Hydrologic Regimen of Salton Sea, California

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By ALLEN G. HELY, G. H. HUGHES, *and* BURDGE IRELAN

WATER RESOURCES OF LOWER COLORADO RIVER—SALTON SEA AREA

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A study of the variations in water level and water quality and their causes

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SYMBOLS AND DIMENSIONS

[The numbers in parentheses refer to the equation (or figure, as indicated) where the symbol first appears]

Symbol	*Dimensions*	*Description*
c	$L^2T^{-2}\theta^{-1}$	Specific heat of water (following 4).
e		Emissivity of water, 0.970 (6).
e_a	$ML^{-1}T^{-2}$	Vapor pressure of the air (7).
e_0	$ML^{-1}T^{-2}$	Vapor pressure of saturated air at the temperature of the water surface (7).
u	LT^{-1}	Average windspeed (8).
E	L^3	Volume of evaporated water (1) or
	L	Depth of evaporated water (8).
E_p	L	Pan evaporation (fig. 7).
E_s	L	Evaporation from Salton Sea (fig. 7).
I_g	L^3	Volume of inflow by ground-water seepage (1).
I_s	L^2	Volume of inflow in surface channels (1).
L	L^2T^{-2}	Latent of heat of vaporization (following 4).
M	M	Mineral content (9).
N		Empirical coefficient (8).
P	L^3	Volume of water precipitated (1) or
	L	Depth of water precipitated (fig. 15) on Salton Sea.
P_a	$ML^{-1}T^{-2}$	Atmospheric pressure (3).
Q_a	ML^2T^{-2}	Incident long-wave radiation from the atmosphere (4).
Q_{ar}	ML^2T^{-2}	Long-wave radiation reflected by the water (4).
Q_{bs}	ML^2T^{-2}	Long-wave radiation emitted by the water (4).
Q_e	ML^2T^{-2}	Energy used by evaporation (4).
Q_h	ML^2T^{-2}	Energy conducted from the body of water as sensible heat (4).
Q_r	ML^2T^{-2}	Solar radiation reflected by the water surface (4).
Q_s	ML^2T^{-2}	Solar radiation incident to the water surface (4).
Q_v	ML^2T^{-2}	Net energy advected into the body of water (4).
Q_w	ML^2T^{-2}	Energy advected by the evaporated water (4).
Q_ϑ	ML^2T^{-2}	Increase in energy content of the body of water (4).
R		Bowen ratio (following 4), defined in equation 7.
S		Salinity, or mineral content per unit mass of water (9).
T_a	θ	Temperature of the air (7).
T_b	θ	An arbitrary base temperature (following 4).
T_e	θ	Temperature at which evaporation takes place (following 4).
T_0	θ	Temperature of the water surface (following 4).
V	L^3	Volume (1). Subscripts, used with the symbol denoting an increment, indicate the source of the increment (see equation 2).
ρ	ML^{-3}	Density of evaporated water (following 4).
σ	$MT^{-3}\theta^{-4}$	The Stefan-Boltzman constant for black-body radiation (6).
Δ		Denotes an increment of the variable following (1).

HYDROLOGIC REGIMEN OF SALTON SEA, CALIFORNIA

By Allen G. Hely, G. H. Hughes, and Burdge Irelan

ABSTRACT

The Salton Sea is sustained almost entirely by drainage from irrigation districts using Colorado River water. Increasing quantities of drainage have maintained an upward trend in the water level for several decades, but this trend would be arrested or reversed if the quantity of water imported to the Salton Sea basin were appreciably reduced or if more of the imported water were consumed by evapotranspiration.

During 1961–62 the U.S. Geological Survey conducted a stream-gaging program, supplementing those of irrigation districts, to increase the reliability of the computed inflow to Salton Sea and of the estimated evaporation, computed by the water-budget method. Also, meteorological data were collected and used to compute evaporation from the sea by the energy-budget and mass-transfer methods.

Annual evaporation computed by the water-budget and energy-budget methods differed by less than 5 percent. Evaporation, as determined by these two methods, was used with data on wind speed and vapor-pressure difference to establish the empirical coefficient (N=0.00156) in the simplified mass-transfer equation, $E=Nu(e_0-e_a)$. The equation, therefore, does not provide an independent determination of total evaporation during the 2-year period, but it does provide an independent determination of the distribution of the total evaporation among the months.

The determinations of annual evaporation were also used to establish a coefficient (0.69) to convert average annual evaporation from three sunken pans at widely separated sites on the shore of Salton Sea to evaporation from the sea. Use of these pans is both adequate and the most practical method for the continuing measurement of annual evaporation, but it is not suitable for accurate determination of monthly evaporation because of the somewhat erratic variation of monthly pan coefficients. The computed evaporation for 1961–62 and the pan data for 1948–62 indicate that normal annual evaporation from Salton Sea is 5.78 feet (69 in.).

The information gained from the 1961–62 investigations was an aid in the reconstruction of a reasonably reliable history of the factors that influence the water level of Salton Sea; it also provided a useful guide for predicting the effects of future changes of the inflow.

Salton Sea was formed in 1904–07 by an uncontrolled diversion of the Colorado River, which probably had an average salinity of less than 500 ppm (parts per million). However, large quantities of soluble minerals that had accumulated in Salton Sink during previous centuries were dissolved by this fresh water, and after 1907 the rapid reduction in volume of Salton Sea caused additional increases in salinity. By 1925, when the sea had stopped receding because of the increasing irrigation drainage, the salinity was near 40,000 ppm, which is somewhat greater than that of ocean water (about 35,000 ppm). Between 1938 and 1964 the salinity was considerably less than 40,000 ppm because of dilution due to an increase in the volume of water.

The stable water level of Salton Sea corresponding to any specific stable rate of inflow is known, provided that no works are constructed to regulate the sea. Increasing interest in recreational uses of the sea and in real-estate developments on its shore has, however, led to proposals of direct action for the control of both the water level and the salinity. Within certain limits and in certain circumstances, this control would be possible, but its feasibility also involves many factors not considered in this report.

INTRODUCTION

The Salton Sea was formed in 1904–07 as a result of an unusual sequence of events involving the diversion of Colorado River water for irrigation in Imperial Valley, Calif., and the occurrence of unexpected floods in the Colorado River. The sea has been sustained chiefly by drainage from irrigated land, and its future will also depend mainly on such drainage.

As are all closed lakes, Salton Sea is saline because of the accumulation of minerals, chiefly salts, left by evaporation. The salinity has varied markedly, but for nearly three decades it has been nearly equivalent to that of ocean water. Although the sea is not suitable as a source of water for irrigation or domestic use, it has become an important resource for recreational uses.

For many years this "sea in the desert" was regarded as little more than a convenient receptacle for drainage and waste water, and the principal interest in the sea concerned encroachment of the water on arable lands and on some real-estate developments on the shore. However, its location in a famous winter-resort area within 150 miles of the metropolitan areas of southern California favors development of parks, marinas, and resorts on its shore. The accelerated pace of such developments in recent years has greatly increased the value of the sea and has also increased the need for reliable information on the hydrologic regimen (fluctuations of the water level and their causes and related changes in chemical characteristics).

Previous investigations of the hydrologic regimen were severely handicapped by limitations of the methods then available for determining evaporation and, also, by the lack of complete inflow data. The development and testing, since 1950, of the energy-budget and mass-transfer methods of determining evaporation (U.S. Geol. Survey, 1954; Harbeck and others, 1958) together with the increasing concern about the trends of water level and salinity of the sea and about the availability of fresh water to supply the entire service area of the lower Colorado River prompted a new hydrologic study of the sea. This report presents results of studies of water level, inflow, evaporation, chemical quality, and their interrelations, based on an intensive investigation conducted during 1961–62 and on available records for previous years.

The investigations in 1961–62 were made under the direction of C. C. McDonald, project hydrologist, as a part of an appraisal of the water resources of the area for which the lower Colorado River is the principal source of water supply. Inflow and water-budget studies were made by Allen G. Hely; energy-budget and mass-transfer studies of evaporation, by G. H. Hughes; and studies of chemical characteristics by Burdge Irelan. Streamflow measurements by the U.S. Geological Survey, as a supplement to those made by the Imperial Irrigation District and the Coachella Valley County Water District, were directed by Walter Hofmann, district engineer, Menlo Park, Calif.

Messrs. R. F. Carter, general manager of the Imperial Irrigation District, and L. O. Weeks, general manager of the Coachella Valley County Water District, cooperated by supplying hydrologic records and other pertinent information. The Sandia Corporation, Albuquerque, N. Mex., granted permission to use some of its facilities at Salton Sea Base (Sandy Beach), and the North Shore Yacht Club granted permission to install a water-stage recorder on its breakwater.

GENERAL DESCRIPTION AND HISTORY

The natural drainage area of Salton Sea includes 8,360 square miles of diverse terrain that is mostly in California but extends about 20 miles into Baja California, Mexico. Mountains on the west and northeast rims of the basin reach altitudes ranging from less than 3,000 feet to 11,500 feet in the San Bernardino Mountains. The south rim is the crest of the Colorado River delta, which extends from an apex near Yuma, Ariz., to the mountains at the west edge of the elongate depression that contains Salton Sea and the Gulf of California. About one-fifth of the basin is below or only slightly above mean sea (ocean) level.

The Colorado River has discharged water and sediments across its delta through many distributaries, some of which flowed northward into the Salton Sea basin. For the last few centuries, however, the flow has generally been southward to the gulf. Consequently, the natural drainage area of Salton Sea is now topographically distinct from that of the Colorado River in the delta region. Early in this century, the construction of levees on the delta to prevent overflow to the north helped to complete the separation of the two drainage basins; later, construction of numerous flood-control reservoirs in the Colorado River basin ensured the permanence of the separation.

Figure 1 shows the principal features of the Salton Sea basin and its geographic relation to the head of the Gulf of California and to the lower Colorado River.

A contour map of the depression occupied by Salton Sea, adapted from a larger scale map (Littlefield, 1966), is shown in figure 2. Contours at and above 240 feet below mean sea level were derived from topographic maps (scale 1:24,000) based on a survey made in 1957 by the Topographic Division of the U.S. Geological Survey. Contours below that level were based on 152 soundings made in 1962 by Shawn Biehler, California Institute of Technology. The positions of the soundings were determined with the aid of radar equipment.

Most of the Salton Sea basin is extremely arid, and the natural runoff is insufficient to maintain a permanent water body. For a few centuries prior to 1901, when irrigation began in Imperial Valley, Calif. (south of Salton Sea), the depression now occupied by the sea—then known as Salton Sink—infrequently contained water as a result of unusual runoff from the bordering mountains or overflow from the Colorado River. McDougal (1914) reported that the sink contained water during at least 8 years of the 19th century.

The low altitude of large tracts of irrigable land within the Salton Sea basin facilitated the gravity diversion of Colorado River water for irrigation in Imperial Valley and, later, in Mexicali Valley, Baja California (an extension of Imperial Valley), and in Coachella Valley, Calif. (northwest of Salton Sea).

