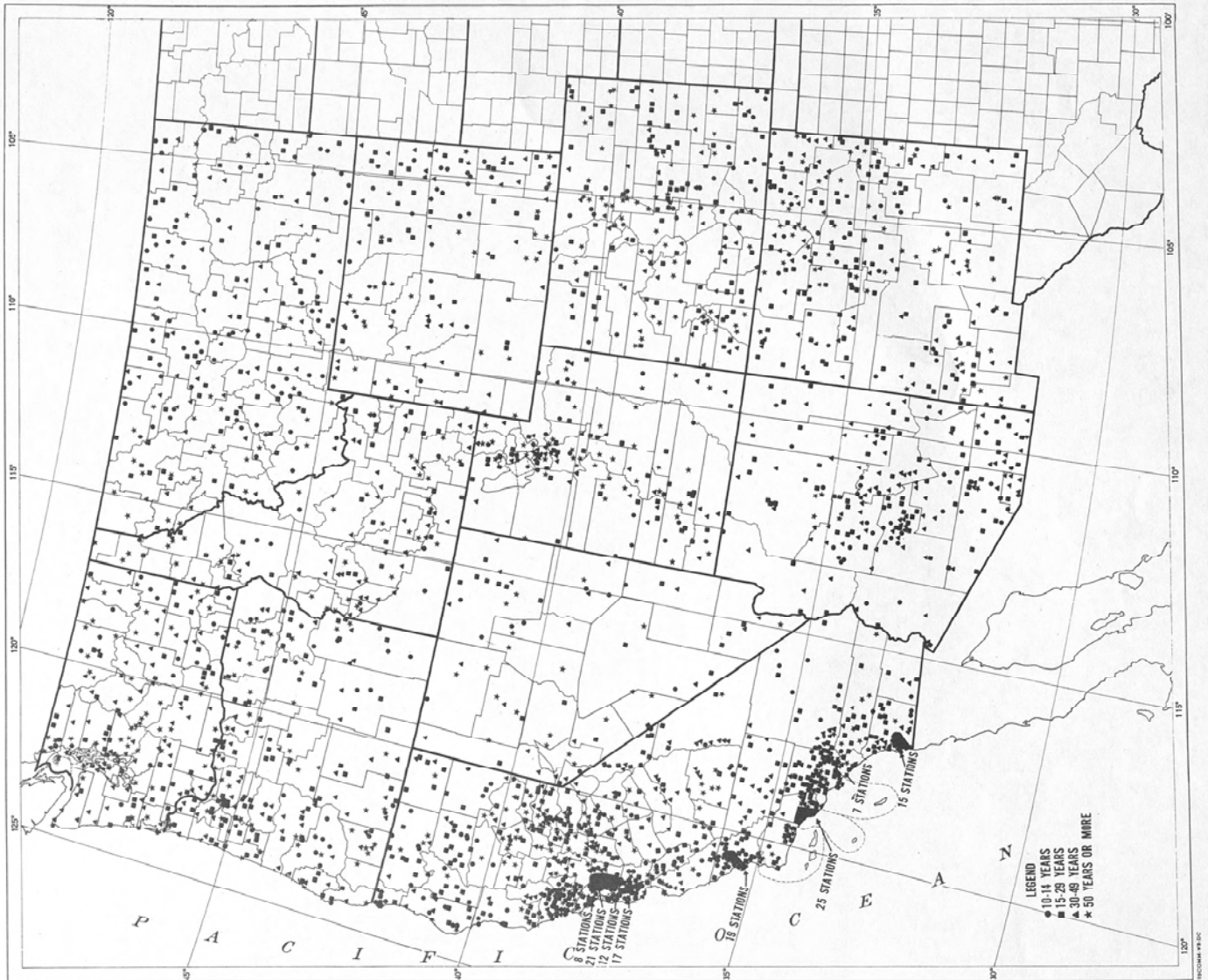


Figure 4. Geographic distribution of stations with nonrecording gages. Symbols indicate total length of record available.

It has not been possible to develop such relations for all regions. Hence, it also was necessary to develop relations that included climatological or meteorological factors. The factors selected for use must be available at locations where precipitation data for durations of between 1 and 24 hrs are available. Otherwise, they would not provide additional information needed for use in interpolating between locations with frequency values. An example of such a factor is normal annual precipitation. In the construction of such a map, data from snow courses, adjusted short records, and storage gages that give weekly, seasonal, or annual accumulations of precipitation can be used. Such records do not yield the short-duration precipitation amounts necessary for this study. Thus, normal annual precipitation data, particularly because it provides greater areal coverage in mountainous regions, might be of definite use in developing the patterns of the precipitation-frequency maps.

Several other meteorologic factors can be used in combination with normal annual precipitation data and topographic factors to interpolate short-duration precipitation-frequency values at intermediate points. Examples of such factors are: (1) number of thunderstorm days, (2) number of days or hours with precipitation above a threshold value, (3) percentage frequencies of various wind directions and speeds, and (4) percentage frequencies of class intervals of relative humidity. Since these factors can be obtained only where there are recording meteorological gages or where there are observers to record the data they do not supplement the available short-duration precipitation-frequency values by providing data at additional sites.

It would have been desirable to develop a single equation, utilizing physiographic factors, to interpolate between locations with short-duration precipitation-frequency values for the western United States. Such an equation could not be developed, so relations for interpolating the precipitation-frequency values were developed for each of several smaller regions considered to be meteorologically homogeneous. The extent of each region was determined from consideration of the weather situations that could be expected to produce large precipitation amounts. Among the questions asked and answered were: What is the source and from what direction does moisture for major storms come and are there major orographic barriers that influence the precipitation process? Figure 7 shows some of the principal paths of moisture inflow for the western United States and the major orographic barriers to such inflow.

The regions selected for their homogeneity normally are river basins or combinations of river basins. The river basins selected were usually bounded by major orographic barriers that significantly influence the precipitation regime. The size of these regions varied, partly because of meteorologic and topographic considerations and partly because of the availability of data. Some regions included more variability in topographic and meteorologic factors than was ideal. Efforts made to reduce the size of the regions were not successful because sample sizes decreased to less than acceptable limits.

After the geographic regions were selected, various topographic factors that could cause variation of precipitation-frequency values within limited regions such as slope, elevation, roughness, and orientation were examined. Individual precipitation-frequency values and exposures around the stations were examined to gain insight into topographic factors that could be im-

Figure 5. Relation between annual and partial-duration series.

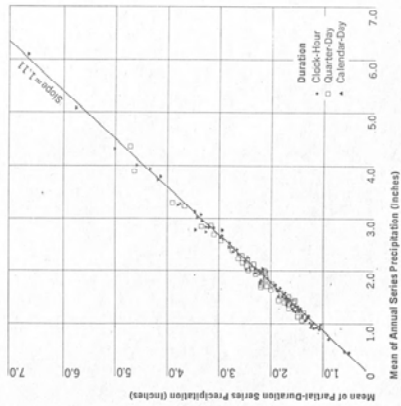
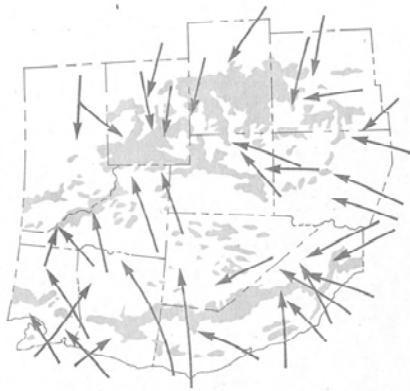


Figure 7. Principal paths of moisture inflow in the western United States for storms producing large precipitation amounts. Toned areas are major orographic barriers.

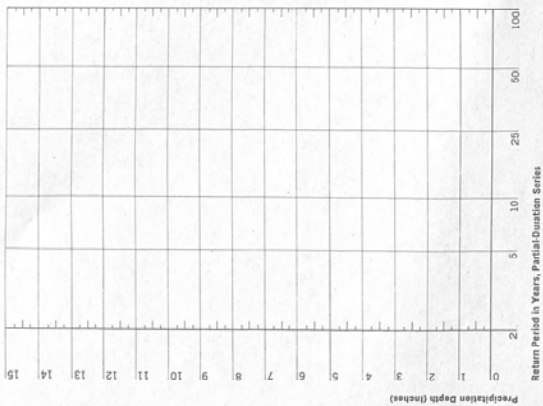


portant. Next, an examination was made of factors that combined topographic and meteorologic considerations, such as distance and direction to moisture sources. Each factor considered was a measure of some physical reality, and each was understandably related to variation in the precipitation-frequency regime.

Finally, various climatological and meteorological factors that could be indexes of variation of the precipitation-frequency values were considered. The procedure used for developing interpolating equations was a multiple-regression screening technique. This process was done by computer using a least-squares technique. The independent variables for as many locations as data were available between 60 and 100. This does not mean that 60 or more completely different factors could be identified. For example, several factors might involve different measures of slope. Moreover, these measures of slope might be over different distances or have different orientations. In each instance, the practice was to permit the computer to select the most critical of the various measures of each factor.

Although the computer program treated each variable as linear during the regression analysis, it was possible through internal comparisons to use logarithm, powers, roots, reciprocals, or combinations of any or all of the factors. The computer program selected the single variable most highly correlated with the precipitation-frequency value under investigation. The next step was to select the variable that, combined with the variable already selected, would explain the greatest variation in the precipitation-frequency values. The third, fourth, fifth, and further variables were selected in a similar manner. The program continued to select

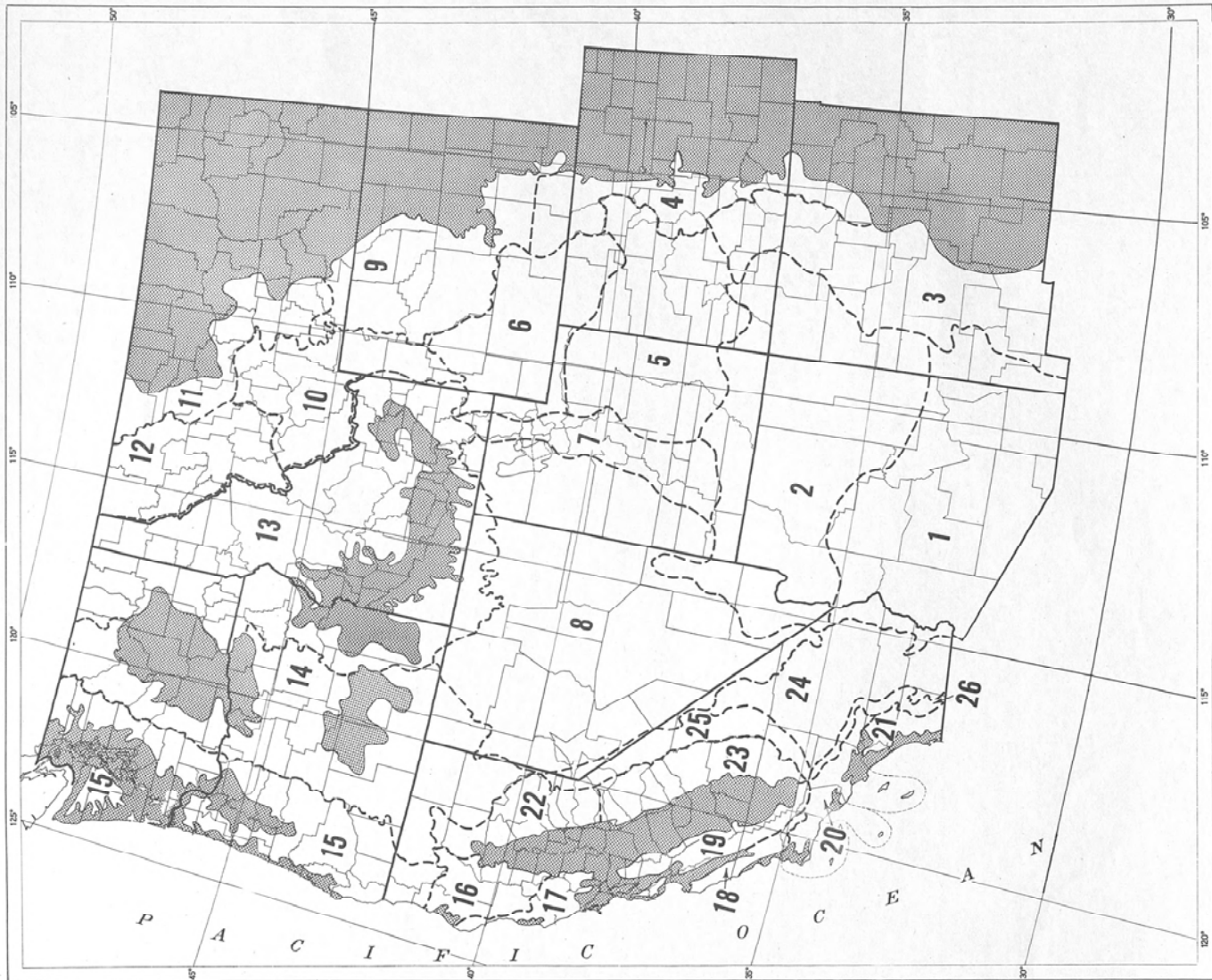
Figure 6. Precipitation depth versus return period for partial-duration series.



| Region of applicability* | Corr. coeff. | No. of stations | Mean of computed sin. values (inches) | Standard error of estimate (inches) |
|--|--------------|-----------------|---------------------------------------|-------------------------------------|
| Gila, Williams, and lower Colorado River Basins (1) | 0.84 | 86 | 1.86 | 0.21 |
| Little Colorado, San Juan, and Virgin River Basins, except higher elevations of south-facing slopes (2) .. | 0.81 | 105 | 1.36 | 0.20 |
| Higher elevations of south-facing slopes of Little Colorado, San Juan, and Virgin River Basins (2) .. | 0.93 | 41 | 1.31 | 0.13 |
| Rio Grande Basin north of El Paso, Tex. (3) | 0.77 | 110 | 1.35 | 0.18 |
| Crest of Continental Divide and Sangre de Cristo Mountains to generalized 7,000-ft contour from southern Wyoming to southern tip of Sangre de Cristo Mountains (4) .. | 0.83 | 122 | 1.43 | 0.22 |
| Upper Colorado and Quantico River Basins and Green River Basin below confluence of Green and Yampa rivers (5) .. | 0.79 | 69 | 1.12 | 0.13 |
| Yampa River Basin, Green River Basin above confluence of Green and Yampa Rivers, and Bear River Basin east of Wasatch Mountains (6) .. | 0.83 | 29 | 1.03 | 0.08 |
| Mountains of central Utah (7) | 0.85 | 86 | 1.35 | 0.18 |
| Western Utah and Nevada, except Snake and Virgin River Basins and spillover zone east of Sierra Nevada crest (8) .. | 0.71 | 79 | 1.03 | 0.13 |
| Western Utah and Nevada, except Snake and Virgin River Basins and spillover zone east of Sierra Nevada crest (8) .. | 0.71 | 55 | 1.04 | 0.15 |
| Big Horn River Basin above Saint Xavier and minor portions of North Platte, Powder, Tongue, and Yellowstone River Basins (9) .. | 0.78 | 55 | 1.25 | 0.21 |
| Upper Missouri River Basin above Hobbs Dam, West, Snake River Basin above Alpine, West, and upper Yellowstone River Basin above Springdale, Mont. (10) .. | 0.76 | 57 | 1.19 | 0.16 |
| From generalized 4,000-ft contour on east to crests of Crazy and Little Belt Mountains and Lewis Range on west (11) .. | 0.80 | 52 | 1.67 | 0.26 |
| West of Continental Divide, but east of Bitterroot Range and Cabinet and Selkirk Mountains (12) .. | 0.85 | 44 | 1.36 | 0.12 |
| Mountainous region of eastern Washington and Oregon east of Knap west of Bitterroot Range east of Cascade Range north of southern base of Snake Range, including Snake River Valley below a generalized 5,000-ft contour (13) .. | 0.78 | 147 | 1.44 | 0.24 |
| Orographic region east of crest of Cascade Range and west of Snake River Basin (14) .. | 0.90 | 115 | 1.75 | 0.35 |
| Western slopes of Coast Ranges, Olympic Mountains, and Cascade Range (15) .. | 0.87 | 125 | 3.69 | 0.48 |
| Eel River Basin; southern portion of Klamath River Basin, and Cottonwood, Elder, Thomas, and Glaston Creeks (16) .. | 0.91 | 39 | 4.19 | 0.50 |
| Russian River, Cache and Plush Creeks, and coastal drainages west of Russian River (17) .. | 0.84 | 63 | 5.31 | 0.78 |
| Sierra Cruz Mountains and La Pinta, Sierra Lucita, and Coast Ranges (18) .. | 0.95 | 55 | 4.32 | 0.45 |
| Diablo, Gabilan, and Temblor Ranges (19) .. | 0.82 | 58 | 2.21 | 0.35 |
| San Rafael, San Bernardino, Santa Monica, and San Gabriel Mountains (20) .. | 0.88 | 149 | 3.98 | 0.59 |
| Santa Ana, Santa Rosa, Coyote, and other extreme southern coastal mountains (21) .. | 0.88 | 34 | 2.44 | 0.33 |
| Northern Sierra Nevada north of Mokelumne River Basin (22) .. | 0.92 | 84 | 4.56 | 0.53 |
| Southern Sierra Nevada south of Consumnes River Basin (23) .. | 0.88 | 61 | 3.43 | 0.53 |
| Southeastern desert region of California (24) .. | 0.89 | 41 | 1.07 | 0.16 |
| Spillover zone east of Sierra Nevada crest (25) .. | 0.94 | 41 | 2.05 | 0.27 |
| Spillover zone east of crest of coastal mountains of southern California (26) .. | 0.97 | 10 | 2.08 | 0.15 |

* Numbers in parentheses refer to geographic regions shown in figure 8.
 † Two different equations were used in region 2. See text for explanation.
 ‡ Two different equations were used in region 6. See text for explanation.

Table 3. Statistical parameters for relations used for interstation interpolation of 2-yr 24-hr precipitation values



variables until the variance explained by an additional variable was less than some prescribed amount or until a fixed number of variables was selected. Final equations did not contain more than five independent variables.

In the development of these equations, data from all stations with daily or hourly observations were considered. The data sample used was not completely adequate. First, it did not include for each factor the full range of values that occur within the region. Application of the equation, therefore, required unavoidable extrapolation. Second, the number of data points used to develop these equations was occasionally less than desirable. Nevertheless, the equations provided the best available method of developing preliminary estimates of frequency values in regions lacking adequate data.

Relations for interpolating between 24-hr precipitation-frequency data points. Figure 8 shows generalized boundaries of the regions used to develop relations for interpolation between locations with 2-yr 24-hr precipitation values. Topographic maps show recognizable topographic barriers chosen as the boundary lines of most regions. For example, the boundary separating regions 3 and 4 from those to the west is the Continental Divide. The boundary separating region 15 from 14 is the crest of the Cascade Range. A few of the boundaries between adjoining regions may appear somewhat arbitrary, but examination of detailed topographic maps will show a physical basis for each.

In areas where topographic variation is gradual and where there are no large differences in elevations or slopes over short distances, precipitation-frequency values at a station usually are representative of a much larger area than are such values in a mountainous region. Within the western United States, some other extensive regions met this criteria. Within these regions, there were also numerous stations with suitable records. The lack of topographic controls means only there is limited variation in precipitation-frequency values, and this variation is such that it can be depicted using the numerous station data points. No equations for interpolating between stations were developed for such regions (shown shaded in fig. 8).

The equations developed for interpolating between locations with 2-yr 24-hr precipitation values in regions of sparse data were not all equally reliable. On the average, the 28 equations developed for estimating the 2-yr 24-hr precipitation values at intermediate points in western United States explained about 70 percent of the variance. The standard error of estimate averaged about 13 percent of the average station value for 2-yr 24-hr precipitation. The correlation coefficient, the number of stations used, the average 2-yr precipitation value, and the standard error of estimate for each equation used to estimate 2-yr 24-hr precipitation values are shown in table 3.

The equation that explained the least variance, only slightly over one-half, was for western Utah and most of Nevada (region 8, fig. 8). This is a region with diverse topography and no well-defined orographic barrier. It is also a region where a wide variety of storms produce large precipitation amounts. The equation developed for the coastal mountains of California (region 18, fig. 8) explained the greatest portion of the variance, about 90 percent. The region consists primarily of mountain ranges oriented north-northwest to south-southeast; within this region, large precipitation amounts generally result from one storm type.

Figure 8. Regions used to develop statistical parameters for interpolation of 2-yr 24-hr precipitation values.

Table 4. Factors most useful in relations for interpolation for 2-yr 24-hr precipitation values

| Factors (by category) | Number of equations using factor | Percent of equations using factor | Number of times each factor used | Percent of total number of times factor used |
|----------------------------------|----------------------------------|-----------------------------------|----------------------------------|--|
| Slope | 18 | 64 | 37 | 42 |
| Normal annual precipitation | 15 | 54 | 15 | 17 |
| Barrier to airflow | 10 | 36 | 11 | 12 |
| Elevation | 10 | 36 | 10 | 11 |
| Distance to moisture | 9 | 32 | 9 | 10 |
| Location (latitude or longitude) | 4 | 14 | 5 | 6 |
| Roughness | 2 | 7 | 2 | 2 |

Two equations were developed for region 8 (fig. 8), which includes western Utah and Nevada except for the Snake and Virgin River Basins and a spillover zone east of the Sierra Nevada. The two regions had nearly equal correlation coefficients and standard error of estimates. The first equation was developed using normal annual precipitation, the second topographic factors only. The equation using normal annual precipitation data was developed using precipitation maps for Utah because reliable normal annual precipitation maps were available. Investigations continued, and a relation that gave about equally reliable results was obtained using both equations for points near the Nevada-Utah border. The results that did not differ greatly. The second equation was then used to prepare the maps for Nevada.

Table 4 shows the factors, grouped in general categories, found most useful in depicting variations in the 2-yr 24-hr precipitation values for the western United States. The first and second columns show the number and percent of equations in which each factor was used. The total for the second column is larger than 100 percent because several factors were used in the equations developed for each region. The third column shows the total number of times each factor was used, and the fourth what percentage each factor used was of the total number of factors. For example, of the 89 different factors used in the 28 equations, 37 were some measure of slope; the use of the slope factor represents 42 percent of the total number of factors used.

The single most important factor considered was slope, a topographic factor. Measurement of slope varied from region to region. In some regions, slope was measured directly by dividing the difference in height between two points by the distance between the points. In the Cascade and Coast Ranges of Washington and Oregon, the difference between the station elevation and the average elevation at a distance of 20 miles in the western quadrant

proved to be the most significant factor. A less direct measure was used in north-central Wyoming and south-central Montana, where the greatest change in elevation between the station and the lowest point within 20 miles was used and the distance between the station and such a point was not involved. In several portions of California, a more complicated method was used. A path 5 miles wide was oriented along the prevailing direction of moist airflow. At 1-mile intervals along this path, the average height was measured. The difference in height between adjoining lines indicated whether there was an upslope or a downslope in this particular segment. The summation of the upslopes and downslopes, separately, was an indirect measurement of slope. A combination of these upslopes and downslopes, each divided by the distance between the station and the center of the area included between two adjoining lines, was a direct measurement of slope.

The second most important topographic factor was found to be the barrier to moist airflow; this factor is actually a combination of meteorology and topography. In selecting a barrier, the first consideration was the direction of moist air inflow. The barrier had to be normal, or nearly normal, to this direction. The barrier range, or ranges, had to be sufficiently massive to cause a significant disruption in the airflow. Barriers of limited lateral extent that would permit air to flow around as easily as over were not considered. A generalized crest line was drawn along the significant barrier, and measurements of barrier height or distances or directions to this barrier were then made from the station to this generalized crestline. The orientation of barriers to moist airflow was determined as appropriate for each region. For example, along the Pacific coast, westerly direction of moist airflow was used; in Colorado and New Mexico, a southeasterly airflow was appropriate. The direction selected was determined from an examination of the moist air inflow in storms that produce large precipitation amounts in these regions. In some regions, the distance behind the barrier was important. In others, the height of the barrier proved to be the significant factor.

The distance to the principal moisture source, a combination of topographic and meteorological influences, was another important factor. In northeastern New Mexico, central Colorado, and southern Wyoming (region 4, fig. 8), examination of a topographic map and consideration of the moisture inflow in storms that produced large precipitation amounts (fig. 7) made it evident that the general moist airflow was from the west of Mexico. Distance to moisture was therefore measured in that direction.

Another topographic factor used frequently was the elevation of the station, either the actual station elevation or, preferably, where narrow valleys and ridges predominate in the area, the average elevation around the station at some distance (effective elevation). Elevation alone usually correlated rather poorly with precipitation-frequency values. In many regions, the simple correlation between elevation and precipitation-frequency values was not statistically significant at either the 0.01 or 0.05 level. It was not elevation alone but a combination of elevation with other factors, such as slope, height of intervening barriers, and distance to moisture source, that was significant.

