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Natural Water Loss and Recoverable Water in Mountain Basins of Southern California

GEOLOGICAL SURVEY PROFESSIONAL PAPER 417-E

Prepared in cooperation with
California Department of Water Resources

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By JOHN R. CRIPPEN

CONTRIBUTIONS TO STREAM-BASIN HYDROLOGY

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NATURAL WATER LOSS AND RECOVERABLE WATER IN MOUNTAIN BASINS OF SOUTHERN CALIFORNIA

By John R. Crippen

ABSTRACT

Most of the local water supply of southern California originates as precipitation on mountain basins. Much of this water is returned to the atmosphere by evaporation and evapotranspiration (natural water loss) before residual or recoverable water can be captured in surface or underground storage for use by man. Long-term records of precipitation and runoff have been obtained from typical mountain basins in the Transverse and Peninsular Ranges. These records provide data whereby estimates can be made of natural water loss and recoverable water in ungaged regions of similar characteristics. Such estimates are needed in planning long-range projects which rely in whole or in part on the development of local water supplies.

This study makes use of the long-term data to relate average annual water loss to annual precipitation, to potential evapotranspiration, and to the water-retaining qualities of geologic formations underlying the basins. Annual precipitation can be determined from isohyetal maps which may be prepared from available data. Potential evapotranspiration is shown to be related to elevation and to geographical environment (for example, coastal or desert), and maps and graphs showing the nature of the relations are presented. Graphs and a table of numerical indexes for surficial rock types are provided by which the effect of geologic formations on natural water loss can be evaluated.

Recoverable water is a residual of precipitation and natural water loss, and in the environment of southern California the residual is relatively small. In the basins studied, recoverable water ranged from 1 inch in a basin having an annual precipitation of 14 inches to 19 inches in a basin having an annual precipitation of 42 inches. In general, the greater the precipitation, the greater the percentage of recoverable water.

INTRODUCTION

Man's utilization of natural resources is everywhere dependent upon the availability of water. In humid regions, where water seems as free and plentiful as the air, this dependency is not always apparent; but when a burgeoning economy rises in an arid or semiarid climate, as in southern California, it is brought to our attention with great force. Every change in the relation between water supply and demand strikes our economy a hammer blow, and on occasion our social and economic structure is strained to meet nature's challenge.

The people of southern California, under the leadership of resourceful and forward-looking planners, have successfully met the recurring problems of water shortages in many ways. The Los Angeles and Colorado River aqueducts have brought water over mountains and deserts to supply the domestic, agricultural, and industrial demands of more than 9 million persons. Construction is under way to bring additional supplies from the northern regions of the State. These supplies will meet the even greater demands anticipated for the future. The conservation of water from rain in nearby areas has been so highly developed that only a small amount does not find itself led to surface or underground reservoirs from which it can be withdrawn on demand.

These projects make us aware of the great cost of obtaining water. Much time and money have been devoted to the gathering of data on precipitation, streamflow, ground-water movement, and evaporation. The most economical water supply is that which occurs naturally near the place of use.

An excellent summary of southern California's water problems is given by H. M. Stafford and H. C. Troxell in the "Mahoney report" (U.S. Congress, 1953, p. 21–50).

The runoff from the mountain-and-foothill areas, or from other parts of the coastal basins, is only a small fraction of the precipitation; it is the residual after evaporation and transpiration have taken their toll. This toll, the natural water loss, is for the most part not directly measurable, and so must be determined as a difference between precipitation and runoff. It is discussed here because the toll is preemptive.

Most of the precipitation in the mountain-and-foothill areas enters the soil mantle; subsequently, much of it is extracted from the root zone by vegetation. Most of the mountain area is covered with a heavy growth of brush (chaparral), with small stands of conifers at higher altitudes and water-loving trees in certain low areas along streams, where the ground-water level is high. The brush cover also extends over the higher foothill and valley areas, but grasses predominate on the lower slopes. The habitats of the native vegetal species indicate their varying water requirements. Thus, the water-loving plants, sensitive to shortages, are restricted to areas of assured and continuing water supply; the extremely hardy chaparral, adapted to a precarious supply, will consume large quantities of water if available but can exist on a mere pittance if necessary.

Thornthwaite (1948) has estimated that the maximum yearly water requirement, or "potential evapotranspiration," of the vegetation in the South Coastal Basin would range from 24 to 36 inches, if at no time were there a deficiency in soil water within the root zone. By comparison, the average yearly precipitation in the mountain-and-foothill areas was 28 inches during the wet period 1935–44, and only 19 inches during the dry period 1945–51. Thus, native vegetation is capable of using more water than was precipitated in the dry period, and perhaps even during the wet period. The runoff from the mountain area, however, is evidence that the vegetation has not done so, presumably because precipitation occurs chiefly in the season of dormant growth, and at times is sufficient to induce penetration of water below the root zone.

In the mountain-and-foothill areas, evapotranspiration has been shown to amount to about 20 inches, or 84 percent of the precipitation. Reducing this loss by only 1 inch would increase recoverable water by about 25 percent—from 500,000 acre-feet to about 628,000 acre-feet. However, much of the loss is an inescapable cost in water for maintaining the native vegetation which slows erosion of the mountain slopes.

PURPOSE AND SCOPE OF REPORT

This report presents a procedure for estimating average annual water loss and recoverable water in mountain basins of southern California. The procedure is based on the synthesis of data from basins where adequate data have been obtained and on extrapolation of the data to other basins where hydrologic data are not adequate. Much of the local water supply originates in such basins, and relatively few mountain areas have been gaged for even short periods. There is therefore need for making such estimates which are essential in planning domestic, agricultural, and industrial development. The specific relationships developed in this report are applicable to much of the region encompassed in the Transverse and Peninsular mountain ranges of southern California, and the procedure recommended is probably valid in many other regions. The estimated values obtained by the procedure are long-term averages and therefore are affected by several factors, but especially by year-to-year variations in precipitation.

ACKNOWLEDGMENTS

This study was a cooperative effort between the U.S. Geological Survey and the California Department of Water Resources. The report was prepared by the Surface Water Branch of the Geological Survey under the supervision of Walter Hofmann, District Engineer. Uncompleted studies made by H. C. Troxell (retired) of the Geological Survey aided materially in the preparation of this report.

GEOGRAPHICAL FACTORS AFFECTING NATURAL WATER LOSS

As water passes through the hydrologic cycle, its use by man usually occurs in the stages between its arrival on the land surface in the form of rain, snow, or condensed water vapor and its return to the atmosphere or to the sea. Water may be taken from surface sources or from aquifers and ground-water storage reservoirs. The volume of water available from these sources in a given land area is equal to the total precipitation on the area less the so-called natural water losses. These losses consist of water directly evaporated into the atmosphere plus water taken up by plant life and subsequently transpired to the atmosphere. The combined processes of evaporation and transpiration are usually called evapotranspiration.

Clearly then, the study of available water and of natural water loss requires knowledge of precipitation and of evapotranspiration. Southern California offers an excellent "laboratory" in which to acquire such knowledge because of its great range of hydrologic characteristics. Moisture zones from humid to arid exist within relatively few miles of each other, and temperatures ranging from hot to cold occur. If the moisture and thermal characteristics of the earth's climate are each broken into four classifications (humid, subhumid, semiarid, and arid; hot, warm, cool, and cold) 16 climates may be defined by the possible combinations. Of these 16 possibilities, 12 occur in southern California (Bailey, 1954).

The classifications of "humid" and "arid" are based on the relative magnitudes of precipitation, or moisture availability, and potential evapotranspiration, or the water loss that could occur if moisture were present at all times. Areas where precipitation exceeds potential evapotranspiration have a surplus of moisture and are humid or subhumid, whereas areas in which potential evapotranspiration generally exceeds precipitation are arid or semiarid.

The hydrology of an area is the resultant of complex relationships among physiography, climate, and geology. The study of precipitation and evaporation, therefore, must start with an understanding of these features.

PHYSIOGRAPHY

The basins which have provided data for this study are all within the Transverse and Peninsular ranges in southern California. Use of the proposed method is recommended over much of the region shown schematically on figure 1—an outline map showing the physiographic divisions of southern California. Areas of use are more specifically shown on figure 2, on which mountain basins are shaded.

Figure 1 indicates that evaporation from the vast ocean area to the west, high mountain barriers a relatively short distance inland, and frequent large-scale eastward air movement can combine to produce consistent weather patterns. The section at the bottom of figure 1 shows this relationship between climate and

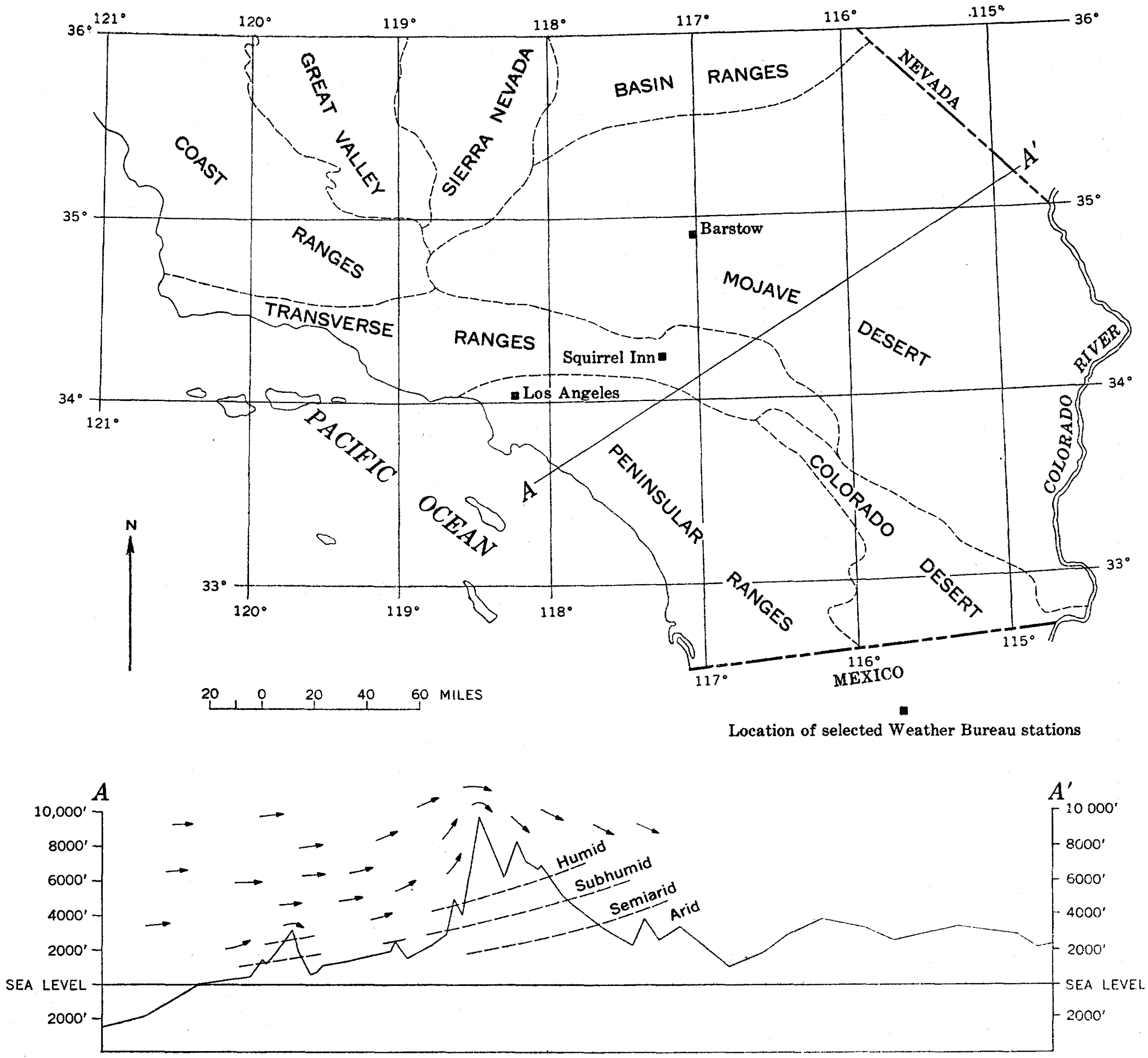

FIGURE 1.—Physiographic map and section showing climatic distribution in southern California.

physiography. The most prominent physiographic feature, as shown by this section, is the steep and rugged Transverse Range system which extends from the western tip of Santa Barbara County to the Salton Sea area in the Colorado Desert. The extreme steepness of these ranges is emphasized by the slopes of six mountain drainage basins in the San Gabriel and San Bernardino Mountains. (See table 1.) In these six mountain basins, 1 percent of the land surface has a slope of 49°–65° or steeper. This slope is equivalent to a vertical rise of 115–214 feet in a horizontal distance of 100 feet. The mean land slope ranges from 20° to 38°.

In addition to their steepness, these mountains are high, rising to more than 10,000 feet above sea level. In the San Bernardino Mountains about 21 percent of the area has an altitude of 7,000 feet or more, and 54 percent has an altitude of 5,000 feet or more. These ranges, shown on figure 1, are formidable barriers to the ocean breezes, and the uplift of incoming maritime airmasses causes considerable precipitation to occur on the windward side.