The first diversion from the Colorado River for irrigation use in the Salton Sea basin was made in 1901 (Mendenhall, 1909). During the next few years, increasing demands for water and accumulations of sediment in the canal and at the headgate, near the California–Baja California border, caused serious water shortages during periods of low streamflow. During the summer of 1904, additional diversions were made at points downstream from the headgate as an emergency measure to relieve the shortage. No headgates were built at that time because of legal problems. Before the new channels could be properly protected, a series of floods eroded them so extensively, that almost the entire flow of the Colorado River was diverted into the

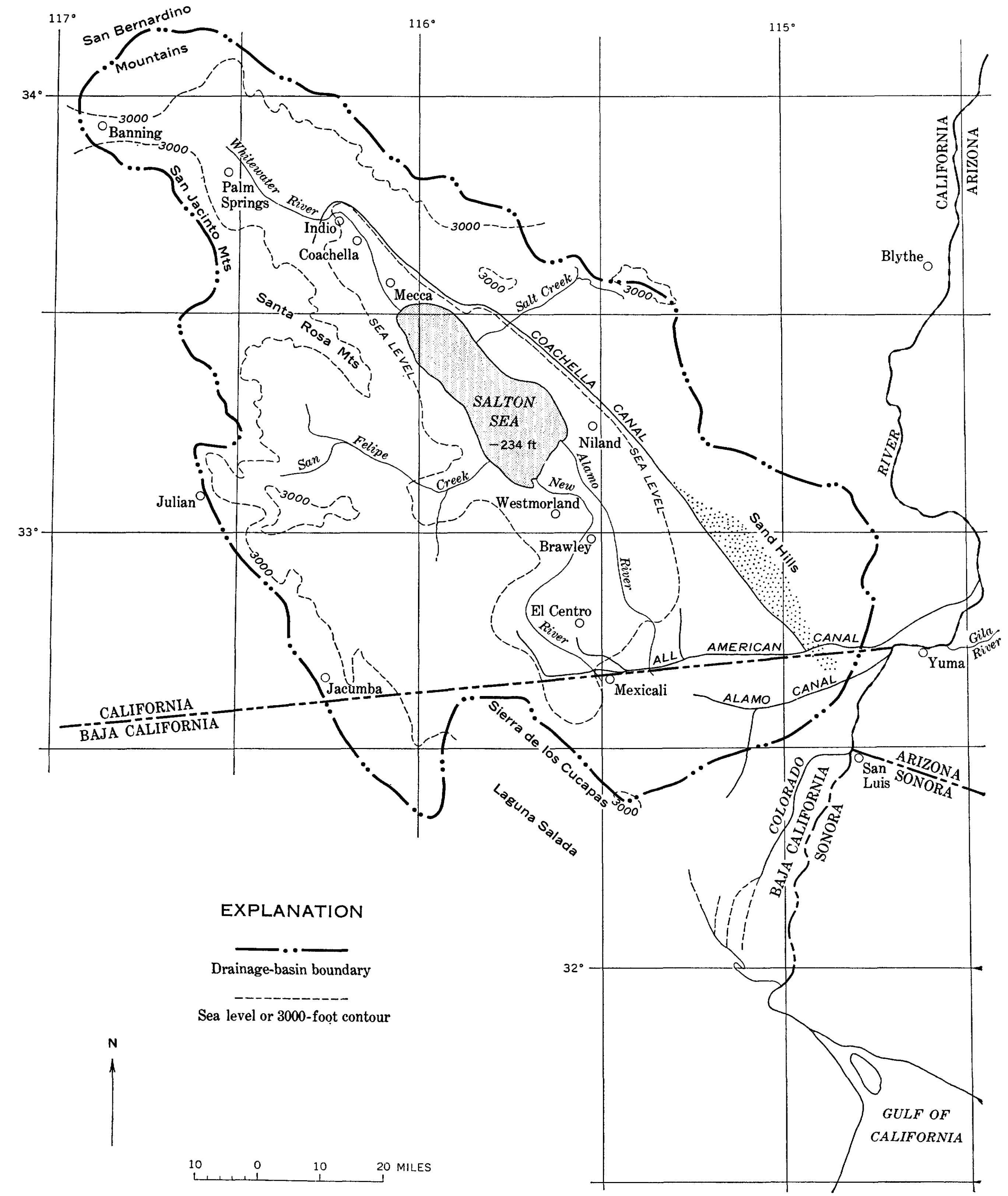

FIGURE 1.—Salton Sea basin.

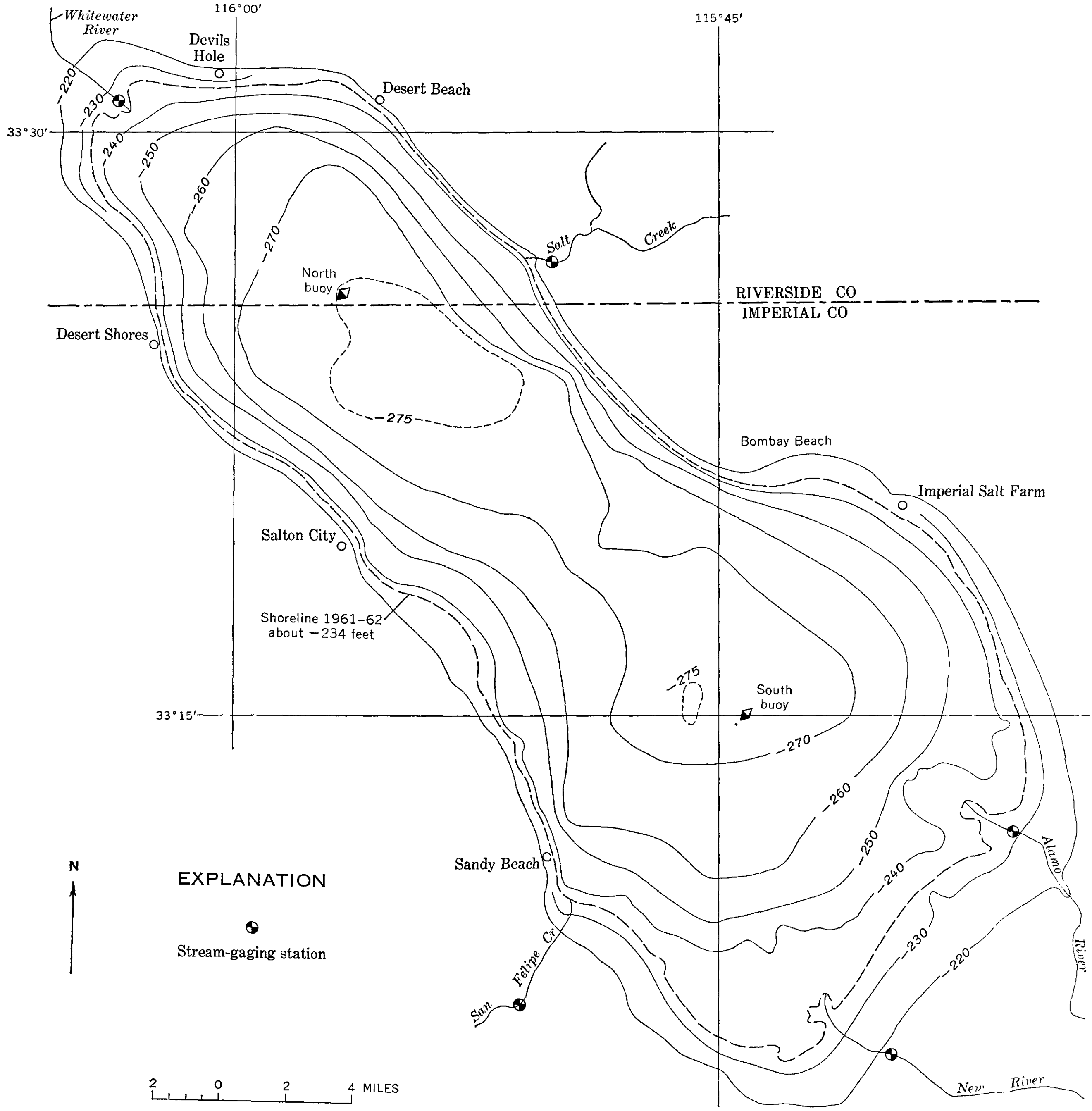

FIGURE 2.—Salton Sea bed. Adapted from Littlefield (1966).

Salton Sea basin. Floodwater began to collect in the sea in November 1904, and the diversion was out of control for more than 2 years, until February 1907.

During the period of uncontrolled diversion, the level of Salton Sea rose to the extent that water covered more than 500 square miles (330,000 acres) and was more than 80 feet deep. During the next 12 years the water level receded 55 feet. Because of the increasing drainage from irrigation, the trend reversed about 1925 and was generally upward from that time until 1963. (A graphic history of the water level and the principal controlling factors is presented in the section "Hydrologic Regimen for 1908–62" of this report.)

The chemical characteristics of the water in Salton Sea, discussed in the section "Chemical Regimen," underwent a continual change because of the events just described.

WATER LEVEL AND VOLUME

The water level and volume of Salton Sea vary continually in response to variations in the rates of inflow and evaporation (the only process by which water can leave this sea naturally). When inflow exceeds evaporation, the water level and volume increase, and the reverse is also true. The relation of the change in volume to inflow and evaporation for a specific period, commonly called a water budget, can be expressed as follows:

$$\Delta V = I_s + I_g + P - E, \tag{1}$$

where

ΔV = change in volume,
I_s = inflow in surface channels,
I_g = inflow as ground-water seepage,
P = precipitation on the water surface,
E = evaporation,

and all quantities are expressed in like units (acre-feet in this report).

Any term of equation 1 can be computed if all other terms are known, but the accuracy of the computed term depends on the degree of error in the terms that are measured or estimated. The result is not reliable if the probable combined error is large in relation to the computed term. Hence, the equation for Salton Sea is best suited to computation of the largest terms, I_s and E, and can provide little or no useful information regarding small terms such as I_g.

In this report the water budget is applied three ways: (a) to estimate evaporation from Salton Sea during 1961–62; (b) to estimate annual surface inflow prior to the beginning of records in 1944; and (c) to derive the relation between stable mean annual inflow and the corresponding water level. The methods of evaluating the terms vary with the information available and are described in following discussions.

The change in volume of a water body is generally derived from a record of water level and a relation of water level to surface area or volume. In figure 3 the relations dated 1965 were based on the maps and soundings, previously described, that were used in preparing figure 2. The lower parts of the relations dated 1958 in figure 3 were based on surveys that were probably made prior to 1905. Part of the difference between the two sets of curves may be a result of lack of refinement in the earlier surveys, and part may be a result of sedimentation on the deltas of the Alamo and New Rivers. Most such sedimentation probably occurred during the uncontrolled diversion of 1904–07. If this assumption is valid, the 1965 relations apply with little error since 1907. Consequently, they were used in this report for all computations involving area or volume.

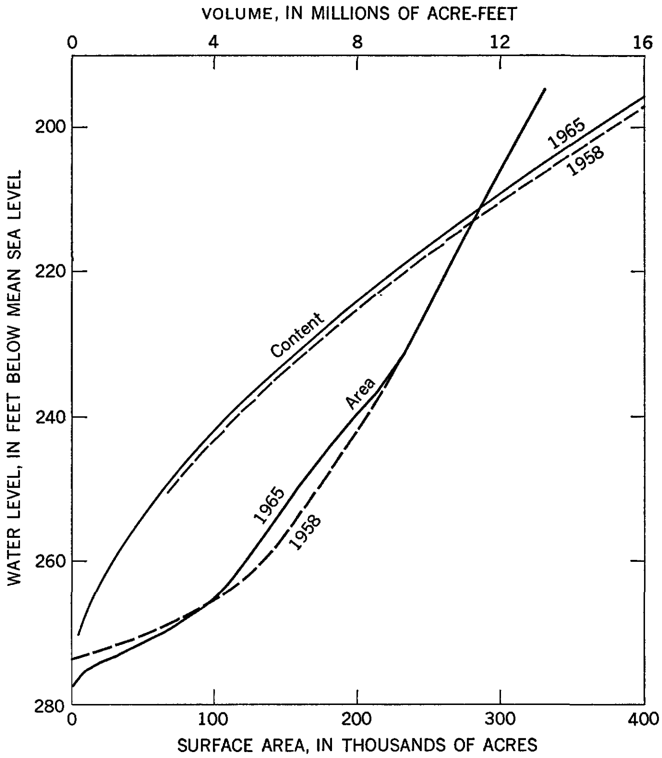

FIGURE 3.—Relations of water level to area and volume of Salton Sea. The relation dated 1965 was used in this report for all years after 1907.