Normal annual precipitation was used in many of these index relations. However, the policy adopted was that normal annual precipitation was not used if an equally reliable relation could be derived solely on the basis of topographic factors, even though normals could have been used in almost every region. The one

exception was the southeastern desert regions of California, where normal annual precipitation did not correlate well with precipitation-frequency values. Normal annual precipitation maps are most exact at points where data are available. Isopeithets used to arrive at estimates in areas where data are not available are only as accurate as the standard error of estimate of the relation used in the interpolation and as the skill of the analyst will permit. Therefore, where estimates of normal annual precipitation (or other climatological factors) are used to develop precipitation-frequency maps, the error incorporated in development of the normal annual precipitation map is combined with the standard error of estimate of the relation for precipitation-frequency maps. Normal annual precipitation maps were, however, helpful and were used. Storage-gage and snow-course data, streamflow data, and vegetation maps are useful for drawing accurate normal annual or seasonal precipitation maps in regions where lack of short-duration precipitation data decreases the reliability of relations between frequency values and topographic factors. Normal annual precipitation was used as a factor where topographic factors could not be quantified to estimate the precipitation-frequency values with sufficient accuracy.

Table 5 shows the statistical parameters of the interpolating equations used to estimate the 100-yr 24-hr precipitation values. The equations were developed for the same regions as those for the 2-yr return period, with one exception (fig. 9). This was in Arizona where data from the Gila, Williams, and lower Colorado Basins were combined with data from the San Juan, Little Colorado, and Virgin River Basins. In regions relatively unaffected by orography, equations were developed that related the 2-yr 24-hr precipitation values to those for the 100-yr return period. These equations were developed as an additional aid for interpolating between stations in these regions because of the relatively few stations with long records available. Although the longest record stations were generally within the monographic regions, most states had less than 20 percent of the stations within these regions with 50 or more years of record. Equations for these regions provided an objective method of providing space-averaged ratios between 100-yr 24-hr precipitation values and 2-yr 24-hr precipitation values.

As with the relations for estimating the values for the 2-yr return period, the equations did not all have the same degree of reliability. The orographic region for which the equation accounted for the least variance (not quite one-half of the variation) was the region including the Yampa River Basin, the Green River Basin above the confluence of the Greer and Yampa Rivers, and the Bear River Basin east of the Wasatch Mountains (region 5, fig. 9). For several regions in California, over 90 percent of the variance was accounted for by the equations. The equation developed for the San Rafael, San Bernardino, Santa Monica, and San Gabriel Mountains (region 20, fig. 9) accounted for the greatest amount of the variation. On the average, the 35 equations developed to interpolate the 100-yr 24-hr precipitation values in this portion of the United States accounted for about 75 percent of the variance, and the standard error of estimate averaged about 12 percent of the average station value.

There was one region (region 7, fig. 9) for which two equations were developed. In the preparation of frequency maps for Utah, basins that were wholly or partly within Utah were investigated. One region extended westward from Utah to include most of Nevada. Within this region, a relation was developed that

accounted for about 60 percent of the variance. During subsequent investigations, a superior relation was developed when frequency maps for Nevada were prepared. The newly developed equation accounted for about 80 percent of the variance.

Table 6 shows the factors found most useful for interpolating variations in the 100-yr 24-hr precipitation values in sparse-data areas of the western United States. This table is in the same format as table 4. The definitions of the variables—slope, distance to moisture, elevation, etc.—are the same as those for table 4. Again, slope is the most important topographic factor. The next most important topographic factor was elevation. In the equations, the 2-yr 24-hr precipitation values were used in interpolation. In table 6, it can be seen that the 2-yr 24-hr precipitation value was the most important variable. However, this may be misleading because about one-fourth of the regions for which equations were developed were considered nonorographic. In such regions, the use of the 2-yr 24-hr precipitation value in an equation was similar to using an average 100- to 2-yr ratio. Frequently, these equations included a location factor that reflected the variation of such a ratio over the region. As with other meteorological or climatological factors—for example, normal annual precipitation—it would have been preferable to avoid the use of precipitation-frequency values in the equations. However, this was not always possible.

Relations for estimating the 6-hr precipitation-frequency values. Data from both recording and nonrecording gages can be incorporated in equations for estimating precipitation-frequency values for the 24-hr duration. For durations of less than 24 hours, only data from recording gages can be used. This frequently reduces the number of data points within a particular region by one-half or more. The effect of topography on precipitation-frequency values decreases as the duration decreases. Thus, there is less variability in the precipitation-frequency values for the 6-hr duration. For these reasons, larger regions are used to develop interpolation equations for 6-hr duration maps. Figure 10 shows the regions used to develop the equations for estimating 2-yr 6-hr precipitation values. The regions used for developing relations for the 100-yr return period were the same with one exception; the region south of the Snake, Bear, Yampa, and North Platte River Basins (region 1, fig. 10). This region was divided approximately along the Arizona-Utah and the New Mexico-Colorado boundary lines into Regions 1A and 1B.

The equation for the northern Sierra Nevada region of California (region 7, fig. 10) accounted for the least amount of variation—about 60 percent—in the 2-yr 6-hr precipitation values (table 7). The equation for the coastal mountains of California (region 6, fig. 10) accounted for over 90 percent of the variation and was the most reliable equation developed. On the average, the equations accounted for over 80 percent of the variations and had a standard error of estimate of about 11 percent of the average 2-yr 6-hr precipitation values.

For the 100-yr 6-hr precipitation values, the equation for the coastal mountains of California (region 6, fig. 10) accounted for the greatest amount of variation in these values (table 8). In this region, over 90 percent of the variation in the data sample was accounted for. The equation for the northern Great Basin region (region 3, fig. 10) accounted for the least variation. In this region, the equation accounted for about 60 percent of the variation. On the average, the equations accounted for over 80 percent of the variation with a standard error of estimate of about 14 percent of the

Table 6. Factors most useful in relations for interpolation for 100-yr 24-hr precipitation values

| Factors (by category) | Number of equations using factor | Percent of equations using factor | Number of times each factor used | Percent of number of times each factor used |
|----------------------------------|----------------------------------|-----------------------------------|----------------------------------|---|
| 2-yr 24-hr precipitation | 27 | 77 | 27 | 29 |
| Slope | 26 | 74 | 26 | 28 |
| Elevation | 20 | 57 | 20 | 22 |
| Distance to moisture | 6 | 17 | 6 | 7 |
| Location (latitude or longitude) | 5 | 14 | 6 | 7 |
| Normal annual precipitation | 4 | 11 | 4 | 4 |
| Barrier to airflow | 2 | 6 | 2 | 2 |
| Roughness | 1 | 3 | 1 | 1 |

average 100-yr 6-hr precipitation values. The factors used most frequently in the equations for estimating the 2-yr 6-hr precipitation values are listed in table 9; those for the 100-yr 6-hr precipitation values are given in table 10. The format and definitions of variables of tables 9 and 10 are the same as those of table 4. For the 2-yr return period, the factor used most frequently was a measurement of slope. Most equations, however, related variations in the 6-hr precipitation values to variations in the 24-hr values. For the 100-yr return period, slope and elevation were equally important topographic factors. As with the 100-yr 24-hr and 2-yr 6-hr maps, precipitation-frequency values were used in the equations for some regions.

Typical multiple linear regression equations. It is beyond the scope of this publication to present all the equations used for estimating precipitation-frequency values for this Atlas. However, it is useful to discuss in some detail two equations used to estimate the 2-yr 24-hr precipitation values. The factors used and the accuracy of the results obtained are typical of other equations developed.

The first of these is the equation for the northern Coast Mountains of California (region 16, fig. 8). This region includes the Red River Basin, some southern portions of the Klamath River Basin, and the western portion of the Sacramento River Basin. This equation is

$$Y = 1.117 + 1.814(X_1) + 0.016(X_2) - 0.349(X_3), \quad (1)$$

where Y is the 2-yr 24-hr precipitation value in inches, and X₁,

| Region of applicability* | Corr. coeff. | No. of stations | Mean of unrounded station values (inches) | Standard error of estimate (inches) |
|--|--------------|-----------------|---|-------------------------------------|
| Arizona, New Mexico, extreme eastern California, Nevada south of the Snake River Basin, Utah south of the Snake and Bear River Basins, and Colorado south of the Yampa and North Platte River Basins (1a and 1b) | 0.92 | 262 | 1.10 | 0.16 |
| Montana and Wyoming east of a generalized crestline extending along the Continental Divide in northern Montana, the Crazy and Little Belt Mountains, the Absaroka Range, and the Continental Divide in southern Wyoming (2) | 0.94 | 125 | 1.37 | 0.10 |
| Region north of the southern boundary of the Snake, Bear, and Yampa River Basins and between the Sierra Nevada crest and the Cascade Range crestline extending along the Continental Divide from the Coast Range and Little Belt Mountains to the Coast Range and the Continental Divide in southern Wyoming and northern Colorado (3) | 0.91 | 151 | 0.73 | 0.07 |
| Drographic regions of western Washington, Oregon, and California from the crest of the Cascade Range to the Pacific Ocean extending southward to include the area drained by the Klamath and Siskiyou Rivers in northern California (4) | 0.78 | 57 | 1.56 | 0.23 |
| Nonorographic coastal lowlands of Washington and Oregon (5) | 0.97 | 59 | 1.11 | 0.10 |
| Coastal mountains of California from the Trinity River Basin in the north to the Mexican border (6) | 0.97 | 87 | 1.35 | 0.16 |
| Northern Sierra Nevada north of Mokelumne River Basin (7) | 0.78 | 31 | 2.03 | 0.34 |
| Southern Sierra Nevada south of Consummes River Basin (8) | 0.92 | 26 | 1.68 | 0.18 |
| Spillover zone east of the crests of the Sierra Nevada and the coastal mountains of southern California and the southeastern desert region of California (9) | 0.86 | 25 | 0.84 | 0.12 |
| Coastal lowlands and San Joaquin and Sacramento Valleys of California (10) | 0.95 | 73 | 1.37 | 0.11 |

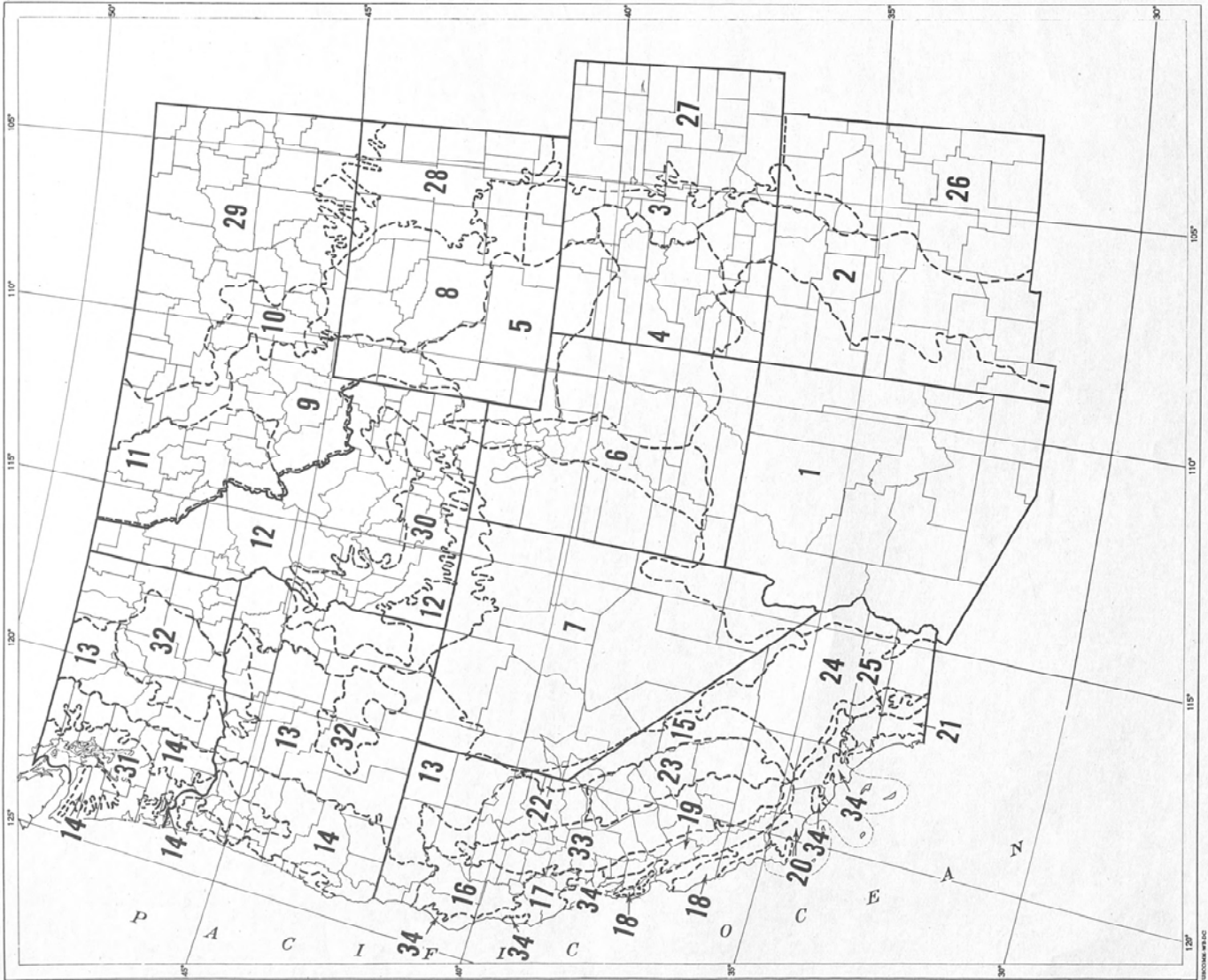
* Numbers in parentheses refer to geographic regions shown in figure 10.

Table 7. Statistical parameters for relations used for interpolation of 2-yr 6-hr precipitation values

| Region of applicability | Corr. coeff. | No. of stations | Mean of unrounded station values (inches) | Standard error of estimate (inches) |
|--|--------------|-----------------|---|-------------------------------------|
| Gila, Williams, San Juan, Little Colorado, and Virgin River Basins (1) | 0.80 | 148 | 3.98 | 0.59 |
| Rio Grande Basin north of El Paso, Tex. (2) | 0.78 | 110 | 3.26 | 0.49 |
| Crest of Continental Divide and Sangre de Cristo Mountains to generalized 7,000-ft contour from southern Wyoming to southern tip of Sangre de Cristo Mountains (3) | 0.91 | 69 | 3.28 | 0.38 |
| Upper Colorado and Gunnison River Basins and Green River Basin below confluence of Green and Yampa Rivers (4) | 0.79 | 53 | 2.57 | 0.31 |
| Yampa River Basin, Green River Basin above confluence of Green and Yampa Rivers, and Bear River east of Wasatch Mountains (5) | 0.68 | 27 | 2.41 | 0.30 |
| Mountains of central Utah (6) | 0.88 | 65 | 2.84 | 0.25 |
| Sierra Nevada crest (7) | 0.77 | 64 | 2.50 | 0.29 |
| Western Utah and Nevada, except Snake and Virgin River Basins and spillover zone east of Sierra Nevada crest (7') | 0.90 | 55 | 2.42 | 0.22 |
| Sierra Nevada crest (7'') | 0.94 | 47 | 3.10 | 0.31 |
| Big Horn River Basin above Saint Xavier and minor portions of North Platte, Powder, Tongue, and Yellowstone River Basins (8) | 0.88 | 48 | 2.68 | 0.34 |
| Upper Missouri River Basin above Holter Dam, Mont.; Snake River Basin above Alpine, Wyo.; and upper Yellowstone River Basin above Springside, Mont. (9) | 0.85 | 41 | 3.71 | 0.44 |
| From generalized 4,000-ft contour on the east to crests of Crazy and Little Belt Mountains and Lewis Range on the west (10) | 0.90 | 37 | 2.87 | 0.20 |
| West of Continental Divide, but east of Blinnert Range and Cabinet and Solikirk Mountains (11) | 0.87 | 99 | 2.74 | 0.32 |
| Mountainous region of eastern Washington, Oregon and of Idaho west of Blinnert Range crest and Continental Divide, and north of southern boundary of Snake River Basin (12) | 0.92 | 115 | 3.76 | 0.61 |
| River Valley below a generalized 5,000-ft contour (12') | 0.80 | 119 | 7.09 | 1.13 |
| Orographic region east of crest of Cascade Range and west of Snake River Basin (13) | 0.91 | 28 | 5.39 | 0.75 |
| Western slopes of Coast Ranges, Olympic Mountains, and Cascade Range (14) | 0.85 | 26 | 8.34 | 1.42 |
| Spillover zone east of crest of Sierra Nevada (15) | 0.88 | 35 | 10.17 | 1.24 |
| Eel River Basin; southern portion of Klamath River Basin; and Cottonwood, Elter, Thomas, and Giddons Creeks (16) | 0.86 | 26 | 10.90 | 1.25 |
| Russian River, Cache and Pulah Creeks, and coastal drainages west of Russian River (17) | 0.97 | 29 | 5.26 | 0.48 |
| Santa Cruz Mountains and La Panza, Santa Lucia, and Coast Ranges (18) | 0.87 | 29 | 6.74 | 1.06 |
| Dibble, Gabilan, and Temblor Ranges (19) | 0.96 | 65 | 9.74 | 1.01 |
| San Rafael, San Bernardino, Santa Monica, and San Gabriel Mountains (20) | 0.89 | 42 | 8.14 | 1.29 |
| Santa Ana, Santa Rosa, Coyote, and other extreme southern coastal mountains (21) | 0.93 | 41 | 3.37 | 0.47 |
| Northern Sierra Nevada north of Mokelumne River Basin (22) | 0.98 | 10 | 6.20 | 0.50 |
| Southern Sierra Nevada south of Consummes River Basin (23) | 0.66 | 136 | 5.28 | 0.88 |
| Southeastern desert region of California (24) | 0.82 | 119 | 4.73 | 0.52 |
| Spillover zone east of crest of coastal mountains of southern California (25) | 0.83 | 66 | 4.08 | 0.45 |
| New Mexico east of Rio Grande Basin (26) | 0.76 | 83 | 3.86 | 0.42 |
| Colorado east of generalized 7,000-ft contour, and southeastern Wyoming east of generalized 7,000-ft contour and south of North Platte River Basin (27) | 0.85 | 48 | 2.25 | 0.21 |
| Eastern Wyoming and southeastern Montana east of generalized 6,000- to 5,000-ft contour and south of generalized 4,000-ft contour in vicinity of Wyoming-Montana border (28) | 0.94 | 146 | 5.47 | 0.62 |
| Montana east and north of generalized 4,000-ft contour (29) | 0.71 | 50 | 2.07 | 0.25 |
| Snake River Valley below 5,000 ft (30) | 0.94 | 102 | 4.07 | 0.51 |
| Coastal Plain, Puget Sound region, and Willamette Valley below 1,000 ft (31) | 0.87 | 180 | 6.65 | 1.03 |
| Nonorographic region east of crest of Cascade Range (32) | | | | |
| Sacramento and San Joaquin River Valleys of California below 1,000 ft (33) | | | | |
| Coastal lowlands of California (34) | | | | |

* Numbers in parentheses refer to geographic regions shown in figure 9.
 * Two different equations were used in region 7. See text for explanation.

Table 8. Statistical parameters for relations used for interpolation of 100-yr 24-hr precipitation values



the station (in hundreds of feet per mile). X_2 was computed by subtracting the average height along a 90° arc centered 10 miles southwest of the station (downwind for the most prevalent storm-wind direction) from the average height along a 90° arc centered 5 miles northeast of the station (upwind for the most prevalent storm-wind direction). X_3 is the average height (in hundreds of feet) of the final crest (measured along a 10° arc) divided by the distance (in miles) between the station and the final crest. The final crest was a generalized crestline that separated the Sacramento River Basin from basins to the west; it was drawn on a 1:1,000,000 World Aeronautical Chart. Distances to the east of this crest were considered negative.

The first factor, X_1 , combines the measurements of the horizontal and vertical distances from moisture. It also measures the average slope between the station and the coast. The second factor, X_2 , is a measure of the lift imparted to the airflow in the vicinity of the station—small-scale slope. The third factor, X_3 , is a measure of large-scale lifting—large-scale slope. It can also be considered to represent the general distortion in the large-scale moist airflow caused by the major orographic barrier.

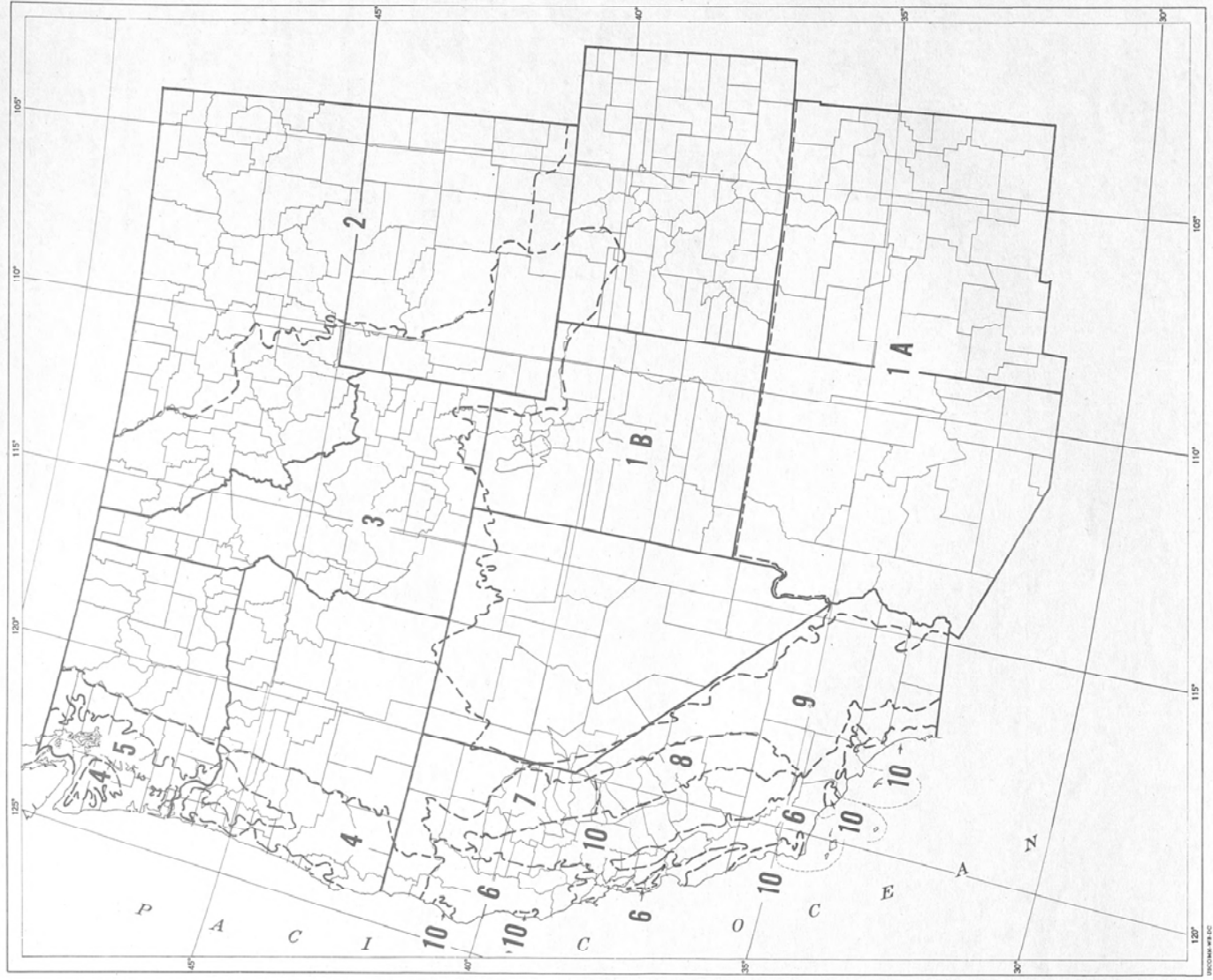
This equation explains about 84 percent of the variance in the 2-yr 24-hr precipitation values, with a standard error of estimate of 0.50 in., which is about 12 percent of the average 2-yr 24-hr precipitation value for stations in the region. Of the total variance, the first variable accounts for about 70 percent, the second, 9 percent, and the third, 4 percent. Other variables examined did not account for significant additional portions of the variance. The geographic distribution of the errors is shown in figure 11. The upper number at each station is the actual difference (in hundredths of inches) between the value computed from observed data and that estimated from the equation. The lower number is the error expressed in a percent of the 2-yr 24-hr precipitation value at the station. No discernible regional pattern in the errors was apparent. Although the factors used in this and the other equations have a physical meaning, the equation is a statistical relation of physical factors. There is no intention to imply a cause-and-effect relation. The requisite knowledge of the precipitation process is not yet available to develop equations that incorporate the dynamics of convection, condensation, and other factors to predict precipitation frequency.