South of the Transverse Ranges and almost as steep are the Peninsular Ranges. Although generally of lower altitude, these mountains also exert considerable influence on the precipitation distribution because of

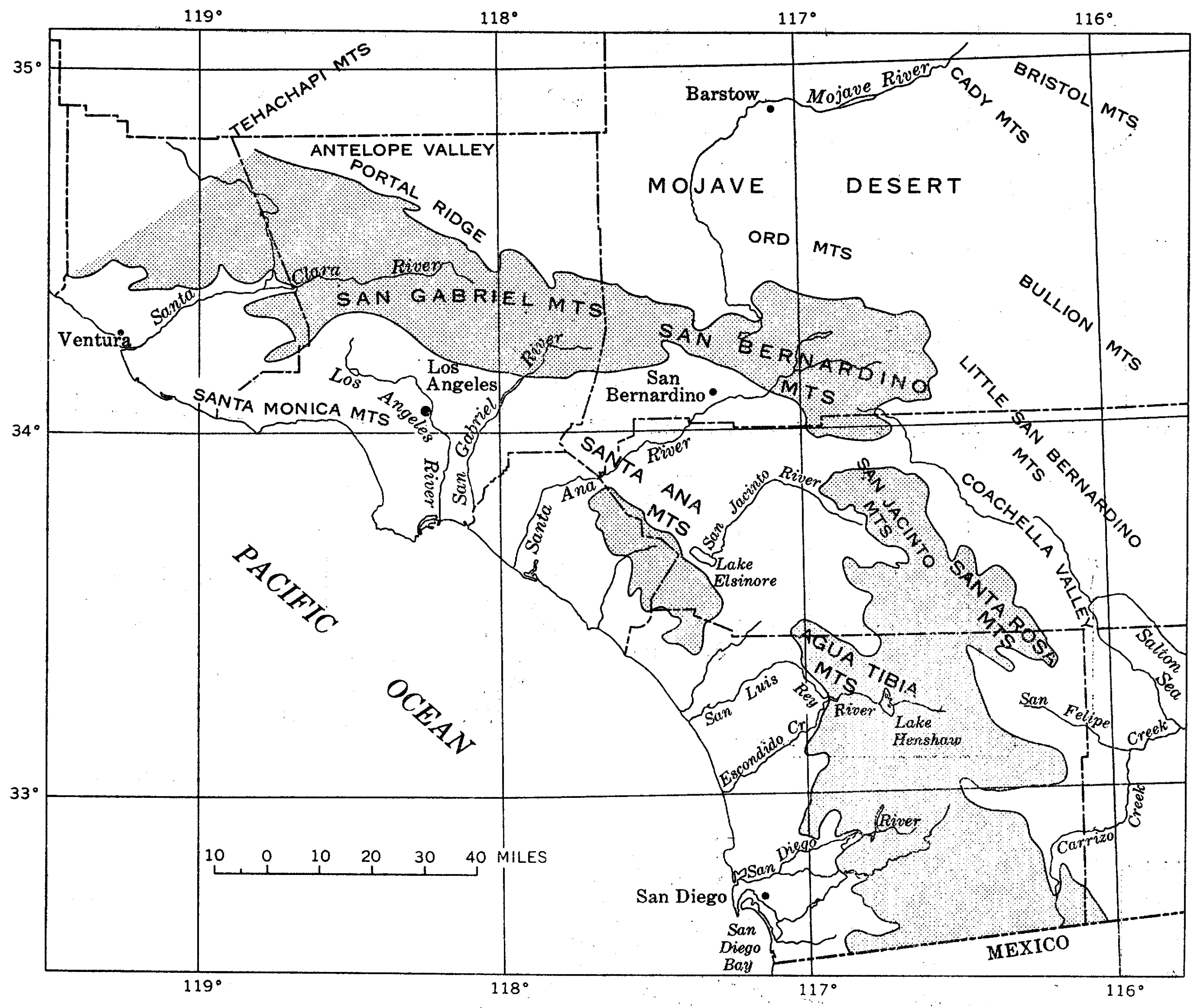

FIGURE 2.—Mountain basins in southern California in which natural water loss and recoverable water can be estimated. Shaded areas indicate mountain basins.

their proximity to the ocean. The population of southern California is largely concentrated in the coastal plains and valleys adjacent to the Peninsular and Transverse Ranges.

To the leeward, east of these two mountain systems, are the Mojave and Colorado Deserts, which have an area of about 40,000 square miles—greater than that of many States. The Mojave Desert is an interior area of isolated mountain ranges and broad arid valleys dotted by numerous dry lakes or playas. The Colorado Desert contains the Salton Sea and lower Colorado River areas. Except for the westernmost part of the

TABLE 1.—*Distribution of land surface slopes in selected basins in the San Gabriel and San Bernardino Mountains*

[Land slope is given as the ratio of the vertical rise to the horizontal distance expressed as a percent. A 58-percent land slope lies at an angle of 30° from the horizontal (tangent 30°=0.58)]

Basin	Land surface slope equaled or exceeded in the percent of basin area indicated									Mean land slope
	1	5	10	20	50	80	90	95	99	
San Antonio Creek	174	124	106	88	64	43	33	25	15	66. 2
Cucamonga Creek	214	151	128	106	75	50	42	34	22	77. 5
Lytle Creek	170	132	114	94	62	38	21	9. 5	4. 1	63. 6
Mill Creek	152	107	91	75	49	33	24	9	6. 5	53. 0
East Twin Creek	115	99	91	81	61	39	30	23	13	59. 5
Santa Ana River	122	89	74	59	31	11	7. 5	4. 6	2. 4	36. 2

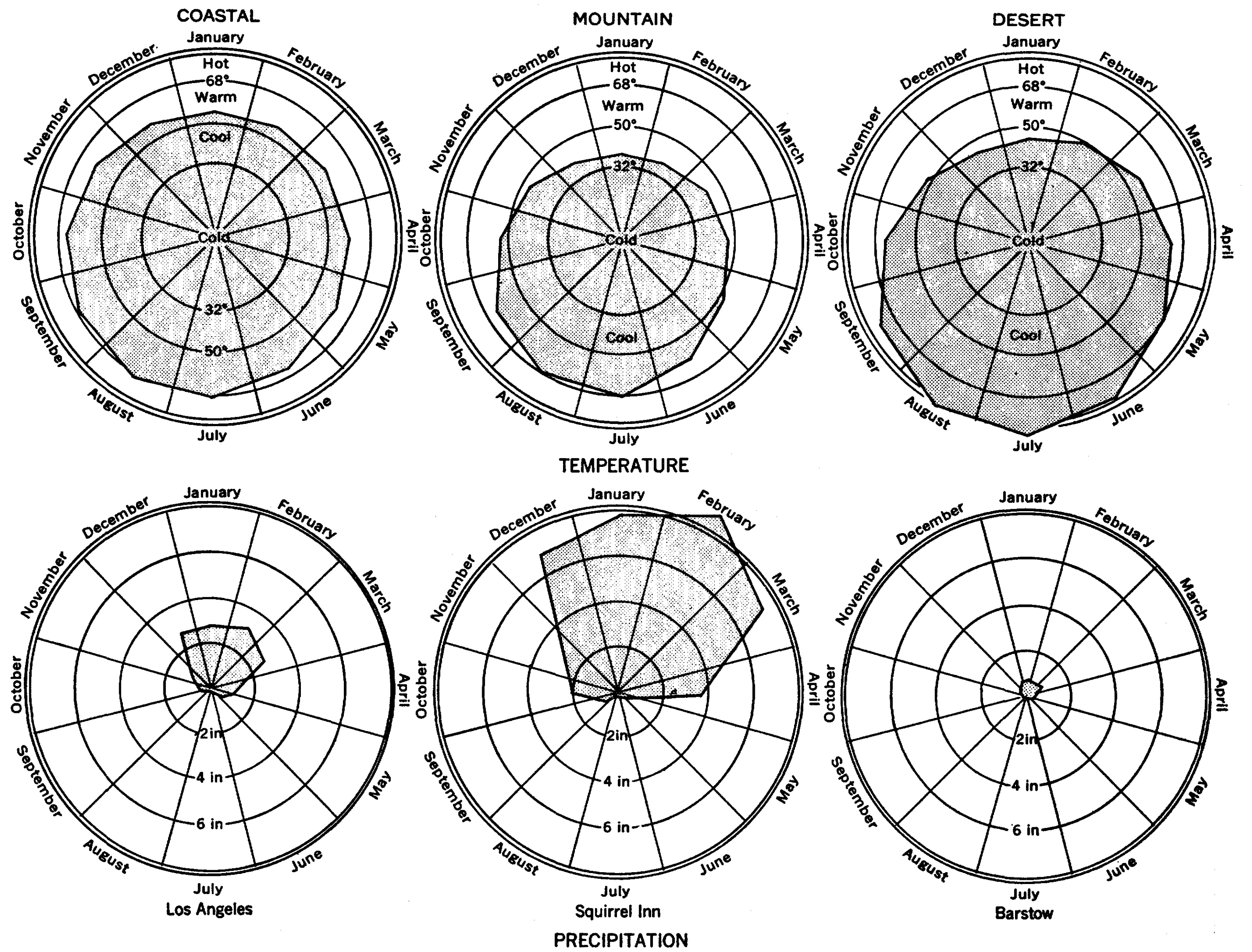

FIGURE 3.—Typical monthly distributions of temperature and precipitation.

Mojave Desert (Antelope Valley) and intensely irrigated regions immediately to the north and the south of the Salton Sea, the population in these deserts has been sparse; however, the establishment of permanent residences and planned communities in some of the more accessible desert regions is increasing.

CLIMATE

Climate is closely associated with the worldwide moisture circulation and is subject to modification from place to place by prominent physiographic features such as the high ranges which exist in southern California. In establishing climatic zones, climatologists have found temperature and precipitation to be the primary meteorological factors. Temperature serves as an index of energy available for evapotranspiration, and precipitation is a measure of the available moisture. The monthly temperature and precipitation at three typical stations—Los Angeles, Squirrel Inn, and Barstow—are shown on figure 3. The temperature classifications used (cold, cool, warm, and hot) are arbitrarily chosen and have limits of 32°, 50°, and 68° F, respectively. The locations of the three stations are shown on figure 1.

The monthly temperature distribution at Los Angeles is typical of most coastal and lower inland valley areas west of the coastal divide. In these areas the temperatures are uniformly mild and are classified as warm except for the 3-month period July through September. This favorable temperature distribution attracts many new inhabitants to the area.

Counterbalancing this favorable temperature distribution at Los Angeles is a low annual precipitation of about 15 inches, most of which occurs in the winter months. The temperature records suggest that the greatest need for water occurs during the hot months of July through September, yet the average precipitation for this period is less than 0.1 inch per month.

Most precipitation occurs from December through March, the period in which the need for water is least. Thus the precipitation, representing the moisture availability, and the temperature, representing the evapotranspiration opportunity, are out of phase by about 6 months. This time distribution, together with low total precipitation, has led most climatologists to classify the Los Angeles area as semiarid (Thornthwaite, 1948).

The second set of diagrams on figure 3, representing the higher mountain area, is based on records obtained at Squirrel Inn, which is on the divide of the San Bernardino Mountains just north of San Bernardino. Because of its 5,750-foot altitude, this station shows considerably lower winter temperatures but only slightly lower summer temperatures than those recorded at Los Angeles. The 6-month period of November through April is cool, and the remaining months are warm.

The lifting of the incoming maritime airmass when it encounters the mountains results in an annual precipitation of more than 40 inches at the higher altitudes, and the monthly distribution is very similar to that observed at Los Angeles; that is, most rainfall occurs in the winter. Thus in the mountains, as at Los Angeles, the temperature and precipitation distribution are about 6 months out of phase. There is one fundamental difference, however, between mountain and valley-floor climates. In the winter the precipitation in the mountains provides a surplus of soil moisture which accumulates in the root zone. This accumulation of moisture is greater than that needed to satisfy the optimum water requirements of the vegetative cover, even in the driest summer months. Because of this moisture surplus the climate in these areas is classified as humid (Thornthwaite, 1948).

