INSTRUCTIONS: READ AND/OR COMPLETE ONLY THE SECTIONS HIGHLIGHTED IN A RED BOX, WITH YELLOW SHADING

LAB 1

WATER BUDGET OF MONO LAKE: PRECIPITATION AND EVAPORATION

PURPOSE:	Familiarize you with components of the hydrologic cycle, hydrologic data sources, and techniques for analyzing these data. Become familiar with hydrologic units in metric units, which are convenient, and American (or English) units, which are necessary in the United States. This first lab will deal with precipitation and evaporation.
OBJECTIVES:	Analyze hydrographic data to determine quantitative values for precipitation and evaporation.
PROBLEM:	Determine the average annual groundwater flow into Mono Lake, CA.
APPROACH:	Analyze the water budget for Mono Lake. Determine precipitation and evaporation.
MATERIALS:	You will need a straightedge, compass (with pencil), calculator, and access to the Internet (can be done before lab). A spreadsheet program will make calculations easier.
ASSIGNMENT:	Read *Hydrology of Mono Basin* below. Additional information is available in *Case Study: Mono Lake*, Fetter, 2001, pp. 9–11.[1] Before or during lab, access the Internet to retrieve precipitation data for Table 1.1 (see *Climate* section that follows).

HYDROLOGY OF MONO BASIN

Location

Mono Basin is an intermontane, closed drainage basin in central Mono County, CA, and Mineral County, NV (Fig. 1.1). The basin is about 300 kilometers east of San Francisco and forms part of the eastern boundary of Yosemite National Park. Lee Vining and June Lake, CA, are the only two towns within the basin.

Basin Morphometry

The shape of the Mono Basin is slightly elongate northeast–southwest, with dimensions of about 50 km by 30 km (30 mi by 20 mi). The enclosed area is 1748 km^2 (675 mi^2), including Mono Lake (215 km^2, 83 mi^2). The lake is fairly elliptical, about 22 km (13 mi) east–west by about 16 km (10 mi) north–south (Fig. 1.1).

The basin floor is relatively flat, sloping gently upward from Mono Lake at 1948 m (6390 ft) to the base of the surrounding rim of mountains at about 2200 m (7200 ft) (Fig. 1.2). The Bodie Hills to the north rise fairly steeply to elevations of about 2500 m (8200 ft), and in the south, the narrow arcuate chain of the Mono Craters, about 2700 m (9000 ft), extend northward to within 1.5 km of the lake.

West of Mono Lake, the Sierra Nevadas rise abruptly from the lake and culminate in snowy crests at elevations near 4000 m (Mt. Lyell, 3997 m, 13,114 ft; Mt. Dana, 3979 m, 13,053 ft; Mt. Gibbs, 3890 m, 12,764 ft). In this region, the Sierra Nevada Divide is the western drainage boundary of the Mono Basin. The mountains exhibit rugged relief

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[1] Some references are made to C.W. Fetter, 2001, *Applied Hydrogeology*, 4th edition: Prentice-Hall, Upper Saddle River, NJ.

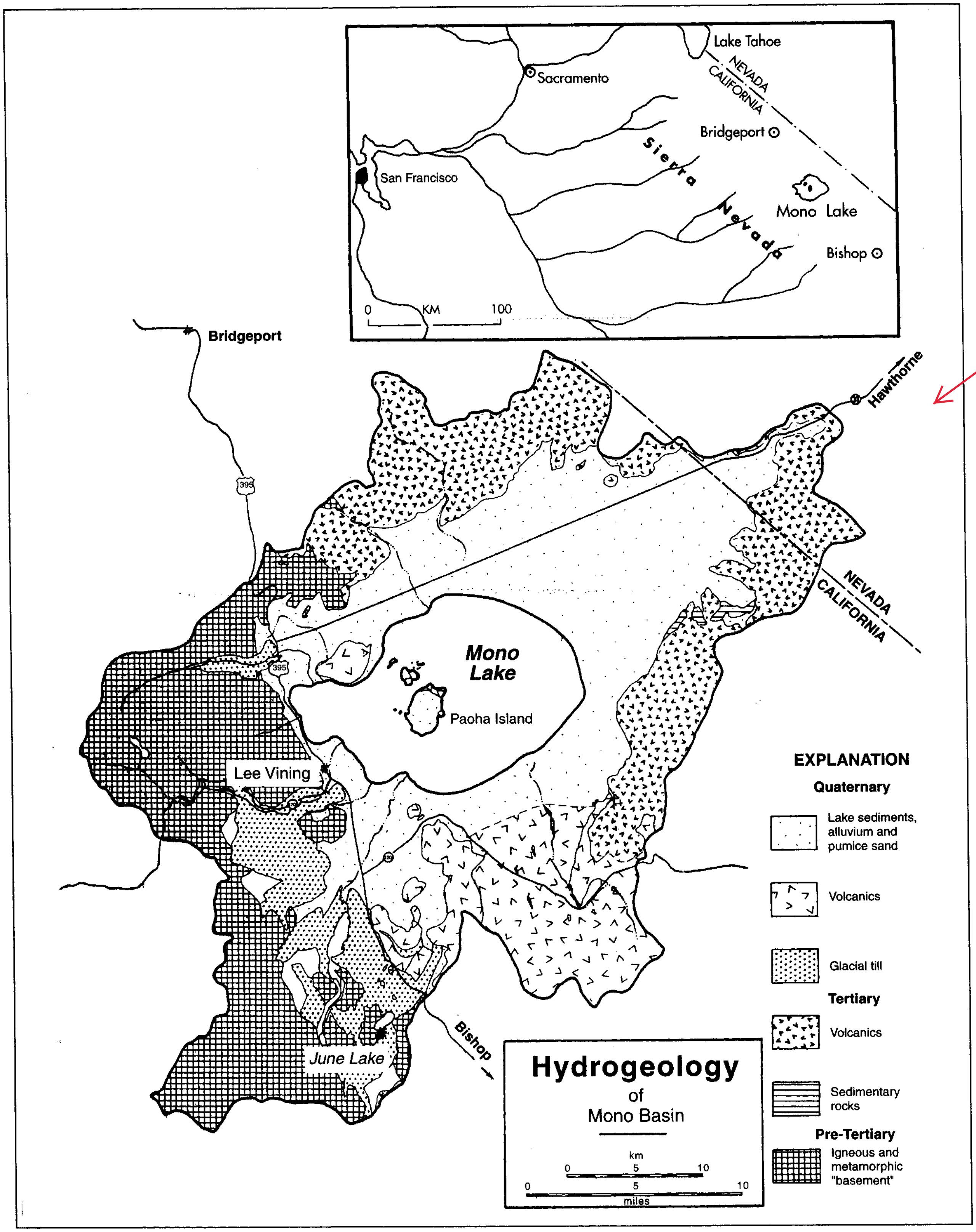


Figure 1.1—Index map and hydrogeologic map of the Mono Basin (Lee, 1969, Figure 6).