The second illustrative equation was developed for the Big Horn River Basin, south of Saint Xavier, Mont. (region 9, fig. 8). Minor portions of the North Platte, Powder, Tongue, and Yellowstone River Basins were also included in this region. The equation is

$$Y = 1.497 + 0.027(X_1) + 0.002(X_2) - 0.023(X_3). \quad (2)$$

Y is the estimated 2-yr 24-hr precipitation value in inches. X_1 is the difference between the station elevation and the lowest elevation within 20 miles (in hundreds of feet). X_2 is the difference between the sum of the maximum heights within 40 miles along radials to the northwest, west, and southwest, and the sum of the maximum elevations within 40 miles along radials to the northeast, east, and southeast (in hundreds of feet). X_3 is the direction to the nearest point on the Continental Divide within the sector from southwest to north. If, however, there is a peak higher than 9,000 ft within this sector and it is closer to the station than is the Continental Divide, X_3 is the direction to this peak.

Figure 9. Regions used to develop statistical parameters for interpolation of 100-yr 24-hr precipitation values.



All three variables are related to the effect of the ground slope in the vicinity of the station. The first two variables measure differences in height over small and medium distances and reflect the importance of the steepness of the slope in the precipitation process. Here, the moist airflow of large storms comes from an easterly direction, frequently associated with a cyclonic center south or southeast of the region, and ground elevation generally increases toward the west or northwest. The third variable relates the orientation of the ground slope and its effectiveness in the precipitation process to an optimum inflow direction. The total amount of the variance accounted for by this relation is about 60 percent, with a standard error of estimate of 0.21 in., or about 17 percent of the average 2-yr 24-hr precipitation value. The first variable accounts for about 41 percent of the variance; the second, 11 percent; and the last, 8 percent. The geographic distribution of the errors from this equation is shown in figure 12.

It would have been possible to include normal annual precipitation in this relation. This factor would have accounted for an additional 15 percent of the variance and a corresponding decrease in the standard error of estimate. Where this factor could be determined from data, the use of normal annual precipitation would have improved the results. As indicated earlier, the results would include some points for which short-duration precipitation data were not available. At points where such data were not available, any improvement would have been dependent on the ability to estimate normal annual precipitation. In using an equation with normal annual precipitation, the standard error of estimate incorporated in the procedure for preparing normal annual precipitation maps is combined with the standard error of estimate for the interpolating equation for 2-yr 24-hr precipitation values. When this combined error is greater than the standard error of estimate for interpolating equation for 2-yr 24-hr precipitation that does not include normal annual precipitation, there is a loss of accuracy through use of the equation including normal annual precipitation. Within this particular region, the uncertainty in estimating normal annual precipitation at nondata points was sufficiently large and an equation developed using only topographic factors was sufficiently reliable that use of the equation containing normal annual precipitation for estimating the 2-yr 24-hr precipitation values was not justified.

Drawing of isopluvial lines on four key maps. In preparing the isopluvial maps, the computed precipitation-frequency values for all stations were plotted. In addition to the computed values, the width of the confidence band, computed according to standard statistical procedures, was plotted for the 100-yr return-period maps. Values estimated from the equations described in the preceding section were plotted for a latitude-longitude grid with 5-min grid points. The total number of grid points was approximately 47,000. Along the boundaries of each region, values were estimated by the equations applicable to each of the adjoining regions.

In the construction of isopluvial lines, the question arises as to how much the station and grid-point data should be smoothed for the most effective use of the maps. When drawing the isopluvial lines through the field of grid points and station data, the standard error of estimate for the various multiple regression equations and the confidence band about the station data must be considered. Also, smoothing between adjoining regions, where multiple regression equations give somewhat different values at the boundary

Figure 10. Regions used to develop statistical parameters for interpolation of 2-yr and 100-yr 6-hr precipitation values.

Table 8. Statistical parameters for relations used for interpolation of 100-yr 6-hr precipitation values

| Region of applicability* | Corr. coeff. | No. of stations | Mean of computed 6-hr values (inches) | Standard error of estimate (inches) |
|--|--------------|-----------------|---------------------------------------|-------------------------------------|
| Arizona, New Mexico, and lower Colorado River Basin in southeastern California (1a) | 0.91 | 103 | 3.16 | 0.50 |
| Nevada south of the Snake River Basin, Utah south of the Snake and Bear River Basins, and Colorado south of the Yampa and North Platte River Basins (1b) | 0.91 | 144 | 2.34 | 0.47 |
| Montana and Wyoming east of a generalized crestline extending along the Continental Divide in northern Montana, the Crazy and Little Belt Mountains, the Absaroka Range, and the Continental Divide in southern Wyoming (2) | 0.92 | 110 | 2.62 | 0.31 |
| Region north of the southern boundaries of the Snake, Bear, and Yampa River Basins and between a generalized crestline of the Cascades and a generalized crestline extending along the Continental Divide in northern Montana, the Crazy and Little Belt Mountains, the Absaroka Range, and the Continental Divide in southern Wyoming and northern Colorado (3) | 0.79 | 120 | 1.62 | 0.22 |
| Oreographic regions of western Washington, Oregon, and California from the crest of the Cascade Range to the Pacific Ocean extending southwest to include the area drained by the Klamath and Salmon Rivers in northern California (4) | 0.89 | 57 | 2.98 | 0.33 |
| Noroographic coastal lowlands of Washington and Oregon (5) | 0.91 | 59 | 2.49 | 0.31 |
| Coastal mountains of California from the Trinity River Basin in the north to the Mexican border (6) | 0.97 | 87 | 3.95 | 0.39 |
| Northern Sierra Nevada north of Mokelumne River Basin (7) | 0.93 | 31 | 3.81 | 0.45 |
| Southern Sierra Nevada south of Consummes River Basin (8) | 0.93 | 26 | 3.87 | 0.50 |
| Spillover zone east of the crests of the Sierra Nevada and the coastal mountains of southern California and the southeastern desert region of California (9) | 0.84 | 25 | 2.29 | 0.36 |
| Coastal lowlands and San Joaquin and Sacramento Valleys of California (10) | 0.87 | 71 | 2.98 | 0.41 |

* Numbers in parentheses refer to geographic regions shown in figure 10.

| Factors (by category) | Number of equations using factor | Percent of equations used | Number of times each factor used | Percent of total number of times each factor used |
|--|----------------------------------|---------------------------|----------------------------------|---|
| Slope | 4 | 40 | 10 | 38 |
| 2-yr 24-hr precipitation | 7 | 70 | 7 | 27 |
| Location (latitude or longitude) | 4 | 40 | 4 | 15 |
| Elevation | 3 | 30 | 3 | 12 |
| Barrier to airflow | 1 | 10 | 1 | 4 |
| Distance to moisture | 1 | 10 | 1 | 4 |

Table 9. Factors most useful in relations for interpolation of 2-yr 6-hr precipitation values

| Factors (by category) | Number of equations using factor | Percent of equations used | Number of times each factor used | Percent of total number of times each factor used |
|---------------------------------------|----------------------------------|---------------------------|----------------------------------|---|
| 2-yr 6-hr precipitation | 5 | 55 | 5 | 23 |
| 100-yr 24-hr precipitation | 4 | 36 | 4 | 19 |
| Elevation | 4 | 36 | 4 | 19 |
| Slope | 4 | 36 | 4 | 19 |
| 2-yr 24-hr precipitation | 1 | 9 | 1 | 5 |
| Normal annual precipitation | 1 | 9 | 1 | 5 |
| Distance to moisture | 1 | 9 | 1 | 5 |
| Location | 1 | 9 | 1 | 5 |

Table 10. Factors most useful in relations for interpolation of 100-yr 6-hr precipitation values

lines, must be considered separately. Isolines can be drawn to fit every point plotted on the map, although this would not allow for some of the random differences between adjoining grid points that result from errors in the multiple regression equation or sampling errors in station data. Also, the coarseness of even a 5-min latitude-longitude grid is such that sometimes narrow ridges and valleys are necessary to make additional computations for such locations. Some subjective smoothing must be used to make allowances for factors that could not be expressed quantitatively.

In analysis, smoothness and closeness of fit are basically inconsistent in that some smoothing cannot be carried beyond a certain point without some sacrifice of closeness of fit, and vice versa. As the isolines were drawn, the sampling error of the station values and the standard error of estimate were considered.

Additional working maps. Additional working maps were prepared showing the 100- to 25-yr ratios for the 6- and 24-hr durations and the 6- to 24-hr ratios for the 2- and 100-yr return periods. To minimize the exaggerated effect of an outlier (anomalous event) from a short record, only data from those stations with a minimum record length of 20 yrs for the 6- and 24-hr durations at the 100-yr return period were used in these working maps. Experience has shown that for long-record station data, the ratio of 6- to 24-hr values for the same return period and the 100- to 2-yr ratio for the same duration do not vary greatly over relatively large areas. The variation present is consistent with the variations in relations between meteorologic and topographic characteristics. Climatic factors that provide general guides on variations of precipitation-frequency values were examined and considered in a qualitative sense. Among these factors are the mean annual number of thunderstorm days (U.S. Weather Bureau 1952, 1947), normal monthly number of days above various threshold values (Environmental Science Services Administration, Weather Bureau, 1966), and mean number of days with rain (Environmental Science Services Administration, Environmental Data Service 1968).

Intermediate maps. The 47,000-point grid described earlier was also used in the analysis of the isohyval patterns of the eight intermediate maps. These maps—for 5-, 10-, 25-, and 50-yr return periods for 6- and 24-hr durations were prepared primarily for the convenience of the user, because it is technically sufficient to provide two points of the frequency curve for a particular duration and to describe the method of interpolation. Four values, one from each of the four key maps, were read for each grid point. These four values were used in a computer program based on the return-period diagram (fig. 6) to compute values for eight additional maps. The key maps were used as underlays to maintain the basic isohyval pattern on all maps.

Figure 11. Geographic distribution of errors for equation used to interpolate 2-yr 24-hr precipitation values for the East River Basin, southern portion of Klamath River Basin, and Cottonwood, Elder, Thomas, and Gladstone Creeks, California.

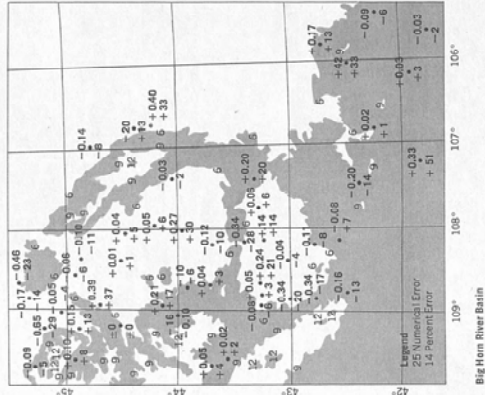
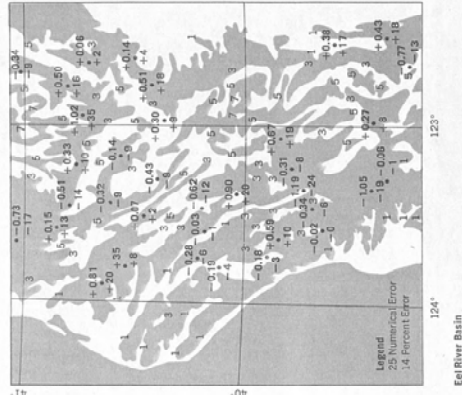


Figure 12. Geographic distribution of errors for equation used to interpolate 2-yr 24-hr precipitation values for the Big Horn River Basin above Saint Xavier, Montana, minor portions of the North Platte, Powder, and Tongue, River Basins in eastern Wyoming, and minor portions of the Yellowstone River Basin in northwestern Wyoming and southeastern Montana.

Interpretation of Results

Season of Occurrence

The maps in this Atlas are based upon data for the entire year. In certain sections of the West, precipitation is highly seasonal. Thus, rainy season precipitation-frequency values approach the annual values. In sections where the greatest annual 24-hour precipitation amount may be observed in any season, seasonal precipitation-frequency maps would differ from those presented in this Atlas. In no case could the seasonal value be greater than the annual value. However, the seasonal values would be a certain percent of the annual values, with the percent varying according to the frequency of large storms during the season under investigation. Generalizations about the seasonal distribution of large storms can be obtained from ESSA, *U.S. Weather Bureau Technical Paper No. 37* (Environmental Science Services Administration, Weather Bureau, 1966). Currently, there is no convenient manner of applying this knowledge to the maps of this Atlas, other than subjectively.

Within Vs. Among Storms

Data for the various duration maps and diagrams in this Atlas were determined independently; that is, there was no requirement that the maximum 6- or 1-hr amount for a particular year be included within the maximum 24-hr amount for that year. The maps, therefore, represent an "among" storm distribution. In regions where winter-type storms predominate, the 6-hr value for a particular return period would more closely approximate the 6-hr value within the 24-hr storm for the same return period than would generally be the case in regions where convective storms predominate. In a study for the United States east of the Mississippi River, Miller (1971) showed that the ratio between the 2-yr 1-hr value computed from the maximum 1-hr amount within the 24-hr maximum and the 2-yr 1-hr value computed using maximum 1-hr amounts varied between 0.52 and 0.91. Studies have not been undertaken of this relation in the West, but a wide range in such ratios and similar ratios for the 6-hr duration could be expected.

Point Probabilities

The maps in this Atlas are derived from used driplet point probabilities; the data points are independent of each other. Precipitation over a region is variable, even in large general area storms; neighboring stations do not necessarily experience maximum annual amounts from the same storm. Thus, the individual points on these maps express individual probabilities. That a point within a particular watershed may receive an amount equal to or greater than its 50- or 100-yr value on a particular day does not affect probabilities for any other point within that watershed. A second point within the watershed may experience an amount equal to or greater than its 50- or 100-yr value within the same storm or on the next day, within the next week or at any other time.

Areal Analysis

A value read from an isopleth map in this Atlas is the value for that point and the amount for that particular duration which will be equaled or exceeded, on the average, once during the period indicated on the individual map. In hydrologic design, engineers are more concerned with the average depth of precipitation

over an area than with the depth at a particular point. Depth-area curves were developed to meet this need. The depth-area curve is an attempt to relate the average of all point values for a given duration and frequency within a basin to the average depth over the basin for the same duration and frequency.

Generally, there are two types of depth-area relations. The first is the storm-centered relation, that is, the maximum precipitation occurring when the storm is centered on the area affected (fig. 13). The second type is the geographically fixed-area relation where the area is fixed and the storm is either centered over it or displaced to only a portion of the storm affects the area (fig. 14). We can say that storm-centered rainfall data represent profiles of discrete storms, whereas the fixed-area data are statistical averages in which the maximum point values frequently come from different storms. At times, the maximum areal value for the network is from a storm that does not produce maximum point amounts. Each type of depth-area relation is useful, but each must be applied to appropriate data. Generally, the storm-centered relations are used for preparing estimates of probable maximum precipitation, while the geographically fixed relations are used for studies of precipitation-frequency values for basins.

Dense networks of precipitation gauges are required to furnish basic data used in developing depth-area relations for fixed areas. The criteria used in selecting dense networks for the determination of areal precipitation-frequencies by the National Weather Service have been:

1. A network should be composed entirely of recording gauges. The use of nonrecording gauges may greatly increase the number and density of stations within a network, but it involves the construction of mass curves and introduces additional subjectivity. Nonrecording gauges are read at various hours, usually early morning, late afternoon, or midnight. Because of conflicting activities, a cooperative observer may not always be able to read his precipitation gauge at the exact hour specified. In these cases, the exact time of the observation may not be available, so it is hard to relate the reported amounts to those of surrounding stations with the precision required for development of depth-area relations.
2. A minimum length of record should be established to ensure a reasonable estimate of the 2-yr areal precipitation during the period of record analyzed.
3. Gauge locations and exposures should remain consistent located within each 100 square-mile area.
4. Gauges should be located so that there is at least one gauge located within each 100 square-mile area.

The average depth-area curves in this Atlas (fig. 14) are for fixed areas and were developed from dense networks meeting the above criteria. The curves were first prepared for an earlier study (U.S. Weather Bureau 1957-60) and have since been rechecked against longer record data; no changes were needed. Application of these curves must be consistent with the manner in which they were developed. The following steps are used:

1. Estimate point values from a grid of many points over the basin of interest for the duration and return period required.
2. Compute an average of the point values obtained in step 1.
3. Use figure 14 to obtain an areal reduction factor required for the precipitation duration and size of area under consideration.
4. Multiply the average value obtained in step 2 by the ratio obtained in step 3. The value obtained in this step provides the areal value for the basin of interest for the duration and return period under consideration.

Figure 13. Examples of (A) isohyetal pattern centered over basin as would be the case for storm-centered depth-area curve; and (B) two possible occurrences of isohyetal patterns over a geographically fixed area as would be the case in development of curves for a geographically fixed area.

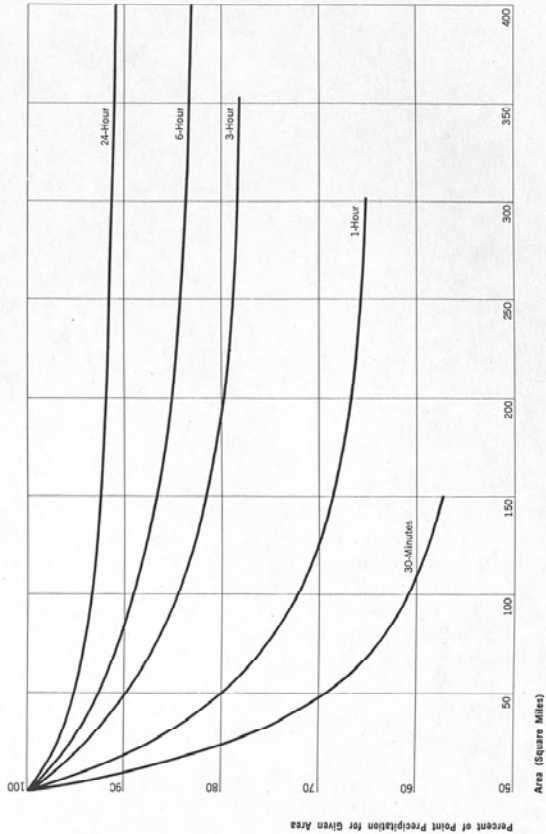
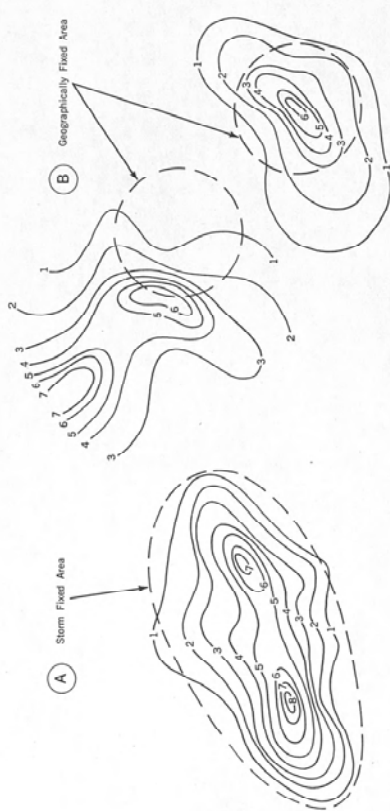


Figure 14. Depth-Area curves.

Data used to develop and validate the curves of figure 14 exhibited no systematic regional pattern. Duration turned out to be the major factor. The curves shown are based on data for the 2-yr return period. Within the accuracy of the data available, it could be shown that neither magnitude nor return period was a significant factor.

Importance of Snow in Estimating Frequency Values

The contribution of snow amounts to the precipitation-frequency values for durations of 24 hours or less has been investigated in most of the western United States. In many parts of this region, particularly at higher elevations, snow accounts for over 50 percent of the normal annual precipitation. Thus, the importance of snowfall to short-duration (6- to 24-hr) precipitation-frequency values is of interest for a more complete understanding of the precipitation-frequency regime.

Mean annual precipitation containing a high percentage of snow occurrences does not necessarily mean that snow contributed significantly to the annual series of maximum 6- or 24-hr precipitation amounts. This problem was investigated by tabulating two sets of data for all stations where snowfall observations were made routinely. The first set of data contained the greatest 24-hr (and 6-hr amounts at recording-gauge stations) precipitation amount for each year, regardless of type of precipitation (water equivalent for snowfall amounts). The second series was restricted solely to rainfall events. In some cases, the second series contained amounts as low as the fifth highest for a particular year. Results of these investigations are reported in the section for each state.

Reliability of Results

The term "reliability" is used here as an indication of the degree of confidence that can be placed in the accuracy of the results obtained from the maps. The reliability of these results is influenced by the sampling errors in time and space, and by the manner in which the maps were constructed. Sampling errors in time and space result from: (1) the chance occurrence of an anomalous storm which has a disproportionate effect on the statistics for one station, but not on those for a nearby station, and (2) the geographic distribution of stations. In the relatively nonorographic regions (shown shaded on fig. 8), the occurrence of large precipitation events can be considered to be relatively random over a limited geographic area. Thus, a large precipitation event (especially of convective nature) at a station could just as easily have occurred at a neighboring station or between stations. Results from a generalized analysis based on space-averaging techniques are considered more nearly correct than results determined from an analysis of only individual station data. In the more mountainous regions, orography has greater control on the location and magnitude of the largest storms and simple space averaging between neighboring stations is inappropriate; consideration must be given to effects of the slopes of surrounding terrain, station elevations, the intervening barrier between station location and moisture source, etc.

The locations of the stations used in the analyses are shown in figures 3 and 4. This geographic network of stations does not reveal with complete accuracy the very detailed structure of the isohyetal patterns in the mountainous regions of the West. The multiple regression equations discussed earlier were used to help in interpolation between values computed for these stations. The standard error of estimate for these relations should be considered when using the precipitation-frequency values shown on the maps. In general, the accuracy of the estimates obtained from the maps of this Atlas varies from a minimum of about 10 percent for the shorter return periods in relatively nonorographic regions to 20 percent for the longer return periods in the more rugged orographic regions.

The values shown on these maps are in general agreement with those of *Weather Bureau Technical Paper No. 40* (U.S. Weather Bureau 1961). Differences are found because of the greater attention paid to physiographic features in the present study. Even though the precipitation-frequency maps presented are prepared considering physiographic factors, only those of a major scale could be considered. There are some basins, therefore, that are more sheltered or exposed than a generalized topographic map would indicate. The map values may not be representative of the precipitation regimes in such basins.

The major centers of large precipitation-frequency values are located on the most exposed and steepest slopes of the mountains. Objective studies (such as the regression analysis previously discussed) and experience in precipitation-frequency analysis have indicated some general guidelines for the placement of isohyetal centers along crests and on slopes of mountain ranges. Two examples will serve to illustrate such guidelines. For an initial completely exposed orographic barrier, where the crest of the range was 3,000 to 4,000 ft. above the plains region to the windward of the mountain and the slope was on the order of 300 ft per mile, the largest isohyetal line should extend past the crest and include a

little of the lee side of the mountain. Where the crest of the range was 8,000 to 10,000 ft above the plains region to the windward of the mountain range and the slope was on the order of 1,000 ft per mile, the isohyetal center would generally be about 4,000 to 6,000 ft above the plains region. For mountain ranges with crests and slopes having other combinations of these values, the placement of the highest precipitation-frequency values would depend upon the degree of exposure of the mountain range to moisture-bearing wind, the steepness of the slope, the height of the crest, and other orographic factors. In general, isohyetal centers for the longer return periods tend to be located at lower elevations than the factors for the shorter return periods. The distance downslope that the center is displaced depends on the exposure and steepness of the slope. Centers will be displaced less on a steep slope than on a gentle slope similarly exposed.

California

Discussion of Maps

Figures 20 through 31 present precipitation-frequency maps for California north of 37° N., and figures 32 to 43 present maps for California south of 37° N. Each set contains maps for 6- and 24-hr durations for return periods of 2, 5, 10, 25, 50, and 100 yrs. The isopleth maps represent the 360- and 1,440-min durations for the partial-duration series. Data were tabulated for clock and observation-day intervals for the annual series and were adjusted by the empirical factors given in the ANALYSIS section.

Isoline interval. Because of the variety of climates represented in different sections of California, the use of a constant isoline interval was neither possible nor desirable. An isoline interval adequate for one area, duration, or return period might prove to be either too large or too small to adequately depict the isopleth interval for another area, duration, or return period. Thus, the isoline intervals selected were designed to provide a reasonably complete description of the isopleth pattern present in each area at each duration and return period. All isolines are clearly labeled and changes in interval from one area to another should present no problems. Dashed intermediate lines have been placed between widely separated isolines and in regions where a linear interpolation between the normal isopleth interval would lead to erroneous interpolation. "Lows" that close within the boundaries of a particular map have been hatched on the low-valued side of the isoline. Values read for points north of 37° should be read from figures 20 to 31 and for points south of 37° reading should be from the maps for southern California (figures 32 to 43).