The Barstow meteorological station is in the Mojave Desert, about 50 miles north of Squirrel Inn and at an

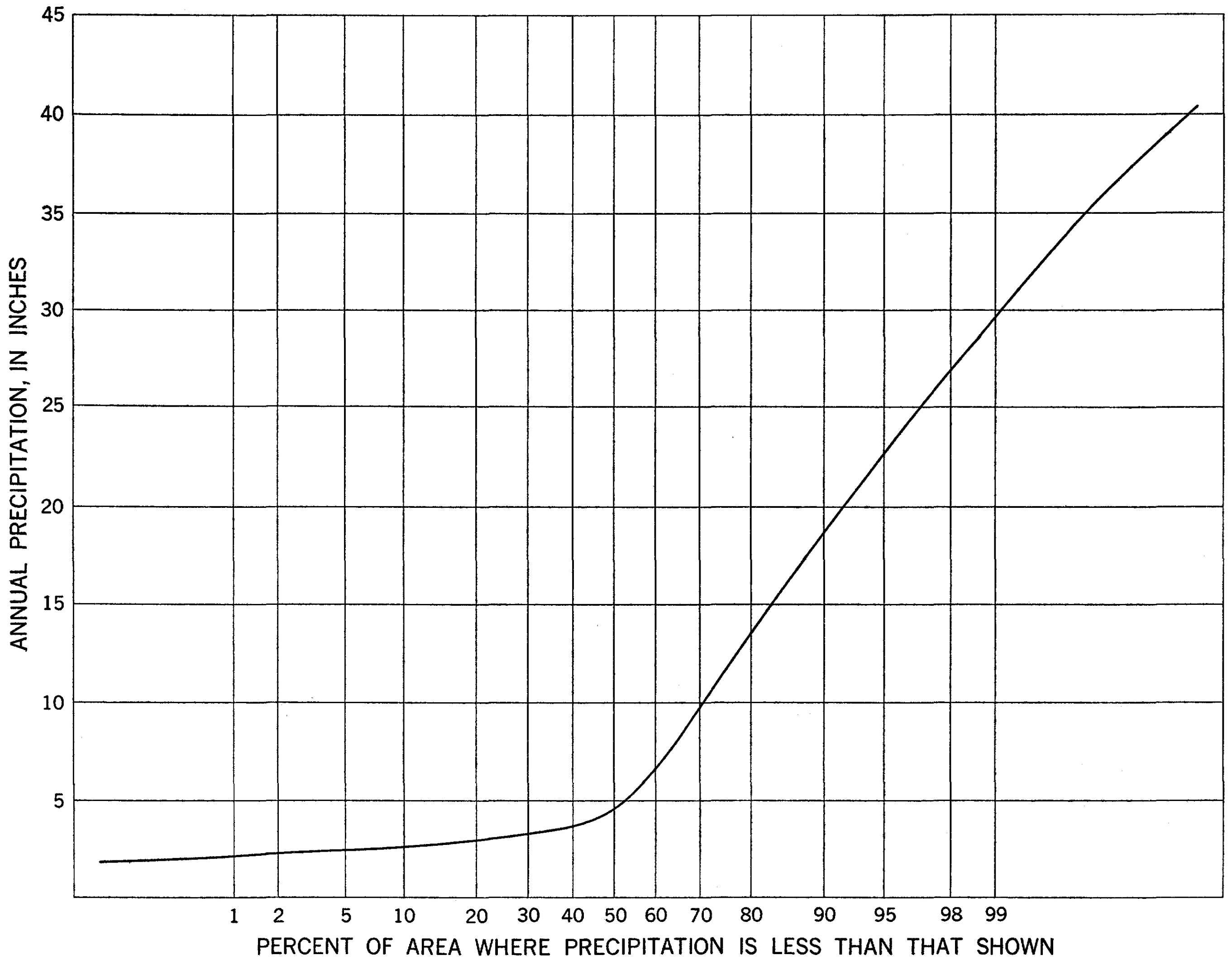

FIGURE 4.—Areal distribution of annual precipitation in southern California.

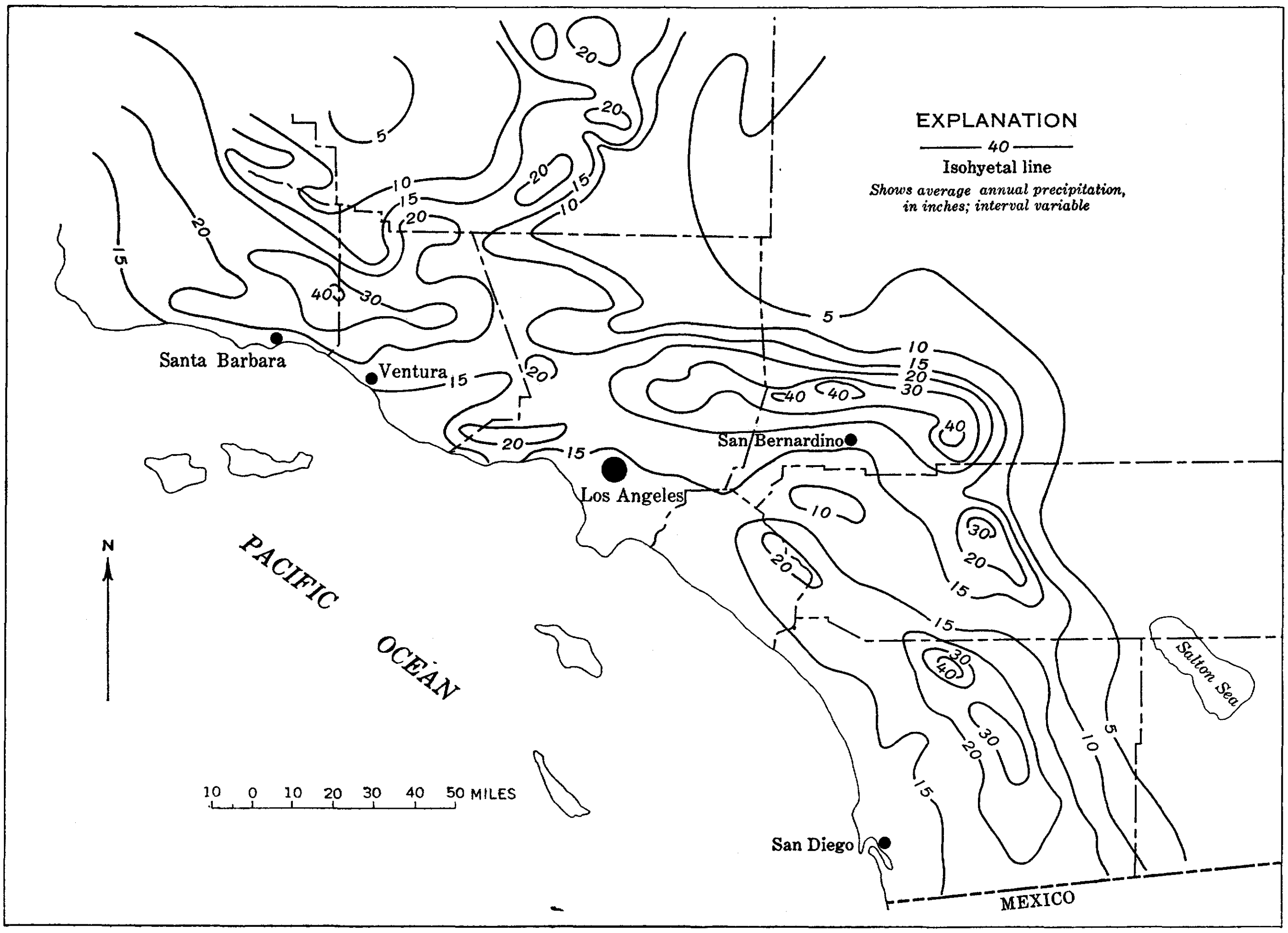

FIGURE 5.—Isohyetal map of the western part of southern California.

altitude of 2,100 feet. The average annual temperature at Barstow is about 64°F, almost the same as that at Los Angeles. However, summer temperatures at Barstow are warmer, and winter temperatures are colder than those at the coastal station (at Los Angeles). In fact, as shown on figure 3, monthly temperatures fall in all three classifications of cool, warm, and hot. The precipitation of about 4 inches per year recorded at Barstow is sufficient to support only drought-resistant desert plant life. Because of this very low precipitation, the desert is largely uninhabited. The aridity is due to the fact that potential evapotranspiration greatly exceeds precipitation.

Records from these and many other meteorological stations have been useful in constructing the section showing climatic distribution in figure 1. As the figure shows, climate changes from humid to arid in rather short distances. These data clearly show that southern California's climate is predominantly arid. Average annual precipitation over the part of the State south of the 35th parallel is about 8 inches. Figure 4 relates the percentage of land area to annual precipitation and shows that more than half of the area receives on the average less than 5 inches per year. Figure 5, an isohyetal map, shows the long-term mean annual precipitation in coastal and western desert regions of southern California. Even at the small scale of figure 5, the great variation of precipitation in relation to altitude and to exposure (type of area) is obvious. Maps of larger scale, in which the isohyets are more detailed, show variation which seems to be closely linked to even small topographic features. For a given exposure, a close relationship apparently exists between long-term average annual precipitation and altitude. The many different conditions of exposure and the lack of long-term records make the determination of such relations for other than a few very small areas impractical at present.

Two characteristics of the precipitation regime of southern California are especially noteworthy. The first is the great variability of annual precipitation. It is almost axiomatic that the year-to-year scatter in magnitude of annual precipitation tends to vary inversely with the magnitude of the annual mean. In other words, the greater the mean annual precipitation, the less it will vary percentagewise from year to year, and vice versa. Thus, at Big Bear Lake Dam the mean annual precipitation is about 37 inches and the coefficient of variation (ratio of standard deviation to mean) is 0.44, whereas at Indio the mean annual precipitation is 3.1 inches and the coefficient of variation is 0.62.

The other characteristic—a result of the pronounced seasonal distribution of precipitation in coastal and mountain regions—is the concentration of precipitation during winter months and the dearth during the summer. This results in an extended period of surface drying even in the most humid areas. Thus, some areas having ample deep water supplies may at the same time have shallow-rooted brush that becomes almost completely desiccated in late summer and autumn. This situation contributes to the threat of devastating brush and forest fires that occasionally plague southern California.

GEOLOGY

Experience has shown that geologic factors are commonly as important as climatic factors in determining the magnitude and distribution of natural water loss. This water loss, or evapotranspiration, is the result of a combination of climatic factors and of moisture availability. Moisture availability is controlled primarily by precipitation distribution and secondarily by geologic factors. The permeability of the soil mantle initially determines how much of the precipitation will contribute to surface runoff and how much will contribute to soil moisture and ground water. In southern California, the major part of precipitation usually enters the mantle. Of this water, the greater part is retained as soil moisture for subsequent evapotranspiration, and the remainder percolates to the underlying ground-water body. Hereafter, the movement of the water is largely controlled by the distribution of permeable rocks.

Sketches and diagrams in figure 6 show the general disposition of precipitation on a section of a typical mountain basin. The upper part of the figure shows a simplified and an idealized geologic section. On either side of this section are mountain blocks of relatively impervious bedrock, whereas the center of the basin is filled to considerable depth with alluvial deposits, which are generally the result of normal weathering of the bedrock and transportation of the fragmented material toward the center of the valley.

The lower part of figure 6 is a series of diagrammatic sketches showing the disposition of precipitation under three different conditions within the basin. Diagram *A* represents conditions prevalent well up on the slopes. In this area, the fractured bedrock is covered by a shallow mantle of weathered and shattered material. The root zone of the vegetative cover is generally within this mantle, which is usually less than 5 feet deep, but some roots penetrate deeply into the fractures of the bedrock.

The moisture available to supply the demands of this root zone comes from two sources: from precipitation that falls on the area and that is retained as soil moisture; and from the surplus ground water originating on contiguous areas of higher elevation. This surplus precipitation residual, moving along the contact with the relatively impermeable bedrock, tends to continuously recharge the moisture in the root zone. It is thus possible for evapotranspiration at the site shown on diagram *A* to exceed the precipitation, although this condition is rare on the higher slopes.

Diagram *B* shows conditions in the upper part of the valley floor, where the alluvial deposits are generally thicker than at *A*. Even though the root systems of the native chaparral might be as much as 20–30 feet deep, few roots penetrate into the ground water or its capillary fringe. Under these conditions, the only moisture available to meet the demands of the root zone is precipitation retained in the soil. The precipitation surplus of contiguous areas of higher elevation passes through this section well below the root zone. The maximum possible evapotranspiration at this location will thus be equal to or less than the precipitation.

The third site, illustrated on diagram *C*, is near the center of the mountain valley floor, or canyon bed. Here the mantle is thicker, and the precipitation surplus from the surrounding contiguous areas maintains the ground-water level to within a few feet of the land surface. As a result, the root zone of the vegetative cover is in contact with the ground-water table and, as soil-moisture deficiencies tend to arise, the roots draw water from the stored ground water. Under this condition, evapotranspiration may greatly exceed precipitation.