Monthly observations of the water level of Salton Sea were made on staff gages at several different sites from November 1904 to September 1951. A water-level recorder at Sandy Beach (fig. 2) has been in operation since that date. All water-level data in this report have been made comparable by reference to mean sea level, datum of 1929—the datum used in U.S. Geological Survey publications for records since 1951. The datum of 1901, which is 0.91 foot lower than that of 1929, was used in previous publications of the data for years prior to 1951.

Some of the computed water levels for years prior to 1948 may be appreciably in error because of undetermined effects of unstable gage supports, earthquakes, or land subsidence. Water-budget computations, however, would be affected for only a few scattered years, and the resulting errors are probably relatively inconsequential.

Although the records of water level at a single site are considered to be generally satisfactory for use in annual water budgets, more accurate records were desired by the authors for monthly water budgets in 1961–62. For short periods strong winds cause a marked lowering of the water surface at the upwind side of Salton Sea and a concurrent raising of the surface at the downwind side. To minimize such effects on the record of water levels for 1961–62, two additional recorders were installed, one at Desert Beach and one at Imperial Salt Farm (fig. 2). All three recorders were set to read alike when the water surface was calm, and the average of the three recorded values was assumed to be the level of the sea. Computed changes in water level during 1961–62 are believed to be generally within 0.01 foot of the actual change.

Graphic presentations of monthly and annual fluctuations of water level are herein included with discussions of "Inflow Studies" and "Hydrologic Regimen for 1908–62."

INFLOW STUDIES

Inflow to Salton Sea consists of discharge from surface channels, ground-water seepage directly to the sea, and precipitation on the water surface. The following discussions concern measured or estimated annual values since 1907, or since the beginning of record, and also monthly values for 1961–62. The monthly values illustrate typical seasonal fluctuations and enable the determination of monthly evaporation by the water-budget method.

SURFACE INFLOW

For this study the surface inflow to Salton Sea is classified according to its source, as follows: (a) Inflow from Imperial Valley, including drainage from Mexicali Valley; (b) inflow from Coachella Valley; and (c) inflow from other areas.

IMPERIAL VALLEY

During most years, more than 90 percent of the surface inflow to Salton Sea is from Imperial Valley. The relatively uniform flows of the Alamo and New Rivers (fig. 1) account for most of the inflow from this valley, but highly variable flows in more than 30 minor channels account for about 10 percent.

The Imperial Irrigation District has maintained records of total inflow from the valley since 1944. These records are computed each month on the basis of discharge measurements and gage-height records of the Alamo and New Rivers near their mouths (near Niland and Westmorland, respectively) and on the basis of estimates of flow in the minor channels based in part on records from numerous gate openings.

The large number of channels, the variability of flow, and other conditions have been serious deterrents to the collection of precise records of the total flow in minor channels. To appraise the accuracy of past records of the inflow from Imperial Valley and to provide a better measure of the inflow for the study period, the U.S. Geological Survey monitored the records of the Alamo and New Rivers during 1961–62 and measured the flow in many of the minor channels.

During 1961 the minor-channel program included (a) operation of 1 water-stage recorder and 2 continuous-flow meters on 3 of the largest channels, (b) computation of flow from continuous gage-height records above 4 rated wasteways,[1] and (c) weekly measurements of flow in each of 18 channels.

Monthly flow in each of the 18 channels (minor-channel program, item c) was estimated as the average of all measurements made during the month or within 3 days of either end of the month. Although such averages for individual channels may differ markedly from the actual monthly flows, the differences tend to compensate when many averages are combined. Consequently, the sums of the computed monthly flows for all channels are considered to be fairly reliable.

Evidence to support this conclusion was obtained by comparing monthly flows in Trifolium drain 1 (near Westmorland) computed from a continuous gage-height record with monthly flows in the same drain computed from weekly measurements only. The percentage differences in computed flows for individual months range from about −17 to +17, but generally the differences for periods of several months are insignificant.

Flow in the channels not gaged during 1961 was estimated to be about 10 percent of the total flow for the 18 channels in item c (about 0.5 percent of the surface inflow from Imperial Valley).

In 1962 an additional continuous-flow meter was installed, and the number of channels measured weekly (item c) was reduced from 18 to 5. Thus, the total number of gaged channels was reduced from 25 in 1961 to 13 in 1962. The recorded flow in these 13 channels accounted for 73.5 percent of the computed total flow in minor channels during 1961, and the same percentage was assumedly applicable in 1962.

Independent computations of the discharge of the Alamo and New Rivers by the Geological Survey corresponded, generally within about 3.5 percent, to the irrigation district's records of monthly flow, and records of annual flow correspond within about 1 percent; consequently the irrigation district's records of flow in the rivers were considered by the authors to be satisfactory.

The Survey's estimates of the total flow in minor channels, however, differ markedly from the estimates made by the irrigation district without benefit of the streamflow measurements just described. Although these differences are large relative to the flow in minor channels, they are small relative to the total surface

[1] Daily discharge in three of the wasteways, and daily gage heights at the fourth, were furnished by the Imperial Irrigation District; however, these records were not used in the district's estimates.

inflow from Imperial Valley. The difference for 1962 (about 4.5 percent of the total inflow) was less than that for 1961 (about 6 percent of the total inflow), probably because the irrigation district made a change in the procedure used in water accounting for their monthly records. Table 1 summarizes inflow from Imperial Valley during 1961–62.

TABLE 1.—*Monthly surface inflow, in acre-feet, from Imperial Valley, 1961–62*

[Records for the Alamo and New Rivers furnished by Imperial Irrigation Dist.]

	1961				1962			
	Alamo River	New River	Minor channels	Total	Alamo River	New River	Minor channels	Total
January	43,280	31,840	7,790	82,900	39,480	37,290	6,430	83,200
February	47,200	33,450	9,910	90,600	36,870	27,780	8,750	73,400
March	64,600	42,660	11,500	119,000	59,810	40,560	15,200	116,000
April	66,920	42,370	11,500	121,000	68,160	41,650	15,100	125,000
May	63,310	39,960	12,000	115,000	61,330	39,050	13,500	114,000
June	57,830	35,050	11,600	104,000	55,680	35,750	13,500	105,000
July	60,330	35,090	11,900	107,000	59,700	35,640	13,700	109,000
August	58,710	36,610	13,000	108,000	63,620	36,980	14,800	115,000
September	61,710	39,600	13,300	115,000	75,630	41,920	15,800	113,000
October	65,670	40,120	11,700	117,000	71,070	40,940	12,400	124,000
November	49,820	30,920	8,910	89,600	50,570	34,300	7,520	92,400
December	36,120	29,310	7,730	73,200	39,420	43,470	7,250	90,100
Annual	675,500	437,000	131,000	1,242,000	681,300	455,300	144,000	1,280,000

The difference between figures for surface inflow during 1961 computed by the Imperial Irrigation District and those computed by the Geological Survey suggests a possibility of appreciable error in records for earlier years. The following evidence, however, indicates that there is no large consistent error in these earlier records. Annual surface inflow to the Salton Sea for 1948–60 computed by using water budgets (described in "Hydrologic Regimen for 1908–62" of this report) differs from the inflow based on available records by more than 5 percent for 4 of the 13 years, but the average values for the 13-year period are almost identical.

Annual inflow from Imperial Valley for 1944–62 is listed in table 4, which summarizes the inflow from all areas.

COACHELLA VALLEY

Coachella Valley is drained by the Whitewater River and 18 minor channels. When the river was in its natural state, most floodwaters tended to spread over the desert and disappear without reaching Salton Sea. The lower reaches of the stream (Coachella Valley Stormwater Channel) have been improved, however, by levees constructed to confine floodflows and by dredging operations which provide drainage for adjacent farmlands. During 1961–62 all channel flow was relatively uniform because it consisted chiefly of ground-water seepage. Since importation of Colorado River water began (about 1948), drainage from irrigated lands has been the source of nearly all the surface inflow from the valley.

The Geological Survey computed records of flow in the Whitewater River at its mouth on the basis of weekly or biweekly measurements and of a continuous gage-height record furnished by the Coachella Valley County Water District. Estimates of the flow in minor channels, based on monthly measurements made by the water district, were added to measurements of the flow of the river to obtain estimates of the monthly inflow from Coachella Valley.

Comparison of these estimates with the water district's records of monthly inflow, based on current operating data, indicated that the water district's records were satisfactory. Differences between corresponding monthly flows were generally less than 10 percent, and differences between corresponding annual flows were less than 2.5 percent. Monthly inflow from Coachella Valley for 1961–62 is summarized in table 2.

TABLE 2.—*Monthly surface inflow, in acre-feet, from Coachella Valley, 1961–62*

[Records of total inflow furnished by Coachella Valley County Water Dist.]

	1961		1962	
	Whitewater River	Total	Whitewater River	Total
January	3,160	5,170	4,690	6,960
February	3,150	5,330	4,920	7,490
March	4,420	6,550	5,740	9,190
April	4,640	7,300	6,140	10,150
May	5,380	7,500	6,560	10,910
June	4,300	7,260	6,100	10,100
July	5,120	7,320	6,350	10,730
August	5,270	9,040	7,060	11,600
September	5,370	8,640	6,950	11,340
October	4,520	7,250	5,760	9,200
November	3,900	6,090	4,530	7,270
December	4,160	6,440	4,790	7,750
Annual	53,390	83,890	69,590	112,700

The annual surface inflows from Coachella Valley for 1948–62 are listed in table 4. Inflow for 1948 was estimated because sections of the Coachella Canal contained water for one or more years prior to its completion in 1949. For previous years, inflow due to storm runoff is treated in this report as a part of the inflow from other areas.

OTHER AREAS

No records of inflow to Salton Sea from areas other than Coachella and Imperial Valleys were made prior to 1961. During the winter of 1960–61 gaging stations were installed at the mouth of Salt Creek, near Mecca, and near the mouth of San Felipe Creek, near Westmorland (fig. 1).

The Coachella Canal crosses the lower part of the Salt Creek basin and several smaller drainage basins southeast of Salt Creek. Seepage from the canal maintains a small base flow in Salt Creek during all seasons and in several of the smaller streams during some months. Less than 5 percent of the total flow of Salt

Creek during 1961–62 was storm runoff; the balance was seepage.

San Felipe Creek drains more than a thousand square miles, including much mountainous area and some small tracts irrigated with local water supplies. During most winters a small base flow persists at the mouth of the creek. Storm runoff accounted for about 90 percent of the flow during 1961–62.

Table 3 indicates the monthly flows in Salt and San Felipe Creeks and the estimated flows from ungaged areas. Ungaged inflow from the northeast, mostly seepage from the Coachella Canal, was estimated to be about the same as flow in Salt Creek, which includes seepage from about half of the reach of canal that is near the shore. Ungaged inflow from the southwest was estimated to be twice the estimated storm runoff in San Felipe Creek (total runoff less base flow—not given in table 3). The latter estimate was based on the assumptions that virtually all measured storm runoff originated near the gaging station and that the storms also caused runoff from the more mountainous area northwest of San Felipe Creek. These estimated quantities of ungaged inflow are very small in comparison to total inflow to Salton Sea; therefore, errors are relatively unimportant.