Importance of snow in precipitation-frequency values. The maps in this Atlas represent frequency values of precipitation regardless of type. For many hydrologic purposes, precipitation falling as rain must be treated in a different manner from that falling as snow. The contribution of snow amounts to precipitation-frequency values in the Pacific Northwest (National Oceanic and Atmospheric Administration 1973) included data from portions of northern California (Regions 1 and 2, fig. 18). This study indicated that snow was a contributing factor to precipitation-frequency values at the higher elevations of the Cascades and immediately to the lee of the crest of the Cascades. The available data indicate that the 2-yr 24-hr values for a series containing only rain events would be 10 to 20 percent lower than the values presented on the precipitation-frequency maps in this Atlas at elevations of 2,000 to 4,000 ft, and the differences above 4,000 ft would range upward, reaching 30 and possibly as much as 50 percent lower above 5,000 ft. The area to the lee of the crest of the Cascades would be limited to somewhat less than 50 miles in width, and in this narrow band, the rain-only series would be from 20 to as much as 35 percent less than the values presented on the 2-yr 24-hr map for California. Estimates for longer return periods would be obtained as outlined below.

For the remainder of California, 59 stations have concurrent observations of daily precipitation and daily snowfall amounts. Nineteen of these stations are equipped with recording rain gauges. For the 59 stations with snowfall data, two series were tabulated as discussed under Interpretation of Results, Importance of Snow in Estimating Frequency Values.

Region 5 (fig. 18), a spillover zone in the lee of the Sierra Nevada and Coast Ranges, extends a short way into Nevada but

is mostly in California. For this reason, three stations with concurrent precipitation and snowfall observations in the Nevada portion of the spillover zone were included with the California data sample. Data from these three stations were tabulated and analyzed in the same manner as the California data.

Examination of the data sample from the 62 stations indicated that at elevations below 4,000 ft there were practically no differences in the return period between the two series of data analyzed; i.e., the estimation of amounts containing some snow did not affect the precipitation-frequency values. At stations with elevations above 4,000 ft, the ratio between the two data series did not reveal a geographic pattern when plotted on a map. Elimination of stations with elevations less than 4,000 ft reduced the data sample to 41 stations. One of these, White Mountain No. 2 (elevation 12,470 ft), had no maximum annual 24-hr event that did not contain snow; and in 2 of the 14 yrs, there were no daily precipitation amounts that consisted entirely of rain. At White Mountain No. 1 (elevation 10,150 ft), only three of the 14 other concurrent observations of short-duration (6- and 24-hr) precipitation and snowfall were available above 8,000 ft, and since the White Mountains extend in California, it was concluded that there is a high probability that the maximum annual precipitation event at elevations above 10,000 ft will be at least partially snow.

The remaining 35 stations had elevations between 4,000 and 8,000 ft. These data were analyzed using regression techniques, and the following relation was found between the series consisting of rain-only values and those containing the maximum annual event without regard to rain or snow:

$$R_{24/6} = 1.33 + 0.885P_{24/6} - 0.029h \quad (3)$$

where $R_{24/6}$ is the 2-yr 24-hr value for the rain-only series, $P_{24/6}$ is the 2-yr 24-hr value computed using all data without regard to type of precipitation (the value indicated on the maps presented), and h is the elevation in hundreds of ft. The addition of other parameters (latitude or longitude for instance) did not materially improve the correlation coefficient, which was well over 0.9. The standard error of estimate of the above equation is less than 15 percent of the mean rain-only 2-yr 24-hr value.

For the 6-hr duration, the differences between the rain-only and all-precipitation series were ones again little or no consequence below 4,000 ft. Between 4,180 and 7,020 ft, there was a data sample of 12 stations. Regression analysis resulted in the following equation:

$$R_{6/6} = 0.641 + 0.871P_{6/6} - 0.12h \quad (4)$$

where $R_{6/6}$ is the 2-yr 6-hr value for the rain-only series, $P_{6/6}$ is the 2-yr 6-hr value computed using all data without regard to type of precipitation (the value indicated on the maps presented), and h is the elevation in hundreds of ft. The coefficient of correlation for this equation is 0.98. The standard error of estimate of this equation is less than 10 percent of the mean rain-only 2-yr 6-hr value.

These two equations can be used to obtain estimates of the rain-only 2-yr return-period values for 6- and 24-hr duration for elevations between 4,000 and 8,000 ft. At the 25-yr return period, there were no differences between results obtained from the two data series for any portion of California. Therefore, it is suggested that to develop rain-only series from 2 to 25 yrs for a

particular location the 2-yr value from the 6- or 24-hr equation be plotted on the return-period diagram (fig. 6). The 25-yr return-period value should be obtained from the maps and a straight line drawn to connect the 2-yr and 25-yr values. For return periods greater than 25 yrs, there are no differences between the two series, and values may be obtained directly from the maps.

The uses of these equations will result in some discontinuities; for example a) along the southern boundary of Regions 1 and 2 (fig. 18) and b) at adjacent points near the elevation bounds stated earlier, e.g., one point may be just under 4,000 ft and the other somewhat over 4,000 ft. Discontinuities of meteorological variables do not exist in nature. Steep gradients normally occur only along major ridge lines or other significant topographic features. The user must keep in mind that these boundaries are the center of a zone of transition from one regime to another. It is suggested that when making estimates along or within a few miles of such boundaries such estimates should include consideration of conditions outlined for both areas and a compromise estimate be adopted.

Results found at the differing elevations are meteorologically realistic. Temperatures usually become colder with increasing elevation. Therefore, large storms may very well bring snow at higher elevations while causing rain at lower elevations. The suggested procedures show no difference between the two sets of curves at the lowest elevations (below 4,000 ft). At intermediate elevations (4,000 to 8,000 ft), differences between the two sets of curves are restricted to the shorter return periods. This is reasonable, since at these elevations the largest storms are almost always associated with an influx of warm air through the lowest levels of the atmosphere. At the highest elevations (above 10,000 ft), the limited data indicate that the only maximum annual events that are all rain come with the smaller storms occurring either early or late in the rainy season (when temperatures are normally warmer than at the height of the rainy season). Such events produce the maximum annual amount only in seasons having no really large storm at the height of the rainy season. If a rain-only frequency curve could be defined for this region, it would show only small values.

There are no concurrent snow and rainfall data at elevations between 8,000 and 10,000 ft. A logical assumption is to expect increasing differences between frequency values based only on rain events and those based on all precipitation events within this elevation band.

Procedures for Estimating Values for Durations Other Than 6 and 24 Hrs

The isopleth maps in this Atlas are for 6- and 24-hr durations. For many hydrologic purposes, values for other durations are necessary. Such values can be estimated using the 6- and 24-hr maps and the empirical methods outlined in the following sections. The procedures detailed below for obtaining 1-, 2-, and 3-hr estimates were developed specifically for this Atlas. The procedures for obtaining estimates for less than 1-hr duration and for 12-hr duration were adopted from *Weather Bureau Technical Paper No. 40* (U.S. Weather Bureau 1961) only after investigation demonstrated their applicability to data from the area covered by this Atlas.

Procedures for estimating 1-hr (60-min) precipitation-frequency values. Multiple-regression screening techniques were used to develop equations for estimating 1-hr values. Factors considered in the screening process were restricted to those that could be determined easily from the maps of this Atlas or from generally available topographic maps.

The 11 western states were separated into several geographic regions. The regions were chosen on the basis of meteorological and climatological homogeneity and are generally composed of river basins separated by prominent divides. There are seven of these regions, some entirely and others only partially, within California. For convenience and use as an overlay on the precipitation-frequency maps, these areas are outlined in figures 18 and 19. Region 1, figure 18, consists of the northern part of the Coast Ranges and western slopes of the Siakyou and Salmon Mountains in California. It is the southernmost part of a larger region extending into Oregon and Washington and consisting generally of the Olympic Mountains, the Coast Ranges, and the western slopes of the Cascade Range. Region 2, figure 18, also extends into Oregon and Washington. This is part of a larger region that includes all the mountainous sections from the crest of the Cascades eastward to the Continental Divide and north of the southern boundary of the Snake River Basin, the Uinta Mountains in Utah, and Danforth Hills in Colorado. The mountainous area along the coast (Region 3, figs. 18 and 19) is comprised of the Eel River Basin; southern portion of the Klamath River Basin; Cotwood, Elder, Thomas, and Gladstone Creeks; Russian River, Cache and Punch Creeks, and coastal drainages west of the Russian River; Santa Cruz Mountains and La Panza, Santa Lucia, and Coast Ranges; Diablo, Gabilan, and Temblor Ranges; San Rafael, San Bernardino, Santa Monica, and San Gabriel Mountains; and the Santa Ana, Santa Rosa, Coyote, and other southern coastal mountains with their spillover zones. Region 4 (figs. 18 and 19) consists of the Sacramento and San Joaquin Valleys and areas of coastal lowlands below 1,000 ft. The Sierra Nevada, including the spillover zone extending into Nevada, comprises Region 5 (figs. 18 and 19). Region 6 (figs. 18 and 19) is the westernmost portion of a large region without major barriers that extends from central Utah through Nevada and into the desert regions of California. Region 7 (fig. 19) is that portion of California defined by the lower Colorado River. This region extends from the Continental Divide, the Sierra de Cristo Range, and the Sacramento Mountains in Colorado and New Mexico westward to southeastern California, the Virgin River Basin in Nevada, and the Wasatch divide in Utah. Equations to provide estimates for the 1-hr duration and for 2- and 100-yr return periods are shown in table 11. Also listed are the statistical parameters associated with each equation. The variable $(X_1)(X_2)(X_3)$ or $(X_3)(X_2)(X_1)$ can be regarded as the 6-hr value times the slope of a line connecting the 6- and 24-hr values for the appropriate return period. The variable Y_2 appears in the right side of the 100-yr 1-hr equations for Regions 1, 3, 4, and 5. If the 2-yr 1-hr value is not required, the equation for Y_2 can be substituted, and the second equation for Y_{100} shown in table 11 can be used.

As with any separation into regions, the boundary can only be regarded as the sharpest portion of a zone of transition between regions. These equations have been tested for boundary discontinuities by computing values using equations from both sides of the

Table 11. Equations for estimating 1-hr values in California with statistical parameters for each equation

| Region of applicability* | Equation | Corr. coeff. | No. of stations | Mean of computed stn. values (inches) | Standard error of estimate (inches) |
|---|--|--------------|-----------------|---------------------------------------|-------------------------------------|
| Northern Coast Ranges and western slopes of Siakiyou and Salmon Mountains (1) | $Y_2 = 0.160 + 0.520[(X_1)(X_2)/X_3]$ | .96 | 70 | 0.54 | 0.054 |
| | $Y_{100} = 0.177 + 0.965[(X_1)(X_2)/X_3]$ | .74 | 66 | 1.10 | .171 |
| | $Y_{100} = 0.177 + 0.154(X_1/X_2)$ | | | | |
| Mountainous regions east of crest of Cascade Range, west of Continental Divide, and north of southern boundary of Snake River Basin (2) | $Y_2 = 0.019 + 0.711[(X_1)(X_2)/X_3]$ | .82 | 98 | 0.40 | .031 |
| | $Y_{100} = 0.338 + 0.670[(X_1)(X_2)/X_3]$ | .80 | 79 | 1.04 | .141 |
| | $Y_{100} = 0.001Z$ | | | | |
| Coast Ranges of California, including spillover zones, from Klamath River Basin in north to Mexican border (3) | $Y_2 = 0.111 + 0.545[(X_1)(X_2)/X_3]$ | .91 | 71 | 0.64 | .073 |
| | $Y_{100} = 0.221 + 0.885[(X_1)(X_2)/X_3]$ | .81 | 71 | 1.44 | .294 |
| | $Y_{100} = 0.221 + 0.098(X_1/X_2)$ | | | | |
| Sacramento and San Joaquin River Valleys and coastal lowlands below 1,000 ft (4) | $Y_2 = 0.107 + 0.315(X_1)$ | .90 | 65 | 0.59 | .054 |
| | $Y_{100} = -0.391 + 1.224[(X_1)(X_2)/X_3]$ | .87 | 63 | 1.30 | .207 |
| | $Y_{100} = -0.391 + 0.131[(X_1)(X_2)/X_3]$ | | | | |
| Sierra Nevada, including its spillover zone (5) | $Y_2 = 0.126 + 0.561[(X_1)(X_2)/X_3]$ | .90 | 57 | 0.58 | .057 |
| | $Y_{100} = -0.030 + 0.816[(X_1)(X_2)/X_3]$ | .78 | 57 | 1.36 | .249 |
| | $Y_{100} = -0.030 + 0.063(X_1)$ | | | | |
| Southeastern desert region of Lower Colorado River Basin within California (6) | $Y_2 = 0.005 + 0.852[(X_1)(X_2)/X_3]$ | .89 | 65 | 0.41 | .047 |
| | $Y_{100} = 0.322 + 0.789[(X_1)(X_2)/X_3]$ | .87 | 65 | 1.25 | .196 |
| | $Y_{100} = -0.011 + 0.942[(X_1)(X_2)/X_3]$ | .95 | 86 | 0.72 | .085 |
| California (7) | $Y_{100} = 0.494 + 0.755[(X_1)(X_2)/X_3]$ | .90 | 85 | 1.96 | .290 |
| | | | | | |

* Numbers in parentheses refer to geographic regions shown in figure 18 and/or 19. See text for more complete description.

List of variables

- Y_2 = 2-yr 1-hr estimated value
- Y_{100} = 100-yr 1-hr estimated value
- X_1 = 2-yr 6-hr value from precipitation-frequency maps
- X_2 = 2-yr 24-hr value from precipitation-frequency maps
- X_3 = 100-yr 6-hr value from precipitation-frequency maps
- X_4 = 100-yr 24-hr value from precipitation-frequency maps
- X_5 = latitude (in decimals) minus 32°
- Z = elevation in hundreds of feet

boundary. Differences were found to be mostly under 15 percent. However, it is suggested that when computing estimates along or within a few miles of a regional boundary, computations be made using equations applicable to each region and that the average of such computations be adopted.

Estimates of 1-hr precipitation-frequency values for return periods between 2 and 100 yrs. The 1-hr values for the 2- and 100-yr return periods can be plotted on the nomogram of figure 6 to obtain values for return periods greater than 2 yrs or less than 100 yrs. Draw a straight line connecting the 2- and 100-yr values and read the desired return-period value from the nomogram.

Estimates for 2- and 3-hr (20- and 180-min) precipitation-frequency values. To obtain estimates of precipitation-frequency values for 2 or 3 hr, plot the 1- and 6-hr values from the Atlas on the appropriate nomogram of figure 15. Draw a straight line connecting the 1- and 6-hr values, and read the 2- and 3-hr values from the nomogram. This nomogram is independent of return period. It was developed using data from the same regions used to develop the 1-hr equations.

The mathematical solution from the data used to develop figure 15 gives the following equations for estimating the 2- and 3-hr values:

- For Regions 1, 2-hr = $0.240(6\text{-hr}) + 0.760(1\text{-hr})$ (5)
- 3-hr = $0.468(6\text{-hr}) + 0.532(1\text{-hr})$ (6)
- and/or 19
- For Region 2, 2-hr = $0.250(6\text{-hr}) + 0.750(1\text{-hr})$ (7)
- 3-hr = $0.467(6\text{-hr}) + 0.533(1\text{-hr})$ (8)
- For Region 6, 2-hr = $0.299(6\text{-hr}) + 0.701(1\text{-hr})$ (9)
- figure 18 and/or 19 3-hr = $0.526(6\text{-hr}) + 0.474(1\text{-hr})$ (10)
- For Region 7, 2-hr = $0.341(6\text{-hr}) + 0.659(1\text{-hr})$ (11)
- figure 19 3-hr = $0.569(6\text{-hr}) + 0.431(1\text{-hr})$ (12)

Estimates for 12-hr (720-min) precipitation-frequency values. To obtain estimates for the 12-hr duration, plot values from the 6- and 24-hr maps on figure 16. Read the 12-hr estimates at the intersection of the line connecting these points with the 12-hr duration line of the nomogram.

Estimates for less than 1 hr. To obtain estimates for durations of less than 1 hr, apply the values in table 12 to the 1-hr value for the return period of interest.

Illustration of Use of Precipitation-Frequency Maps, Diagrams, and Equations

To illustrate the use of these maps, values were read from figures 32 to 43 for the point at 34°00' N. and 117°00' W. These values are shown in boldface type in table 13. The values read from the maps should be plotted on the return-period diagram of figure 6 because (1) not all points are as easy to locate on a series of maps as are latitude-longitude intersections, (2) there may be some slight registration differences in printing, and (3) precise interpolation between isolines is difficult. This has been done for the 24-hr values in table 13 (fig. 17a) and a line of best fit has been drawn subjectively. On this nomogram, the 5- and 10-yr values appear to be somewhat off the line. The value read from the maps is corrected (as shown by the knockout in table 13); such corrected values are adopted in preference to the original readings.

The 2- and 100-yr 1-hr values for the point were computed from the equations applicable to Region 3, figures 18 and 19 (table 11). The 2-yr 1-hr is estimated at 0.60 in. (2-yr 6- and 24-hr values from table 13); the estimated 100-yr 1-hr value is 1.38 in. (100- and 2-yr 6-hr from table 13 and 2-yr 1-hr as computed above). By plotting these 1-hr values on figure 6 and connecting them with a straight line, one can obtain estimates for return periods of 5, 10, 25, and 50 yrs.

The 2- and 3-hr values can be estimated by using the proper nomogram of figure 15 or equations (3) and (4). The 1- and 6-hr values for the desired return period are obtained as above. Plot these points on the nomogram of figure 15 and connect them with a straight line. Read the estimates for 2 or 3 hrs at the intersections of the connecting line and the 2- and 3-hr vertical lines. In the example shown in figure 17b, the intersections are close to the values of 0.84 and 1.07, which would result from application of equations (3) and (4).

Table 12. Adjustment factors to obtain n-min estimates from 1-hr values

| Duration (min) | 5 | 10 | 15 | 30 |
|----------------|------|------|------|------|
| Ratio to 1-hr | 0.29 | 0.45 | 0.57 | 0.79 |

(Adopted from U.S. Weather Bureau Technical Paper No. 40, 1961.)

Table 13. Precipitation data for depth-frequency atlas computation point 34°00' N., 117°00' W.

| | 1-hr | 2-hr | 3-hr | 6-hr | 24-hr |
|--------|------|------|------|------|-------|
| 2-yr | 0.60 | 0.84 | 1.07 | 1.60 | 2.85 |
| 5-yr | | | | 1.86 | 4.10 |
| 10-yr | | | | 2.20 | 4.88 |
| 25-yr | | | | 2.78 | 5.90 |
| 50-yr | | | | 3.00 | 6.75 |
| 100-yr | 1.38 | | | 3.50 | 7.75 |

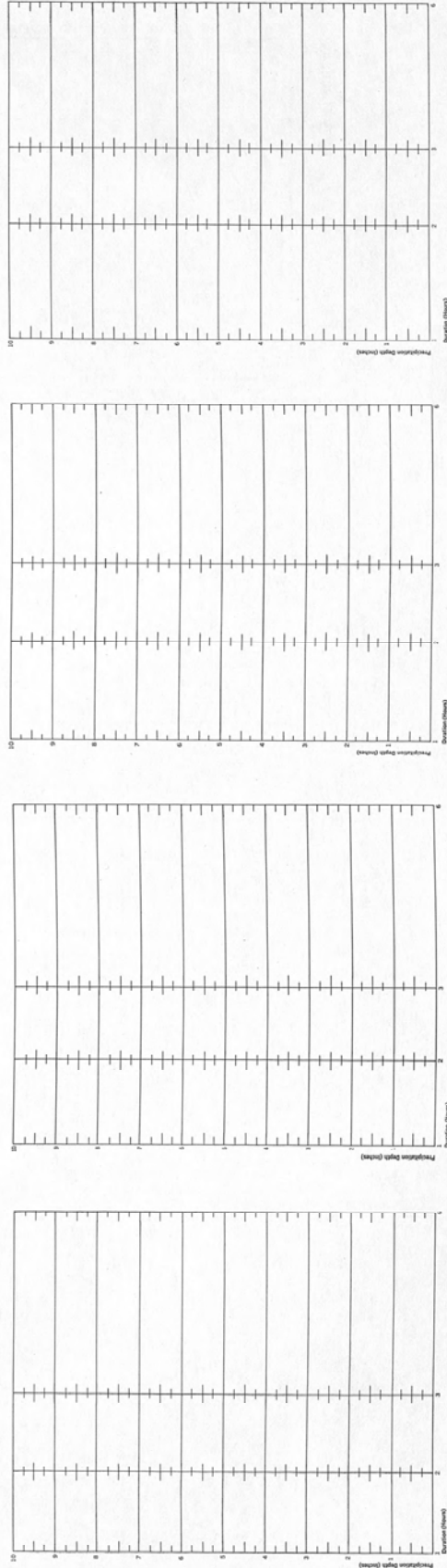


Figure 15. Precipitation depth-duration frequency (1- to 6-hr).
 a. Northern Coast Ranges and western slopes of Sierrita and Salmon Mountains (Region 1, fig. 18).
 Coast Ranges of California, including spillover areas, from Klamath River Basin in north to Mexican border (Region 5; figs. 18 and 19).
 Sacramento and San Joaquin River Valleys and coastal lowlands below 1,000 ft (Region 4, figs. 18 and 19).

b. Mountainous regions east of crest of Cascade Range, west of Continental Divide, and north of the southern boundary of the Snake River Basin (Region 2, fig. 18).

c. Southeastern desert region of California (Region 6, figs. 18 and 19).

d. Lower Colorado River Basin within California (Region 7, fig. 19).

Figure 17. Illustration of use of precipitation-frequency diagrams using values from precipitation-frequency maps and relations.