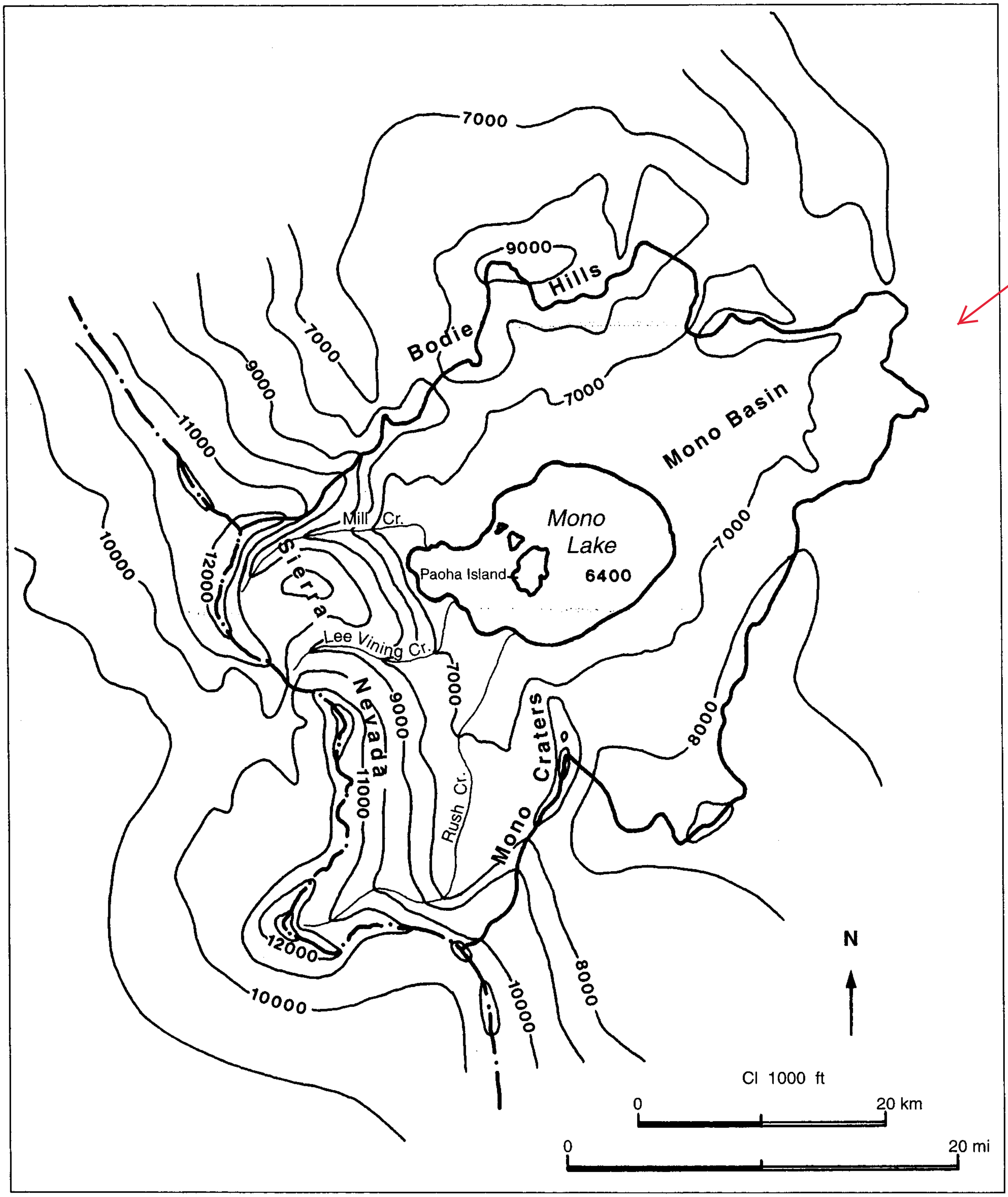


Figure 1.2—Topographic map of the Mono Lake–Sierra Nevada region (contour interval 1000 ft; heavy line is the divide of Mono Basin; dash–dot line is the divide of the Sierra Nevada).

characteristic of glacially sculpted mountains, with deep, narrow, U-shaped valleys and horn-shaped peaks. The steep eastern flank of the Sierras is accentuated by a very steep scarp (500 m/km, 2600 ft/mi) immediately alongside Mono Lake.

Climate

The climate of the Mono Basin is continental, with cold winters, during which most of the annual precipitation occurs, and dry summers with hot days and cool nights. The basin lies in an area of strong gradients; elevations rise precipitously from the basin floor to the crest of the Sierra Nevadas, and as a consequence, mean annual temperatures drop with increasing elevation (environmental lapse rate is −5.8°C/1000 m).

The United States Weather Bureau (USWB, now Environmental Data Services of NOAA) records meteorological observations at three stations within the Mono Basin and at several stations nearby. In addition, the Los Angeles Department of Water and Power maintains a station at Cain Ranch. These stations are shown on the map in Figure 1.3. Pertinent data are summarized in Table 1.1, *except for Ellery Lake, for which you will need to retrieve precipitation data from the Internet.*

1. Go to the California Data Exchange Center, maintained by the California Department of Water Resources as the access point to hydrologic data, at: http://cdec.water.ca.gov.
2. From the "CDEC Quick Search," select "Station Information" to find the 3-letter code for the Ellery Lake station.
3. From the "CDEC Quick Search," select "Download CSV Data," use the "Monthly Data Sorted By Years" form, and retrieve data from the entire period of record (sensor number is 2).
4. Drop these data into a spreadsheet for quick calculation of average precipitation. Calculate average monthly precipitation for the period of record, and sum these values to obtain the mean annual precipitation for the period of record.

Table 1.1—PRECIPITATION, MONO BASIN AREA

Station	Elevation		Average Annual Precipitation		
	m	**ft**	**cm**	**in.**	**from records of**
Bodie	2551	8370	41.1	16.2	1965–1968, 1996–1999 (8)
Benton	1661	5450	19.3	7.6	1965–1968 (4)
Ellery Lake	2940	9645			1924–2000 (75)
Gem Lake	2760	9054	53.3	21.0	1924–2000 (75)
Mark Twain Camp	2204	7230	17.3	6.8	1950–1955 (4)
Mono Lake	1966	6450	34.3	13.5	1951–1980, 1982–1988 (36)
Cain Ranch	2097	6880	28.1	11.1	1921–1964 (34)

WATER BUDGET

Write a continuity equation for the water budget of Mono Lake, including all components that you think might possibly be significant (the continuity equation is also known as the law of mass conservation and is referred to as the *hydrologic equation* by Fetter). Consider addition to the lake as positive and removal as negative.

PRECIPITATION

Arithmetic Average Method

Precipitation is measured at recording stations that provide point data of linear depth. In order to determine the volume of precipitation falling within a basin, these point data somehow must be extrapolated over an area that they represent (the *effective uniform depth* of Fetter). The easiest way of doing this is the arithmetic averaging method, in which one simply multiplies the average of the point data by the area of the entire basin.

1. Determine the average annual precipitation (m^3) by averaging the precipitation data for stations within the Mono Basin (Table 1.1). Calculate precipitation in the Mono Basin and, separately, on Mono Lake.

Thiessen Method

A more accurate method for determining basin precipitation, the Thiessen method, accounts for nonuniform distribution of recording stations by weighting each data point differently, according to the percentage of the basin the station represents. The method assumes that the precipitation at any point in the basin is that of the nearest station, or (another way of saying this) the precipitation is assumed to vary linearly between stations. A description of the Thiessen method is available in most textbooks (e.g., Fetter, 2001, pp. 34–37).

2. Determine the average annual precipitation on Mono Lake (m^3) by the Thiessen method (do this for the *lake only*), using the map in Figure 1.3. Areas within each polygon normally are measured with a planimeter, but for the sake of this exercise, you can estimate the areas by "counting squares," using quad-ruled paper.

Compare your result with precipitation calculated by the averaging method (No. 1).

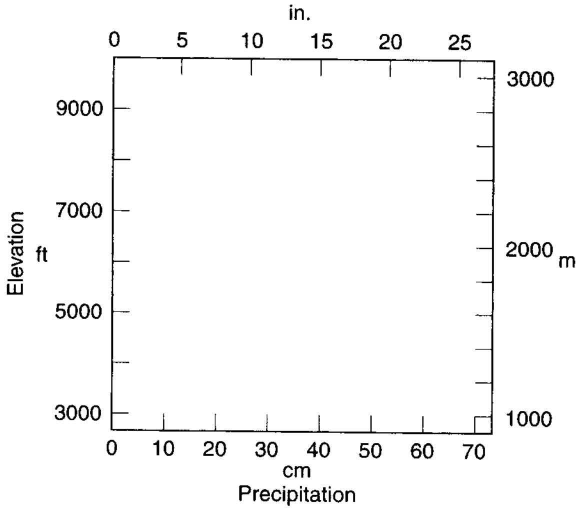
Isohyetal Method

Where orographic effects are significant, the isohyetal method gives a more accurate estimate because it accounts for topography. The method takes into account not only a nonuniform distribution of stations, but it allows for nonlinear variations in precipitation as well, as might be expected along a mountain range.

3. Plot precipitation as a function of elevation on the graph. Does there appear to be an orographic effect?

   Estimate a regression line, and determine the precipitation gradient.

Here in the rain shadow of the Sierras, where gradients are strong, the isohyetal method gives the most effective estimate of precipitation.



Using the isohyetal method, precipitation values are plotted at each station and contoured with lines of equal precipitation, or isohyets, taking into account the topography and using your knowledge of prevailing wind directions and orographic precipitation. After the isohyetal map is completed, precipitation is determined by measuring the areas between successive isohyets and multiplying each area by the average precipitation between its bounding contours.