TABLE 3.—*Monthly surface inflow, in acre-feet, from areas other than Imperial and Coachella Valleys, 1961–62*

	1961				1962			
	Salt Creek	San Felipe Creek	Un-gaged	Total	Salt Creek	San Felipe Creek	Un-gaged	Total
January	[1] 470	23	470	960	474	336	1, 110	1, 920
February	391	23	390	800	430	15	430	880
March	393	13	390	800	449	11	450	910
April	226	0	230	460	392	1	390	780
May	176	0	180	360	344	0	340	680
June	129	0	130	260	266	0	270	540
July	108	0	110	220	184	0	180	360
August	186	944	2, 100	3, 230	198	0	200	400
September	215	0	220	440	309	0	310	620
October	298	0	300	600	377	0	380	760
November	354	0	350	700	441	0	440	880
December	528	123	760	1, 410	554	11	560	1, 120
Annual	3, 470	1, 130	5, 630	10, 200	4, 420	374	5, 060	9, 850

[1] Partly estimated.

Surface inflow from areas other than the principal irrigated valleys is very small during most years but is appreciable during periods of maximum storm intensity. For example, a field reconnaissance in 1951 indicated that considerable storm runoff had occurred in several tributaries during July or August of that year. Also, during the period September 1–11, 1939, the level of Salton Sea rose 0.8 foot, which corresponds to an increase in volume of about 150,000 acre-feet. An unknown amount of this increase was caused by rainfall on the water surface, but the major part was probably caused by storm runoff. The official records of rainfall during the period include 6.33 inches at Brawley and 2.03 inches at Indio. An unofficial observation of 11 inches in 6 hours near Coachella was reported by the Coachella Valley County Water District (Gatewood, 1945).

For the years prior to 1961 the surface inflow from areas other than the principal irrigated tracts (including Coachella Valley prior to 1948) was assumed to be about the same as that for 1961–62, which was about 10,000 acre-feet each year, because there is no basis for reliable estimates for individual years. Seepage from the Coachella Canal which was a major component of the inflow from these areas in 1961–62, was not a factor prior to 1948. Nevertheless, this assumption is reasonable because Coachella Valley was included with "other areas" prior to 1948, and also because precipitation was above normal for several years prior to 1948. Precipitation during the period prior to 1948 was about two or more times the normal amount in 7 years, but since 1948 it has exceeded the normal amount only once, and then only slightly.

SUMMARY OF SURFACE INFLOW

Most of the surface inflow to Salton Sea during 1961–62 was determined at conventional stream-gaging stations or continuous-flow meters, a much smaller part was estimated on the basis of periodic measurements, and a very small part was not measured. The percentages of the inflow in each category are summarized as follows:

	1961	*1962*
Gaging stations	91.6	91.4
Periodic measurements	7.5	5.5
Ungaged	.9	3.1

The errors in computed annual inflow for 1961–62 are probably less than 5 percent. Errors in other annual values and in monthly values for 1961–62 probably are generally less than 10 percent.

The monthly surface inflows to Salton Sea for 1961–62, itemized in tables 1–3, are summarized with other items of the water budget in the discussion of evaporation. The annual flows for 1944–62, described by areas in the preceding sections, are summarized in table 4.

GROUND-WATER INFLOW

Salton Sea and the surrounding area are underlain by thick deposits of alluvium, which are rather impermeable except in Coachella Valley and locally at the mouth of San Felipe Creek. The relative impermeability in Imperial Valley is indicated by the extremely low yields of wells near the sea and by data from a line of auger holes that extends across the valley just south of the sea. The greater permeability of the alluvium in Coachella Valley is demonstrated by the yields of many artesian and water-table wells.

TABLE 4.—*Annual surface inflow to Salton Sea, in thousands of acre-feet, 1944–62*

[Total inflow for each year from 1944 to 1960 is the sum of flows from Coachella and Imperial Valleys plus an estimated 10,000 acre-feet of inflow from other areas. Records for Imperial Valley for 1944-60 were furnished by Imperial Irrigation Dist. Records for Coachella Valley were furnished by Coachella Valley County Water Dist., except the one for 1948, which was estimated]

Year	Imperial Valley	Coachella Valley	Total
1944	1,090		1,100
1945	1,070		1,080
1946	1,120		1,130
1947	1,070		1,080
1948	1,050	20	1,180
1949	1,130	36	1,180
1950	1,140	65	1,220
1951	1,210	108	1,330
1952	1,300	86	1,400
1953	1,380	63	1,450
1954	1,300	72	1,380
1955	1,120	85	1,220
1956	1,170	71	1,250
1957	1,080	53	1,140
1958	1,080	56	1,150
1959	1,140	57	1,210
1960	1,180	70	1,260
1961	1,242	84	1,340
1962	1,280	113	1,400

The total ground-water inflow to Salton Sea was estimated to be about 50,000 acre-feet per year. The California Department of Water Resources (1964, p. 133–137) estimated the annual ground-water inflow from Coachella Valley to be about 30,000 acre-feet (including the discharge of uncontrolled flowing wells), on the basis of hydrologic investigations conducted during 1960–61. On the basis of geologic and hydrologic studies made during 1961–64, J. H. Robison of the U.S. Geological Survey (oral commun., 1964) estimated that the annual inflow through the alluvium bordering San Felipe Creek was about 10,000 acre-feet and that inflow through the alluvium of Imperial Valley was less than 2,000 acre-feet.

Seepage from the Coachella Canal is a source of recharge for aquifers northeast of Salton Sea, but most of the water lost from the canal appears to be discharged by evapotranspiration and surface inflow rather than by ground-water inflow. The average annual loss from the canal in the reach bordering the sea is about 26,000 acre-feet, of which about 8,000 acre-feet enters the sea from surface channels. Evaporation from the canal, evapotranspiration from wet areas (chiefly stream channels covered with dense vegetation), and increasing ground-water storage could reasonably account for the rest.

Although both seasonal and long-term variations in ground-water inflow may occur, the magnitude and nature of the fluctuations are not sufficiently well known to justify estimates for individual months and years. Consequently, the rate of ground-water inflow was assumed to be constant.

PRECIPITATION ON THE WATER SURFACE

The best available index of precipitation on the water surface for 1948–62 is the average computed from three rain gages on the shore. These gages are located at Sandy Beach, Devils Hole, and Imperial Salt Farm (fig. 2) and are part of the set of three evaporation stations subsequently described in this report.

For the period 1908–47, Weather Bureau records of precipitation at Brawley, Imperial, Indio, and Mecca (fig. 1) provide an index of precipitation on the water surface. Records for all four stations were available for 23 of the 40 years, and records for three stations were available for all but one of the remaining years. Because precipitation at Indio generally is slightly higher than at the other three stations and is included in all multiple-station averages, these averages were multiplied by 0.95 to derive the estimated depth of precipitation on the Salton Sea. The conversion factor, 0.95, is the ratio of the average for Brawley and Mecca (the stations nearest the sea) to the four-station average for 23 years.

The average annual depth of precipitation on Salton Sea for 1931–60 (corresponding to the current Weather Bur. normal) is 0.21 foot (2.5 in.), and the average for 1908–62 is 0.22 foot. Quantities of precipitation on the water surface (average depth, in feet, times the surface area, in acres) are summarized with other water-budget data in later sections.

The amount of precipitation during most years was so small that any errors involved have relatively little effect on computations in this report, but the precipitation during exceptional storm periods may have differed significantly from the quantities corresponding to precipitation at the index stations.

EVAPORATION STUDIES

As all known methods of determining evaporation from Salton Sea involve considerable error, relatively independent determinations by the water-budget and energy-budget methods were made for the period 1961–62. These results were then combined with mass-transfer data and evaporation-pan data in an effort to determine the most practical means of continuing measurements of evaporation and estimating evaporation for previous years.

WATER-BUDGET METHOD, 1961–62

The best known method of determining evaporation from a water body is the solution of the water-budget equation. (The measurement of evaporation from pans is a small-scale application of the method.)

For many applications of the water budget, use of equation 1, wherein the change of volume, ΔV, is determined as previously described, is adequate. The effects of bank storage and thermal expansion of water, however, must sometimes be considered in order to obtain the most reliable estimates of evaporation.

Bank storage.—The term "bank storage" applies to the quantity of ground water that drains into a water body as a direct result of a recession of the water level. Conversely, the term applies to the quantity that flows from the water body into the banks or that is prevented from draining from the banks into the water body as a direct result of a rise in the water level. Such storage is fully effective only during long-term changes of water level because of the slow movement of the ground water.

Rough estimates of the effect of bank storage at Salton Sea (based on length of shoreline and estimates of ground-water gradients and soil porosity) indicate that is was negligible for monthly changes in water level during 1961–62 and was probably less than 5 percent of the change in volume, indicated by the 1965 relation in figure 3, during the rapid recession of 1908–20. Therefore, no adjustments for the effects of bank storage were included in computations for this report.

Thermal expansion.—Changes in the volume within a water body may be caused by thermal expansion or contraction of the water as well as by a net gain or loss of water. The effects of expansion and contraction are generally negligible for budget periods of one or more years but are often significant for periods of a month or less when the water is rapidly warming or cooling.

To account for the effects of thermal expansion and contraction, the following relation was used in monthly water budgets for Salton Sea:

$$\Delta V_w = \Delta V - \Delta V_t \,, \qquad (2)$$

where

ΔV_w = the net gain or loss of water,

ΔV = the total change in volume indicated by the change in water level, and

ΔV_t = the change in volume resulting from thermal expansion (ΔV_t is negative when the volume of water is contracting).

The method of computing the thermal expansion term is described in the Lake Hefner report (U.S. Geol. Survey, 1954) and is illustrated by the following computation for the month of June 1961. Interpolation between average temperatures determined by thermal surveys of Salton Sea (described in the discussion of the energy budget) indicated that the water temperature was about 23°C at the beginning of the month and about 29°C at the end. If the relative volume of water at 4°C (the temperature for maximum density) is assigned the value of 1.00000, then the volume at 23°C is 1.00244, and at 29°C, 1.00405 (Hodgman and others, 1957, tables of relative density and volume of water). The ratio of the volume of a given mass of water at the end of the month to the volume of the same mass at the beginning is 1.00405/1.00244=1.00161. The approximate change in volume due to thermal expansion is equal to (1.00161−1) multiplied by the average volume of the sea for that month (5,590,000 acre-ft), which is 9,000 acre-feet.

For some types of gage installation, thermal expansion of the structure must be considered in the determination of the changes in water level and in total volume. The basic reference gage for Salton Sea, however, consisted of 3.3-foot-long enameled-steel sections attached to a wooden pile in shallow water, and the effects of expansion and contraction of the gage were considered to be negligible.

Computed evaporation.—Monthly and annual evaporation is computed from the water level and inflow data, previously described, by solving equation 1 for E and using the equivalent of ΔV_w (as defined by equation 2) for ΔV as follows:

$$E = I_s + I_g + P - \Delta V + \Delta V_t. \qquad (3)$$

Each term of the budget (except ground-water inflow, which has been treated as a constant) is listed in table 5.

The accuracy of the computed evaporation is affected by errors in all other terms of equation 3. The resulting error is probably less than 7 percent for annual values and less than 12 percent for most monthly values, but errors of 20 percent or more may affect values for some months. The smallest computed monthly values are generally affected by the largest percentage errors.

The principal source of error in computed evaporation is the error in surface inflow records, which is generally less than 5 percent for annual flows and less than 10 percent for monthly flows. An error of 50 percent in the estimated ground-water inflow would correspond to an error of less than 2 percent of annual evaporation or of 10 percent of evaporation for some winter months. The amount of precipitation is so small that errors are inconsequential.

An error of 0.01 foot in water level corresponds to a change in volume of about 2,200 acre-feet—that is, about 7 percent of the smallest monthly evaporation. Although the correction for thermal expansion is insignificant relative to the total volume of Salton Sea, it is as much as 7 percent of the monthly evaporation and is greater than the change in volume indicated by water levels for some months.