The middle part of figure 6 shows the distribution of precipitation and of evapotranspiration across the basin. Precipitation is greater at higher altitudes and diminishes towards the valley floor. Evapotranspiration (actual, not potential), although greatest on the valley floor, is also high near the tops of the basin divides because of the greater precipitation. The combination of the two distributions results in regions of moisture surplus at high altitudes and in a deficiency at low altitudes, as shown on figure 6. The difference between precipitation and evapotranspiration at any given site represents recoverable water, and the basin-wide recoverable water is represented by the sum of all

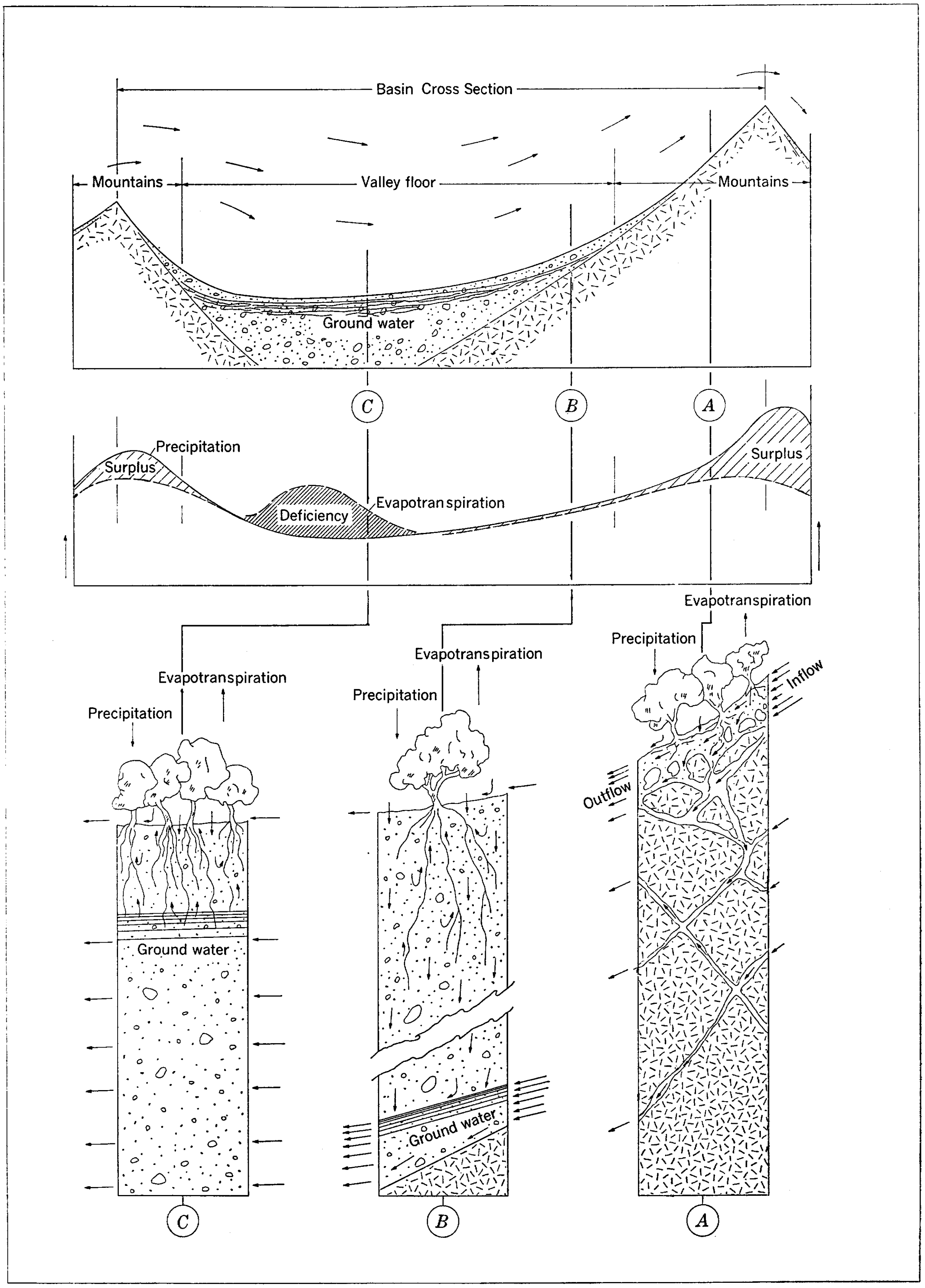

FIGURE 6.—Disposition of precipitation in a mountain basin.

such water existing in the basin, as at the sites shown on *A*, *B*, and *C*.

POTENTIAL EVAPOTRANSPIRATION

EVAPORATION FROM A FREE WATER SURFACE AS A MEASURE OF POTENTIAL EVAPOTRANSPIRATION

Evapotranspiration is usually defined as the conversion of water into vapor by transpiration and evaporation from vegetative cover and by evaporation from the soil. The term "consumptive use" is also applied to this process.

Thornthwaite (1944) defined the term "potential evapotranspiration" as "the water loss which will occur, if at no time there is a deficiency of water in the soil for the use of vegetation." With moisture continuously available, the climatic factors in the evapotranspiration process are the only regional variables that affect potential evapotranspiration. Thornthwaite (1948) indicated, in a generalized manner, that potential evapotranspiration ranges from 24 inches to more than 60 inches in the area covered by this analysis. No other known area of comparable size in the United States has such a wide range.

These generalized potential evapotranspiration values have not proven completely satisfactory for use, chiefly because they lack the sharp areal differentiation necessary in the small basins of southern California where climatic factors change over very short distances. One of the prime purposes of this analysis is to develop an index of potential evapotranspiration properly reflecting all of the more important climatic factors. These climatic factors are (a) temperature, which is an index of the energy available from the sun, (b) relative humidity, the measure of moisture deficiency of the air, and (c) wind, the agency of transport of both energy and water vapor.

Of the climatological data usually available, evaporation from a free water surface most nearly approaches potential evapotranspiration. Evaporation from standard Weather Bureau class A pans has been observed for long periods at many stations in the densely populated coastal regions and at a few stations in the interior desert regions. Most observations have been made at low elevations, but some observations were made in the mountains. Pan evaporation is generally greater than evaporation from natural water surfaces, primarily because of the boundary effect of the pan and because the response of the pan water to daily and seasonal heat changes is faster owing to its shallow depth. A natural body of water tends to maintain an even temperature, whereas the water in a pan heats more rapidly and is thereby subjected to conditions favoring rapid evaporation. Many studies have been made of this tendency of pan evaporation, and detailed information regarding it may be found in appropriate references. The consensus of these studies is that evaporation from a natural free water surface annually averages 0.70 times that from a standard Weather Bureau pan. A recent publication of the Weather Bureau presents areal refinements of this annual coefficient (U.S. Weather Bur., 1959).

Because pan evaporation observations are far from complete in their coverage, various methods have been proposed for utilizing other data and environmental characteristics to estimate the amount of evaporation. At present, the most useful of these are the methods which depend on the "energy-budget" approach. This method is based on the hypothesis that a complete heat inventory of a water body over a period of time will have as residual a net heat (or energy) loss which is used in evaporation.

Much interest has been shown by researchers in the relations between pan evaporation and potential evapotranspiration. Potential evapotranspiration, by definition, might lead one to conclude that pan evaporation is closely equivalent because of its freedom from the heat-reservoir effect operative in lakes and reservoirs. However, evapotranspiration is also affected by the heat stored in the soil mantle, the shading and protective effect of vegetation, and other factors of the physical environment. Most investigators now believe that lake evaporation is closely equivalent to potential evapotranspiration.

Evaporation records from southern California have been assembled and studied, and a group of 62 station records has been selected on the basis of location, length of record, and type of equipment used. Table 2 shows the evaporation data used in this report. Three types of pans have been included, the "Colorado," "screened," and "class A" pans. Coefficients relating annual evaporation from these pans to equivalent lake evaporation are fairly well established. There are no reliable conversion factors to relate pan data directly to lake data on a monthly basis. The previously mentioned energy-budget method and a recent modification of the mass-transfer (turbulent transport) method are used at present to obtain what is probably the most accurate annual and monthly evaporation data, but data obtained through these methods are not as yet of a long enough period to be considered representative of long-term averages. Thus far, annual values appear to check reasonably well with adjusted pan data.

As shown in table 2, evaporation in southern California ranges from 30 to 90 inches; however, at most stations it ranges between 40 and 80 inches. This variation is in close agreement with recent Weather Bureau findings (U.S. Weather Bur., 1959).

TABLE 2.—*Average annual evaporation at selected sites in southern California*

[Type of evaporation pan: (1) Standard U.S. Weather Bur. class A pan, coefficient from U.S. Weather Bur. (1959); (2) screened pan, coefficient 1.32 × class A pan coefficient; (3) Colorado pan, coefficient 1.20 × class A pan coefficient]

Station		Period of record	Latitude	Longitude	Elevation (feet)	Type of evaporation pan	Equivalent lake evaporation (inches)
No.	Name						
1	Acton, near	1932–59	34°40′	118°16′	3, 075	2	76. 0
2	Backus Ranch	1936–57	34°57′	118°10′	2, 620	1	76. 5
3	Baldwin Park	1932–54	34°06′	117°58′	387	1	43. 5
4	Barrett Reservoir	1926–45	32°41′	116°40′	1, 600	3	57. 7
5	Beaumont	1939–57	33°56′	116°56′	2, 589	1	58. 2
6	Big Dalton Dam	1946–59	34°10′	117°48′	1, 575	2	41. 7
7	Bonsall Basin	1939–43	33°19′	117°10′	215	1	45. 2
8	Bouquet Canyon Reservoir	1935–54	34°35′	118°22′	3, 000	3	71. 8
9	Cachuma Dam	1956–61	34°35′	119°59′	781	1	57. 8
10	Camp Singer (Opid's Camp)	1930–58	34°15′	118°06′	4, 350	2	40. 0
11	Chatsworth Reservoir	1947–59	34°14′	118°37′	865	2	55. 8
12	Chula Vista	1919–61	32°36′	117°06′	9	1	47. 7
13	Cogswell Dam	1935–54	34°15′	117°58′	2, 335	2	63. 3
14	Dalton Ranch	1932–42	34°10′	117°54′	800	2	68. 3
15	El Capitan Reservoir	1935–45	32°53′	116°48′	613	3	63. 0
16	El Segundo	1932–39	33°55′	118°25′	135	2	70. 2
17	Encino Reservoir	1933–59	34°09′	118°31′	1, 020	1	58. 7
18	Fairmont Reservoir	1924–59	34°42′	118°14′	3, 050	3	90. 0
19	Fern Canyon	1937–43	34°12′	117°42′	5, 100	1	53. 0
20	Fullerton evaporation station	1935–45	33°52′	117°59′	92	1	50. 0
21	Gibraltar Reservoir	1931–54	34°31′	119°37′	1, 210	1	48. 1
22	Hayfield evaporation stations 1 and 2	1934–45	33°42′	115°38′	1, 460	1	85. 7
23	Henshaw Reservoir	1922–54	33°14′	116°46′	2, 700	3	55. 0
24	Huntington Beach	1934–45	33°43′	118°02′	15	1	45. 6
25	Jameson Lake	1932–45	34°30′	119°30′	2, 230	1	41. 4
26	Lake Elsinore	1938–43	33°40′	117°20′	1, 260	1	55. 5
27	Lake Hodges	1934–45	33°02′	117°07′	330	3	67. 5
28	Lake Mathews	1939–54	33°51′	117°26′	1, 400	1	53. 6
29	Lake Wohlford	1941–45	33°10′	117°00′	1, 510	1	43. 8
30	Lower Otay Reservoir	1927–45	32°37′	116°56′	490	3	52. 4
31	Lower San Fernando Reservoir	1931–54	34°17′	118°29′	1, 140	1	65. 0
32	Mission Basin	1939–44	33°13′	117°21′	35	1	40. 2
33	Morena Reservoir	1935–45	32°41′	116°31′	3, 045	3	54. 6
34	Morris Reservoir 2	1934–49	34°11′	117°53′	1, 210	1	42. 6
35	Newhall	1932–45	34°23′	118°32′	1, 243	2	67. 1
36	Pacoima Dam	1931–59	34°20′	118°24′	1, 500	2	64. 8
37	Palmdale	1946–59	34°35′	118°07′	2, 648	2	80. 5
38	Pasadena	1938–45	34°10′	118°10′	915	1	40. 2
39	Pine Canyon	1932–45	34°40′	118°26′	3, 275	2	72. 6
40	Prado	1931–54	33°53′	117°38′	480	1	56. 7
41	Puddingstone Dam	1946–60	34°06′	117°48′	1, 030	2	46. 1
42	Puente Hill	1931–45	33°57′	117°55′	675	2	44. 7
43	Riverside Citrus Station	1925–54	33°58′	117°20′	1, 040	1	47. 7
44	San Bernardino	1929–32	34°07′	117°16′	1, 050	1	45. 6
45	San Dimas Canyon	1939–43	34°09′	117°46′	1, 480	1	39. 7
46	San Gabriel Divide	1939–43	34°13′	117°43′	4, 350	1	47. 1
47	San Gabriel Dam 1	1939–45	34°12′	117°51′	1, 481	2	66. 8
48	San Jacinto	1939–53	33°47′	116°57′	1, 550	1	51. 5
49	San Pasqual	1947–54	33°06′	116°59′	350	1	51. 7
50	Santa Ana	1929–32	33°45′	117°57′	70	1	51. 3
51	Santa Anita Dam	1931–45	34°11′	118°01′	1, 400	2	52. 4
52	Santiago Dam	1946–61	33°47′	117°44′	790	1	56. 2
53	Tanbark Flat	1935–57	34°12′	117°46′	2, 680	1	45. 1
54	Torrance	1931–54	33°52′	118°19′	57	2	51. 7
55	Trona	1920–23	35°46′	117°22′	1, 623	1	72. 9

TABLE 2.—*Average annual evaporation at selected sites in southern California*—Continued

[Type of evaporation pan: (1) Standard U.S. Weather Bur. class A pan, coefficient from U.S. Weather Bur. (1959); (2) screened pan, coefficient 1.32 × class A pan coefficient; (3) Colorado pan, coefficient 1.20 × class A pan coefficient]

Station		Period of record	Latitude	Longitude	Elevation (feet)	Type of evaporation pan	Equivalent lake evaporation (inches)
No.	Name						
56	Tujunga Spreading Ground	1933–44	34°13′	118°25′	815	1	55.3
57	Vail Lake	1953–60	33°30′	116°59′	1,480	1	57.8
58	Van Nuys	1942–45	34°11′	118°27′	695	1	31.4
59	Victorville	1931–33	34°34′	117°17′	2,700	1	52.0
60	West Saddle Peak	1931–44	34°04′	118°41′	890	2	45.7
61	Yuma Citrus Station	1924–61	32°37′	114°39′	181	1	72.1
62	Yuma Valley	1917–40	32°45′	114°36′	127	1	56.9

AREAL DISTRIBUTION OF POTENTIAL EVAPOTRANSPIRATION RATES

The combined distribution of precipitation and potential evapotranspiration is known to be the key to the ecology of an area and therefore to the natural water loss.