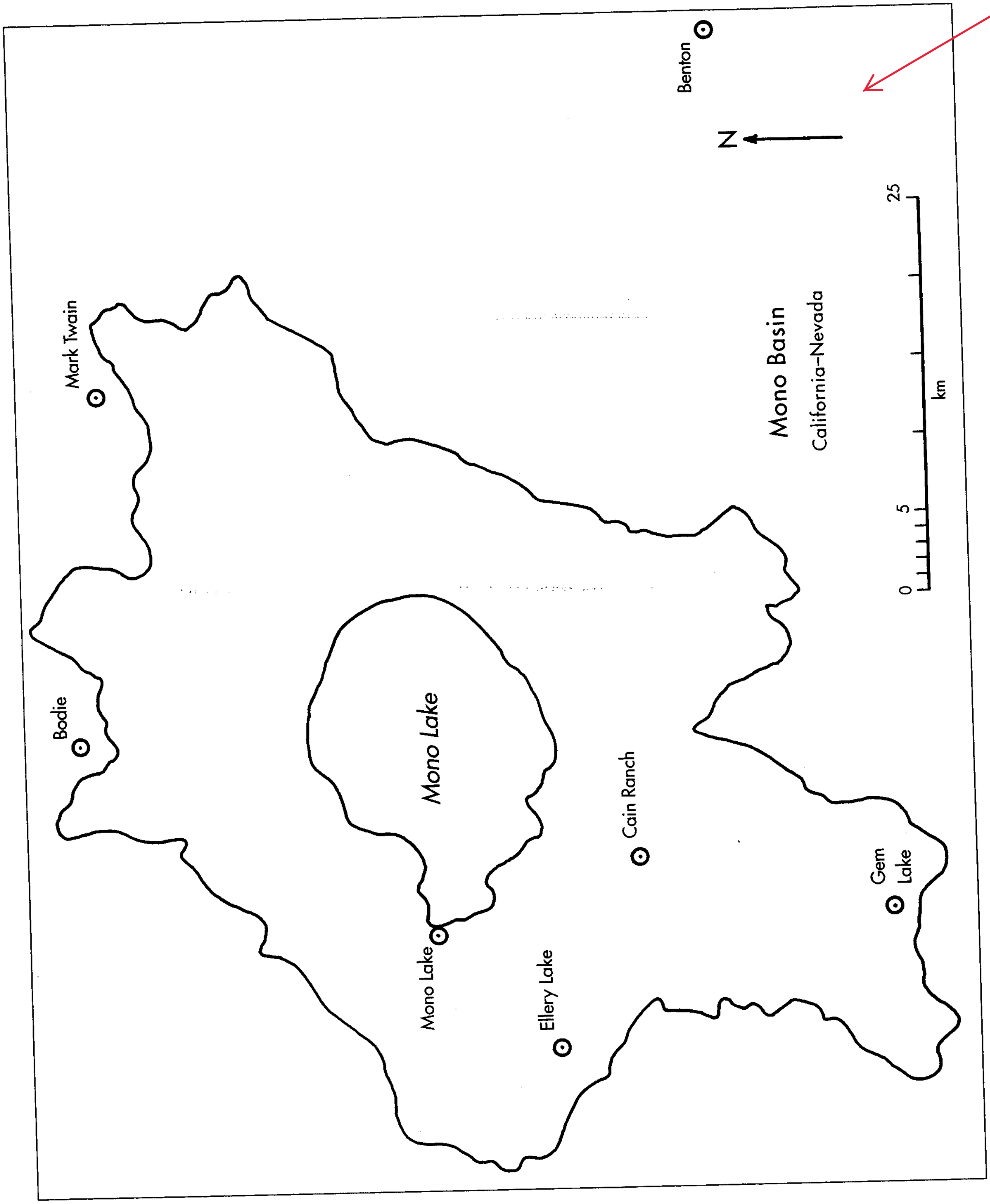


Figure 1.3—Precipitation stations in and around Mono Basin.

4. Construct an isohyetal map of the Mono Basin on Figure 1.4, making reference to the topographic map in Figure 1.2. Compute the average annual precipitation on Mono Lake by this method. Compare your result with precipitation determined by the other two methods (Nos. 1 and 2).

EVAPORATION

You will estimate the evaporation at Mono Lake in two ways: (1) by referring to a published map and (2) by reducing data from an evaporation pan at Cain Ranch.

1. Estimate average annual evaporation, or lake evaporation (m), by viewing the evaporation map in Figure 1.5. For conversion tables from American units to SI units, refer to your textbook (e.g., Fetter, 2001, Appendices 7–9).

The data for the lake evaporation map compiled by Kohler and others (1959) were derived from measurements of water evaporated from a standardized pan: a 4-ft-diameter, galvanized pan known as the Class A land pan. These measurements of pan evaporation are shown on the map in Figure 1.6.

Because evaporation pans have greater evaporation rates than lakes, typically about 140 percent, they must be corrected by applying an empirically derived pan coefficient. The variation in pan coefficients is shown on a similar map in Figure 1.7. In effect, the lake evaporation map you used (Fig. 1.5) is a derivative of the other two maps—measured pan evaporation (Fig. 1.6) multiplied by a pan coefficient (Fig. 1.7).

2. The following pan data were recorded at Cain Ranch.

Cain Ranch Station

Elevation: 6880 ft

Class A evaporation pan, water level held constant by float valve; volume of water needed to recharge pan (corrected for precipitation) is recorded.

May	33.71 gal	August	73.94 gal
June	51.41 gal	September	49.41 gal
July	94.10 gal	October	33.51 gal

(a) Calculate the pan evaporation (m) for this period.

(b) Data for the winter months are usually not recorded because in much of the United States, freezing prevents measurement. Extrapolate for annual pan evaporation using the map in Figure 1.8.

(c) Correct for the pan effect, using the map in Figure 1.7 to determine annual lake evaporation.

(d) How does this measurement compare with the reading you took directly from the map (No. 1)?

3. Calculate the annual evaporation (m^3) from Mono Lake.

LAB REPORT

Prepare a lab report summarizing the analysis to date, showing all calculations.

For all quantitative values, ensure that you report significant figures (significant digits) only (e.g., see Fetter, 2001, p. 19).