TABLE 5.—*Monthly water budgets, in acre-feet, for Salton Sea, 1961–62*

Ground-water inflow (I_t) estimated as 50,000 acre-feet per year, or 4,170 acre-feet per month. Evaporation shown here is computed from the water budget, and is compared with other determinations in table 7]

	1961					1962				
	Surface inflow (I_s)	Precipitation (P)	Change in volume (ΔV)	Thermal expansion (ΔV_t)	Evaporation (E)	Surface inflow (I_s)	Precipitation (P)	Change in volume (ΔV)	Thermal expansion (ΔV_t)	Evaporation (E)
January	89,000	4,500	+67,000	+1,100	31,700	92,100	9,000	+62,900	−700	41,700
February	96,700	0	+44,800	+1,200	57,300	81,800	2,300	+38,300	+700	50,700
March	126,000	0	+51,700	+3,000	81,500	126,000	0	+61,000	+3,100	72,300
April	129,000	0	+20,300	+3,100	116,000	136,000	0	+47,600	+4,500	97,100
May	123,000	0	−29,300	+2,300	159,000	126,000	0	−38,500	+1,300	170,000
June	112,000	0	−4,500	+9,000	130,000	116,000	0	0	+6,400	127,000
July	115,000	0	−29,200	+5,100	153,000	120,000	0	−36,200	+5,700	166,000
August	120,000	15,700	−38,100	−3,400	175,000	127,000	0	−33,800	+700	166,000
September	124,000	2,200	−44,700	−6,000	169,000	145,000	2,300	−4,500	−4,000	152,000
October	125,000	0	−15,600	−7,900	137,000	134,000	0	+4,500	−7,400	126,000
November	96,400	0	+13,400	−4,500	82,700	101,000	0	+6,800	−5,600	92,800
December	81,000	11,200	+51,400	−1,800	43,200	99,000	9,000	+54,200	−2,800	55,200
Annual	1,337,000	33,600	+87.200	+1,100	1,335,000	1,404,000	22,600	+162,300	+1,900	1,317,000

The figures for surface inflow and evaporation given in table 5 illustrate typical seasonal fluctuations of these quantities. In figure 4 these figures are graphically shown in relation to corresponding fluctuations of water level.

The evaporation determined by the water-budget method is compared with other evaporation data in a later section.

ENERGY-BUDGET METHOD, 1961–62

The energy budget is an accounting for all heat energy reaching, stored in, and leaving a water body, the objective being to determine the amount of energy utilized in the evaporation process and, hence, the quantity of water evaporated. The results are only slightly dependent on the water budget because the energy content of the inflowing water is relatively small. Evaporation determined by the energy-budget method, consequently provides a means for verifying that determined by the water-budget method (which has obvious deficiences).

The energy-budget method, its underlying theory, and the required instrumentation are described in considerable detail in a report of studies at Lake Hefner, Okla. (U.S. Geol. Survey, 1954), where the first field tests were made, and in a report on studies at Lake Mead, Arizona-Nevada (Harbeck and others, 1958). The method has also been used on several other lakes, although few investigations have provided as good opportunities as the one on Salton Sea for comparison of results obtained by different methods and for a critical evaluation of the different methods. The basic

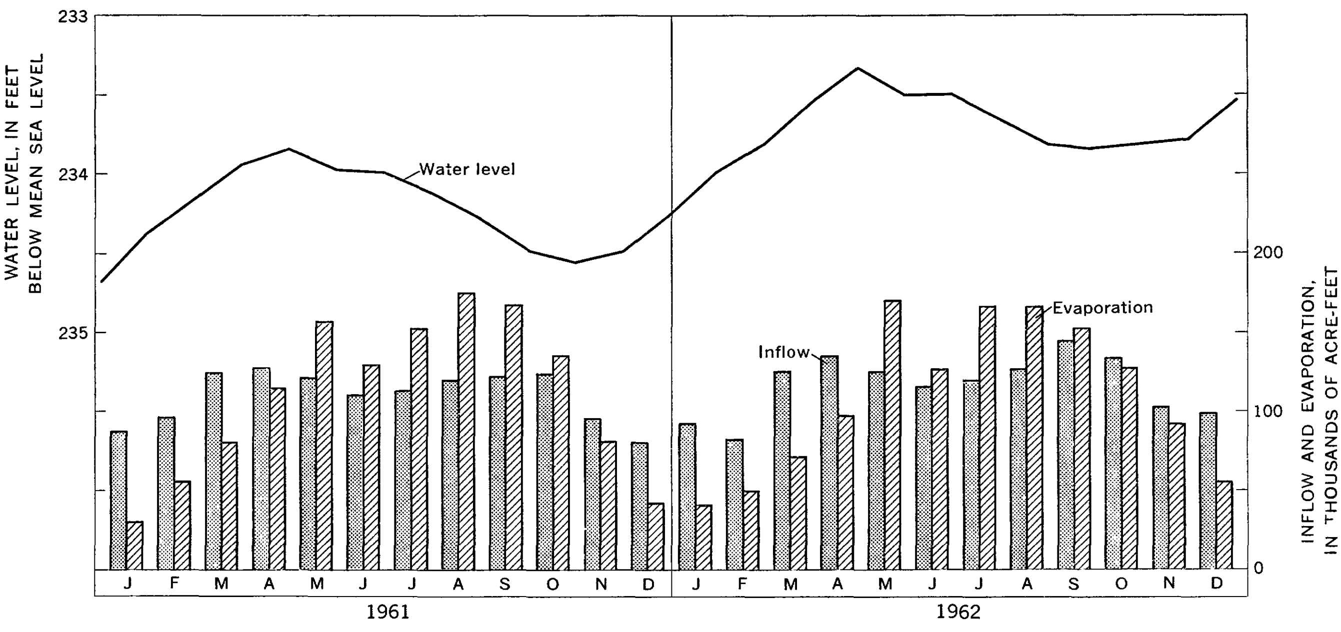

FIGURE 4.—Monthly fluctuations of water level, surface inflow, and evaporation, 1961–62. (Water level at the end of each month and evaporation determined by water-budget method.)

data and an evaluation of methods are given in a separate technical report (Hughes 1966). The following discussion summarizes results and indicates the general nature of the method as applied to Salton Sea during the period January 9, 1961–January 8, 1963.

The energy budget for a body of water can be expressed as follows:

$$Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} + Q_v - Q_\vartheta = Q_e + Q_h + Q_w, \quad (4)$$

where

Q_s=solar radiation incident to the water surface,
Q_r=solar radiation reflected by the water surface,
Q_a=incident long-wave radiation from the atmosphere,
Q_{ar}=long-wave radiation reflected by the water surface,
Q_{bs}=long-wave radiation emitted by the body of water,
Q_v=net energy advected into the body of water,
Q_ϑ=increase in energy content of the body of water,
Q_e=energy used by evaporation,
Q_h=energy conducted from the body of water as sensible heat, and
Q_w=energy advected by the evaporated water.

This equation does not include minor terms, such as conduction of energy through the bottom of the water body, heating due to chemical and biological processes, and transformation of kinetic into thermal energy.

The terms on the left side of equation 4 are either measured directly or computed from theoretical or empirical relations. Their algebraic sum represents the total energy available for evaporation processes and conduction to the atmosphere. As of 1961–62 direct determination of the terms on the right side was not practical, but the distribution of the available energy among them was determined by the use of the Bowen ratio (discussed in a following paragraph headed "The Bowen Ratio") and the fact that the mass of water involved in Q_e and Q_w is the same. To convert equation 4 to a usable form, the following equivalents are substituted for the three terms on the right:

$$Q_e = \rho EL; \; Q_h = RQ_e; \text{ and } Q_w = \rho cE(T_e - T_b),$$

where

ρ=density of evaporated water,
E=volume of evaporated water,
L=latent heat of vaporization,
R=the Bowen ratio,
c=specific heat of water,
T_e=temperature at which evaporation takes place (usually taken as water-surface temperature, T_0), and
T_b=base temperature (arbitrarily selected as 0° C; when T_e and T_b are defined as above, $T_e - T_b = T_0$).

Thus, E is expressed in terms of measurable or known quantities as follows:

$$E = \frac{Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} + Q_v - Q_\vartheta}{\rho[L(1+R) + cT_0]}. \quad (5)$$

If quantities are expressed in terms of unit area and unit time, E is the volume per unit area (depth) of evaporated water.

The instruments and methods used to obtain each quantity in equation 5 are described in the following paragraphs. Instruments at Sandy Beach (fig. 2) were used for all measurements of radiation and air temperature, and the values measured there were assumed to be applicable to the entire sea.

EQUIPMENT AND PROCEDURES

Incident solar radiation.—Incident solar radiation (Q_s) was measured by an Eppley pyrheliometer connected to a potentiometer recorder. Measurements were recorded at 3-minute intervals. Mean hourly values were obtained from the recorder chart and added to determine total radiation for 1 day. During periods of broken cloud cover, when radiation was extremely variable, values for periods shorter than 1 hour were computed.

Reflected solar radiation.—The amount of solar radiation reflected from the water surface (Q_r) was computed as the product of hourly values of the measured incident solar radiation and corresponding values of the reflectivity (ratio of reflected radiation to incident radiation).

Anderson (1954, p. 78–88) showed that reflectivity is primarily a function of sun altitude but that it is also affected by the extent and height of cloud cover, and he presented empirical equations relating these factors. The sky over Salton Sea during this study was clear most of the time, particularly during the summer months, when evaporation was high. As relatively little information on the extent and height of cloud cover was available, clear-sky conditions were assumed for all computations of reflectivity. An analysis of the probable effects of this assumption indicated that the resulting error in computed evaporation might be as much as 5 percent for some winter months but is negligible for annual values.

Incident long-wave radiation.—A total hemispherical radiometer, calibrated by the manufacturer, was used to measure total incident radiation. At night all incident radiation is long-wave radiation from the atmosphere (Q_a). To obtain incident long-wave radiation during daylight hours, the solar radiation was subtracted from the total.

The radiometer output was recorded on the stripchart potentiometer at 3-minute intervals. Mean hourly values were corrected for variations due to change in temperature of the radiometer surface in accordance with the Stefan-Boltzman law (discussed in this section under the paragraph heading "Long-wave Radiation Emitted by the Water").

Reflected long-wave radiation.—Reflected long-wave radiation (Q_{ar}) was computed as 0.030 times the measured incident long-wave radiation. This computation was based on a study made in connection with the Lake Hefner investigation (Anderson 1954, p. 96–98), which indicated that the reflectivity for long-wave radiation from the atmosphere varies only slightly from 0.030 regardless of the water temperature or salinity.

Long-wave radiation emitted by the water.—Thermal radiation emitted by any body depends on the emissivity and temperature of the surface. Under conditions governing the exchange of radiant energy between the atmosphere and the Salton Sea, the emissivity of the water surface may be considered to be the complement of its reflectivity (Anderson 1954, p. 96). As the reflectivity is 0.030 (preceding section), the emissivity is computed to be 0.970.

Thermal surveys, subsequently described in this report, indicate that the average temperature of the entire water surface for a period of several days is closely approximated by the average of the water temperatures recorded continuously at the two buoys indicated in figure 2. Daily values of long-wave radiation emitted by the water were computed by use of these temperatures in the equation expressing the Stefan-Boltzman law:

$$Q_{bs}=e\sigma(T_0+273)^4, \tag{6}$$

where,

e=the emissivity (0.970),

σ=the Stefan-Boltzman constant for black-body radiation (1.171×10^{-7} cal cm^{-2} deg^{-4} day^{-1}),

T_0=water-surface temperature in °C.