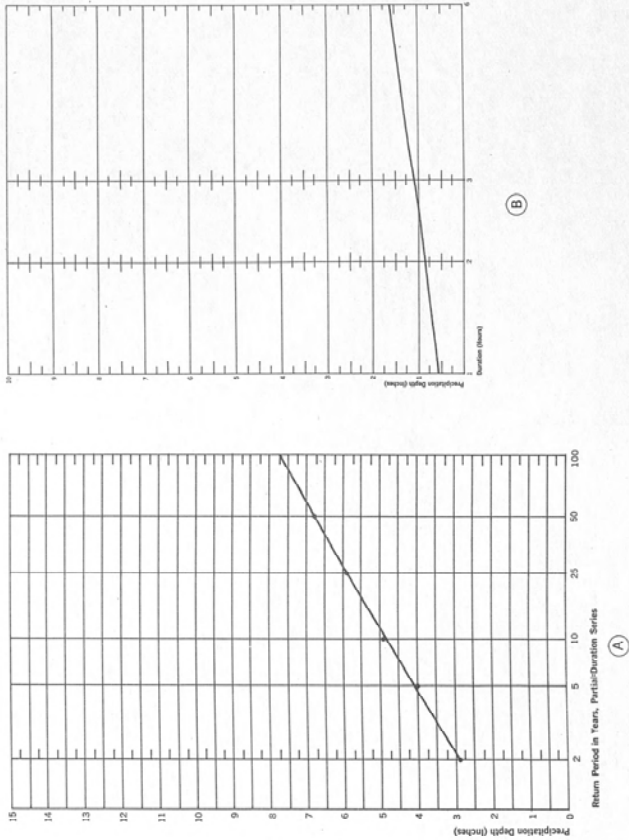
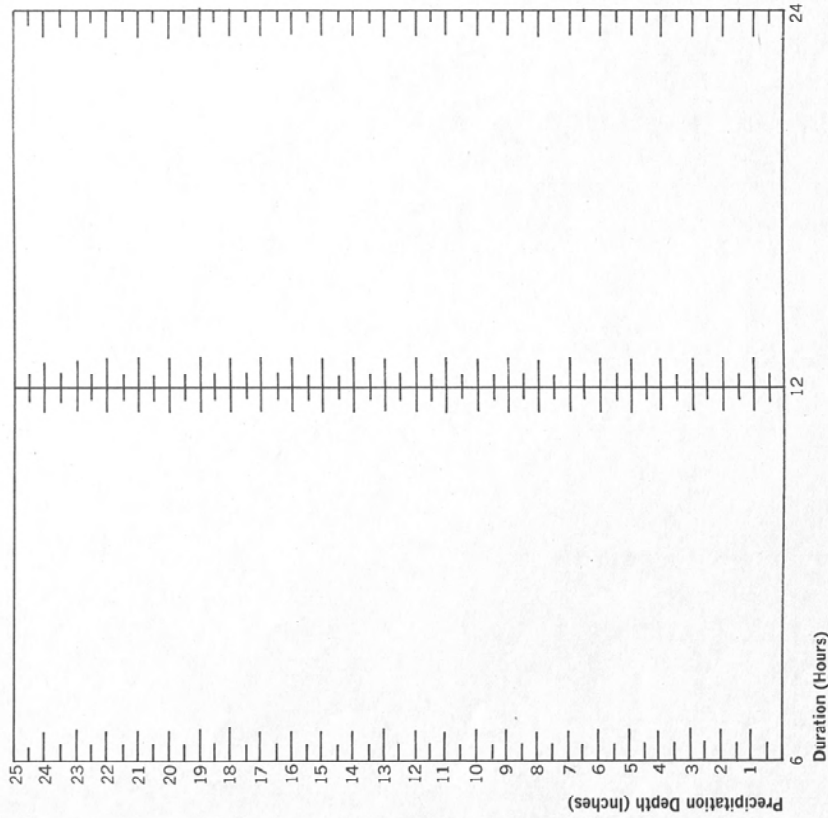
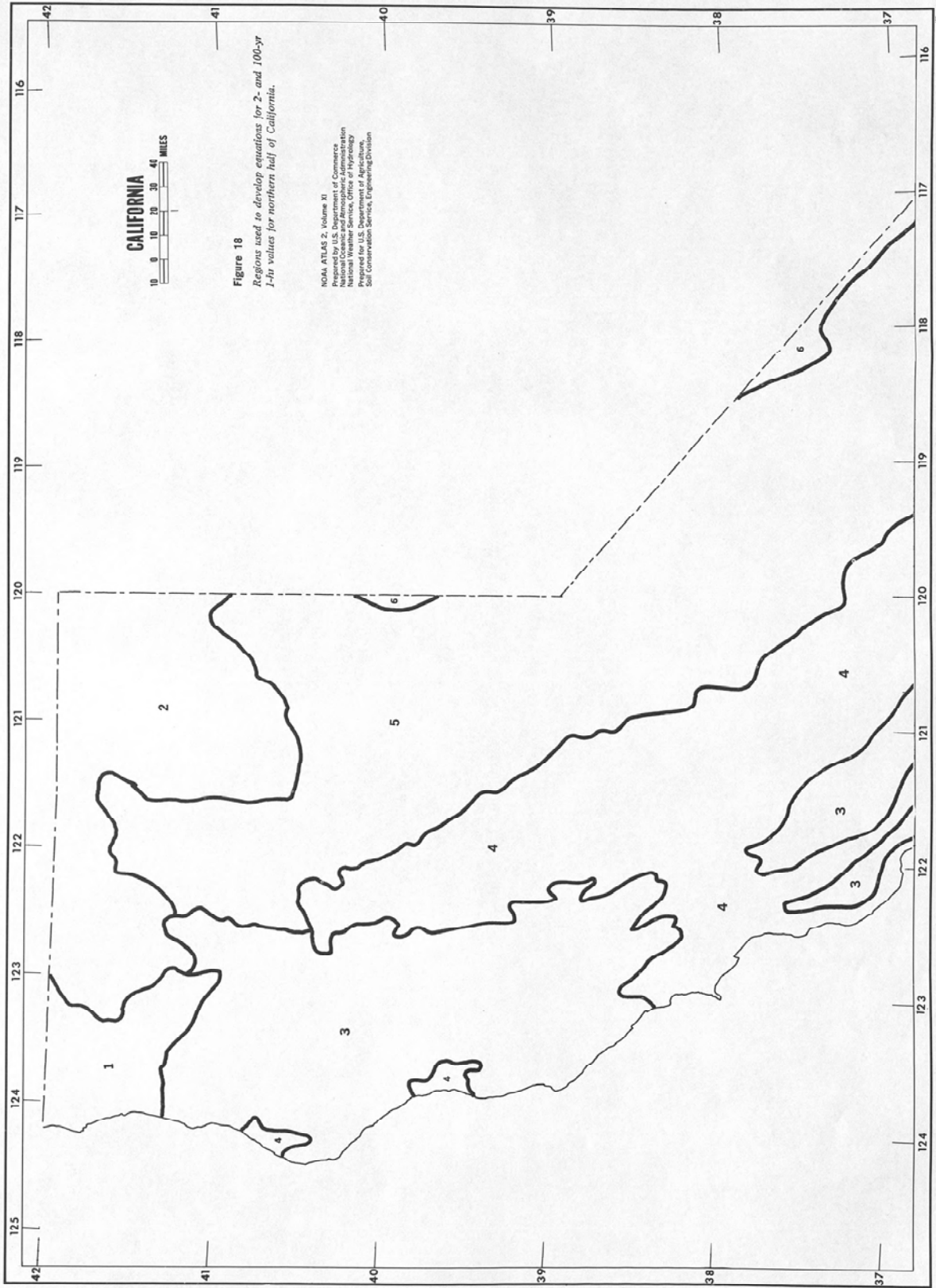


Figure 16. Precipitation depth-duration diagram (6- to 24-hr).





CALIFORNIA



Figure 18
*Regions used to develop equations for 2- and 100-yr
 1-hr values for northern half of California.*

NOAA ATLAS 2, Volume XI
 Prepared by U.S. Department of Commerce
 National Weather Service, Office of Hydrology
 Prepared for U.S. Department of Agriculture,
 Soil Conservation Service, Engineering Division

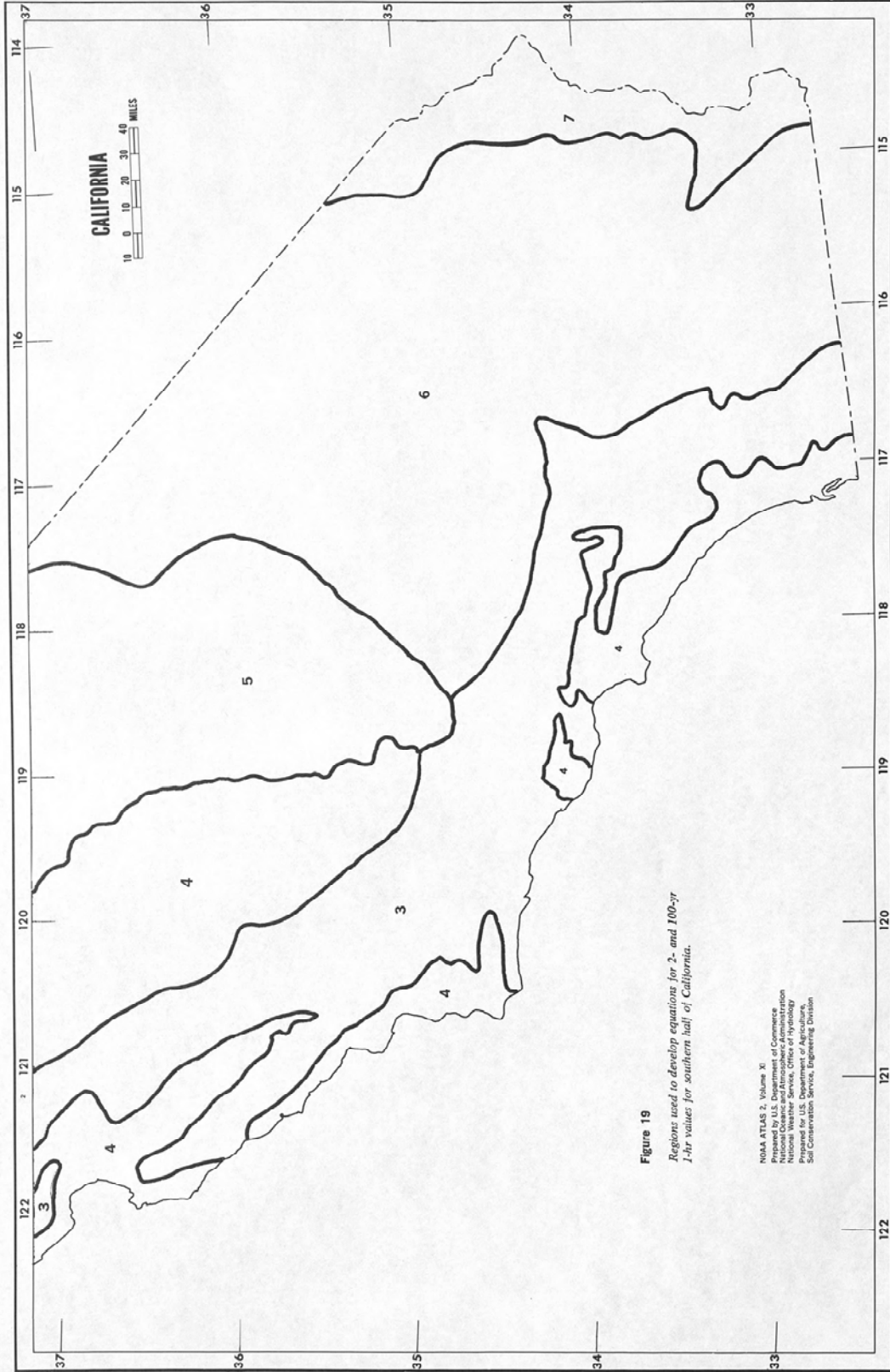
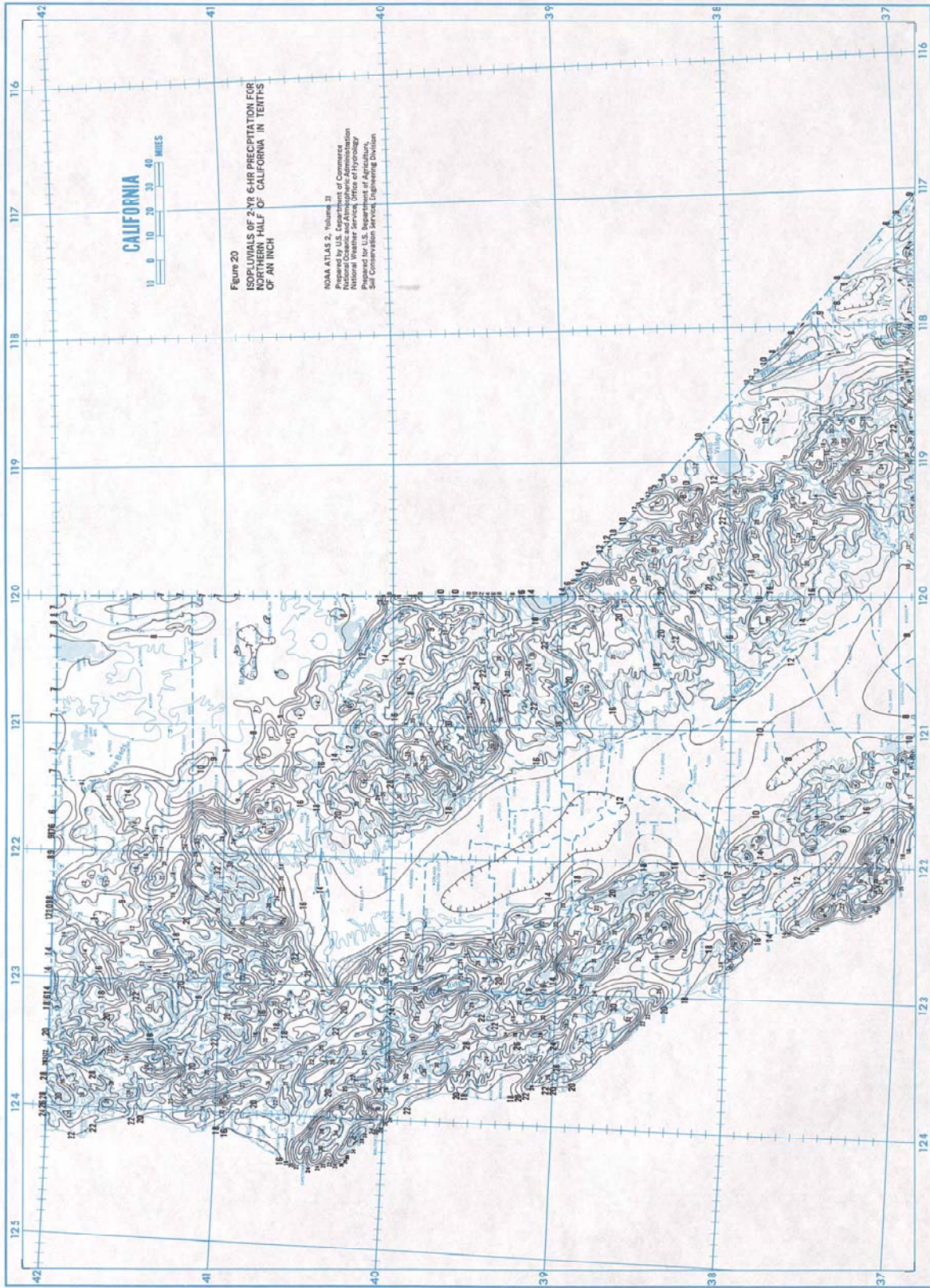


Figure 19
*Regions used to develop equations for 2- and 100-yr
 1-hr values for southern half of California.*

NOAA ATLAS 2, Volume XI
 Prepared by U.S. Department of Commerce
 National Oceanic and Atmospheric Administration
 National Weather Service, Office of Hydrology
 Prepared for U.S. Department of Agriculture,
 Soil Conservation Service, Engineering Division





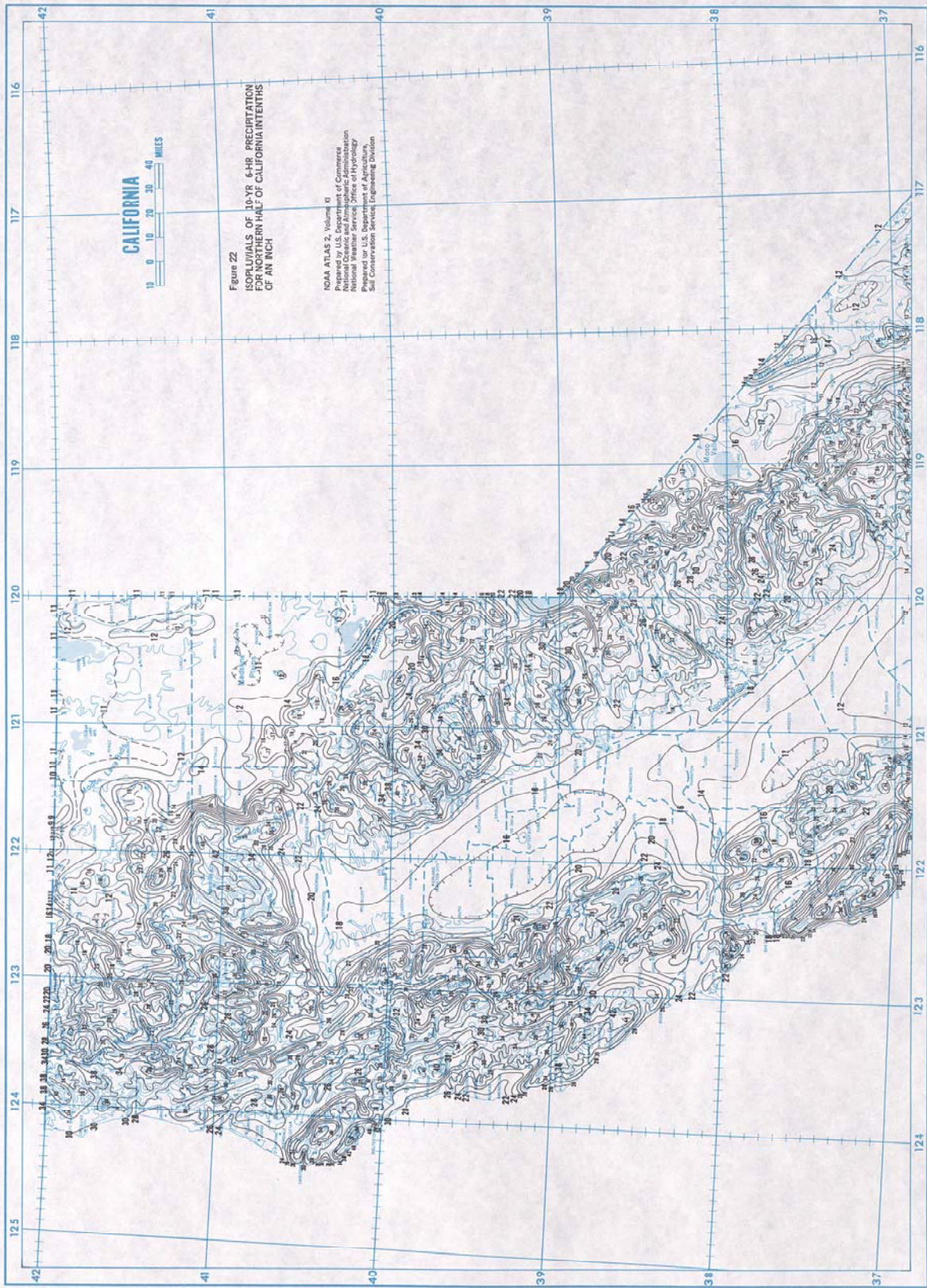
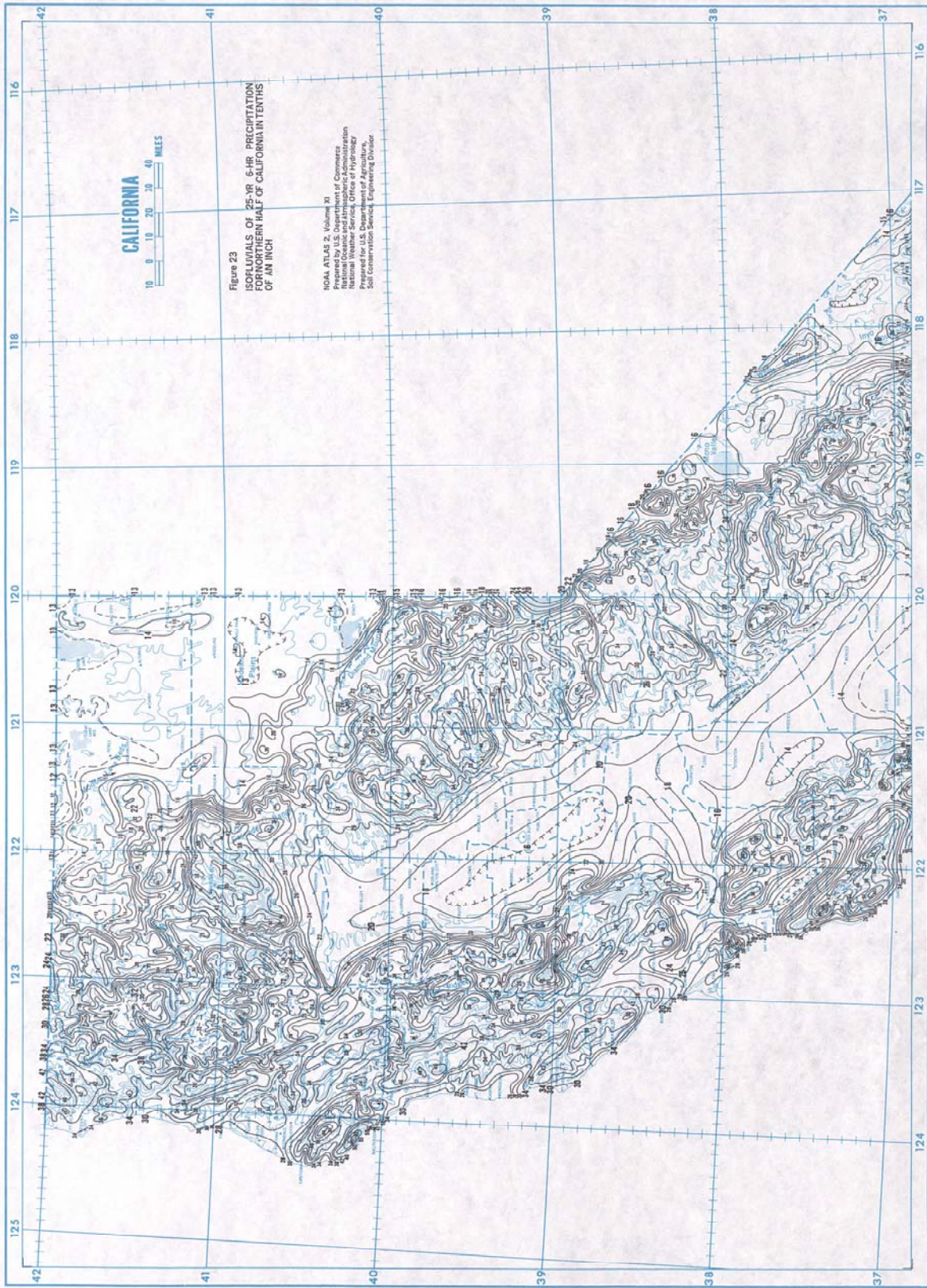
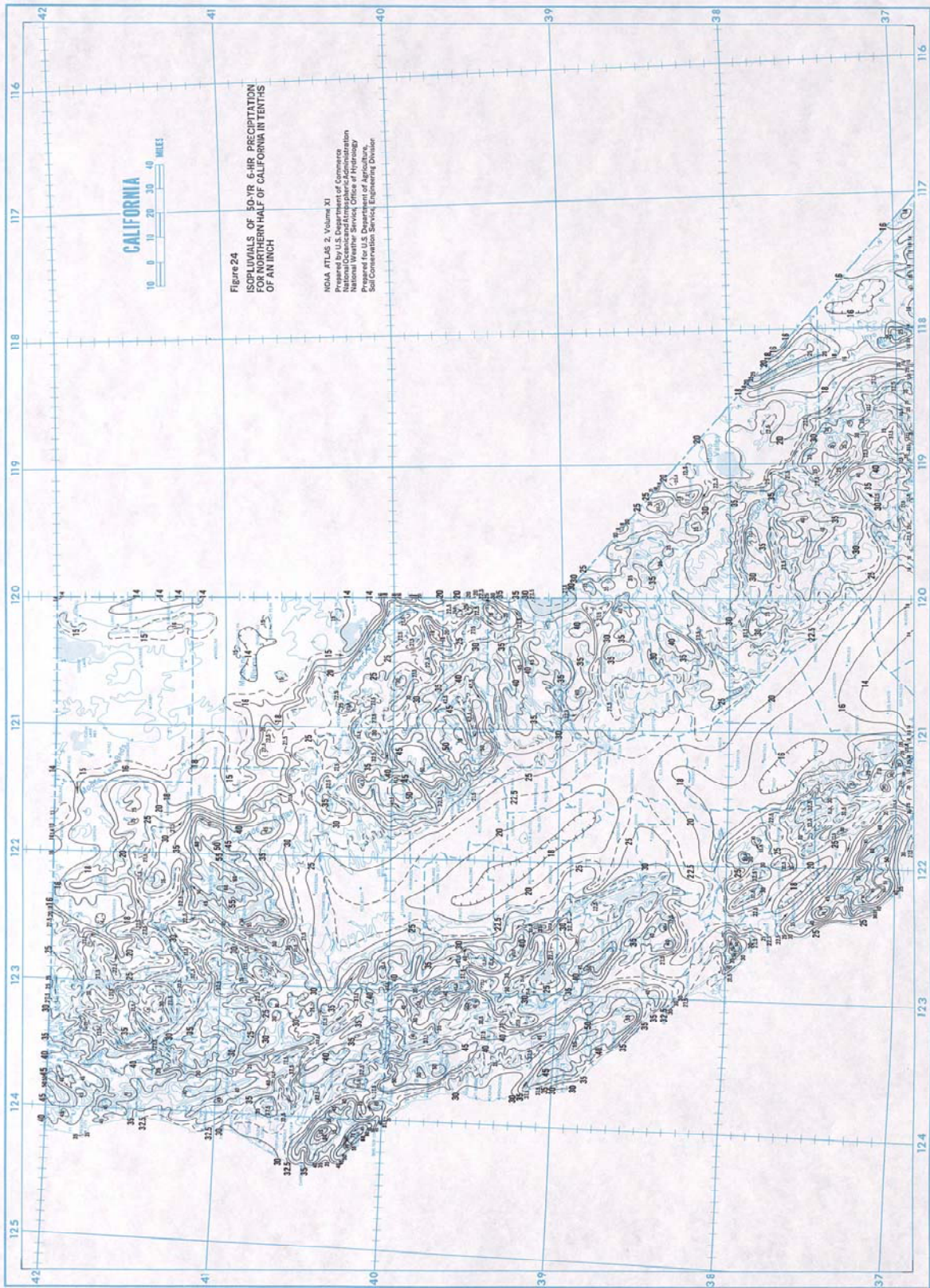