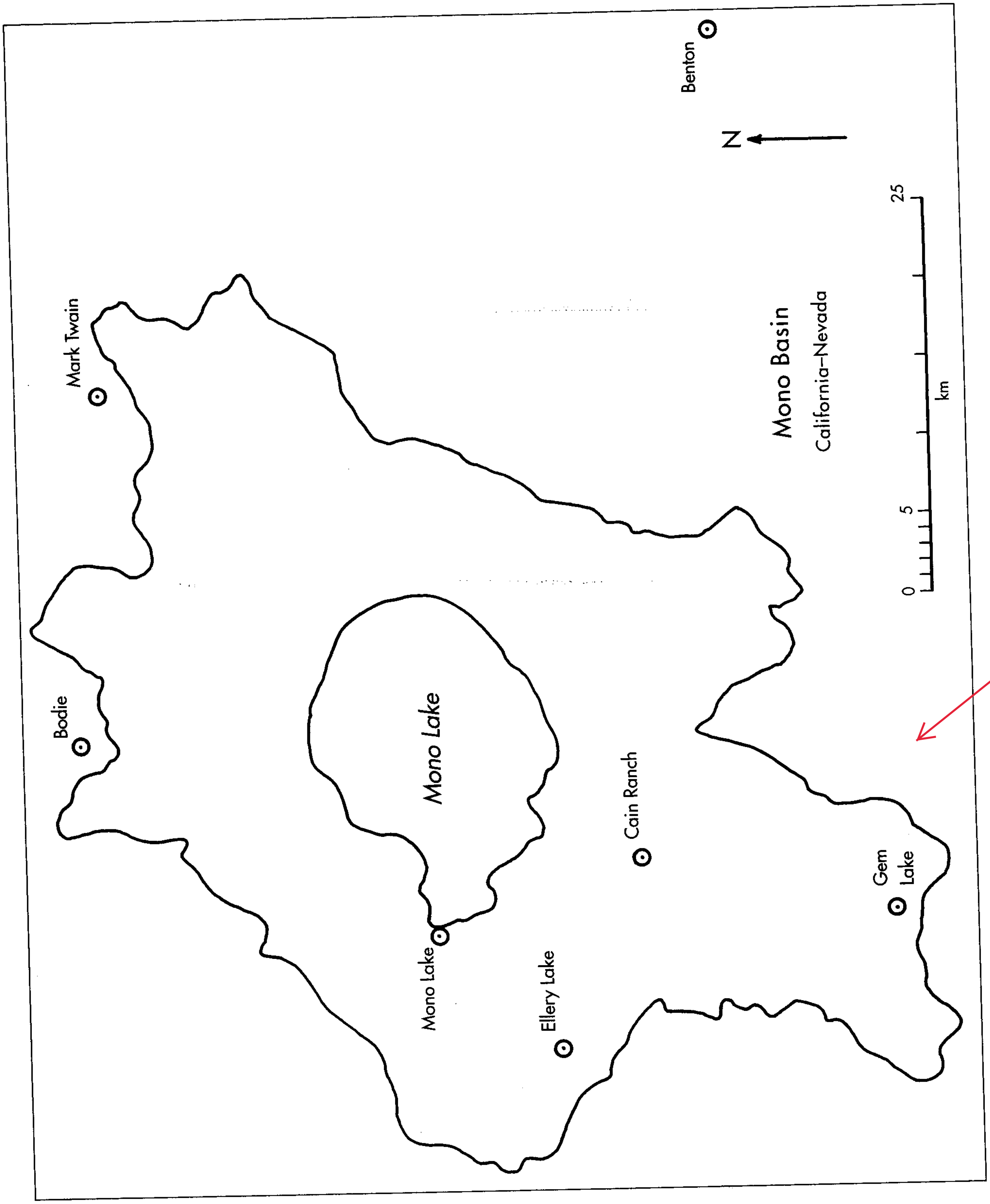


Figure 1.4—Precipitation stations in and around Mono Basin.

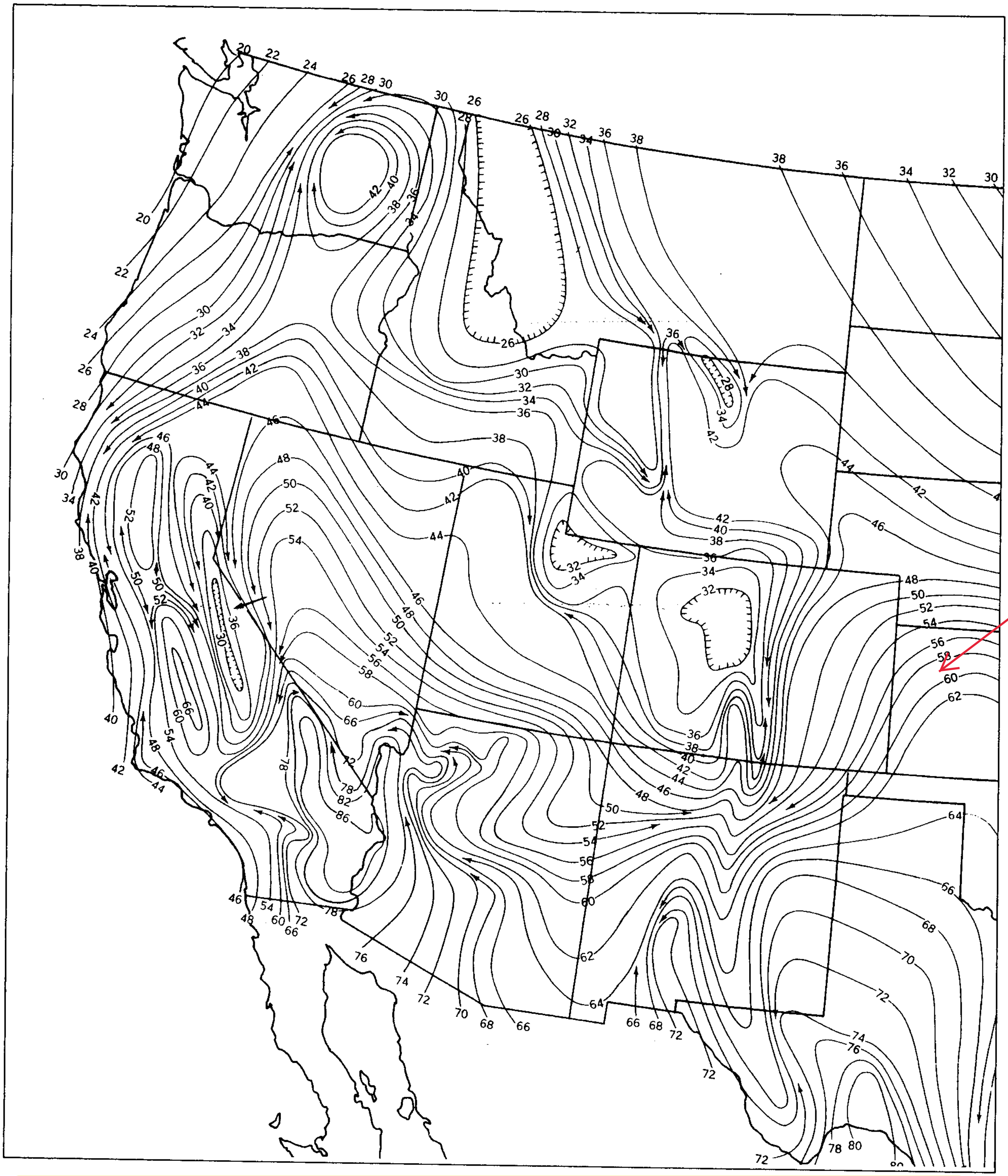


Figure 1.5—Average annual lake evaporation (in inches) in the western United States for the period 1946–1955 (from Kohler et al., 1959, Plate 2).

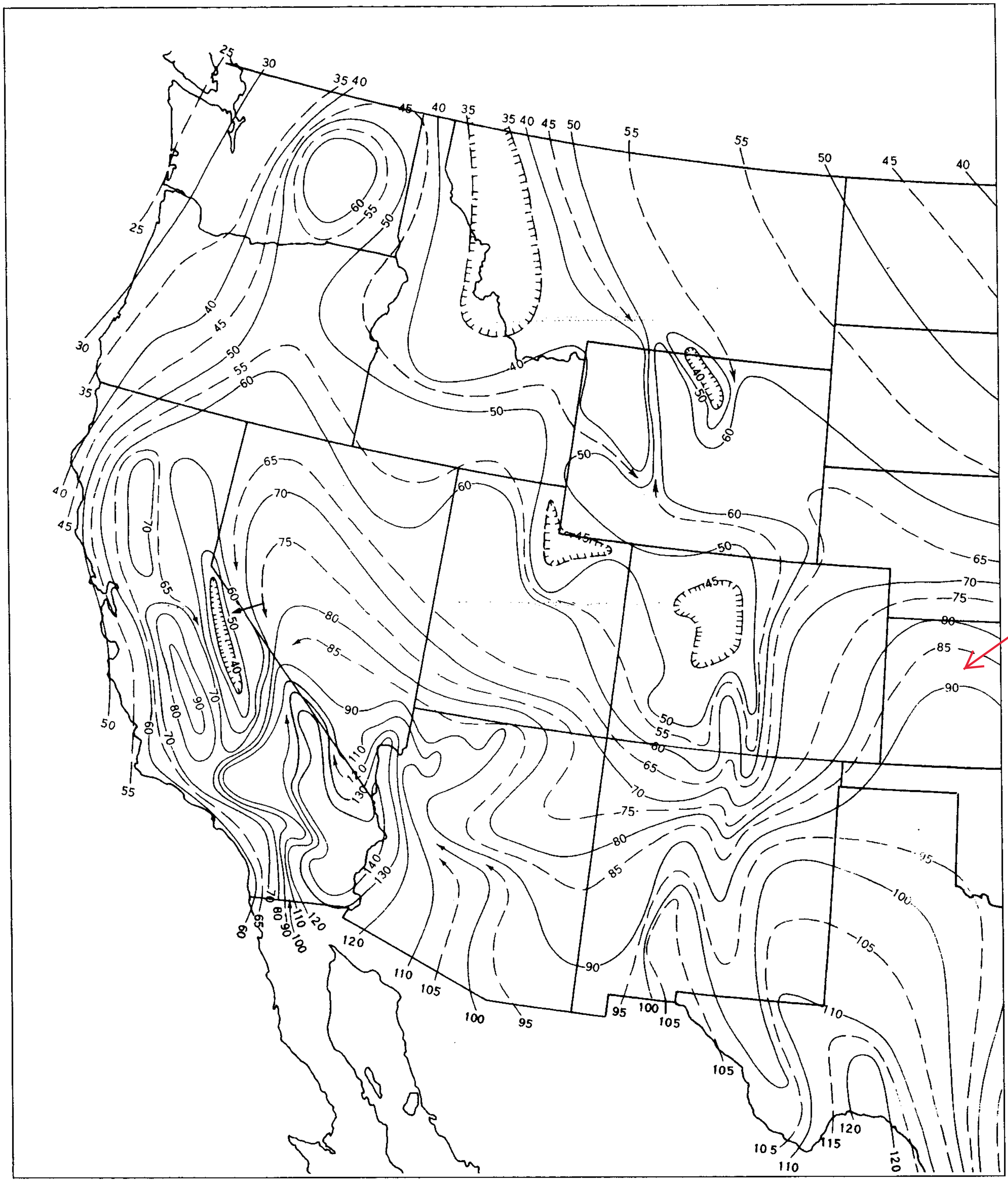


Figure 1.6—Average annual Class A pan evaporation (in inches) in the western United States (from Kohler et al., 1959, Plate 1).