Advected energy.—The advected-energy term (Q_v) for Salton Sea represents the energy content (relative to that at an arbitrary base of 0°C) of the inflowing water from all sources and was computed as the product of the volume, density, specific heat, and temperature of the inflow. The volume of the inflow was discussed in the section "Water-Budget Method, 1961–62"; the density and specific heat are nearly the same as those of pure water—1.00 g per cu cm and 1.00 cal per g per °C, respectively. Frequent or continuous temperature measurements of all components of the inflow would be impractical. However, the daily average water temperature for shallow streams generally differs only slightly from the daily average air temperature. Moreover, the flow of the Alamo and New Rivers is about three-fourths of the total inflow to the sea. Hence, a relation between water temperatures periodically measured near the mouths of the two rivers and daily air temperatures from a continuous record at Sandy Beach provided a suitable basis for estimating with little error the average temperature of all inflow.

Energy content.—Determination of the increase in energy content (Q_ϑ) during any given period of time requires a determination of the energy content of the water (above that at the arbitrary base of 0°C) at the beginning and at the end of that period. The energy content at any time depends on the volume, density, specific heat, and temperature of the water. The basis for determining the volume of water in Salton Sea is described in the section "Water Level and Contents." The density was determined to be 1.023 g per cu cm. The specific heat of ocean water, 0.94 cal per g per °C, was used because the salinity of Salton Sea at the time of this investigation was approximately the same as that of ocean water. The temperature of the water, however, varies with both depth and areal location. Consequently, computation of the energy content required many temperature observations.

The necessary temperature data were obtained from thermal surveys of the Salton Sea made at about 14-day intervals. Each thermal survey consisted of a series of temperature measurements at each of 35 stations spaced so as to provide representative sampling of the sea on an areal basis. Station locations were generally determined only approximately by observation of the two buoys (fig. 2) and of the landmarks on shore. The measurements were made at selected depths below the surface so that each was made at the center of a uniformly thick layer of water. Because the widest variations in temperature generally occur near the surface, temperature measurements were made within layers 2 feet thick above a depth of 10 feet and 4 feet thick below that depth. Assumedly, the average temperature of the water in each layer was the average of the temperatures measured in that layer.

The energy content of each layer (above the arbitrary base temperature) was computed as the product of the average temperature, density, specific heat, and volume; and the total energy content at the time of any thermal survey was the sum of the values computed for all layers. The change in energy storage was determined only for the periods between thermal surveys, and equation 5 was applied only to such periods.

The Bowen ratio.—When a temperature difference exists between the air and the water surface, energy is transferred by convective and conductive processes that cannot be readily measured. The ratio of energy so transferred to that used by evaporation was expressed by Bowen (1926) as follows:

$$R=\frac{0.61(T_0-T_a)P_a}{(e_0-e_a)1{,}000}, \tag{7}$$

where

T_0=water-surface temperature in °C,

T_a=air temperature in °C,

e_0=vapor pressure, in millibars, of saturated air at the temperature of the water surface,

e_a=vapor pressure, in millibars, of the air at a selected point,

P_a=atmospheric pressure, in millibars.

The water-surface temperature, T_0, was that measured at the two buoys and used to obtain the long-wave radiation emitted by the water. The saturation vapor pressure of air, e_0, corresponding to values of T_0, was taken from standard vapor-pressure tables for a sodium-chloride solution of concentration approximately equal to the salinity of Salton Sea.

The temperature, T_a, and vapor pressure, e_a, of the air were obtained from wet-bulb and dry-bulb temperatures at a level about 8 m above the average water level of Salton Sea, recorded at 16-minute intervals at Sandy Beach.

RESULTS OF ENERGY-BUDGET COMPUTATIONS

The basic computations of evaporation were made for intervals between thermal surveys (budget periods) as explained in the discussion of energy content. Values of each term in the energy budget (eq 4) for selected budget periods and for one period of a few days more than 1 year are shown in table 6 to illustrate the relative magnitudes and seasonal variations of the terms.

TABLE 6.—*Representative values, in calories per square centimeter per day, of each term in the energy budget for Salton Sea*

Period	Q_s	Q_r	Q_a	Q_{ar}	Q_{bs}	Q_v	Q_θ	Q_e	Q_h	Q_w
Jan. 15–29, 1962	275	27	591	18	754	6	−2	72	+1	2
Apr. 2–16, 1962	571	39	772	23	853	15	+216	256	−38	9
July 16–30, 1962	591	38	953	29	970	17	+102	428	−29	23
Nov. 5–20, 1962	303	30	648	19	869	9	−210	223	+20	9
Jan. 2, 1962–Jan. 8, 1963	464	35	736	22	868	12	+3	283	−11	12

To obtain monthly evaporation from that computed for budget periods, it was necessary to prorate the evaporation for those periods that include parts of 2 months. This was done on the basis of mass-transfer data (described in the next section), because these data reflect the variations in the rate of evaporation within the budget period. Evaporation for the first 9 days of January 1961 (prior to the beginning of energy-budget measurements) was assumed to be equal to that determined by the mass-transfer method.

Monthly evaporation determined by the energy-budget method is shown in table 7 with other determinations for convenient comparison.

MASS-TRANSFER METHOD, 1961–62

In contrast with the energy-budget and water-budget concepts, in which either the energy used by evaporation or the volume of water evaporated is considered as one item in a complete budget for the water body, the mass-transfer concept involves only the process by which the water vapor is transferred from the water body to the atmosphere. The application of mass-transfer theory to field determination of evaporation is described in previous reports on the energy-budget method (U.S. Geol. Survey, 1954; Harbeck and others, 1958), and the basic data and evaluation of the method for Salton Sea are presented in the report by Hughes (1966). The general nature of the method and a summary of results are presented herein.

A simplified mass-transfer equation, developed during the Lake Hefner studies, relates evaporation from a water surface to the product of the windspeed multiplied by the humidity gradient of the air. A single empirical coefficient represents the combined effect of other properties of the atmosphere and of the water body that may influence the interchange of water vapor between the water surface and the atmosphere. The magnitude of the coefficient is influenced by the size and shape of the water body and by exposure of its surface to wind (Harbeck, 1962); hence, a determination of the coefficient is required for each site. Once the coefficient is established, however, the mass-transfer equation provides a convenient means of computing evaporation for any period for which base data are available.

The empirical mass-transfer equation is:

$$E=Nu(e_0-e_a), \tag{8}$$

where

E=evaporation, in inches per day,

N=an empirical coefficient,

u=average windspeed, in miles per hour, at a selected height above the water surface,

e_0=vapor pressure, in millibars, of saturated air at the temperature of the water surface, and

e_a=vapor pressure of the air, in millibars, at a selected height above the water.

At Salton Sea, the windspeed was measured at a height 2 m above the water surface by anemometers mounted on two buoys located as shown in figure 2. The average of the windspeeds measured at the two buoys was assumed to be the average for the entire water surface. Since anemometer readings of cumulative movement, in miles, were obtained only when thermal surveys were made, average windspeed at the buoys could be computed only for the previously described energy-budget periods.

To obtain windspeed data for partial energy-budget periods, for computation of monthly evaporation, the wind movement at the two buoys for the entire period was assumed to be distributed between the two partial periods in the same proportion as the wind movement continuously measured at Sandy Beach.

The methods by which values of e_0 and e_a were obtained have been described in the discussion of the Bowen ratio (p. C13–C14). The vapor pressure difference, $e_0 - e_a$, was computed from average values of each for the energy-budget periods or partial periods; consequently, the adequacy of the values obtained is comparable to that of the values of windspeed.

Using the total evaporation during the study period (Jan. 9, 1961–Jan. 8, 1963), determined by the water-budget and energy-budget methods, with the corresponding value of the product of windspeed and vapor-pressure difference, the coefficient, N, was determined to be 0.00156. It should be noted that this coefficient value is valid only for the Salton Sea and only when base data are obtained at virtually the same points as those used during the study.

Because of the manner in which the coefficient was determined, the total evaporation for the 2-year period computed by the mass-transfer equation depends on results of the other two methods. Distribution of the evaporation within the period, however, is entirely independent of the water budget, and it is nearly independent of the energy budget because a factor of major importance in one method is of minor importance in the other.

COMPARISON OF RESULTS OBTAINED BY THE THREE METHODS

Monthly evaporation determined by each of the three previously described methods and reduced to a common unit (inches of depth) is listed in table 7 and plotted in figure 5.

TABLE 7.—*Monthly evaporation from Salton Sea, in inches, determined by three methods*

	1961				1962			
	Water budget	Energy budget	Mass transfer	Average evaporation	Water budget	Energy budget	Mass transfer	Average evaporation
January	1.70	1.28	1.77	1.58	2.23	1.73	2.59	2.18
February	3.07	2.63	3.14	2.95	2.70	2.24	2.55	2.50
March	4.35	4.73	5.26	4.78	3.84	3.96	4.10	3.97
April	6.18	6.98	6.69	6.62	5.14	6.77	6.11	6.01
May	8.47	9.60	9.34	9.14	9.00	9.67	8.86	9.18
June	6.93	9.09	7.85	7.96	6.73	8.50	7.22	7.48
July	8.17	9.18	7.55	8.30	8.81	10.07	8.12	9.00
August	9.36	10.09	8.61	9.35	8.83	10.02	9.29	9.38
September	9.08	9.55	8.78	9.14	8.10	7.56	7.56	7.74
October	7.36	6.74	7.15	7.08	6.77	6.16	7.42	6.76
November	4.45	3.62	3.82	3.96	4.94	3.21	4.67	4.27
December	2.32	1.53	2.22	2.02	2.93	1.07	2.64	2.22
Annual	71.4	75.0	72.2	72.9	70.0	71.3	71.1	70.7

The approximately independent values of aggregate evaporation from Salton Sea during the 2-year period, determined by the water-budget and energy-budget methods, differ by about 3 percent. The maximum difference between annual values determined by the three methods for a particular year is about 5 percent. Monthly values, however, differ by substantially larger percentages.

The comparisons in table 7 and figure 5, as well as several other comparisons of evaporation and basic data (Hughes 1966), show that the differences between monthly evaporation computed by water-budget and mass-transfer methods are as much as 21 percent of computed evaporation, but the distribution of these differences tends to be random rather than seasonal. Monthly evaporation determined by the energy-budget method differs, however, from that determined by either of the other methods or their means by substantial amounts that vary in a distinctly seasonal pattern; energy-budget values are too high in spring and summer and too low in fall and winter.

EVAPORATION-PAN DATA, 1948–62

Evaporation from pans of various types is a useful index of evaporation from Salton Sea if the relation between the respective rates of evaporation is known. Because of the wide differences between the physical characteristics of pans and of the sea, however, the relation was unknown until evaporation from the sea was determined by some method that does not depend on data on pan evaporation.

Several attempts to determine evaporation from Salton Sea by using evaporation-pan data have been made, but only one set of pans that has been maintained continuously since 1948 is discussed herein.

Three evaporation stations—Sandy Beach, Devils Hole, and Imperial Salt Farm (fig. 2)—were established in 1947 by the U.S. Soil Conservation Service; operation of these stations was taken over by the Imperial Irrigation District in 1951. Each station includes a recording rain gage, an anemometer with a cumulative wind-movement indicator, and a 2-foot sunken and screened evaporation pan.

Monthly evaporation during 1961–62 from each of the three pans is shown in figure 6. The large differences in rates of evaporation at the three sites are consistent with corresponding differences in the measured windspeed. Hence, they may be due mainly to the local differences which affect pan exposure rather than to their location in relation to Salton Sea and the direction of prevailing winds. Comparison of evaporation at the three sites suggests that a single pan record would not be a reliable index of evaporation from the sea. Because the three stations appear to be well located to sample the meteorological environment of the sea, however, the average evaporation from the three pans is probably a reliable index.