Although precipitation is one of the basic factors to be considered, its discussion in this text is unnecessary because of the many excellent summaries of data available, such as the "Climatic Summaries" of the U.S. Weather Bureau. The same is not true of potential evapotranspiration data. Many spot studies of pan and lake evaporation (considered synonymous with potential evapotranspiration) have also been made. There are ready sources available for precipitation data, but no such sources for evaporation data. For this reason, the information from table 2 and other sources must be utilized in estimating potential evapotranspiration in the study area.

Figure 7 shows the areal distribution of evaporation stations from which data were obtained. There appears to be a sharp difference in station density between the

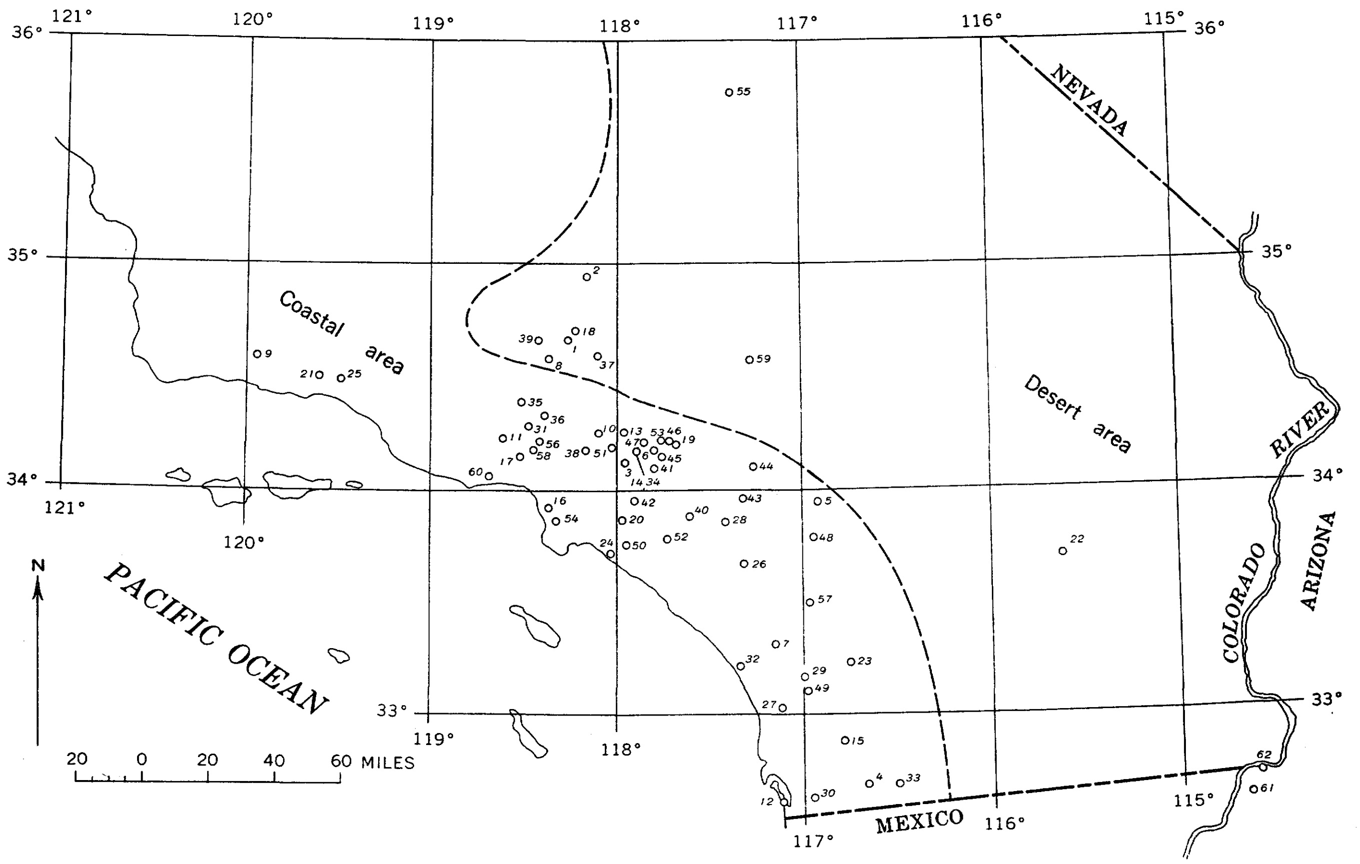

FIGURE 7.—Selected evaporation stations in southern California. Numbers correspond to those of table 2.

desert regions and the mountain and coastal regions. The concentration of stations in the more heavily populated regions is very apparent. There is now more interest in obtaining evaporation data for desert areas than previously because of increasing population, but data at present are still sketchy.

In addition to the data of table 2, several studies have been made on meteorological phenomena related to evaporation in southern California. Information from airborne instruments has been analyzed to determine the characteristics of temperature, wind, and vapor-pressure deficiency at high altitude. Blaney (1960) and H. C. Troxell (written commun.), as well as others, have defined the probable evaporation at high altitudes and have provided reliable estimates of evaporation at uninstrumented sites. Various theoretical methods of estimating potential evapotranspiration or evaporation have been developed (Thornthwaite, 1948; Penman, 1948), but in general they are most suitable for application to areas having humid or subhumid climates, and their application to much of southern California, which has a generally arid climate, appears questionable.

The relations shown in figure 8 (equivalent lake evaporation, altitude, and coastal or desert exposure) for areas below 4,000 feet in altitude have principally been determined on the basis of the data in table 2 and generalized Weather Bureau maps of evaporation, whereas the curves for areas above 4,000 feet in altitude are based on the previously cited work of Blaney and Troxell. The difference in lake evaporation between desert and coastal and mountain areas is recognized, as is the temperature inversion that has often been observed in this region. As altitude increases above 3,000 feet (the altitude of the highest desert flatlands), the two curves tend to merge, and above 6,000 feet there is only one curve.

NATURAL WATER LOSS

DETERMINATION BY PLOT STUDIES

Natural water loss from an area, as previously mentioned, varies not only with potential evapotranspiration, but also with the availability of water. Measurement of natural water loss is not a simple process. Often a test area or block of undisturbed soil and vegetation is isolated in some manner, and precise measurements are made of the precipitation and the ground-water level. Other experimenters have made use of the lysimeter, a device so placed in the soil as to intercept and measure downward percolating water. The difference between incoming water (precipitation, if a plot is insulated against seepage from adjoining regions) and outgoing water (estimated from lysimeter measurements) is considered natural water loss. Other estimates have been based on the water budget of entire basins, where unmeasured seepage or surface runoff in or out of the basin can be considered negligible.

The relationship involved in such studies can be expressed thus:

Natural water loss = (precipitation + subsurface inflow + net change in soil moisture + net change in ground-water storage) − (surface outflow + subsurface outflow).

If the algebraic sum of surface and subsurface flow and change in ground-water storage is defined as "recoverable water," the relationship can be simplified to:

Natural water loss = precipitation − recoverable water − change in soil moisture,

The last factor (change in soil moisture) is generally negligible if the time period chosen for computing the hydrologic balance is the water year.

For many years investigators have been attempting to measure these water losses, mostly through use of the lysimeter or plot tests of various sizes and types. Generally, precipitation, surface runoff, and changes in soil moisture were observed, and the remaining data were obtained by indirect means.

One of the first of these tests was begun in 1928 by C. A. Taylor, who found that the water loss from basins in native chaparral cover in the foothills near San Bernardino, Calif., was about 19 inches of water a year. These results were confirmed by subsequent tests made by other individuals.

In more recent years, a series of observations was made to determine natural water loss in the San Dimas Experimental Forest of southern California, 25 miles east of Los Angeles. These observations were made at an altitude of about 2,700 feet on test plots of about 0.01 acre on the steep slopes of San Dimas canyon. The soil mantle was about 4–5 feet deep and was a residual, it being weathered from a badly fractured dioritic rock. Table 3 gives the disposition of the precipitation falling on a plot of mixed chaparral as reported by Rowe and Colman (1951).

TABLE 3.—*Disposition of precipitation, in inches, on chaparral in the San Dimas Experimental Forest*

	1940–41	1941–42	1942–43	Mean
Precipitation	47.8	16.8	45.1	36.6
Natural water loss	22.9	17.6	20.4	20.3
Change in soil moisture in root zone	1.1	−.8	.7	.4
Recoverable water	23.8	0	24.0	15.9

The annual natural water loss ranged from 17.6 to 22.9 inches, and averaged 20.3 inches for the 3-year period. In 1941–42 the natural water loss exceeded

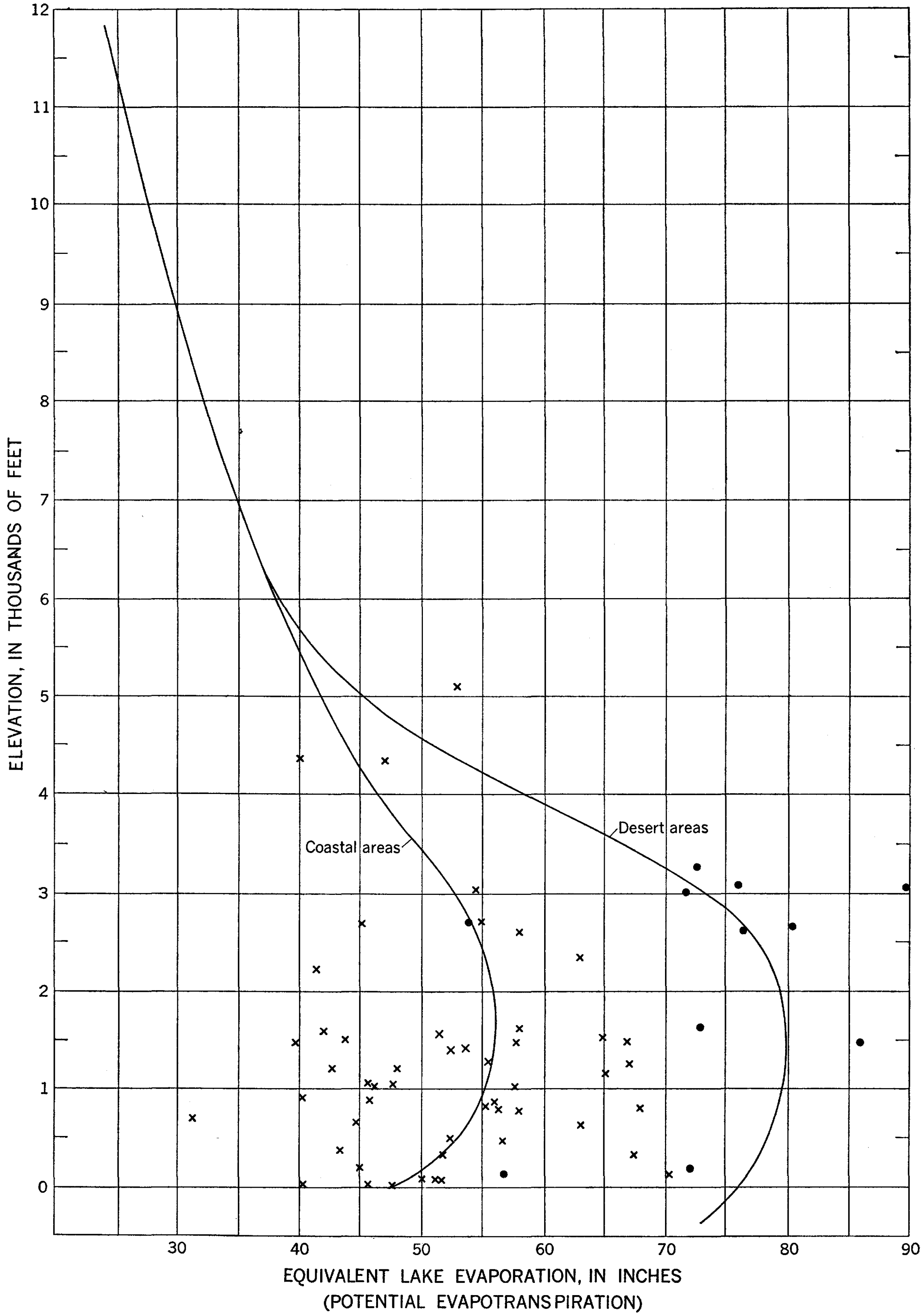

FIGURE 8.—Relations between lake evaporation and altitude in southern California. Points indicate desert stations; × indicate coastal stations. Datum is mean sea level.

the precipitation; this situation was possible because of depletion of the soil moisture in the root zone.

Table 3 also shows the recoverable water, or the precipitation residual after satisfying the natural water loss. This recoverable water is made up of surface runoff and recharge to ground-water storage. During this 3-year period, the annual recoverable water ranged from 0 to 24.0 inches and averaged 15.9 inches. The data are not entirely complete, as no allowance was made at the observation plot for ground-water recharge from water which originated at higher altitudes and which moved along the contact between the soil mantle and the bedrock. A situation of this type is illustrated in diagram *C* of figure 6.