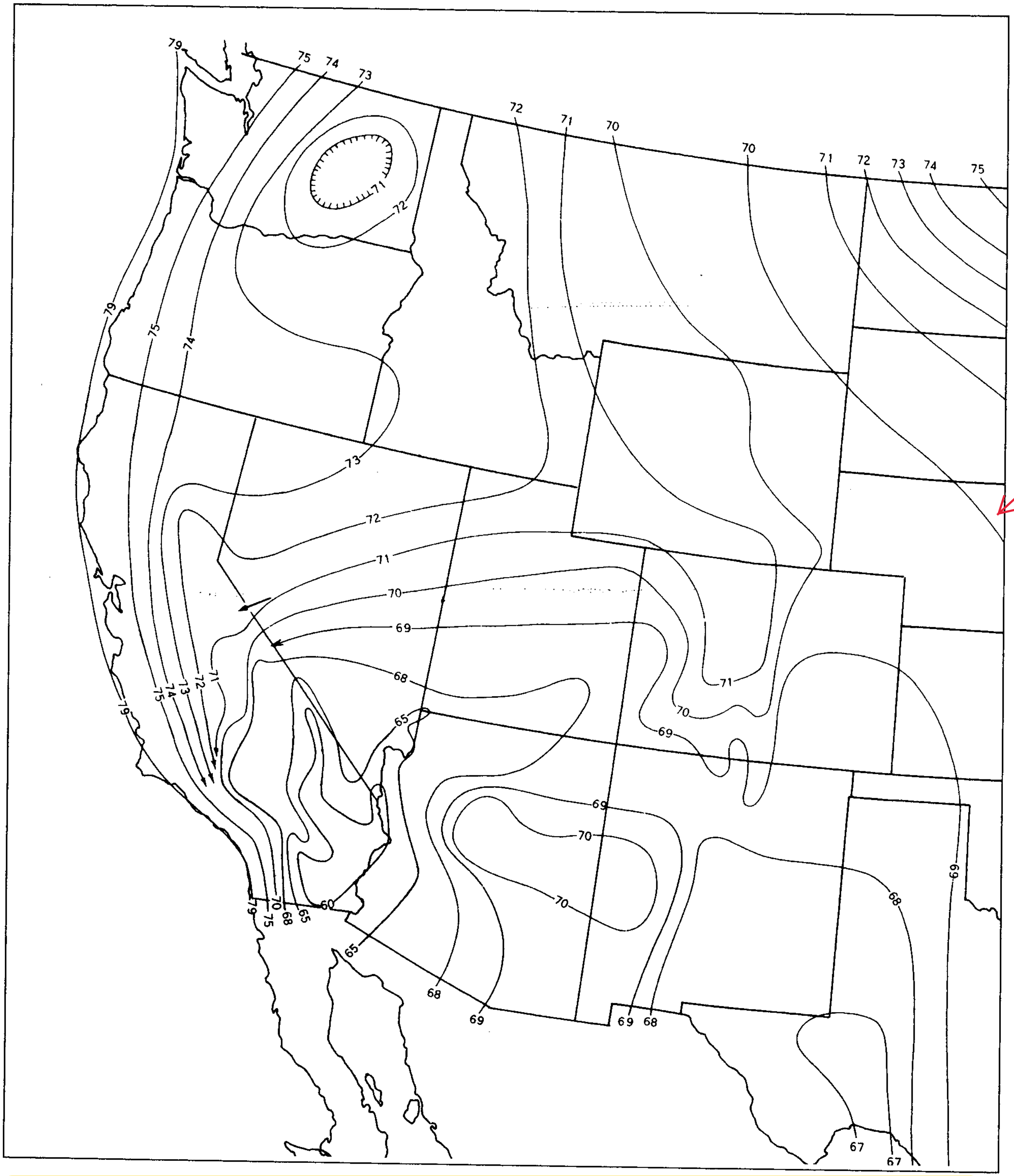


Figure 1.7—Average annual Class A pan coefficient (in percent) in the western United States (from Kohler et al., 1959, Plate 3).

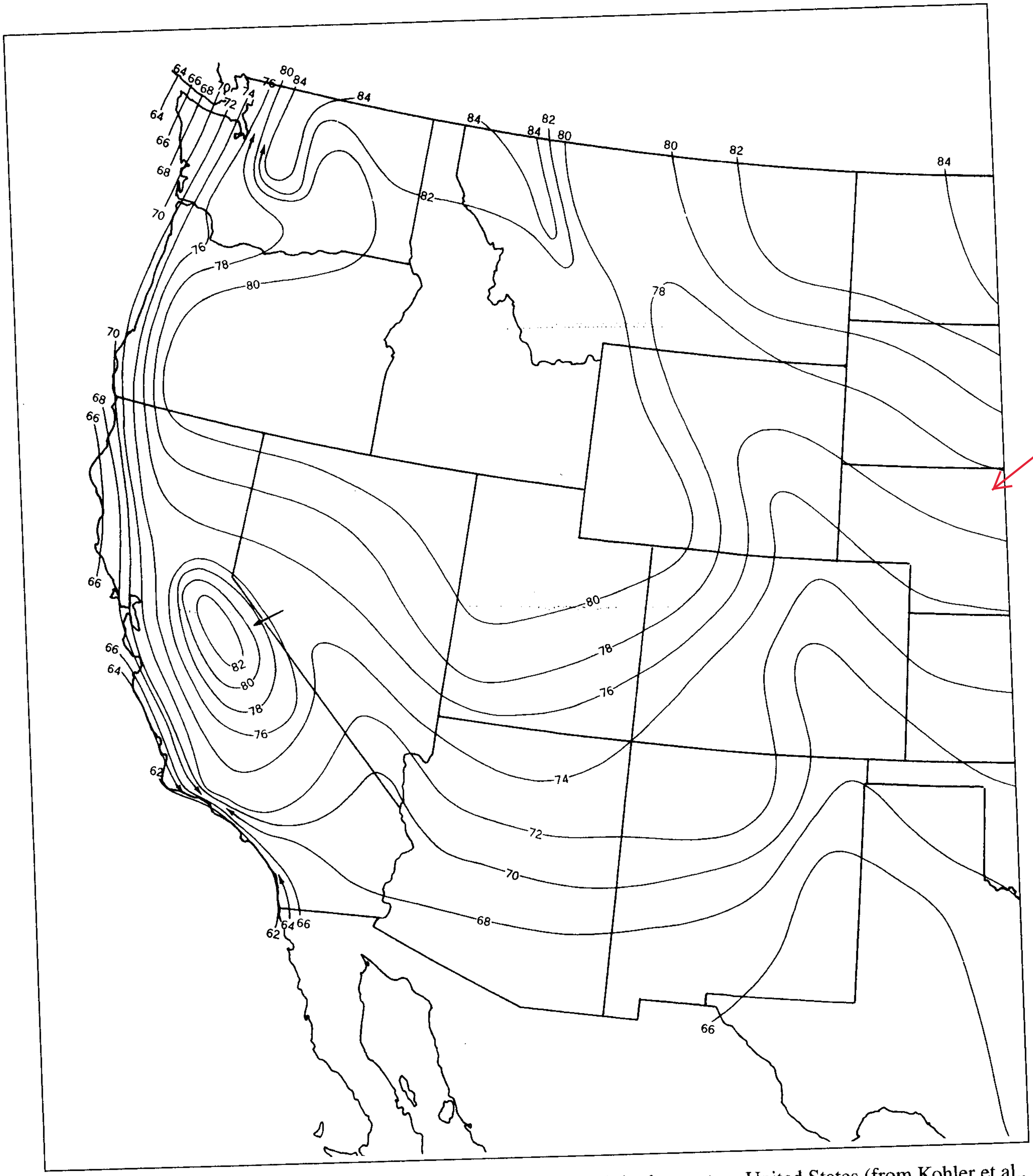


Figure 1.8—Average May–October evaporation (percent of annual) in the western United States (from Kohler et al., 1959, Plate 4.)