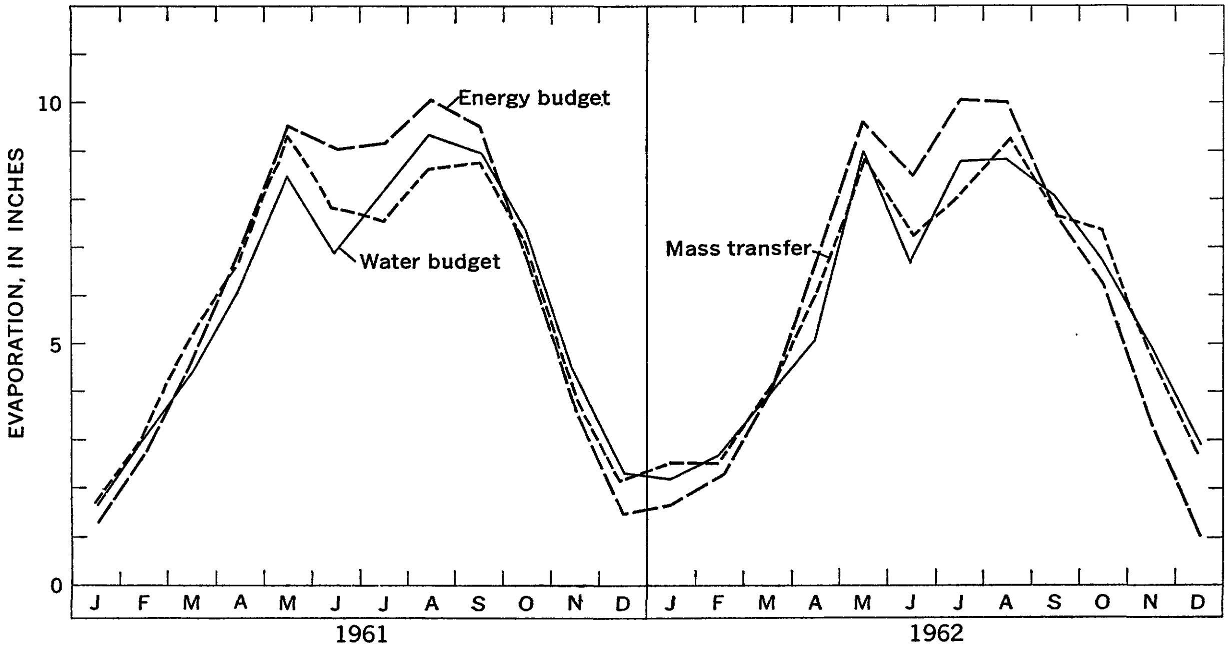

FIGURE 5.—Comparison of three determinations of monthly evaporation from Salton Sea.

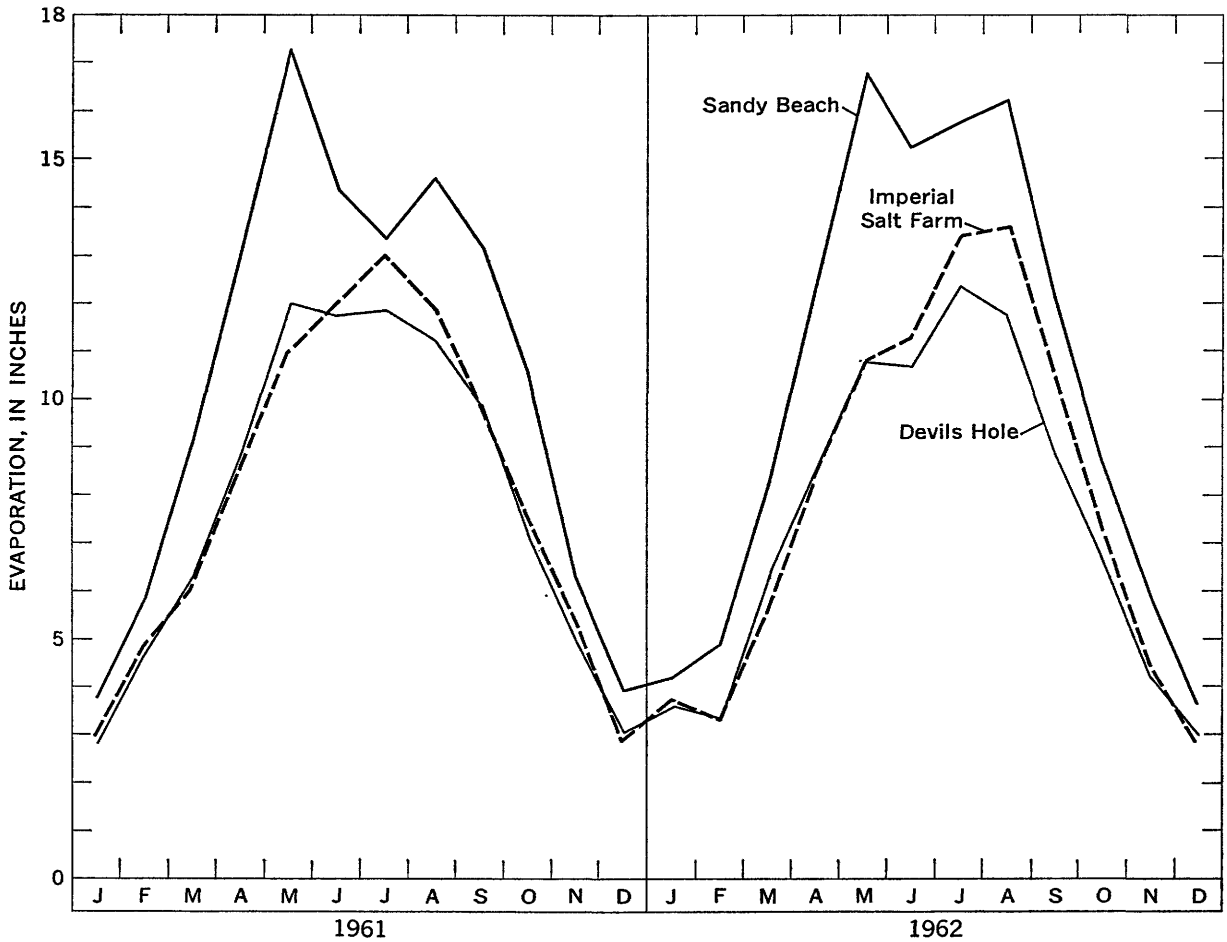

FIGURE 6.—Comparison of monthly evaporation from sunken screened pans at three sites on the shore of Salton Sea.

The ratio of evaporation from Salton Sea (E_s, average from table 7) to the corresponding evaporation from pans (E_p, average for three pans) for each month during 1961–62 is shown in figure 7. The plotted ratios vary from month to month and also for corresponding months of the 2 years. Comparison of the monthly evaporation computed by three methods indicated the probability of seasonal bias in the energy-budget evaporation; accordingly, values of the ratio based on evaporation computed by the other two methods were plotted (not shown), but the resulting variations were no less erratic than those shown. The available data are sufficient to indicate only the general nature of the seasonal changes in the ratio.

Most of the variation of the ratio, E_s/E_p, is caused by factors that vary seasonally. Disposition of the energy that reaches a water body is strongly influenced by the water temperature and its relation to the temperatures of the air and the surrounding earth. As the temperature of a large water body responds to changes in air temperature much more slowly than that of a small one, the respective rates of evaporation respond similarly to changes in air temperature. Appreciable differences between ratios for corresponding months of different years are to be expected because the seasonal fluctuations of temperature and other meteorological variables are not identical from year to year.

The ratio for annual values varies much less than that for monthly values because of the cyclical nature of the fluctuations just discussed. Although some variations are to be expected, they are undoubtedly small enough to be within the limits of accuracy of definition of the ratio.

The ratio E_s/E_p for 1961 is 0.694, and that for 1962 is 0.685. The average of these two ratios, 0.69, is considered by the authors to be a good estimate of the normal value of the annual coefficient for the three sunken pans. This coefficient should not be confused with the coefficient of 0.70 commonly applied to U.S. Weather Bureau Class A evaporation-pan data. The similarity is purely coincidental.

The 15-year record of evaporation from the three sunken pans is summarized in figure 8 and in table 8. Table 8 lists the annual evaporation from each pan, the averages for all three pans, and the evaporation from Salton Sea computed as 0.69 multiplied by the three-pan average (except for 1961–62). Figure 8 indicates the

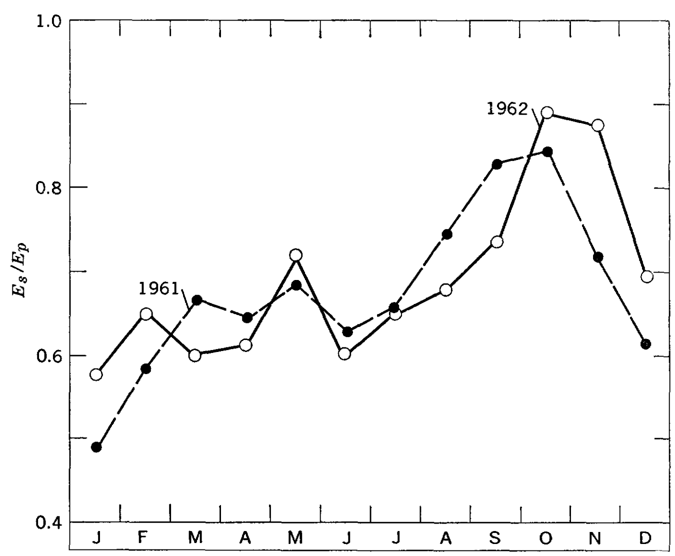

Figure 7.—Monthly variations of the ratio (E_s/E_p) of evaporation from Salton Sea to pan evaporation (average for three sunken pans).

TABLE 8.—*Annual evaporation, in feet, from sunken pans at three stations and from Salton Sea, 1948–62*

[Records of pan evaporation furnished by Imperial Irrigation Dist. Evaporation from Salton Sea for 1948–60 is average pan evaporation multiplied by 0.69. Average value from table 7 given for 1961–62]

Year	*Sandy Beach*	*Devils Hole*	*Imperial Salt Farm*	*Pan average*	*Salton Sea*
1948	10.13	8.27	7.89	8.76	6.04
1949	9.54	8.01	7.50	8.35	5.76
1950	9.37	7.60	7.38	8.12	5.60
1951	10.24	7.81	7.52	8.52	5.88
1952	9.62	7.41	7.24	8.09	5.58
1953	10.67	7.89	7.33	8.63	5.95
1954	9.39	7.18	6.78	7.78	5.37
1955	11.21	7.40	6.91	8.51	5.87
1956	11.29	7.56	7.35	8.73	6.02
1957	9.76	7.25	6.91	7.97	5.50
1958	10.09	7.11	7.02	8.07	5.57
1959	10.20	7.41	7.46	8.36	5.77
1960	10.37	7.48	7.62	8.49	5.86
1961	10.44	7.85	7.98	8.76	6.08
1962	10.35	7.52	7.94	8.60	5.89
Average, 1948–62	10.18	7.58	7.39	8.38	5.7

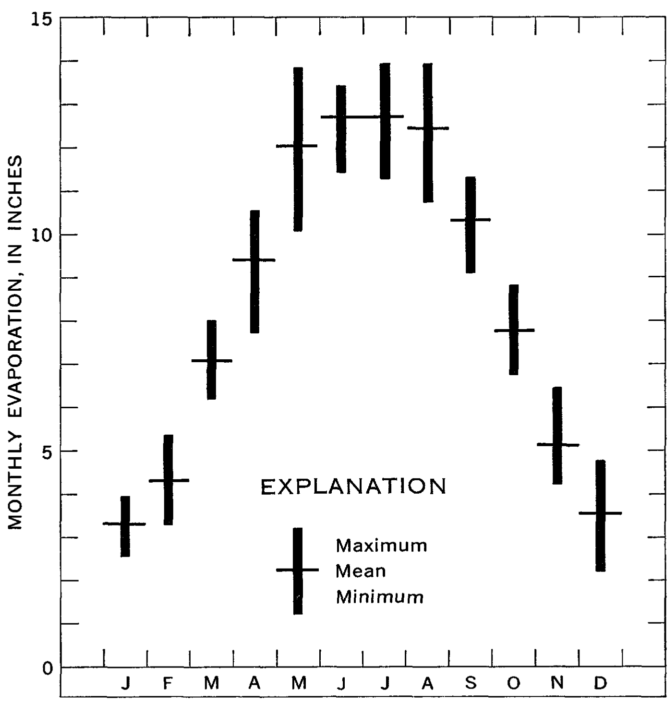

Figure 8.—Means and extremes of monthly pan evaporation, 1948–62 (average for three sunken pans on the shore of Salton Sea).

seasonal pattern of the average values and the range of values for each month.