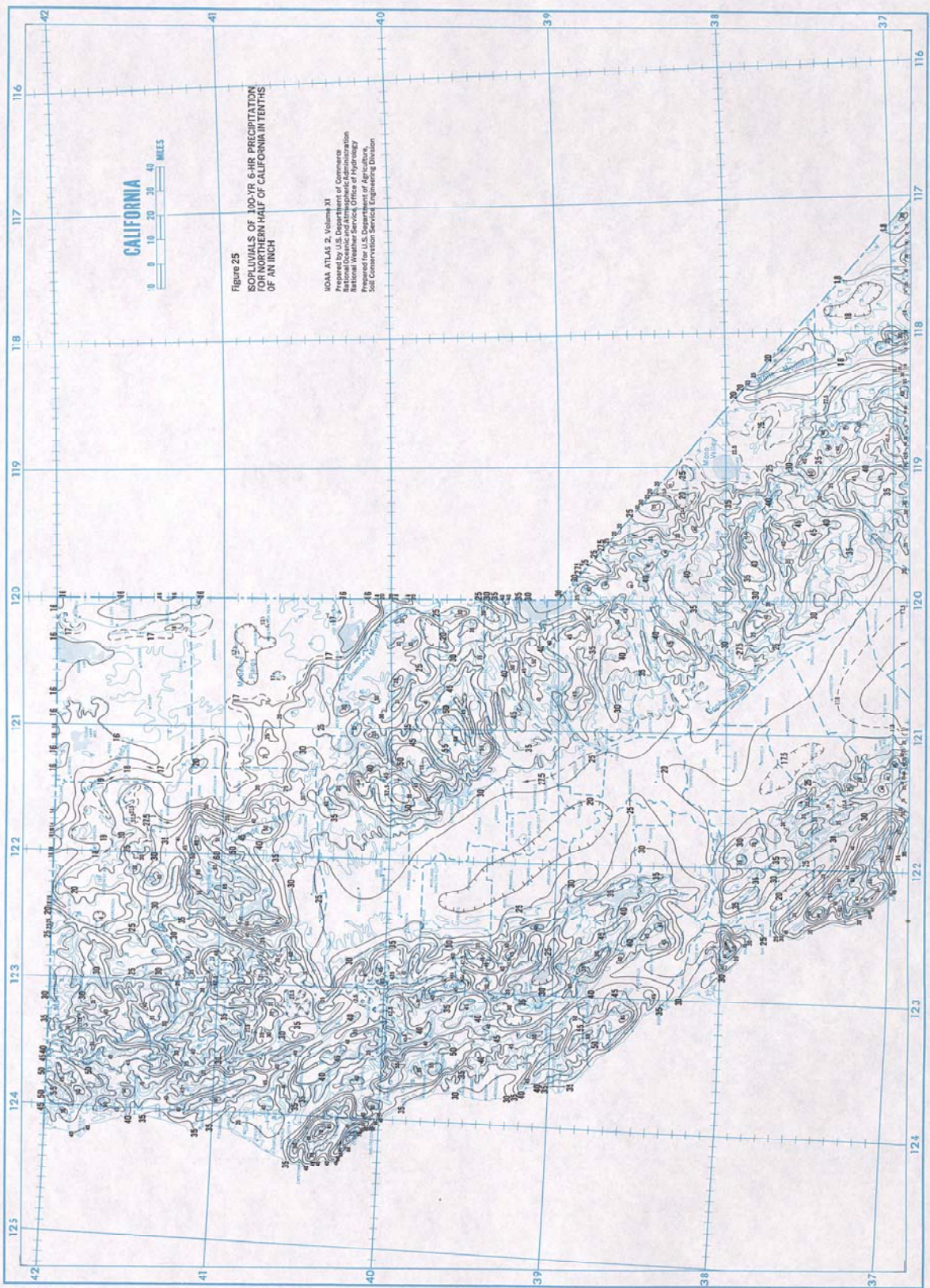
Figure 22
ISOHYETALS OF 10-YR 6-HR PRECIPITATION
OF THE SOUTHERN HALF OF CALIFORNIA IN TENTHS
OF AN INCH

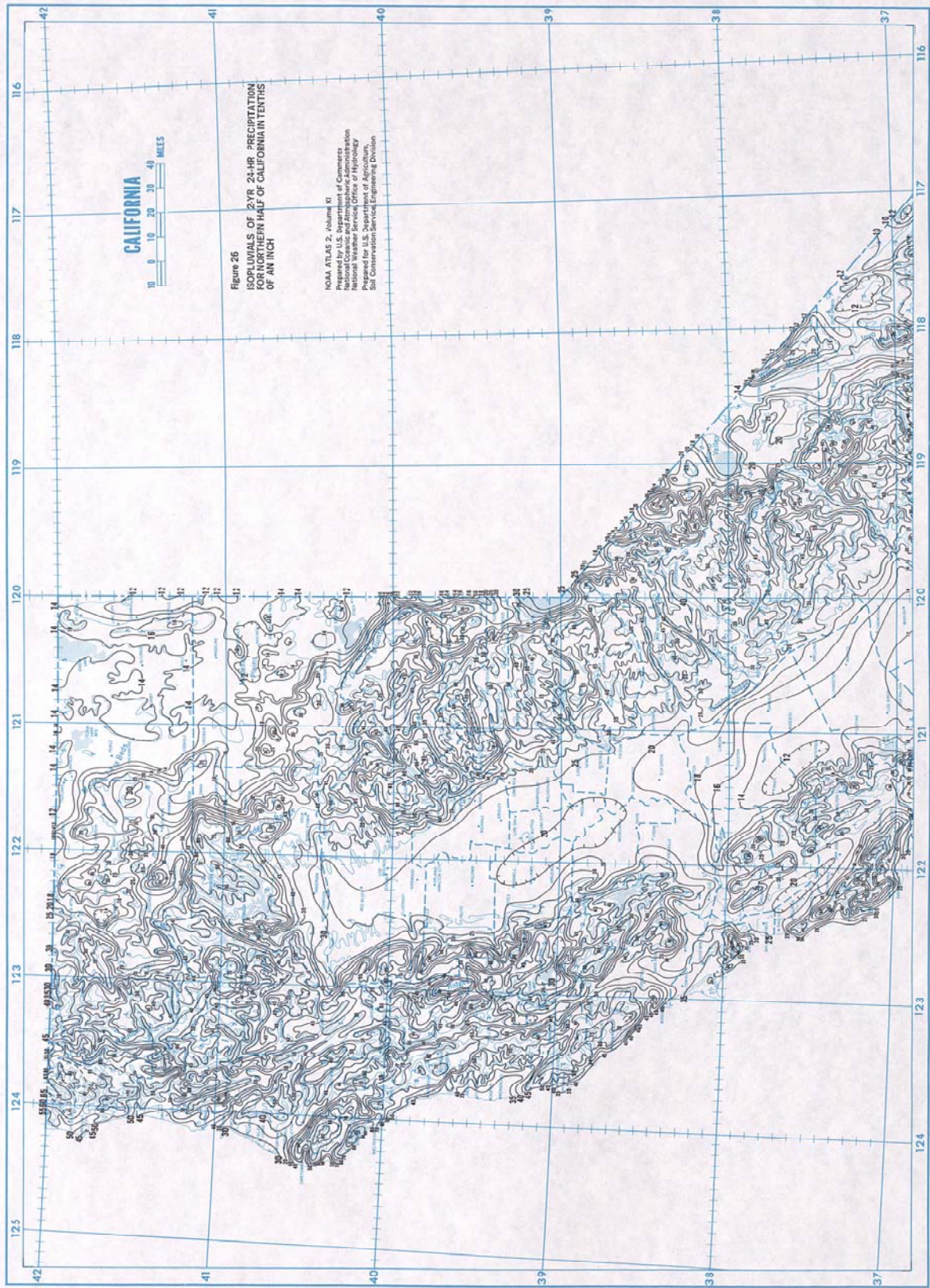
NOAA ATLAS 2, Volume 01
Prepared by U.S. Department of Commerce
National Weather Service Office of Hydrology
Prepared for U.S. Department of Agriculture,
Soil Conservation Service, Engineering Division

CALIFORNIA
0 10 20 30 40
MILES







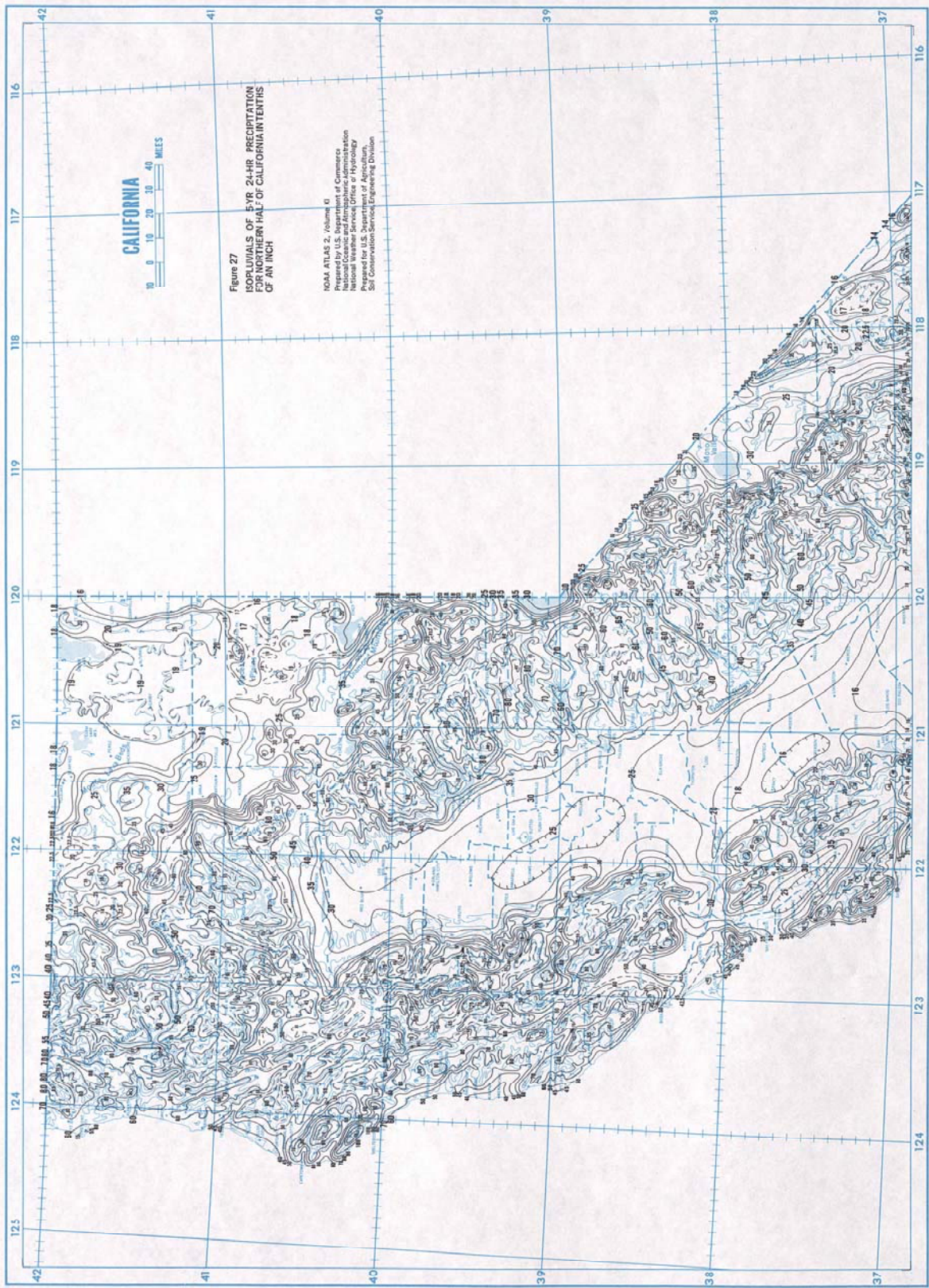


CALIFORNIA

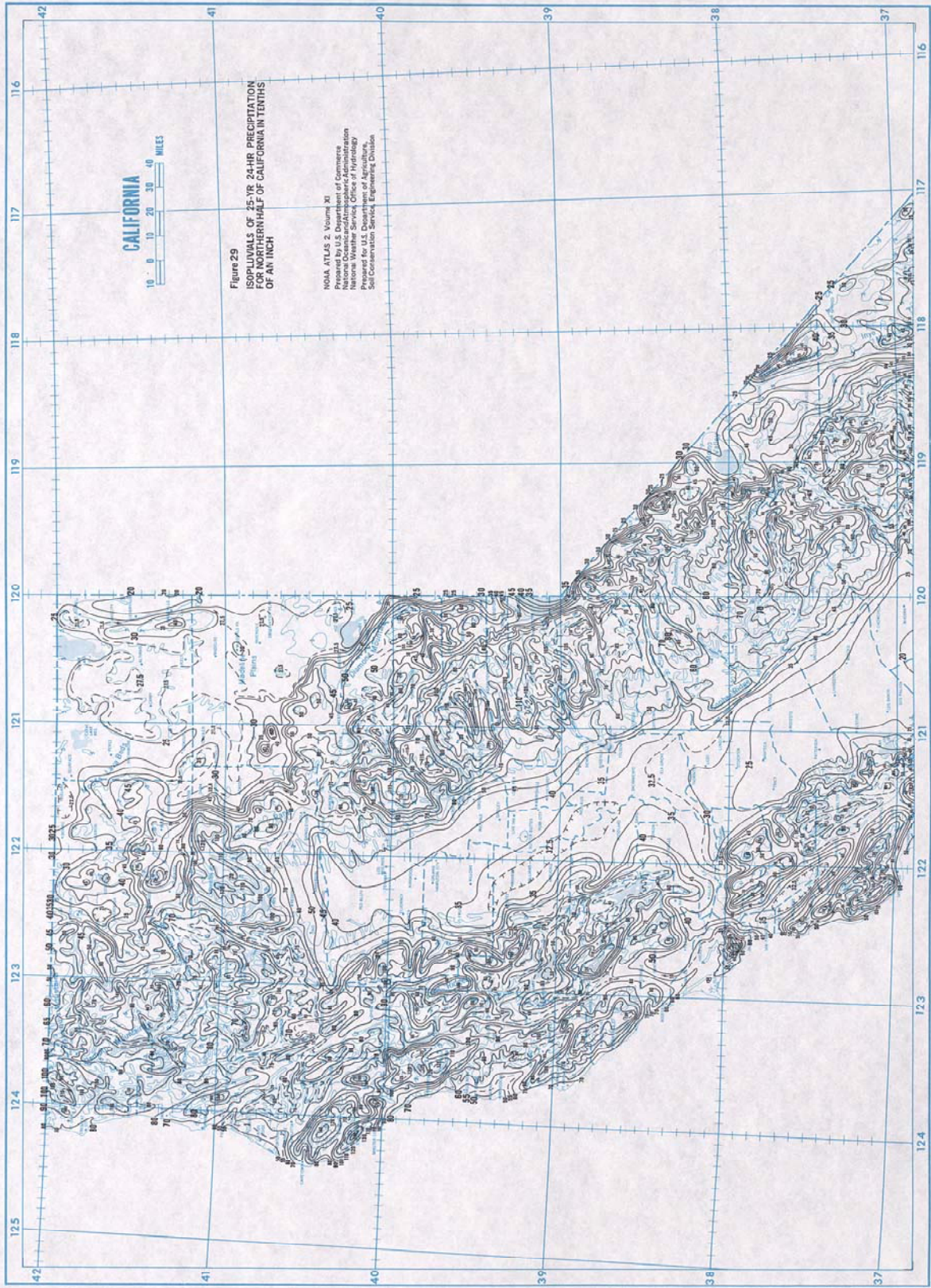
0 10 20 30 40 MILES

Figure 26
ISOPLETHS OF 2-YR 24-HR. PRECIPITATION
IN THE CENTRAL HALF OF CALIFORNIA
IN TENTHS OF AN INCH

NOAA ATLAS 2, Volume XI
Prepared by U.S. Department of Commerce
National Weather Service
National Weather Service Office of Hydrology
Prepared for U.S. Department of Agriculture
Soil Conservation Service Engineering Division







CALIFORNIA

0 10 20 30 40 MILES

Figure 29
ISOPLETHS OF 25-YR 24-HR PRECIPITATION
FOR NORTHERN HALF OF CALIFORNIA IN TENTHS
OF AN INCH

NOAA ATLAS 2, Volume XI
Prepared by U.S. Department of Commerce
National Weather Service, Office of Hydrology
Presented for U.S. Department of Agriculture,
Soil Conservation Service, Engineering Division

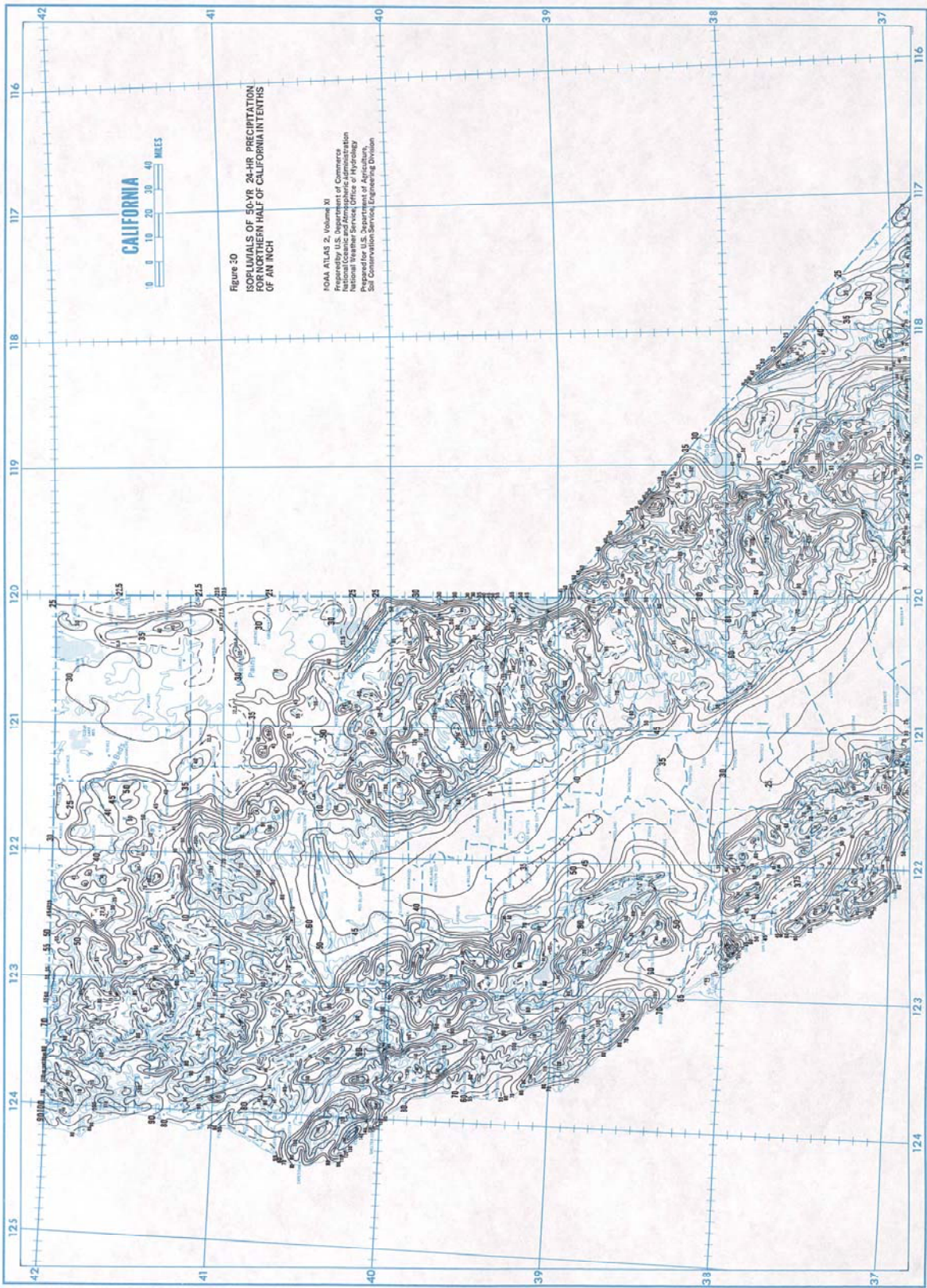
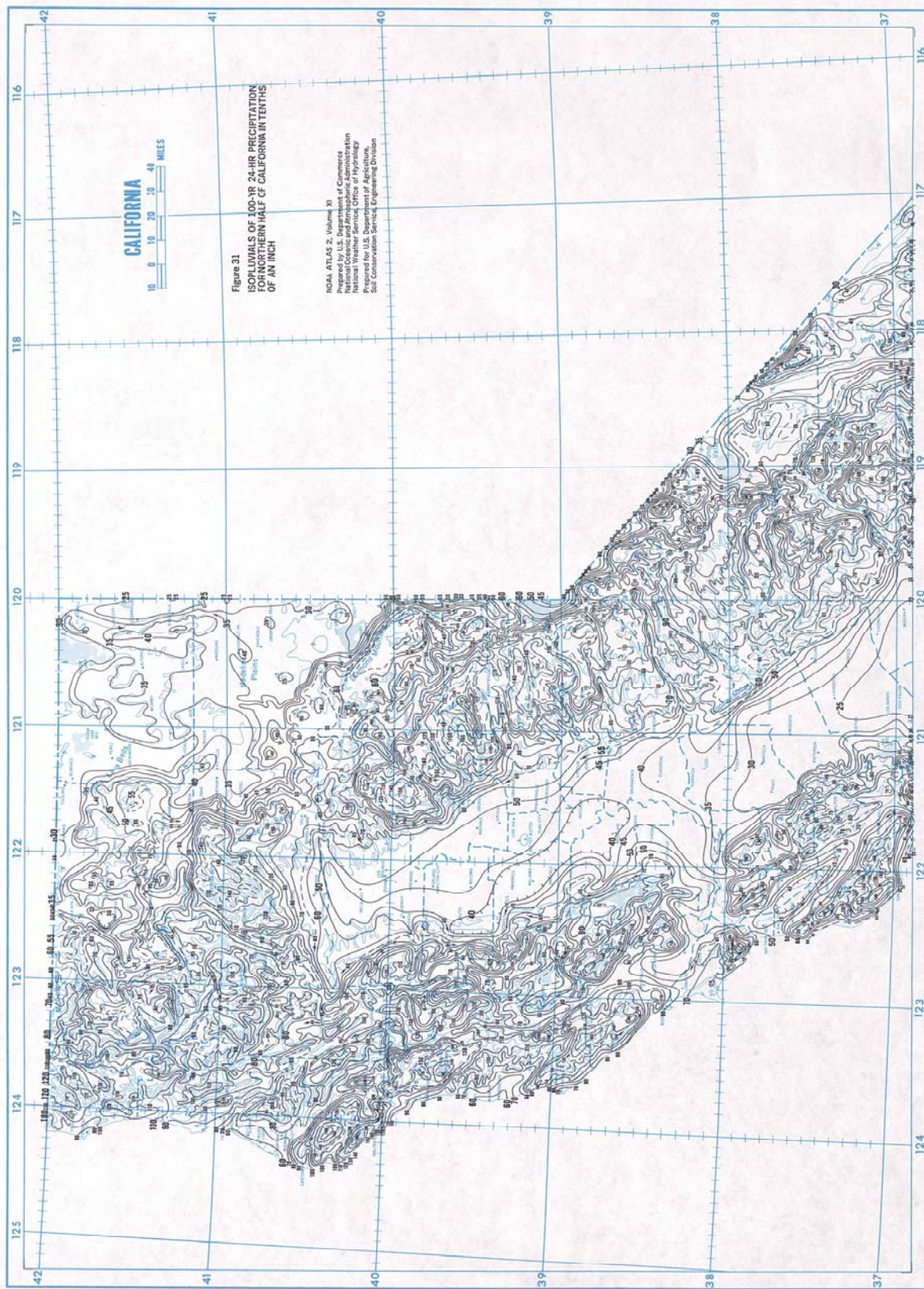


Figure 30
 ISOFLOWS OF 50-YR 24-HR PRECIPITATION
 FOR NORTHERN HALF OF CALIFORNIA IN TENTHS
 OF AN INCH

NOAA ATLAS 2, Volume XI
 Prepared by U.S. Department of Commerce
 National Weather Service Office of Hydrology
 Prepared for U.S. Department of Agriculture,
 Soil Conservation Service, Engineering Division