ADDITIONAL
READING
FROM
FEITER (2001)

the concept of a **ground-water basin,** which is the subsurface volume through which ground water flows toward a specific discharge zone. **Ground-water divides** surround it. The boundaries of a surface-water basin and the underlying ground-water basin do not necessarily coincide, although the water budget of the area must account for both ground and surface water. Many times hydrologic budgets are made for areas surrounded by political boundaries and not hydrologic boundaries; however, one still must know the location of the hydrologic boundaries, both surface and subsurface, to perform a water-budget analysis. Water will flow from the hydrologic boundary toward the point of discharge and hence may flow into the study area if the boundary of the study area does not coincide with the hydrologic boundary. The hydrologic inputs to an area may include (1) precipitation; (2) surface-water inflow into the area, including runoff and overland flow; (3) ground-water inflow from outside the area; and (4) artificial import of water into the area through pipes and canals. The hydrologic outputs from an area may include (1) evapotranspiration from land areas; (2) evaporation of surface water; (3) surface water runoff; (4) ground-water outflow; and (5) artificial export of water through pipes and canals. The changes in storage necessary to balance the hydrologic equation include changes in the volume of (1) surface water in streams, rivers, lakes, and ponds; (2) soil moisture in the vadose zone; (3) ice and snow at the surface; (4) temporary depression storage; (5) intercepted water on plant surfaces; and (6) ground water below the water table. The application of the hydrologic equation to a watershed is illustrated in the following case study.

Case Study: Mono Lake

> *Half a dozen little mountain brooks flow into Mono Lake, but not a stream of any kind flows out of it. What it does with its surplus water is a dark and bloody mystery.*
>
> Mark Twain

Mono Lake lies on the eastern slope of the Sierra Nevada near the east entrance to Yosemite National Park. Mono Lake is a terminal lake, which means that although water enters the lake by precipitation and by streams and ground water flowing into it, water can leave only by evaporation. The lake level fluctuates with climatic changes. The volume of water that leaves the lake by evaporation is the product of the surface area times the depth of evaporation. If the volume that leaves by evaporation is exactly balanced by the inflow, the lake level will not change. If the inflow exceeds evaporation, the water level will rise. If the inflow is less than evaporation, the lake level will fall. The Mono Lake basin has an area of 695 square miles (mi^2) [180,000 hectares (ha)]. Inputs to the lake under natural conditions are direct precipitation, with an estimated annual average of 8 in. (0.2 m); runoff from the land areas via gauged streams, which is estimated to average 150,000 acre-feet (ac-ft)* per year [1.85×10^8 cubic meters (m^3)]; and ungauged runoff and ground-water inflow, which is estimated to average 37,000 ac-ft per year (4.56×10^7 m^3). The average annual rate of lake evaporation is about 45 in. (1.1 m) (Vorster 1985). When it was first surveyed in 1856, the elevation of Mono Lake was 6407 ft (1953 m) above sea level. Climatic effects of moister and drier periods caused the lake level to rise to as much as 6428 ft (1959 m) in 1919 and then to fall to 6410 ft (1954 m) by 1941. In that year, water was first diverted from four of the five major streams feeding Mono Lake into the Los Angeles Aqueduct and then into southern California.

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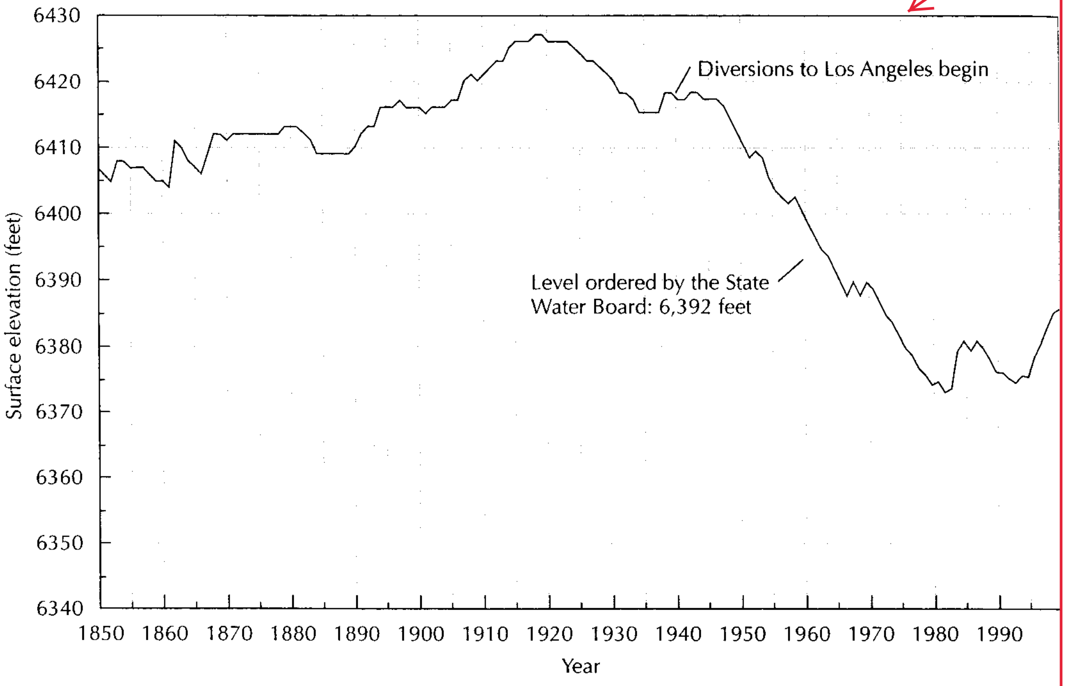
*An acre-foot is a measure of the volume of water that is commonly used in the western United States. It is the amount of water that will cover an acre of land to a depth of 1 ft (43,560 ft^3).



▲ FIGURE 1.6

Changes in the surface elevation of Lake Mono from the year 1850 to 2000. *Source:* Mono Lake Committee (*http://www.monolake.org*). *Used with permission.*

Since the beginning of diversions in 1941, the surface elevation of Mono Lake has declined substantially (Figure 1.6). Diversions amounted to as much as 100,000 ac-ft (1.23×10^8 m^3) per year. The historic low was reached in December 1981, when the lake elevation was 6372.0 ft (1942.2 m). The decline was arrested and the level rose to 6381 ft (1945 m) during a very wet period from 1982 through 1984. A return to more normal precipitation conditions meant that the lake level began to fall again. In 1989, the diversions were halted under a temporary court restraining order that prohibited any such diversions that would result in a lake level of less than 6377 ft (1944 m). However, even without any diversions the level of Mono Lake still declined due to very dry conditions in the eastern Sierra Nevada, so that by the end of 1992 it was 6373.5 ft (1942.6 m).

In 1994 the California State Water Resources Control Board issued Decision 1631, which established permanent stream-flow values for the tributary streams to Mono Lake in order to protect fish in the streams. In addition, a permanent lake elevation of 6,392 ft (1949 m) was set for Mono Lake. No diversions of influent water are permitted when the lake level is below that set by the decision.

In 1941, the year that diversions began, the surface area of Mono Lake was 53,500 ac (21,670 ha). When the lake elevation declined by 38 ft (12 m) from 1941 to 1981, the surface area shrank to about 40,000 ac (16,200 ha). The annual diversion of 100,000 ac-ft (1.23×10^8 m^3) would cover the 40,000-ac (16,200-ha) lake to a depth of 2.5 ft (0.76 m). The water level fell because the amount of the diversion plus the natural evaporation from the lake was far in excess of the amount of precipitation onto the lake surface plus the remaining surface inflow and the ground-water inflow.

Since 1992, sufficient precipitation has fallen over the Mono Lake drainage basin for lake levels to rise inasmuch as no diversions were permitted. As of January 2000 the lake level stood at 6384.3 ft (1947.2 m). It will take several more years before the lake level reaches the minimum elevation of 6392 ft (1949 m) set in Decision 1631.