These data are supplemented by additional observations made by Rowe and Colman (1951) of a plot at Bass Lake having a native Ponderosa pine cover. This plot was at an altitude of about 3,500 feet in the Sierra Nevada near Yosemite National Park. The soil mantle was about 6 feet deep, overlying shattered bedrock, and the mantle had a field capacity of 23.4 inches. The observations made at this site are summarized in table 4.

TABLE 4.—*Disposition of precipitation, in inches, on Ponderosa pine at Bass Lake, Calif.*

	1940–41	1941–42	1942–43	1943–44	1944–45	Mean
Precipitation	58.6	50.6	50.9	38.5	49.6	49.6
Natural water loss	22.0	21.2	23.4	24.4	22.8	22.8
Change in soil moisture in the root zone	.7	−.3	1.4	−.3	−1.5	−.1
Recoverable water	35.9	29.7	26.1	14.4	28.3	26.9

During the observation period the annual precipitation averaged 49.6 inches, exceeding that at San Dimas by 13 inches. Despite this greater precipitation, the natural water loss was only about 2.5 inches more than that at San Dimas. Most of the additional precipitation appeared as some form of recoverable water.

TABLE 5.—*Disposition of precipitation, in inches, on woodland chaparral in the North Fork area, California*

	1936–37	1937–38	1938–39	1939–40	Mean
Precipitation	40.7	60.1	24.6	40.8	41.6
Natural water loss	13.9	17.5	16.2	17.8	16.4
Change in soil moisture in the root zone	0	.1	.1	−.2	0
Recoverable water	26.8	42.5	8.3	23.2	25.2

Table 5 shows the results of Rowe and Colman's observations on a plot of native woodland chaparral in the North Fork area of the Sierra Nevada about 10 miles south of Bass Lake. This plot had a land slope of about 32 percent and was at an altitude of about 3,000 feet. The shallower soil mantle had a field capacity of only 8.9 inches. Natural water loss for this plot, given in table 5, was less than that for the other three observation plots. This situation was probably in a large measure due to the limited field capacity of the shallow soil mantle. The recoverable water was 25.2 inches, only about 1.6 inches less than that observed at Bass Lake, where the precipitation is much greater.

In an environment somewhat different from that found in southern California, Croft and Monninger (1953) measured the natural water loss of a plot having an aspen-herbaceous cover (table 6). This plot in the Wasatch Mountains of northern Utah is in a region where the major part of the annual precipitation occurs as snow, and the surface runoff results largely from snowmelt and summer rainfall.

TABLE 6.—*Disposition of precipitation, in inches, on an aspen-herbaceous covered plot in northern Utah*

	1947	1948	1949	Mean
Precipitation	52.60	54.75	50.96	52.77
Natural water loss	23.09	24.33	19.64	22.36
Recoverable water	39.51	30.42	31.32	30.41

In these four experimental plots, the mean annual precipitation ranged from 36.6 inches on the chaparral plot of San Dimas to 52.77 inches on the aspen-herbaceous plot of northern Utah. Despite this wide range in precipitation, the mean annual natural water loss ranged only 6.4 inches, from 16.4 inches on the woodland chaparral in the North Fork area to 22.8 inches at Bass Lake. The variation in natural water loss from year to year, as well as from place to place, is also slight.

DRAINAGE-BASIN ANALYSIS

Table 7 shows the average annual natural water loss for a group of southern California mountain basins. The values were obtained by use of the basic inflow-outflow equation given earlier (p. E13). These basins were selected because the subsurface outflow from the basin and the inflow to the basin from adjacent areas were probably negligible or could be estimated with reasonable accuracy. The effects of ground-water storage and of soil moisture storage in the root zone have been minimized by beginning and ending the period with years of equal wetness. Adjustments have been made, where necessary, for any subsurface seepage bypassing the gaging station in the alluvial canyon deposits.

These areas are still largely in their native state, as they have only been slightly encroached upon by man's activities. The areas range from 3.9 to 319 square

TABLE 7.—*Precipitation, water loss, recoverable water, and potential evapotranspiration in selected basins of southern California*

[Data adjusted to the 50-year period 1896–1946. Results are in inches]

No.	Basin	Area (Sq mi)	Average elevation (feet)	Mean annual precipitation	Mean annual recoverable water	Mean annual natural water loss	Potential evapo-transpiration
	Mojave River basin						
1	Deep Creek below Green Valley Creek [1]	15.8	6,600	37.5	19.1	18.4	36.3
2	Crab Creek [1]	3.9	6,400	30.6	12.0	18.6	36.7
3	Deep Creek near Hesperia	137	5,800	21.6	7.1	14.5	39.6
4	West Fork Mojave River	74.8	4,000	27.1	8.1	19.0	57.5
	Santa Ana River basin						
5	San Antonio Creek	16.9	6,700	41.9	18.9	23.0	36.7
6	Cucamonga Creek	10.1	5,100	38.0	11.8	26.2	42.2
7	Day Creek	4.6	5,100	38.0	17.4	20.6	39.2
8	Lytle Creek	46.9	5,400	39.3	11.8	27.5	41.0
9	Lone Pine Creek	15.0	4,700	26.2	1.6	24.6	47.6
10	Cajon Creek	40.9	3,900	18.2	3.4	14.8	54.1
11	Waterman Canyon Creek	4.6	3,600	32.9	8.8	24.1	48.8
12	East Twin Creek	8.6	3,500	32.2	8.4	23.8	49.4
13	City Creek	19.8	3,800	34.8	7.8	27.0	47.6
14	Santa Ana River near Mentone	202	7,000	29.3	6.5	22.8	36.6
15	Mill Creek near Yucaipa	42.9	6,600	39.1	13.2	25.9	36.8
	Santa Margarita River basin						
16	Temecula Creek at Vail Dam	319	3,500	20.1	1.7	18.4	51.7
	San Dieguito River basin						
17	Santa Ysabel Creek at Sutherland Dam	54.0	3,400	29.8	4.7	25.1	50.5
	Whitewater River basin						
18	Snow Creek	11.0	6,200	33.2	12.2	21.0	40.7
19	Palm Canyon Creek	94.0	3,900	14.2	1.2	13.0	59.5

[1] From private records.

miles, and have altitudes ranging from 3,400 to 7,000 feet. Owing to differences in both altitude and physiography, the mean annual precipitation ranges from 14 inches in Palm Canyon Creek basin, in the Colorado Desert, to 42 inches in the rugged frontal San Antonio Creek basin in the San Gabriel Mountains. Natural water loss ranges from 13 inches in the Palm Canyon Creek basin to more than 27 inches in the Lytle Creek basin of the San Gabriel Mountains.

The data of table 7 have been obtained thus: Average elevation is computed from a hypsometric curve for the basin, as in columns 1 and 2 of tables 8 and 9. Precipitation is computed on the basis of isohyetal maps and the area-altitude distribution, by utilizing the data of columns 1, 2, and 3 of tables 8 and 9. Recoverable water is measured outflow, adjusted where necessary for subsurface seepage—in these basins a very minor factor. Natural water loss is the difference between precipitation and recoverable water. Potential evapotranspiration is computed by use of the area-altitude distribution and the curves of figure 8, as shown in tables 8 and 9.

Recoverable water can be in the form of surface water or ground water. It generally ranges from about 1 inch, as in the Palm Canyon Creek basin, to 19 inches, as in the upper Deep Creek basin. This range of values is indicative of the water available from the mountain areas for man's use.

DETERMINATION OF NATURAL WATER LOSS FROM HYDROLOGIC RELATIONS

The relations involving precipitation, natural water loss, and recoverable water are many and complex. Some fundamental considerations may be used, however, to establish a working hypotheses.

The first consideration is that natural water loss is a combined function of potential evapotranspiration and moisture availability. Potential evapotranspiration has previously been discussed, and methods have been presented for estimating its magnitude in the study region. Moisture availability has been shown to be related to precipitation and to soil and geological environment; however, precipitation assumes greater importance in mountainous areas. Because the concepts and methods presented in this report can be applied only to mountain basins, moisture availability will be considered synonymous with precipitation.

The second consideration is the assumption that there is always some recoverable water left from precipitation—recoverable water will be zero only when precipitation is zero. The amount of recoverable water may be extremely small for slight amounts of precipitation, but it is finite. This assumption is borne out by the fact that even in desert areas, having a mean annual precipitation as low as 2 inches, flood channels of local origin are found. These channels are evidence of the existence of recoverable water, which probably occurs only as very infrequent flood runoff.

Another consideration is that natural water loss cannot be greater than potential evapotranspiration. The validity of this assumption is evinced by the definitions of natural water loss and potential evapotranspiration. The assumption limits the ratio of natural water loss (L) to potential evapotranspiration (E) thus:

$$\left(0 \leq \frac{L}{E} \leq 1\right).$$

Finally, if soil-moisture changes are considered negligible, the following relation can be deduced from a previously stated equation: natural water loss = precipitation − recoverable water, which is symbolically expressed as

$$L=P-R, \text{ or } R=P-L.$$

If all terms are divided by E, the equation becomes dimensionless:

$$\frac{R}{E}=\frac{P}{E}-\frac{L}{E}.$$

When there is no natural water loss (a condition which, over a period of years, never exists in nature, but which imposes a theoretical limit), then

$$\frac{R}{E}=\frac{P}{E},$$

and when natural water loss is equal to potential evapotranspiration (a condition rarely if ever occurring in a mountainous region)

$$\frac{R}{E}=\frac{P}{E}-1.$$

These four considerations provide a basis for constructing limiting curves wherein must lie all points of a relation of P/E to R/E. These limits are shown on figure 9, which has as ordinate the ratio P/E and as abscissa the ratio R/E. The lower limit, $R/E=P/E$, is a straight line through the origin, and the upper limit, $R/E=(P/E)-1$, is a straight line parallel to the lower limit but one unit above.

The relations and limitations of curves expressing the interdependence of P/E, R/E, L/E, described in the preceding paragraph, provide a practical tool for use in studying natural water loss in the mountain areas of southern California. The data of table 7 provide values of P, L, R, and E for basins having a wide range of physical characteristics. Values of E were computed from figure 8 and from the area-altitude (hypsometric) relations for each basin. The method of computing E is explained later.

The curves of relation must lie within the stated limits. Because they describe a relation expressed as

$$\frac{R}{E}=\frac{P}{E}-\frac{L}{E}$$

and because L/E will never quite reach unity but will tend to approach a constant value at high ratios of P/E,

$$\frac{R}{E}=\frac{P}{E}-C,$$

in which C approaches a constant positive value, less than one, at high values of P/E. The constant C, equal to L/E, varies from basin to basin, especially where the nature of the geology and soil mantle varies.

The data of table 7 have been plotted on figure 9, where the points lie between the limiting curves. A curve of relation between P/E and R/E is also shown on figure 9. This curve starts at $R/E=(P/E)-0.2$ and approaches the line $R/E=(P/E)-0.6$; in other words, the data of the 19 basins indicate that in this region natural water loss for the 50-year base period generally ranged from 20 to 60 percent of potential evapotranspiration.

The curve on figure 9 shows an average of the data about which the points are scattered. The departure of the points from the curve is due to several causes, such as the errors in the data of table 7 and the differences in physical characteristics among the basins. The error in data is probably small as compared to the physical differences; therefore, an adjustment for each individual point scattered about the curve has been made by use of a retention factor, K, which will numerically express the effect of physical differences. The computation of the K factor for two typical basins is shown in tables 8 and 9.