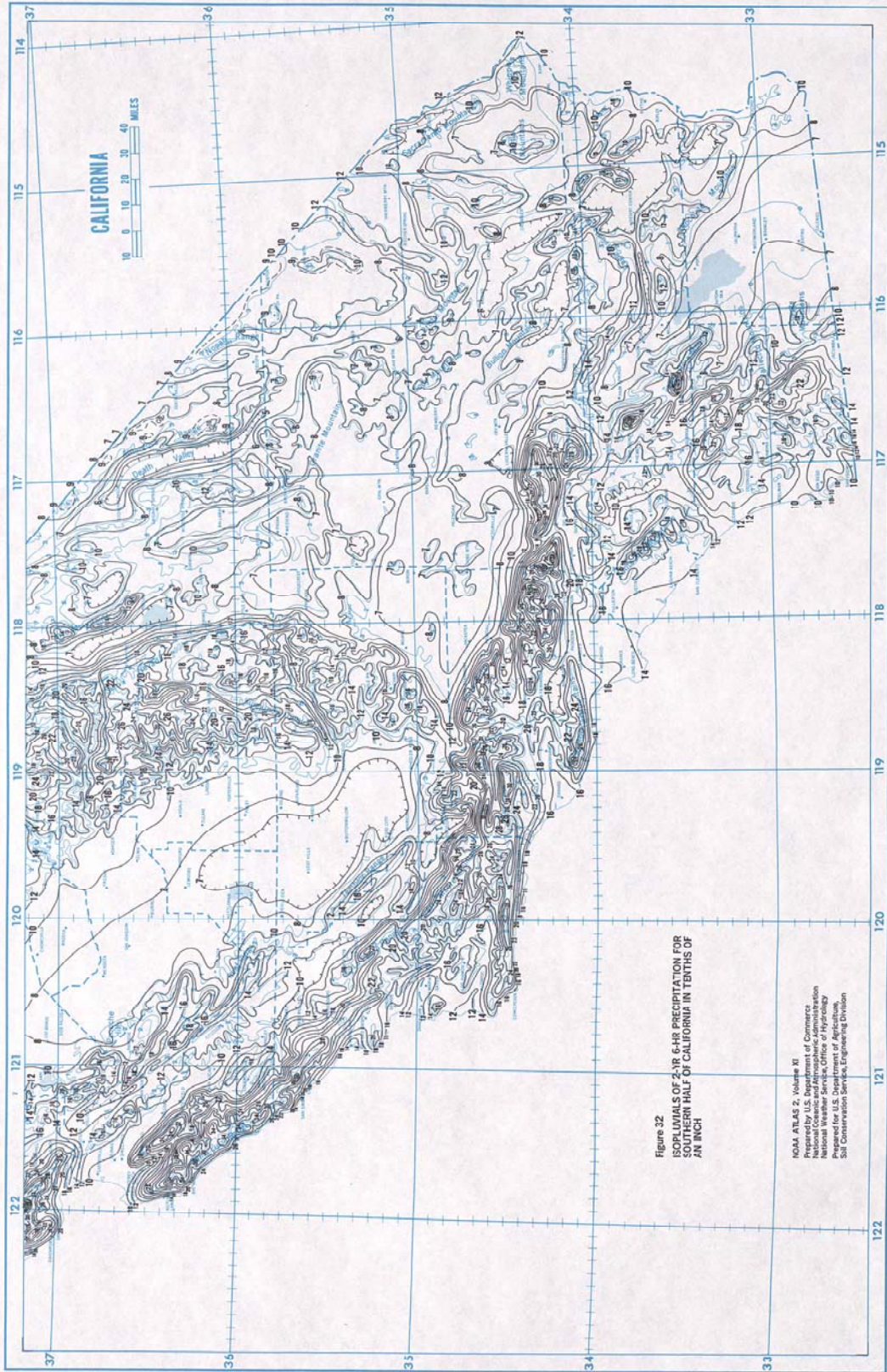


Figure 32
ISOPLETHS OF 2-YR. 6-HR. PRECIPITATION FOR
SOUTHERN HALF OF CALIFORNIA IN TENTHS OF
AN INCH

NOAA ATLAS 2, Volume XI
Prepared by U.S. Department of Commerce
National Weather Service, Office of Hydrology
Prepared for U.S. Department of Agriculture,
Soil Conservation Service, Engineering Division

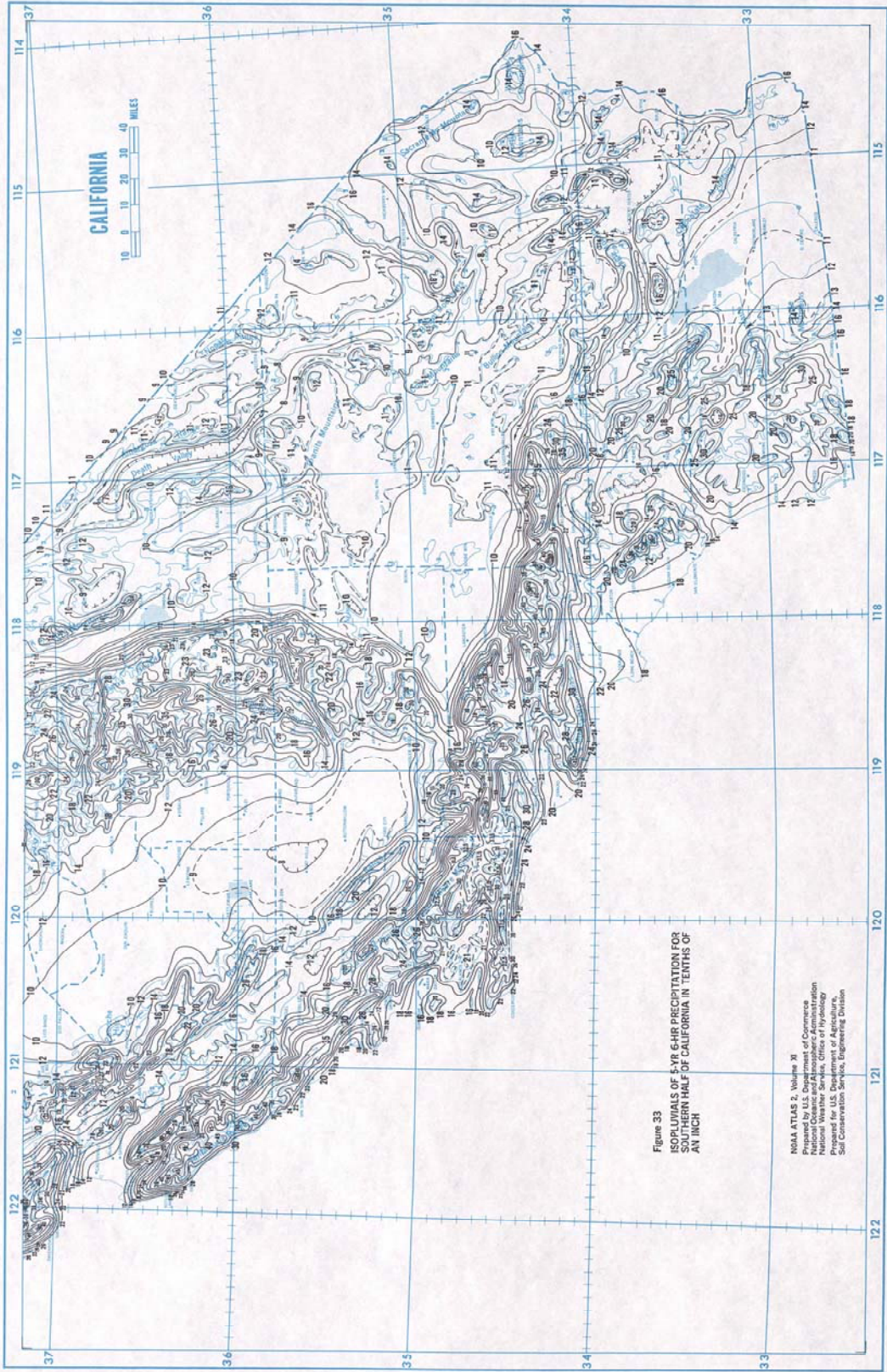


Figure 33
ISOPLETHS OF 5-YR 6-HR PRECIPITATION FOR
SOUTHERN HALF OF CALIFORNIA IN TENTHS OF
AN INCH

NOAA ATLAS 2, Volume XI
National Oceanic and Atmospheric Administration
National Weather Service, Office of Hydrology
Silver Spring, MD, U.S.A.
Source: U.S. Department of Agriculture,
Soil Conservation Service, Engineering Division

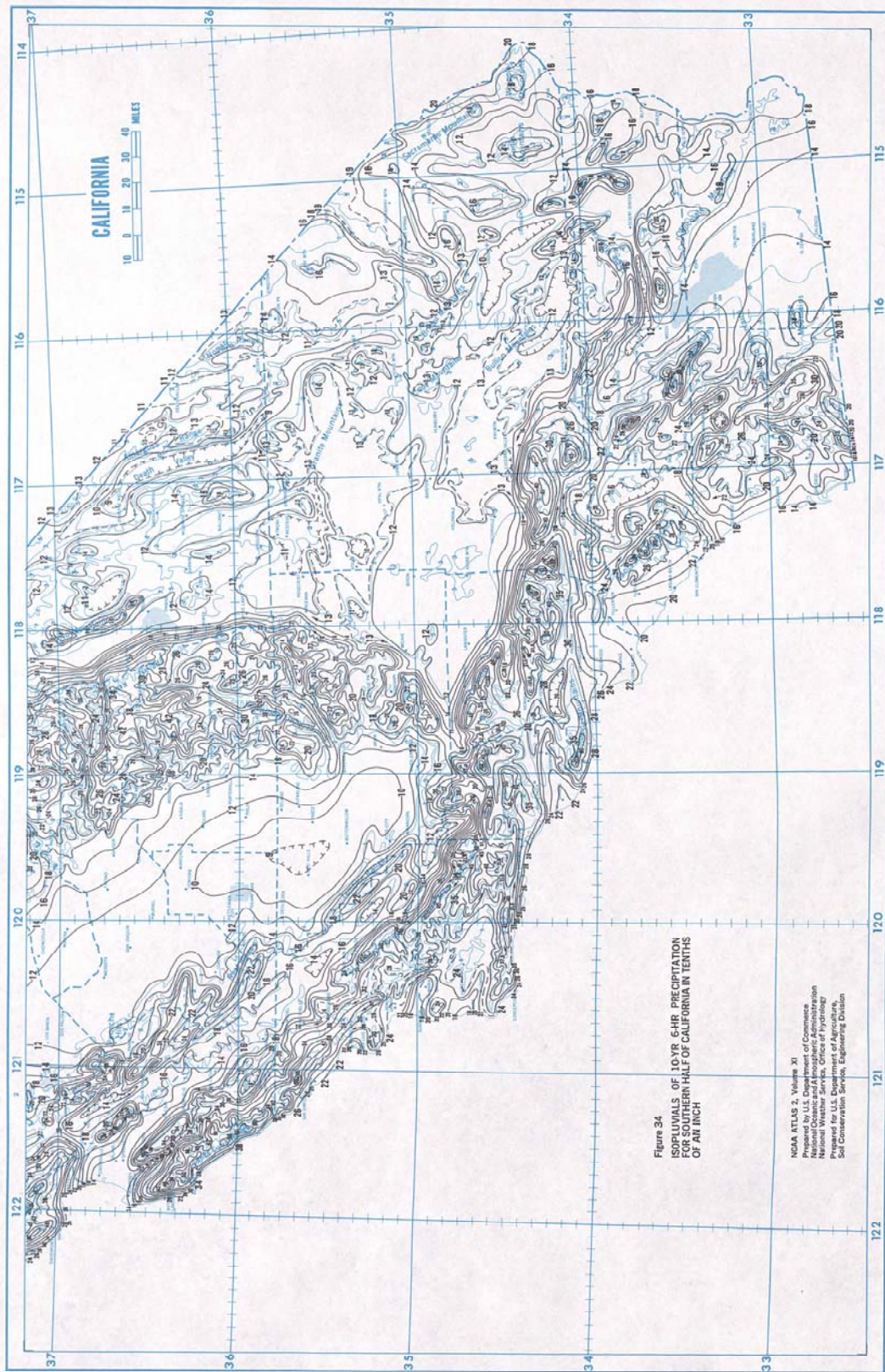


Figure 34
ISOPLETHS OF 10-YR 6-HR PRECIPITATION
OF SOUTHERN HALF OF CALIFORNIA IN TENTHS
OF AN INCH

NGSA ATLAS 2, Volume XI
National Oceanic and Atmospheric Administration
National Weather Service, Office of Hydrology
National Weather Service, Engineering Division
Soil Conservation Service, Engineering Division

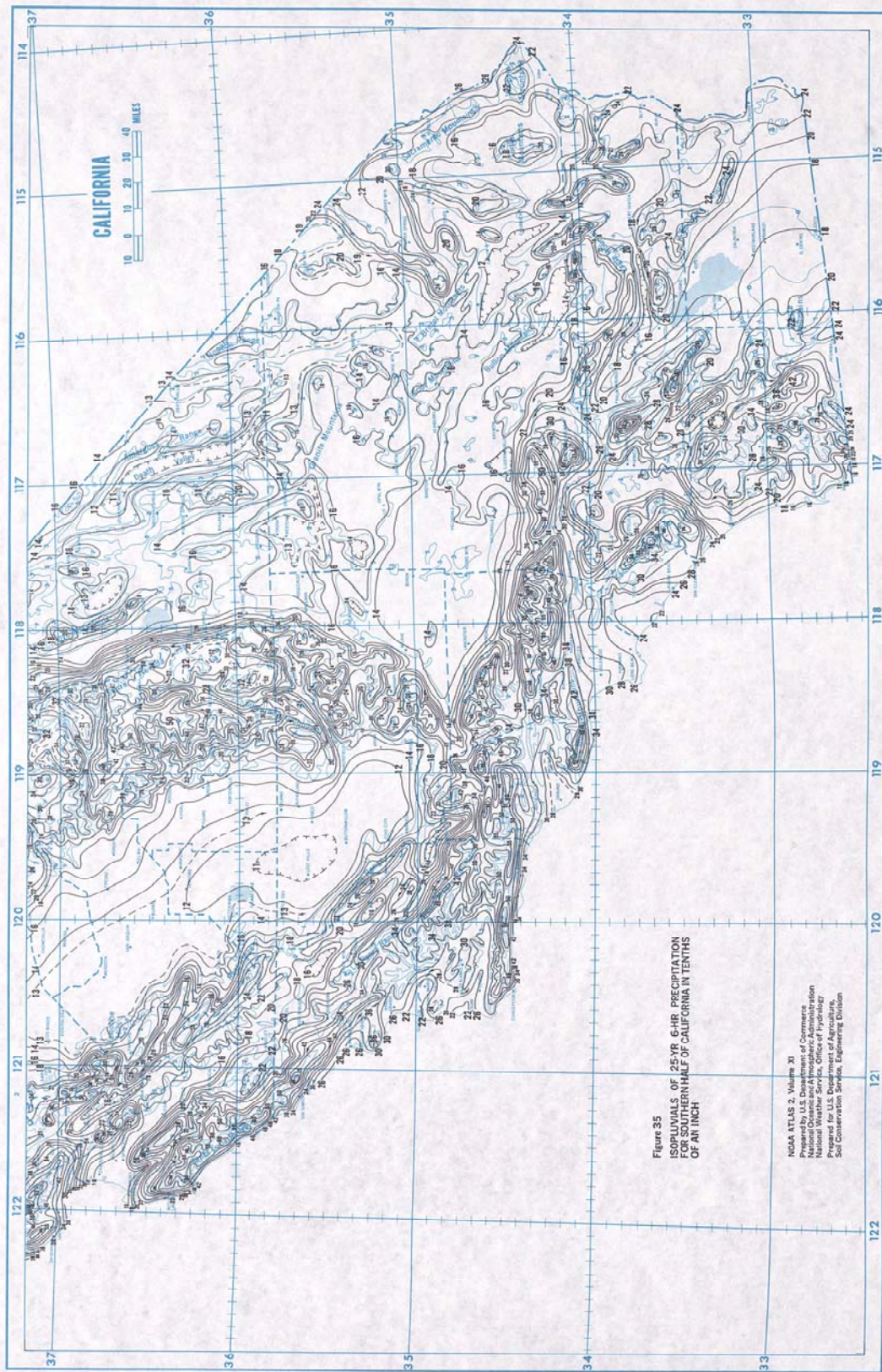


Figure 35
ISOPLETHS OF 25-YR 6-HR PRECIPITATION
FOR SOUTHERN HALF OF CALIFORNIA IN TENTHS
OF AN INCH

NOAA ATLAS 2, Volume 20
National Oceanic and Atmospheric Administration
National Oceanic and Atmospheric Administration
National Weather Service, Office of Hydrology
National Weather Service, Office of Hydrology
Soil Conservation Service, Engineering Division

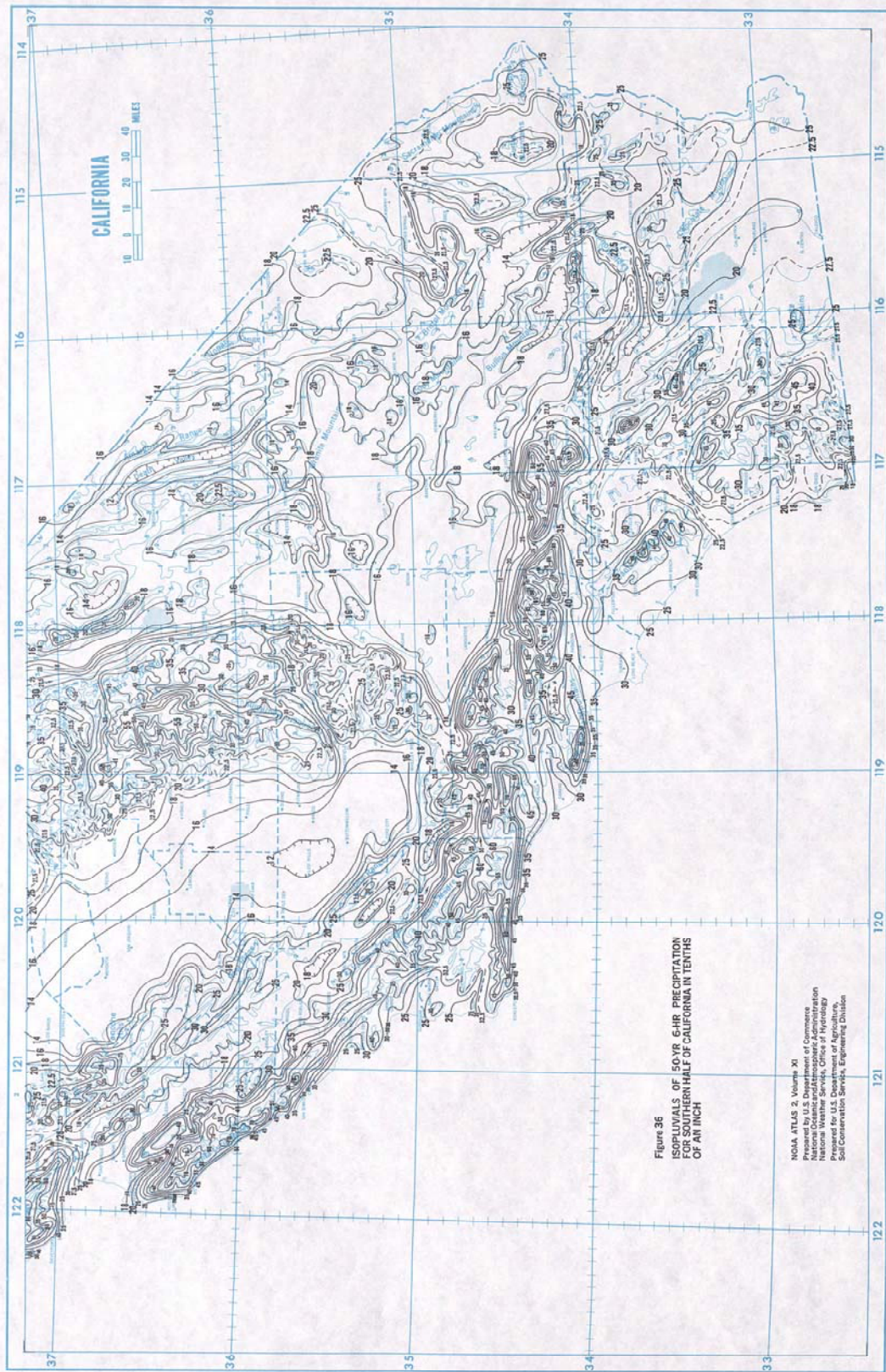


Figure 36
ISOPLUVIALS OF 50-YR 6-HR PRECIPITATION
FOR SOUTHERN HALF OF CALIFORNIA IN TENTHS
OF AN INCH

NOAA ATLAS 3, Volume VI
Prepared by the U.S. Department of Commerce
National Oceanic and Atmospheric Administration
National Weather Service, Office of Hydrology
and Water Resources, Engineering Division
Soil Conservation Service, Engineering Division

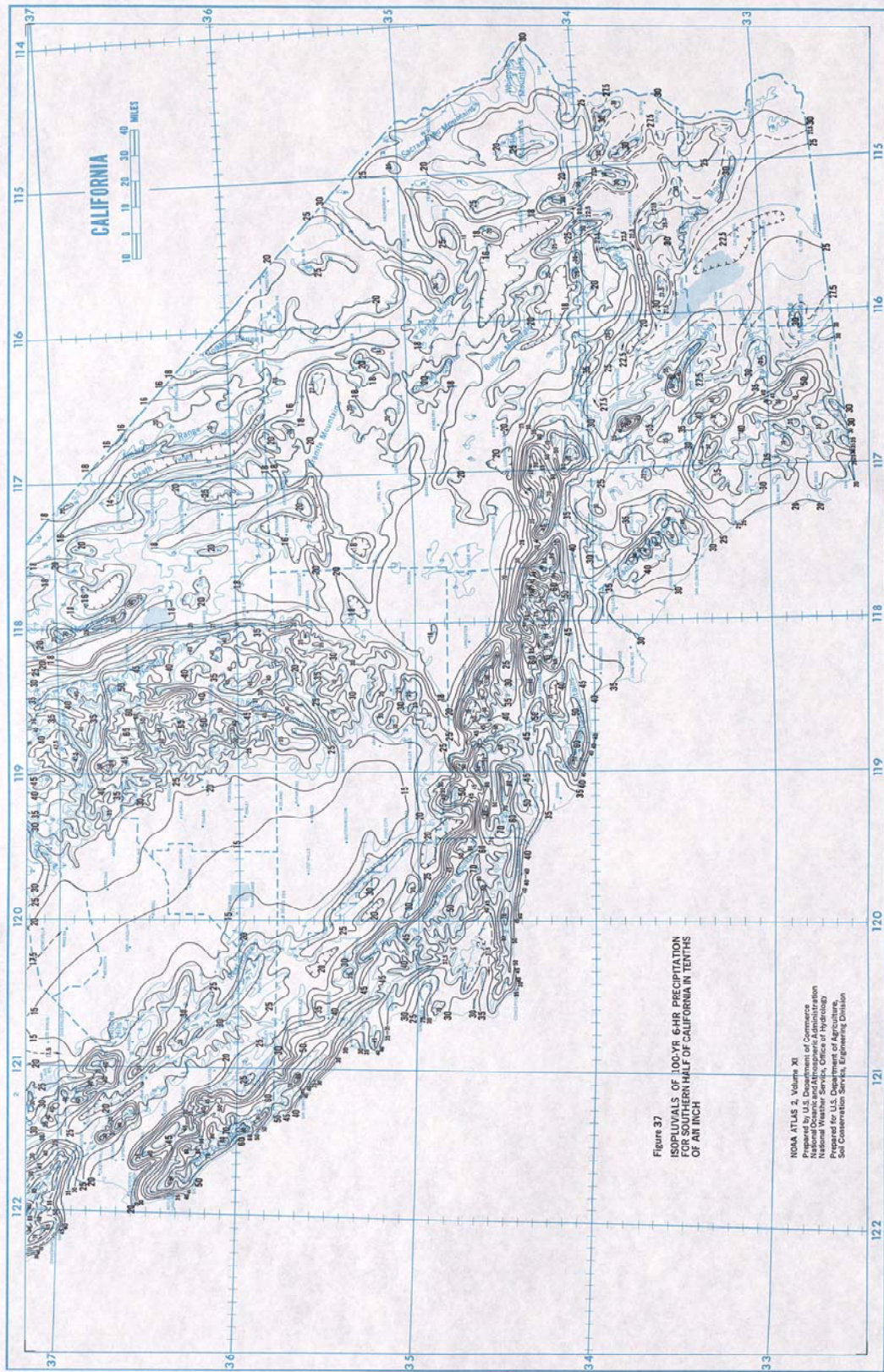


Figure 37
ISOPLUVIALS OF 100-YR 6-HR PRECIPITATION
OF SOUTHERN HALF OF CALIFORNIA IN TENTHS
OF AN INCH

NOAA ATLAS 2, Volume XI
National Oceanic and Atmospheric Administration
National Weather Service, Office of Hydrology
Hydrological Services Division
Soil Conservation Service, Engineering Division