One consequence of the volume reduction of Mono Lake was an increase in the salinity of the lake. In its original, natural condition with a surface elevation of 6410 ft (1954 m), the salinity of Mono Lake was 5.4%. At an elevation of 6377 ft (1944 m), the salinity rose to 9.3%. The increase in salt concentration resulted in a reduction of the brine shrimp population of the lake. There is a commercial fishery in Mono Lake for brine shrimp, and the shrimp also serve as an important food source for nesting and migratory birds. Brine flies also inhabit the shallow waters of the lake edge and provide a second food source for the many species of birds that migrate through the area and the nesting colonies of California gulls and snowy plovers. With the elimination of diversions from the lake, and the subsequent rise in water levels, the salinity has been reduced to 8.1%.

1.6 Hydrogeologists

The professional hydrogeologist has a wide variety of occupations from which to choose. Employment may be found with federal agencies, United Nations groups, state agencies, and local governments. Energy and mining companies may call upon the services of hydrogeologists to help provide water where it is needed or perhaps remove it where it is unwanted. Private consulting organizations also employ many individuals trained in hydrogeology. Water resource management districts and planning agencies often include hydrogeologists on their staffs. Hydrogeology is an interdisciplinary field. The hydrogeologist usually has training in geology, hydrology, chemistry, mathematics, and physics. Hydrogeologists are also being trained in such areas of engineering as fluid mechanics and flow through porous media, as well as in computer science. Such training is necessary, as hydrogeologists must be able to communicate effectively with engineers, planners, ecologists, resource managers, and other professionals. By the same token, an understanding of the basic principles of hydrogeology is useful to soil scientists, engineers, planners, foresters, and others in similar fields. For example, modeling of hydrologic systems is an area requiring knowledge of numerous disciplines.

1.7 Applied Hydrogeology

Many topics fall within the general rubric of hydrogeology. These include such diverse topics as the role of fluids in the folding of a faulting of rocks, hydrothermal fluids and mineral formation, land subsidence, geothermal energy, cave and karst formation, and water as a resource.

In this text we consider the topic of water as a resource. Classical studies in hydrogeology focused either on the mathematical treatment of flow through porous media or on a general geologic description of the distribution of rock formations in which ground water occurs. One occasionally even finds a paper describing the theoretical flow of fluids through an idealized porous medium that probably does not occur in nature. Likewise, many reports on the ground-water geology of an area made no attempt to evaluate how much water is available for use. Neither type of study has much practical value. Applied hydrogeology integrates the geological occurrence of water with the mathematical description of its movement and its chemical state. Typical outcomes of applied hydrogeological investigations might include plans for development of a ground-water supply, determination of the capture zone for a well field to protect it from contamination, evaluation of the impact of a mine dewatering plan on overlying surface-water bodies, or the delineation of a plume of contaminated ground water.

Hydrogeologists are problem solvers and decision makers. They identify a problem, define the data needs, design a field program for collection of data, propose alternative solutions to the problem, and implement the preferred solution.

sible to avoid wind. They should be in the open, away from trees and buildings. Low bushes and shrubs can provide a windbreak. Level ground is best, with the top of the gauge horizontal. On steep slopes, it may be desirable to have the orifice opening parallel to the slope. The effect of wind is greatest for light rain or snow. Some rain gauges are equipped with a shield, or wind deflector, around the opening to overcome wind problems. This will improve the catch of snow, but it will still be less than 100% effective in substantial winds.

Several available types of recording rain gauges can automatically measure or weigh the precipitation. The temporal distribution of precipitation through a day can thus be obtained. Such data are necessary for any studies of precipitation intensity. For remote areas, recording rain gauges can be used to record daily precipitation for long time periods. In such circumstances, manual gauges could provide only a total rainfall for the period between readings.

In the United States there are approximately 13,500 precipitation stations, for the most part operated by trained volunteers. Daily records from these weather stations are published monthly on a state-by-state basis in *Climatological Data;* data from recording stations are published in *Hourly Precipitation Data.* Both of these are publications of the U.S. Environmental Data Service. Data are also available at the National Oceanographic and Atmospheric Administrations website. Canada has about 2000 precipitation stations, the data from which are published by the Canadian Atmospheric Environment Service in the *Monthly Record of Observations.*

Radar can be used to measure the intensity of precipitation over a wide area. In the United States, the NEXRAD radar system is being implemented. It offers a better detailed view of the spatial distribution of rainfall than the traditional point measurements of gauging stations. In one study of a basin with a fairly dense network of precipitation stations, NEXRAD detected numerous storms with a precipitation intensity of 50 mm/h that were completely missed by the network of gauges (Smith et al. 1996).

The measurement of snowfall in standard rain gauges is subject to error due to turbulence around the gauge. The snow that is caught is melted and the water equivalent reported. If only an approximation is required, a water content of 10% of the snow depth can be assumed. However, as anyone who regularly shovels snow knows, the density of newly fallen snow can vary considerably.

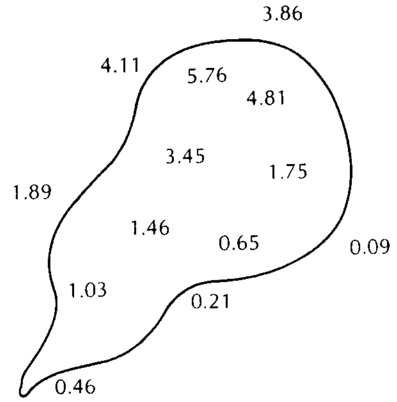
In northern and mountainous climates, the accumulation of snow on the ground is an important hydrologic parameter. In some areas, the runoff of melting snow in the spring is a predominant source of water for reservoirs used for water supply, irrigation, and power generation. A thick accumulation of snow can also mean a high flood potential when snowmelt occurs in the spring. Melting snow also recharges soil moisture and the water table. Snow surveys are made periodically through the winter to measure the thickness and water content of the snow in some areas.

2.7 Effective Depth of Precipitation

In water-budget studies, it is necessary to know the average depth of precipitation over a drainage basin. This may be determined for time periods ranging from the duration of part of a single storm to a year. The data are generally measurements of precipitation and/or equivalent snowfall at a number of points throughout the drainage basin.

Data that are missing at one or more stations as a result of equipment malfunction or operator absence creates a problem. To solve the problem, three close precipitation stations with full records that are evenly spaced around the station with a missing record are used. The following equation yields an estimate of the missing data at station Z. The mean annual precipitation (N) at station Z and the three index stations, A, B, and C, and the actual

► FIGURE 2.4
Rain gauge network over a drainage basin. Precipitation amounts are given in centimeters. Station locations are at decimal places.



precipitation (P) at the index stations for the time period over which data are missing, are needed:

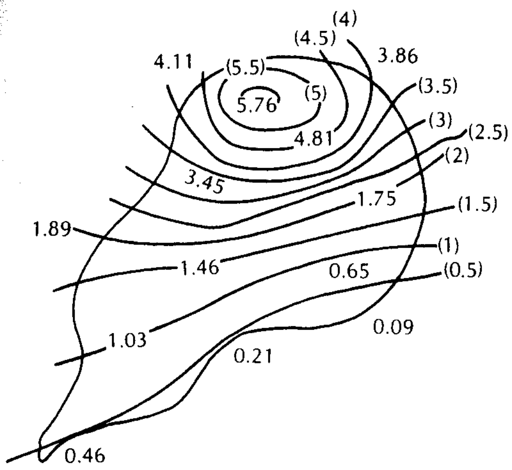
$$P_Z = \frac{1}{3}\left[\frac{N_Z}{N_A}P_A + \frac{N_Z}{N_B}P_B + \frac{N_Z}{N_C}P_C\right] \tag{2.2}$$

If the rain gauge network is of uniform density, then a simple arithmetic average of the point-rainfall data for each station is sufficient to determine the **effective uniform depth (EUD) of precipitation** over the drainage basin (Figure 2.4).