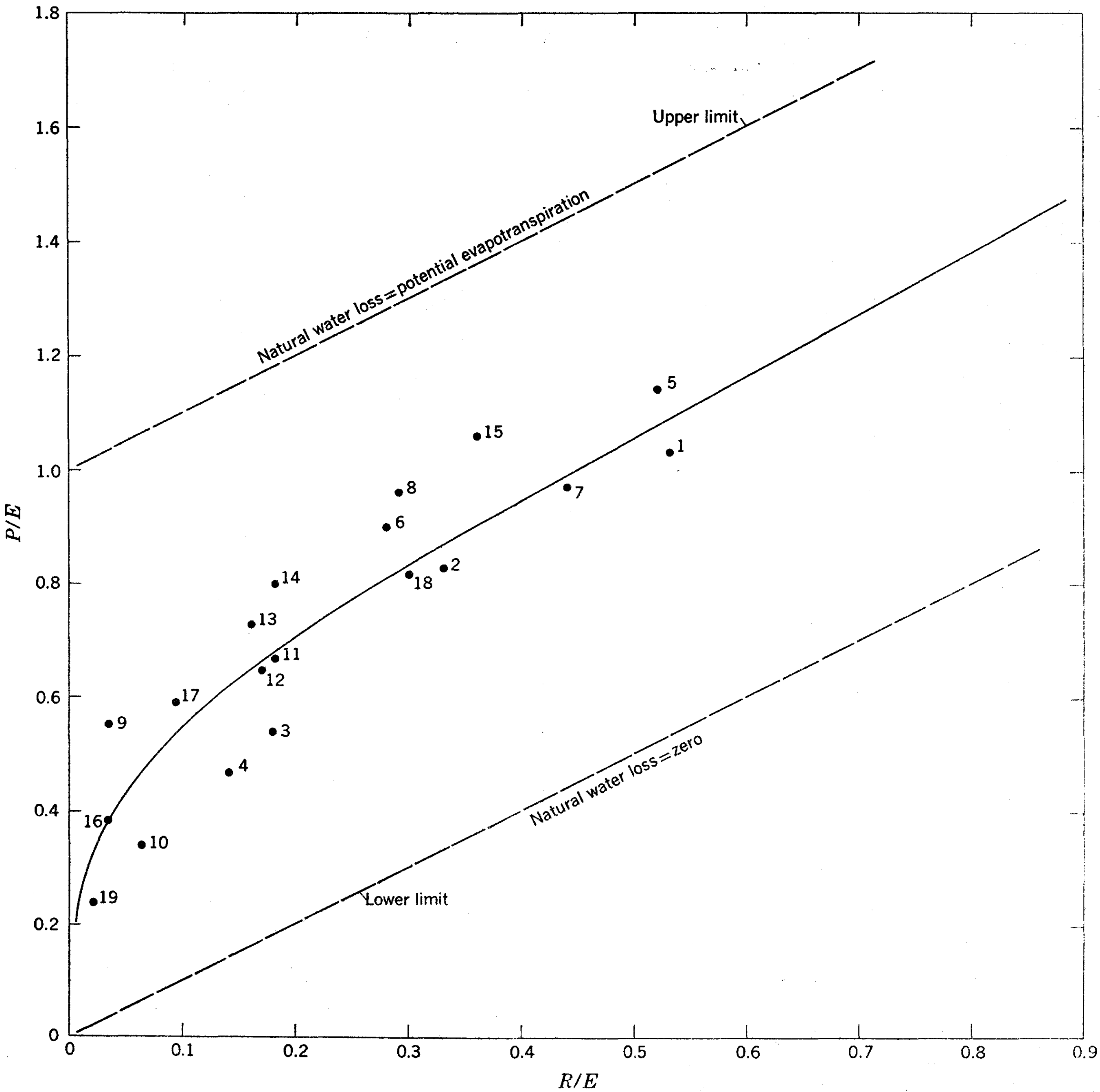

FIGURE 9.—Relation between P/E (the ratio of precipitation to potential evapotranspiration) and R/E (the ratio of recoverable water to potential evapotranspiration). Ratios for individual basins from data given in table 7. For extreme values of P/E, use the following tabulation:

P/E	R/E
<0. 20	0
0. 20– . 28	0. 01
. 29– . 34	. 02
. 35– . 38	. 03
1. 46–1. 90	P/E less 0. 59
>1. 90	P/E less 0. 60

Curve equation:

$$(R/E+0.6)^{3.6}-(P/E)^{3.6}=0.16$$

TABLE 8.—*Computation of retention factor* K *for San Antonio Creek basin*

Altitude (thousands of feet)	Percent of basin between given altitudes	Precipitation	Potential evapotranspiration	*P/E*	*R/E*	*R*	*R* (adjusted)	*L*
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
10. 1–10. 0	0. 2	50. 7	27. 6	1. 84	1. 25	34. 4	30. 4	20. 3
10. 0–9	3. 2	49. 6	28. 8	1. 72	1. 13	32. 5	28. 7	20. 9
9–8	13. 7	47. 6	31. 0	1. 54	. 95	29. 5	26. 0	21. 6
8–7	26. 4	45. 6	33. 6	1. 36	. 78	26. 2	23. 1	22. 4
7–6	21. 0	42. 4	36. 5	1. 16	. 59	21. 5	19. 0	23. 4
6–5	19. 0	38. 2	40. 0	. 96	. 41	16. 4	14. 5	23. 7
5–4	14. 1	33. 6	43. 9	. 76	. 25	11. 0	9. 7	23. 9
4–3. 4	2. 4	29. 5	48. 4	. 61	. 14	6. 8	6. 0	23. 5
Total	100. 0							
Weighted basin mean		41. 9	36. 7			21. 4	18. 9	23. 0

NOTE. $K=\frac{18.9}{21.4}=0.883$. Col. 6 is obtained by entering data from fig. 9 with *P/E* from col. 5; col. 7=col. 6×col. 4; col. 8=col. 7×*K*; col. 9=col. 3−col. 8.

TABLE 9.—*Computation of retention factor* K *for Palm Canyon Creek basin*

Altitude (thousands of feet)	Percent of basin between given altitudes	Precipitation	Potential evapotranspiration	*P/E*	*R/E*	*R*	*R* (adjusted)	*L*
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
8–7	1. 0	27. 4	33. 5	0. 82	0. 29	9. 7	11. 1	16. 3
7–6	5. 8	22. 9	36. 6	. 63	. 15	5. 5	6. 3	16. 6
6–5	12. 9	19. 2	41. 1	. 47	. 06	2. 5	2. 9	16. 3
5–4	31. 1	15. 8	51. 1	. 31	. 02	1. 0	1. 1	14. 7
4–3	23. 9	12. 6	66. 7	. 19	0	0	0	12. 6
3–2	13. 8	9. 7	77. 8	. 125	0	0		9. 7
2–1	10. 8	7. 4	80. 0	. 092	0	0		7. 4
1–0.5	. 7	6. 2	79. 1	. 078	0	0		6. 2
Total	100. 0							
Weighted basin mean		14. 2	59. 5			1. 05	1. 2	13. 0

NOTE. $K=\frac{1.2}{1.05}=1.143$. Col. 6 is obtained by entering data from fig. 9 with *P/E* from col. 5; col. 7=col. 6×col. 4; col. 8=col. 7×*K*; col. 9=col. 3−col. 8.

The computations for tables 8 and 9 were performed by using zones of altitude, because of the profound effect of altitude on the climate of a mountain basin. The values of precipitation, potential evapotranspiration, and recoverable water in each basin are therefore weighted according to percentages of the basin lying between selected altitudes.

Tables 8 and 9 are intended as aids in computing recoverable water (*R*, col. 7) within the selected altitude zones by means of the relations so far developed. We can thereby find the retention factor *K*, which is used to adjust the weighted basin mean of *R* (bottom value of col. 7) to a value representative of a specific basin, as shown in table 7. The adjusted values appear in column 8 of tables 8 and 9, and the weighted basin mean given at the bottom of column 8 is equal to the value of *R* for the basin, as shown in table 7. Later in the report, after the development of a method for estimating the retention factor *K* for an ungaged basin is treated, the same procedure will be utilized in computing a value for the weighted basin mean of *R* to which *K* may be applied. The result will be an adjusted value of the weighted basin mean of *R*, or an estimate of recoverable water leaving the ungaged study basin.

In tables 8 and 9, the computations for columns 1–4 have previously been described in the discussion of table 7, and the computations required for columns 5 through 9 are obvious.

By applying the retention factors to the base curve of figure 9, a family of curves can be constructed which fit the data of the individual streams. *K* values, ranging from 0.28 to 1.34, have been computed for the 19 basins listed in table 7 and are shown in table 10.

TABLE 10.—*Values of the retention factor* K *of selected mountain basins in southern California*

No.	Basin	Drainage area (sq mi)	*K*
1	Deep Creek below Green Valley Creek	15.8	1.10
2	Crab Creek near Green Valley Lake	3.9	1.07
3	Deep Creek near Hesperia	137	1.10
4	West Fork Mojave River near Hesperia	74.8	1.16
5	San Antonio Creek near Claremont	16.9	.88
6	Cucamonga Creek near Upland	10.1	.75
7	Day Creek near Etiwanda	4.6	1.12
8	Lytle Creek near Fontana	46.9	.69
9	Lone Pine Creek near Keenbrook	15.0	.28
10	Cajon Creek near Keenbrook	40.9	1.34
11	Waterman Canyon Creek near Arrowhead Springs	4.6	.94
12	East Twin Creek near Arrowhead Springs	8.6	.92
13	City Creek near Highland	19.8	.68
14	Santa Ana River near Mentone	202	.56
15	Mill Creek near Yucaipa	42.9	.71
16	Temecula Creek at Vail Dam	319	.58
17	Santa Ysabel Creek at Sutherland Dam	54.0	.70
18	Snow Creek near White Water	11.0	.90
19	Palm Canyon Creek near Palm Springs	94.0	1.14

THE RETENTION FACTOR AND ITS RELATION TO GEOLOGIC FORMATIONS

The considerations used in this report to determine natural water loss are: (1) the average relation between P/E and R/E, (2) the area-altitude relation, (3) the areal distribution of precipitation and potential evapotranspiration in the basin, and (4) the retention factor K. The average relation between P/E and R/E is shown in figure 9, the area-altitude relation can be determined from topographic maps, the areal distribution of precipitation can be taken from isohyetal maps, and the areal distribution of potential evapotranspiration can be determined from figure 8. A method of determining K remains to be developed.

Inspection of figure 9 indicates that, for given values of P and E, an increase in K is associated with a greater amount of recoverable water, and a decrease in K is associated with a greater natural water loss. Streamflow is the most easily observed index of recoverable water in mountain basins; this fact indicates that there may be an association between the value of K and basin characteristics conducive to sustained flow, such as type and depth of soil mantle, type and density of vegetal cover, and average basin slope.

The geology of most mountain regions of southern California has been mapped to varying degrees of refinement over the past years. Because this information is widely available and because geology and soil type are strong determinants of the hydrologic regime, the possibility of establishing a correlation between geology and K factors was explored. By outlining the study basins on geologic maps, listing the main formations in each basin, and grading first the runoff, and then K values, against formation type, a relation was soon apparent, which was further refined by trial-and-error assignment of values to the various formations. In the final relation, the following retentivity values were assigned to the surficial rock types:

A. Quaternary, except old alluvium	10
B. Old alluvium	100
C. Tertiary, except Potato Sandstone	0
D. Potato Sandstone of F. E. Vaughan	100
E. Mesozoic	10
F. Paleozoic	20
G. Precambrian	40

TABLE 11.—*Distribution, in percent of area, of surficial rock types in selected basins in Southern California and geologic index*

[Rock types are described in text]

No.	Basin	Distribution (percent of area) of surficial rocks by type and for value indicated							Index (*I*)
		A (10)	B (100)	C (0)	D (100)	E (10)	F (20)	G (40)	
1	Deep Creek below Green Valley Creek	0	0	0	0	100	0	0	1,000
2	Crab Creek near Green Valley Lake	0	0	0	0	100	0	0	1,000
3	Deep Creek near Hesperia	1	0	2	0	89	8	0	1,060
4	West Fork Mojave River near Hesperia	16	1	17	0	66	0	0	920
5	San Antonio Creek near Claremont	19	2	0	0	75	0	4	1,300
6	Cucamonga Creek near Upland	3	6	0	0	91	0	0	1,540
7	Day Creek near Etiwanda	0	0	0	0	100	0	0	1,000
8	Lytle Creek near Fontana	16	2	0	0	38	0	44	2,500
9	Lone Pine Creek near Keenbrook	27	1	5	0	11	0	56	2,720
10	Cajon Creek near Keenbrook	25	10	46	0	19	0	0	1,440
11	Waterman Canyon Creek near Arrowhead Springs	0	6	0	0	94	0	0	1,540
12	East Twin Creek near Arrowhead Springs	0	5	0	0	95	0	0	1,450
13	City Creek near Highland	0	8	2	0	90	0	0	1,700
14	Santa Ana River near Mentone	3	21	4	0	55	17	0	3,020
15	Mill Creek near Yucaipa	8	0	0	7	85	0	0	1,630
16	Temecula Creek at Vail Dam	11	8	0	0	70	11	0	1,830
17	Santa Ysabel Creek at Sutherland Dam	2	0	0	0	98	0	0	1,000
18	Snow Creek near White Water	0	0	0	0	0	100	0	2,000
19	Palm Canyon Creek near Palm Springs	0	7	0	0	54	39	0	2,020

A geologic index has been computed for each basin by multiplying these assigned values by the percentage of basin predominantly underlain by each category of mantle. Such data are shown in table 11, from which the Mill Creek basin provides the following example:

8 percent category A, $8\times 10=$	80
7 percent category D, $7\times 100=$	700
85 percent category E, $85\times 10=$	850
Sum=index	1,630

The geologic index (I) values thus determined provided a measure of the retentivity that was plotted against K. There appears to be a loose but useable relation, which is expressed by the curve of figure 10. From figure 8, the I value of 1,630 for Mill Creek yields $K=0.70$. This value is reasonably close to the K value of 0.71, computed on the basis of hydrologic data from the basin (table 7). The relation between I and K is fairly well defined for basins on the coastal side of the mountain crests. The three basins (Cajon, Palm Canyon, and Snow Creeks) on the desert slopes of the mountains all appear to indicate a higher K value for a given I value. These curves are shown on figure 10.

Available hydrologic data for this study, as for many others, do not justify a refined statistical analysis because of a lack of refinement. This does not mean, however, that the data cannot be used to provide a practical basis for choosing the best of several choices involved in a given problem. In this study, for example, the K values determined by the geologic index I are generally very close to those determined from hydrologic data. Of course, no standard of absolute accuracy is available for comparison. Data corresponding to table 7, collected for another 50-year period, would probably differ somewhat from those used in this study.

It is noteworthy that the magnitude of error in computation of recoverable water affects the magnitude of error in natural water loss in a nonlinear manner. In regions of high precipitation natural water loss is generally not much more than 50 percent of precipitation, and error in computed recoverable water is about equal, percentagewise, to the error in natural water loss. In more arid regions, recoverable water is a much smaller part of total precipitation, and an error in computed recoverable water produces a smaller relative error in natural water loss. For example, if the K value of 0.45, from figure 10, were used to compute natural water loss in the Lone Pine basin (No. 9), the error in R would be about 62 percent, but the resulting error in L would be only 4 percent.