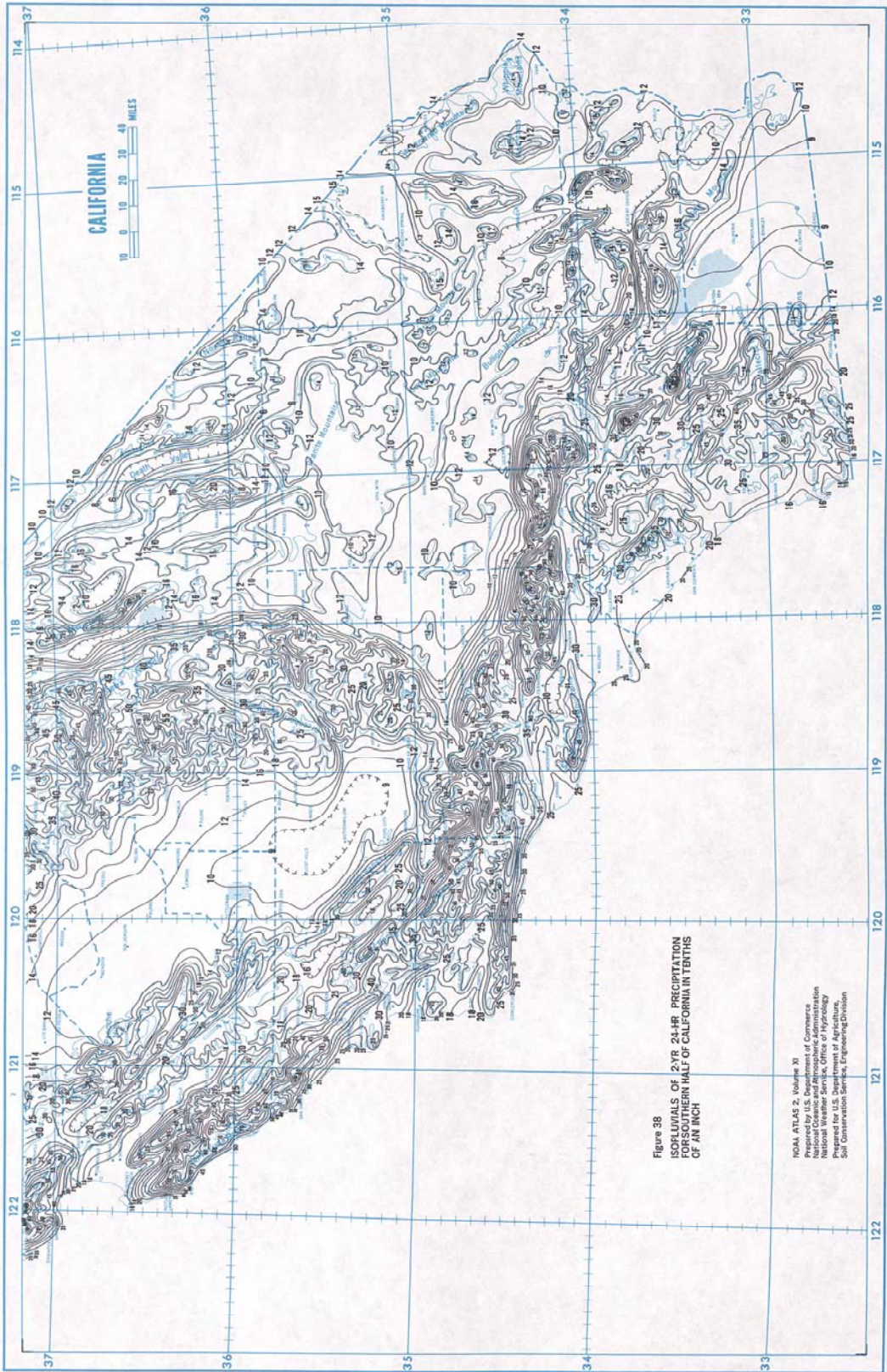


Figure 38
 ISOPHYETS OF 2-YR 24-HR PRECIPITATION
 FOR SOUTHERN HALF OF CALIFORNIA IN TENTHS
 OF AN INCH

NOAA ATLAS 2, Volume XI
 Prepared by U.S. Department of Commerce,
 National Weather Service, Office of Hydrology
 Prepared for U.S. Department of Agriculture,
 Soil Conservation Service, Engineering Division

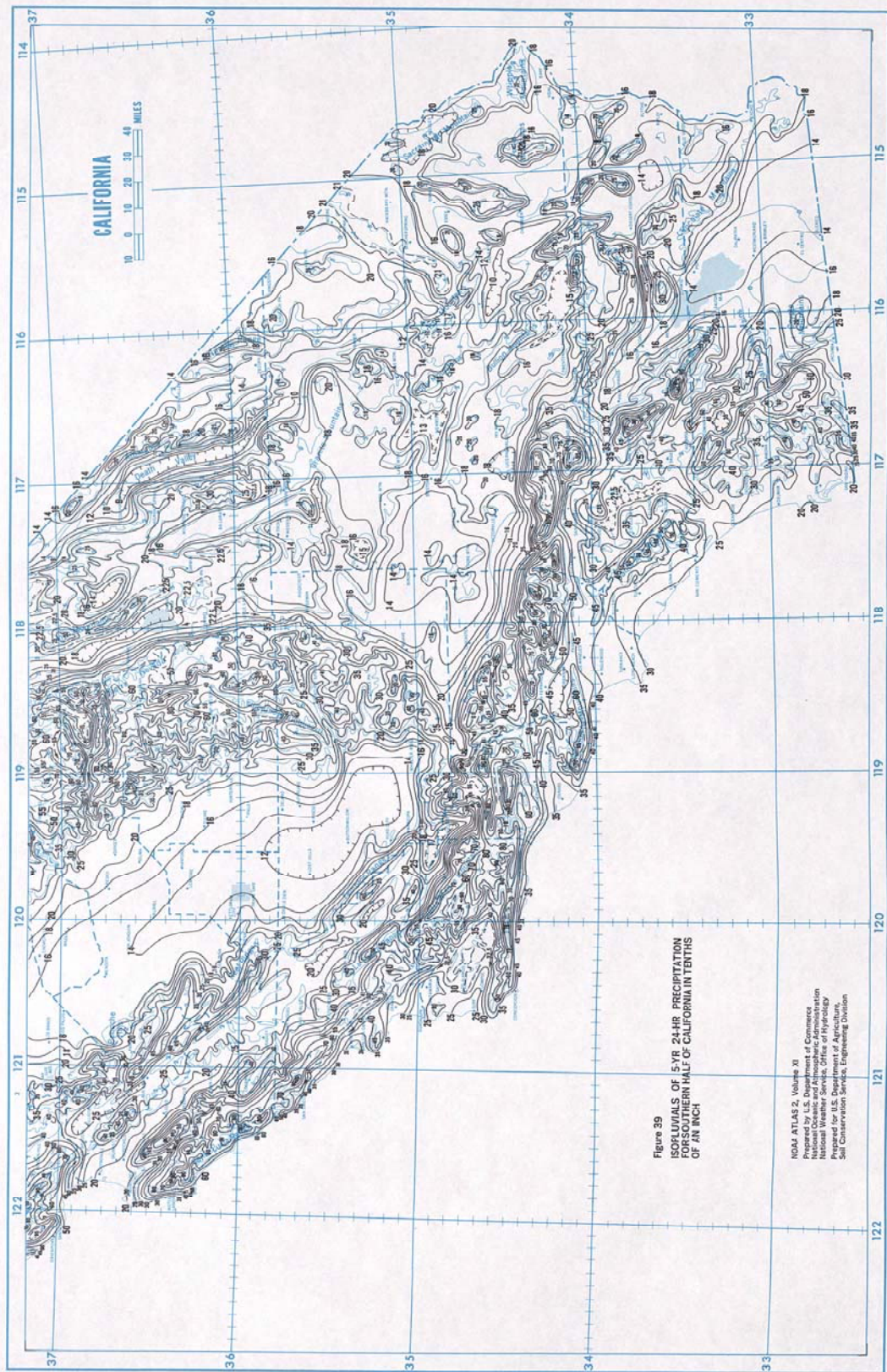


Figure 39
ISOBARS OF 1.5-YR. 24-HR. PRECIPITATION
FOR SOUTHERN HALF OF CALIFORNIA IN TENTHS
OF AN INCH

NOAA ATLAS 2, Volume XI
Prepared by U.S. Department of Commerce
National Oceanic and Atmospheric Administration
National Weather Service
Prepared for U.S. Department of Agriculture
Soil Conservation Service, Engineering Division

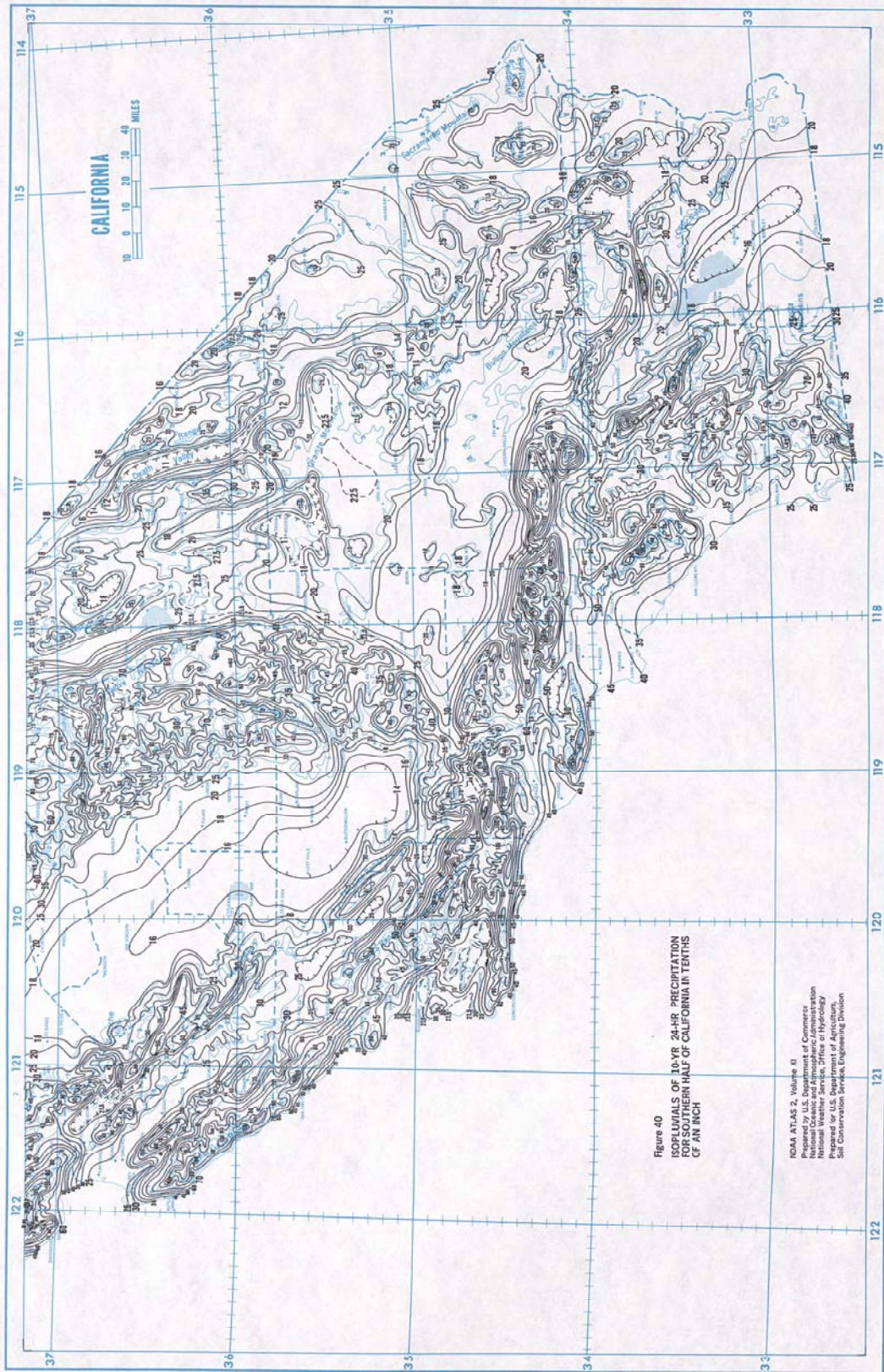


Figure 40
ISOPLETHS OF 10-YR. 24-HR. PRECIPITATION
FOR SOUTHERN HALF OF CALIFORNIA IN TENTHS
OF AN INCH

NOAA ATLAS 2, Volume 61
Prepared by the National Center for Environmental Prediction
National Oceanic and Atmospheric Administration
National Weather Service, Office of Hydrology
1200 Wilson Boulevard, Silver Spring, Maryland 20910
Soil Conservation Service, Engineering Division

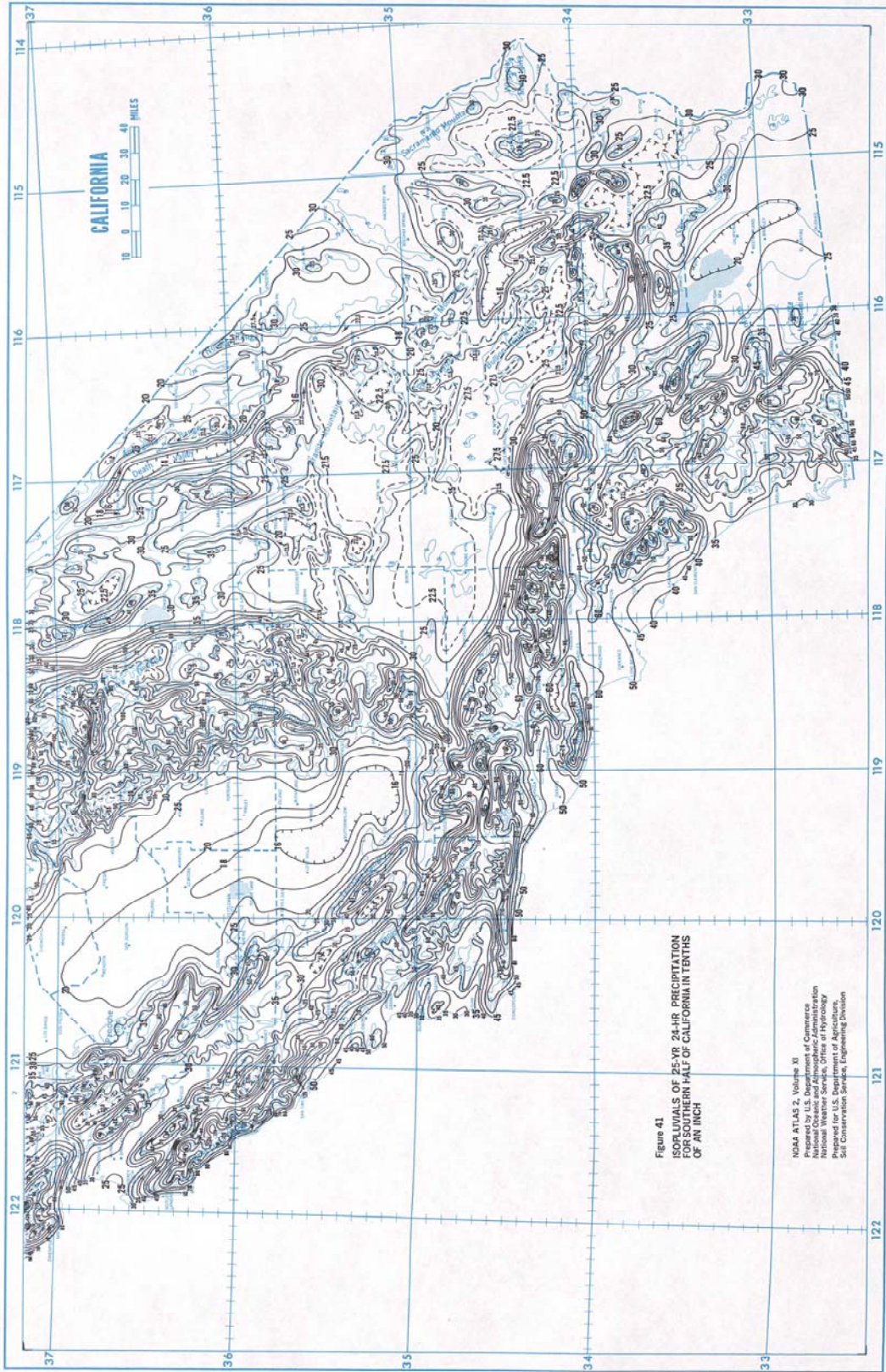


Figure 41
ISOFLUVIALS OF 25-YR 24-HR PRECIPITATION
FOR SOUTHERN HALF OF CALIFORNIA IN TENTHS
OF AN INCH

NOMAL ATLAS 2, Volume XI
Department of Commerce
National Oceanic and Atmospheric Administration
National Weather Service, Office of Hydrology
1966
Soil Conservation Service, Engineering Division

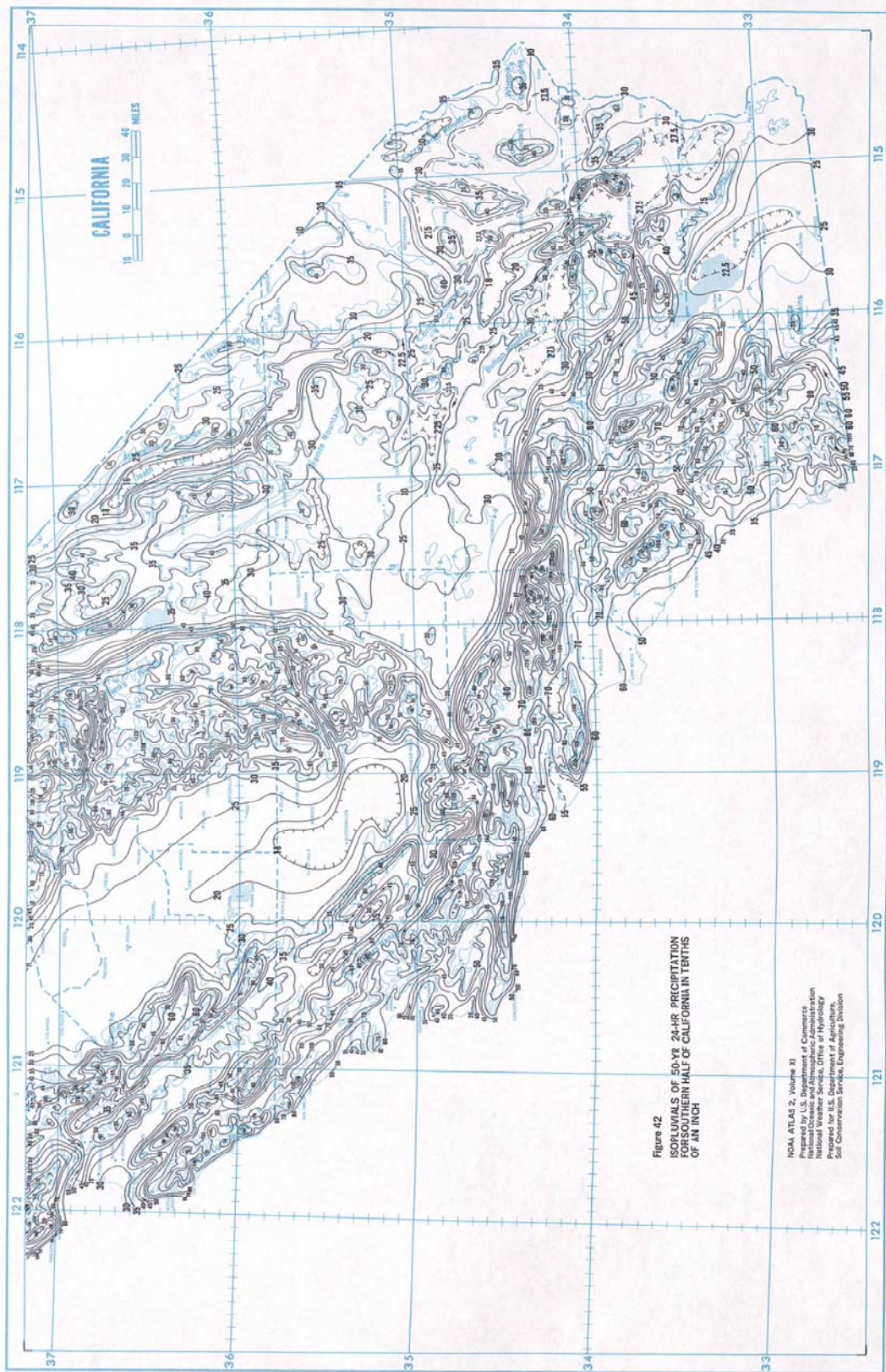


Figure 42
 ISOPLETHS OF 50-YR 24-HR PRECIPITATION
 FOR THE SOUTHWESTERN HALF OF CALIFORNIA IN TENTHS
 OF AN INCH

NOAA ATLAS 2, Volume XI
 Prepared by U.S. Department of Commerce
 National Oceanic and Atmospheric Administration
 National Weather Service
 Prepared for U.S. Department of Agriculture
 Soil Conservation Service, Engineering Division

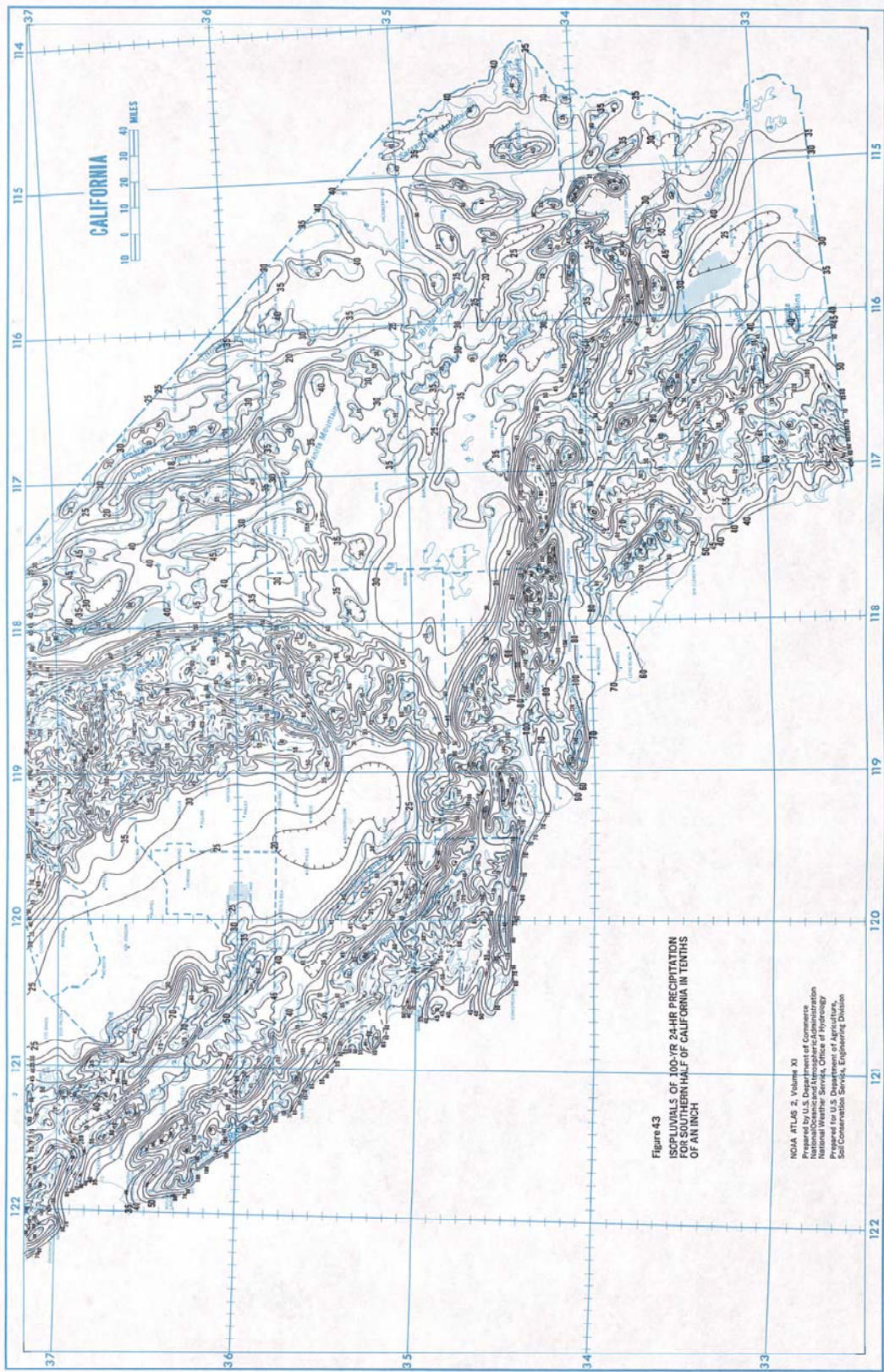


Figure 43
 ISOHYALS OF 100-YR 24-HR PRECIPITATION
 FOR SOUTHERN HALF OF CALIFORNIA IN TENTHS
 OF AN INCH

NOAA ATLAS 2, Volume XI
 Prepared by U.S. Department of Commerce
 National Oceanic and Atmospheric Administration
 National Weather Service, Office of Hydrology
 Prepared for U.S. District of Agriculture
 Soil Conservation Service, Engineering Division