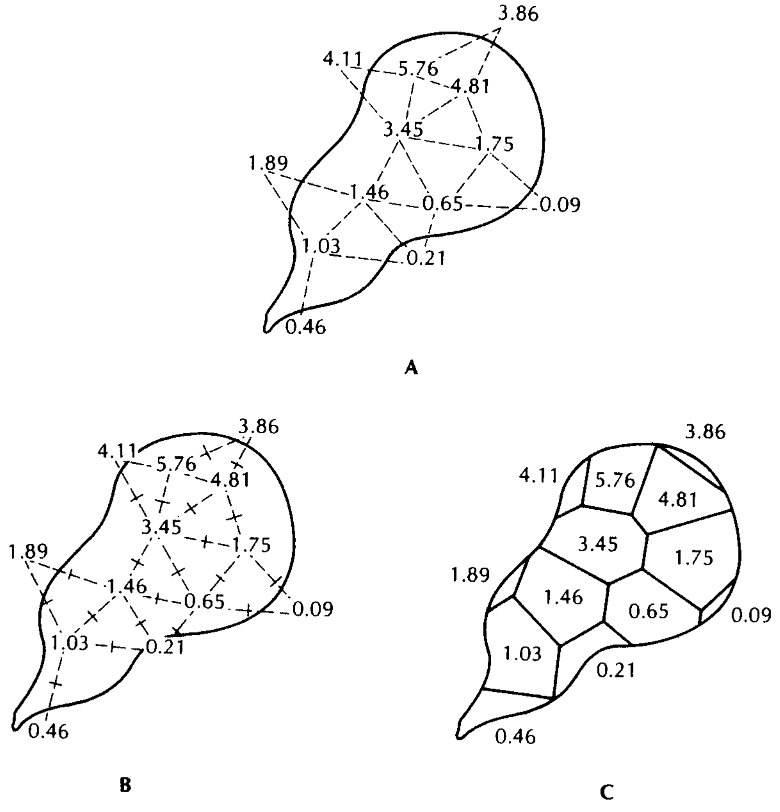
If the rain gauge network is not uniform, then some adjustment is necessary. The most accurate method, excluding use of radar data, is to draw a precipitation contour map with lines of equal rainfall (**isohyetal lines**). In drawing the isohyets, such factors as known influence of topography on precipitation can be taken into account. Simple linear interpolation between precipitation stations can also be used. The area bounded by adjacent isohyets is measured with a planimeter, and the average depth of precipitation over the area is the mean of the bounding isohyets. The effective uniform depth of precipitation is the weighted average based on the relative size of each isohyetal area (Figure 2.5). The drawback of the isohyetal method is that the isohyets must be redrawn and the areas remeasured for each analysis.

The Thiessen method to adjust for nonuniform gauge distribution uses a weighing factor for each rain gauge. The factor is based on the size of the area within the drainage basin that is closest to a given rain gauge. These areas are irregular polygons. The method of constructing them can be described rather easily; however, it takes a bit of practice to master the technique. The rain gauge network is drawn on a map of the drainage basin. Adjacent stations are connected by a network of lines (Figure 2.6A). Should there be doubt as to which stations to connect, lines should be between the closest stations. A perpendicular line is then drawn at the midpoint of each line connecting two stations (Figure 2.6B), and extensions of the perpendicular bisectors are used to draw polygons around each station (Figure 2.6C). It is best to start with a centrally located station and then expand the polygonal network outward. The area of each polygon is measured, and a weighted average for each station's precipitation is used to find the EUD.

In mountainous areas, orographic effects can create vastly different microclimates over small distances. Significant precipitation can fall on one side of a ridge but little on the other. In such regions the Thiessen method and contouring by linear interpolation can yield erroneous results. Detailed study of the vegetation can identify wet and dry slopes. This information, in conjunction with topographic maps, can be used to make interpreted contour maps with isohyetal lines reflecting the presence of wet and dry slopes.



◄ FIGURE 2.5
Isohyetal lines for the rain gauge network of Figure 2.4. The isohyets show contours of equal rainfall depth, with a contour interval of 0.5 cm. The contours are based on simple linear interpolation.



▲ FIGURE 2.6
Construction of Thiessen polygons based on the rain gauge network of Figure 2.4. **A.** The stations are connected with lines. **B.** The perpendicular bisector of each line is found. **C.** The bisectors are extended to form the polygons around each station.

PROBLEM

Determine the effective uniform depth of precipitation using the arithmetic mean, isohyetal, and Thiessen methods.

Arithmetic Mean Method

Figure 2.4 shows a drainage basin with seven stations in its boundaries. An additional six stations are located outside the drainage divide. In the arithmetic mean method, only the gauges inside the drainage basin boundary are considered.

$$\text{Mean} = \frac{1.03 + 0.65 + 1.46 + 1.75 + 4.81 + 3.45 + 5.76}{7} = 2.70 \text{ cm}$$

Isohyetal Method

The first step is to draw lines of equal precipitation (isohyets) on the drainage basin map. Isohyets are usually whole numbers or decimals (every 0.1 in., every 0.5 in., every 1 mm, etc.). The following rules apply:

1. Isohyets never cross.
2. Isohyets never split.
3. Isohyets never meet.
4. A station that does not fall on an isohyet will be between two isohyets. The isohyets will both be equal (either larger or smaller than the station value) or one will be larger and one smaller.
5. Adjacent isohyets must be equal or only one contour interval difference in value.
6. Isohyets should be scaled between stations using linear interpolation.

Figure 2.5 shows the isohyetal map of the problem area. The area between adjacent isohyets is determined by use of a planimeter. The equivalent uniform depth of precipitation between isohyets is usually assumed to be equal to the median value of the two isohyets. For example, the EUD between a 1-cm isohyet and a 2-cm isohyet is 1.5 cm. Areas enclosed by a single isohyet require judgment when estimating the equivalent uniform depth. The weighted average precipitation is based on the equivalent uniform depth of precipitation between adjacent isohyets and their areas.

A Isohyet (cm)	B Estimated EUD	C Net Area (km^2)	D Percent of Total Area	E Weighted Precipitation (cm) (B × D)
5.5+	5.6	1.1	0.8	0.045
5.0–5.5	5.25	7.6	5.3	0.278
4.5–5.0	4.75	10.6	7.4	0.352
4.0–4.5	4.25	9.5	6.7	0.285
3.5–4.0	3.75	8.6	6.0	0.225
3.0–3.5	3.25	8.3	5.8	0.189
2.5–3.0	2.75	10.7	7.5	0.206
2.0–2.5	2.25	12.3	8.6	0.194
1.5–2.0	1.75	15.1	10.6	0.186
1.0–1.5	1.25	23.8	16.7	0.209
0.5–1.0	0.75	31.2	21.8	0.164
<0.5	0.3	4.0	2.8	0.008
Total		142.8 km^2		2.34 cm Net EUD

Thiessen Method

The Thiessen method provides for the nonuniform distribution of gauges by determining a weighting factor for each gauge. A weighted mean of the precipitation values can then be computed. Thiessen polygons for the example problem are shown on Figure 2.6C. The area of each polygon is determined by a planimeter.

A Station Precipitation (cm)	B Net area (km²)	C Percent of Total Area	D Weighted Precipitation (cm) (A × C)
5.76	16.9	11.9	0.686
4.81	16.1	11.4	0.546
4.11	3.4	2.4	0.099
3.86	1.6	1.1	0.044
3.45	19.3	13.6	0.470
1.89	2.5	1.8	0.033
1.75	12.0	8.5	0.148
1.46	19.8	14.0	0.204
1.03	18.0	12.7	0.131
0.65	17.0	12.0	0.078
0.46	6.0	4.2	0.019
0.21	7.2	5.1	0.011
0.09	2.0	1.4	0.001
Total	141.8 km²		2.47 cm Net EUD

2.8 Events During Precipitation

During a precipitation event, some rainfall is **intercepted** by vegetation before it reaches the ground. This may later fall to the ground or evaporate. In a heavily forested area, most of the precipitation is caught by leaves and twigs. Initially, during a summer thunderstorm, no raindrops reach the forest floor, although drops can be heard striking the leaves overhead. When the storage capacity of the leaf surfaces is exhausted, water will run down tree trunks and drip downward (**stem flow**). The amount of water intercepted by dense forests ranges from 8% to 35% of total annual precipitation (Dunne & Leopold 1978). In a mixed hardwood forest in the northeastern United States, intercepted rainfall averaged 20% in the summer and winter seasons (Trimble & Weitzman 1954). Although evaporation of intercepted water reduces the net transpiration by the plants, in some cases most of the evaporated water is simply lost. One study concluded that only about 10% of the intercepted water actually reduced evapotranspiration (Thorud 1967).

The rate of interception is greatest at the beginning of a precipitation event and declines exponentially with time. If the rain is short lived and light, a large percentage of the precipitation may be intercepted. If it is heavy and long lived, only a small percentage may be intercepted.

Rainfall reaching the land surface can **infiltrate** into pervious soil, which has a finite and variable capacity to absorb water. The **infiltration capacity** varies not only from soil to soil, but also is different for dry versus moist conditions in the same soil. If a soil is initially dry, the infiltration capacity is high. Surface effects between the soil particles and the water exert a tension that draws the moisture downward into the soil through