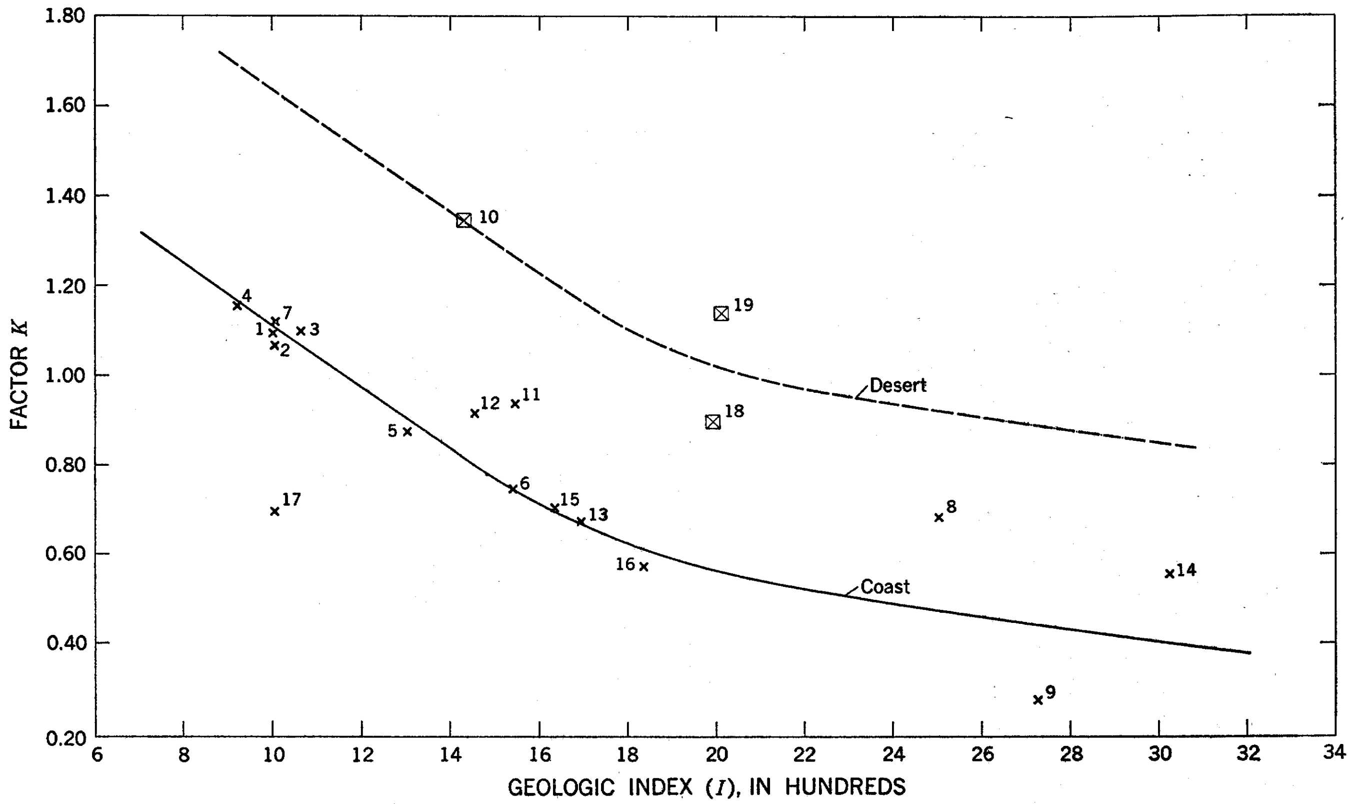

FIGURE 10.—Relation between basin-retention factor (K) and geologic index (I). Data from tables 10 and 11.

SUMMARY OF PROCEDURES

Use of the method of estimating natural water loss and recoverable water presented herein requires knowledge of long-term precipitation averages, which may be obtained from U.S. Weather Bureau reports and can often be supplemented by data from other sources. Precipitation data are most easily used from isohyetal maps, which may be already available or which can be prepared from available data. A refinement of the results by use of the geologic index requires use of geologic maps so that a breakdown of rock types into categories corresponding to or similar to those of table 11 can be made. The use of the precipitation and geologic data in conjunction with the concepts and relations presented in this report probably provides the most reliable estimates available.

The procedure is outlined as follows:

1. From topographic maps of the basin or region studied, derive the relation between selected altitudes and percentage of area above those altitudes (the hyposmetric curve).
2. Based on the characteristics of the hypsometric curve, establish from 8 to 12 zones of altitude, as shown in columns 1 and 2 of table 8. Determine the long-term mean annual precipitation, P, for each altitude zone and compute the basin mean annual precipitation, as has been done in column 3 of table 8.
3. Complete column 4, altitude zone and basin mean values of potential evapotranspiration, E, by use of figure 8. Compute the ratio P/E for each zone of altitude as shown in column 5, table 8.
4. From figure 9, determine the R/E ratio and compute R (cols. 6 and 7, table 8).
5. Compute the value for geologic, index I. A table similar to table 11 may be helpful, and the criteria for the retentivity of formations should correspond to those tabulated on p. E20. The geologic index applied to figure 10, showing the relation between K and I, will provide the K factor applicable to the basin.
6. Multiply each value of R, in column 7, by K to obtain the adjusted R, column 8. Compute the basin mean adjusted R.
7. For each zone of altitude, subtract adjusted R from P to obtain L, and compute basin mean L.
8. Within the limits of computational error, basin mean L should be equal to basin mean P less basin mean adjusted R. This equality is a check on the arithmetic only, not on the accuracy of the data.

The method may also be used, with some loss of accuracy, for regions in which geologic information is not available. For such regions, follow steps 1–4. The K factor must be determined by a method other than that described in step 5. Perhaps general knowledge of the basin and comparison with a basin for which K is defined can provide a basis for an estimated value of K for the basin in question. If no such basis is apparent, inspection of figure 10 indicates that for desert basins a value of K of 1.10 would be a reasonable estimate, and for other regions a K value of 0.8 might be appropriate. After a K value is decided upon, steps 6–8 as previously described should be followed.

APPLICATION OF THE DERIVED RELATIONS

The data and procedures outlined in this report provide a means of making consistent estimates of natural water loss and recoverable water within the mountain regions of southern California. The method is based on long-term records of past history, and therefore the predictions should be considered applicable to long-term periods, perhaps 25 years or more. The study of climatic variations, such as trends in annual precipitation and the random or nonrandom grouping of wet and dry years, is beyond the scope of the report. However, because these factors seem applicable in some measure to short periods, they cannot be ignored and must be recognized as introducing a considerable degree of uncertainty into short-term predictions. For example, we can be reasonably certain that there was more recoverable water in southern California during the wet period 1904–13 than during the comparable period 1945–54. Precipitation brought about 70 percent as much water into the area during the latter period as was made available during the 10 wet years, and recoverable water probably differed by an even larger percentage.

There are two limiting conditions to the use of the suggested methods: time and area of use. The limitations imposed by time have already been discussed. The data and the estimates must be based on a length of time that is relatively long, as compared to the time span of most hydrologic records. This limitation is forced upon us because in short-term periods precipitation may differ greatly from that in long-term periods and because the change in volume of ground-water storage may be relatively large in the short term.

Limitations on the area of use are not as clearly defined as those of time. The most reliable estimates are those for moderate-sized basins lying entirely within the Transverse and Peninsular Mountain Ranges of southern California, as shown on figure 2. To some degree, the methods can be used in more level regions, but complications may be introduced by the inflow of ground water from areas contiguous to the region being studied, a condition which might produce "recoverable" water bearing little relationship to characteristics of the region itself. The underground outflow of relatively large volumes of water will not affect the total volume which is theoretically recoverable, but for practical considerations such water might be very difficult to utilize fully. The general concepts of the approach of this report are applicable in hydrologic basins everywhere, but the relations presented are defined only for the area loosely described as the Southwest. It is to be expected that the relations of potential evapotranspiration to altitude, and of *P*/*E* to *R*/*E* will vary with changes in general climatic conditions, topography, and latitude, and therefore the relations should be those found to hold in the region under study.

This report demonstrates a method of making quantitative estimates of average annual water loss and recoverable water in mountain basins of southern California. Recoverable water, as shown, is only a relatively small part of the total introduced by precipitation. It can be expected to range from 1 inch to 20 inches, for the long run, and it varies from basin to basin because of climatic and physiographic differences among basins. In general, the greater the precipitation, the greater is the percentage of recoverable water. Figure 11 graphically shows the relationship between mean annual precipitation and mean annual recoverable water. In regions of less than 20 inches of precipitation, recoverable water may range from 1 inch or less

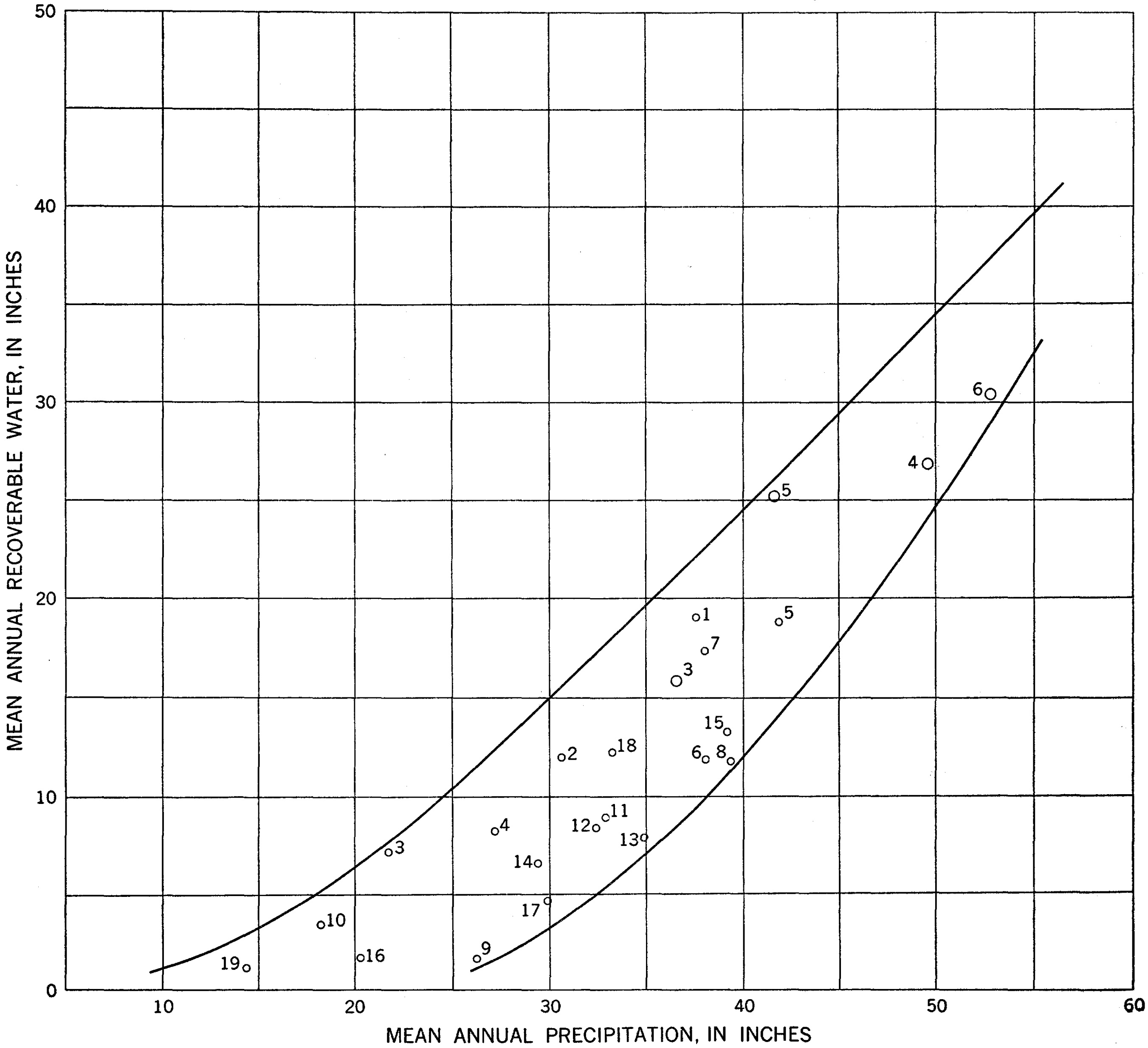

FIGURE 11.—Relation between precipitation and recoverable water. Smaller circles indicate data from basins used in formulating relations. Larger circles indicate basin data from tables 3 to 6.

to 6 inches; at 30 inches of precipitation, recoverable water may be from 3 to 15 inches; and at 40 inches of precipitation (which occurs only at high altitudes), recoverable water may range from 12 inches to 24 inches. The shape of the envelope of figure 11 is due to the fact that precipitation increases with altitude while potential evapotranspiration decreases.

In the future there will be longer records of data from more widely scattered sites. This data, together with increased knowledge of the relations among contributing factors, may make possible a more definitive analysis of hydrologic phenomena. Also, the science of meteorology may progress to the point where short-term estimates will be justified. The data and methods presented in this report are only as reliable as our present-day knowledge.

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