CONCLUSIONS FROM EVAPORATION STUDIES

Determinations of the annual evaporation from Salton Sea for 1961–62 by the water-budget and energy-budget methods closely correspond. The average of these two determinations was used to establish the empirical coefficient ($N=0.00156$) in the mass-transfer equation, and to establish an annual coefficient of 0.69 for use with the average evaporation from three sunken pans. These coefficients are applicable only when the mass-transfer data and evaporation-pan data are obtained in the same manner as they were obtained during the study.

Agreement of monthly evaporation values computed by different methods is less satisfactory than for annual values, and energy-budget data appear to be affected by seasonal bias. Monthly pan coefficients vary somewhat erratically from month to month, and for corresponding months in different years; consequently, observed pan evaporation without additional water-temperature and meteorological data is suitable for only rough estimates of monthly evaporation.

The principal need for evaporation data on Salton Sea is for annual rather than monthly values, and these may be obtained most readily by means of the three sunken evaporation pans. Consequently, no data for either energy-budget or mass-transfer computations have been gathered since 1962. If future inflows are determined with sufficient accuracy, the water budget may be used to verify the evaporation determined from pan data.

The average annual evaporation from Salton Sea for 1948–62 was 5.78 feet (69 in.), and this is considered to be a good estimate of the normal annual evaporation. This estimate closely corresponds to those of some previous investigators. For example, LaRue (1916, p. 142) estimated the average annual evaporation to be 5.8 feet, and Blaney (1955) concluded that the average was about 6.0 feet.

The average annual evaporation from Salton Sea determined herein is markedly lower than that from Lake Mead, which is the nearest large body of water in a desert environment and is about 200 miles northeast of the sea. The average annual evaporation from Lake Mead for 1948–62 was about 86 inches [2]—17 inches more than the evaporation from the sea during the same period.

Part of this difference in average annual evaporation may be due to errors in computed evaporation, but most of it can be accounted for by the effects caused by certain characteristics of the two water bodies and their environments, including the salinity, the volumes and temperatures of inflow and outflow, and the mean distance traveled by the wind over the water.

Salinity depresses the evaporation from Salton Sea relative to that from fresh water by about 2 percent (Harbeck, 1955). Thus, salinity accounts for only 1.4 inches of the 17-inch difference.

The volume and temperature of water entering Salton Sea are nearly the same as the volume and temperature of the water evaporated; hence, they have little effect on the average rate of evaporation. Although the long-term average volumes of water entering and leaving Lake Mead are nearly the same and the water evaporated may be at about the same temperature as that of the inflow, most water leaving the lake (as streamflow below Hoover Dam) has a much lower average temperature. Kohler, Nordenson, and Fox (1958, p. 57, table 25) calculated that the resulting gain of energy caused an increase of about 5.5 inches in the annual evaporation from Lake Mead during 1941–53.

As air moves across a water surface, evaporated moisture tends to increase the humidity of the air and thereby decrease the rate of evaporation. Consequently, the rate of evaporation tends to decrease with distance from the windward shore, and average rates for different water bodies tend to vary inversely with the mean over-water distance traveled by the prevailing winds. However, lake-evaporation data available at the time of the Lake Hefner studies, although admittedly not conclusive, indicated that for lakes of approximately circular shape with diameters ranging from 12 feet to about 4 miles the diameter had no appreciable influence on the rate of evaporation (Kohler, 1954, p. 148).

Later, the evaporation data for Lake Mead tended to confirm the conclusion that the rate of evaporation is independent of the size of the water body. If the mean over-water distance rather than surface area is considered to be the measure of size, however, Lake Mead is not much larger than the largest lakes represented by the original data, because Lake Mead is composed of several basins nearly surrounded by desert and connected by narrow water-filled canyons.

When evaporation data for Salton Sea are included with the previous data, the range of mean over-water distances (effective diameters) is extending to about 20 miles and considerable influence of effective diameter on the evaporation rate is indicated.

Although a precise accounting of the proportions of the 17-inch difference between evaporation rates at Lake

[2] The average for 1952–62 was 85.9 inches, from records published in annual reports on the surface-water supply of the United States. The average was not appreciably altered by inclusion of evaporation for the water years 1948–51, which was computed by Kohler, Nordenson, and Fox (1958, table 25), who used evaporation-pan and meteorological data and adjusted for advected energy.

Mead and Salton Sea attributable to each cause is not possible, the authors believe that the factors previously discussed considered with other factors, such as effects of surrounding terrain on the turbulence of the air over the water bodies, satisfactorily account for the difference and that no large error in either rate is involved.

The U.S. Weather Bureau evaporation map of the United States (Kohler and others, 1959, pl. 2; Meyers, 1962, pl. 3; Hely and Peck, 1964, pl. 6) is based on scant data for the Salton Sea area and is highly generalized; it indicates 82 inches of annual evaporation at the site of Salton Sea. Although the possibility of an appreciable difference between the indicated map rate and the actual rate of evaporation at a specific locality must be recognized, the map rates may be approximately correct for evaporation from small bodies of fresh water. Because of its large effective diameter, the Salton Sea probably modifies the overlying air sufficiently to account for most of the 13-inch difference between the map rate and the rate derived herein for the sea. About 1.4 inches of the difference is accounted for by salinity, as prevously noted in the comparison of rates for Salton Sea and Lake Mead.

HYDROLOGIC REGIMEN FOR 1908–62

By combining information gained from the investigations conducted during 1961–62 with other hydrologic records, all terms of the annual water budgets for Salton Sea since 1908 could be determined with sufficient accuracy to indicate trends of surface inflow and evaporation. The annual values of all terms are listed in table 9.

The available records of water level are generally adequate for determination of the annual change in volume; precipitation records provided a suitable basis for computing the quantity of rainfall on the water surface; and ground-water inflow was estimated to be 50,000 acre-feet per year.

Annual amounts of evaporation from Salton Sea during 1948–62 are adequately defined by the annual rates in table 8 and the corresponding values of surface area. None of these annual rates differ from the average by as much as 10 percent, and only two differ by as much as 5 percent. Similarly, the annual evaporation from Lake Mead, Arizona-Nevada, differed from the average rate by more than 5 percent in only 2 of the 11 years, 1952–62. Consequently, the average annual evaporation rate for the Salton Sea (5.78 ft per yr) is considered to be satisfactory for computation of approximate amounts of evaporation prior to 1948.

Suitable records of the major part of the surface inflow are available only since 1944 (table 4), but because approximate values of all other terms of the water budget are known, surface inflow for earlier years can be computed by equation 1. The values computed in this manner are adequate for determination of trends or averages for several years, but they are not regarded as reliable estimates for individual years. Computed annual inflow is affected by the use of the average rather than actual annual rate of evaporation, as well as the usual errors in other budget terms.

Annual water-budget equations for 1944–62 based on data from table 9 do not balance because none of the terms for those years were derived from the equations. Surface inflow determined by the water budget differs from that shown by as much as 11 percent, but the averages for the 19-year period differ by little more than one percent.

Figure 9 shows the average annual evaporation and

TABLE 9.—*Annual water-budget data, in thousands of acre-feet, for Salton Sea, 1908–62*

[Ground-water inflow (I_g) was estimated to be 50,000 acre-feet per year. Evaporation prior to 1948 was computed by using average annual rate (table 8); surface inflow prior to 1944 was computed by the water-budget method and is only a rough approximation]

Year	Surface inflow (I_s)	Precipitation (P)	Change in volume (ΔV)	Evaporation (E)
1908	160	74	−1,520	1,800
1909	370	93	−1,220	1,730
1910	190	23	−1,400	1,660
1911	300	44	−1,180	1,570
1912	330	63	−1,080	1,520
1913	300	33	−1,080	1,460
1914	410	70	−869	1,400
1915	110	76	−1,100	1,340
1916	220	67	−917	1,250
1917	500	26	−568	1,140
1918	250	29	−725	1,050
1919	440	32	−437	960
1920	610	68	−208	940
1921	700	69	−94	910
1922	740	20	−92	900
1923	920	29	+108	890
1924	670	9	−169	900
1925	910	38	+122	880
1926	1,060	81	+285	910
1927	1,000	81	+180	950
1928	930	7	+17	970
1929	1,130	17	+219	980
1930	1,080	31	+156	1,010
1931	930	67	+18	1,030
1932	940	63	+35	1,020
1933	850	18	−105	1,020
1934	390	5	−536	980
1935	750	51	−81	930
1936	940	40	+97	930
1937	1,180	15	+297	950
1938	1,090	48	+206	980
1939	1,290	127	+446	1,020
1940	890	64	−55	1,060
1941	1,200	102	+278	1,070
1942	950	32	−56	1,090
1943	1,020	77	+56	1,090
1944	1,100	51	+38	1,100
1945	1,080	57	+85	1,100
1946	1,130	25	−18	1,100
1947	1,080	19	0	1,110
1948	1,080	27	−58	1,150
1949	1,180	29	+105	1,110
1950	1,220	4	+117	1,090
1951	1,330	30	+228	1,160
1952	1,400	45	+316	1,140
1953	1,450	1	+197	1,260
1954	1,380	24	+219	1,170
1955	1,220	18	+99	1,290
1956	1,250	2	−18	1,330
1957	1,140	33	+16	1,210
1958	1,150	40	−3	1,230
1959	1,210	33	+53	1,280
1960	1,260	36	+113	1,310
1961	1,340	34	+87	1,360
1962	1,400	23	+162	1,330

surface inflow, as listed in table 9, and the corresponding annual changes in the water level. The water-level graph is based on several observations during each year prior to 1908 and on the observed or recorded level for December 31 of each succeeding year, and normal seasonal fluctuations (fig. 4) are thereby eliminated from figure 9.

The tendency for the water surface to rise when inflow exceeds evaporation and to fall when the inflow is less than evaporation is evident if an approximate allowance is made for the additional inflow that occurs as ground-water seepage and precipitation on the water surface (table 9). The unusually low inflow during 1934 was a result of low flow in the Colorado River, which was not controlled by Hoover Dam until 1935.

CHEMICAL REGIMEN

The role of Salton Sea in the economy of southern California depends on the chemical characteristics of the water, as well as the water levels and other factors previously discussed. Suitability of the water for fish and for recreational uses is controlled to a large degree by its salinity (concentration of dissolved solids), which is subject to wide fluctuations but which has a tendency to increase with time. Commercial fresh-water fishing was carried on for a few years after formation of the sea (1904–07) but ceased when the increase in salinity prevented fish from propagating. More recently, salt-water fish were introduced into Salton Sea, and sport fishing has become popular.

Ancient shorelines visible in parts of the Salton Sea basin indicate that water stood for long periods at about the level of the divide between Salton Sea and the Gulf of California. The latest existence of such a lake, known as Lake Cahuilla, may have been as recent as a few centuries ago. Evaporation of the tremendous volume of water from Lake Cahuilla, and from an unknown number of smaller lakes that followed it, left large deposits of soluble minerals on the surface in Salton Sink when it was dry. Some of the mineral residues may have been blown away, and some were probably buried under sediments, but some remained on the

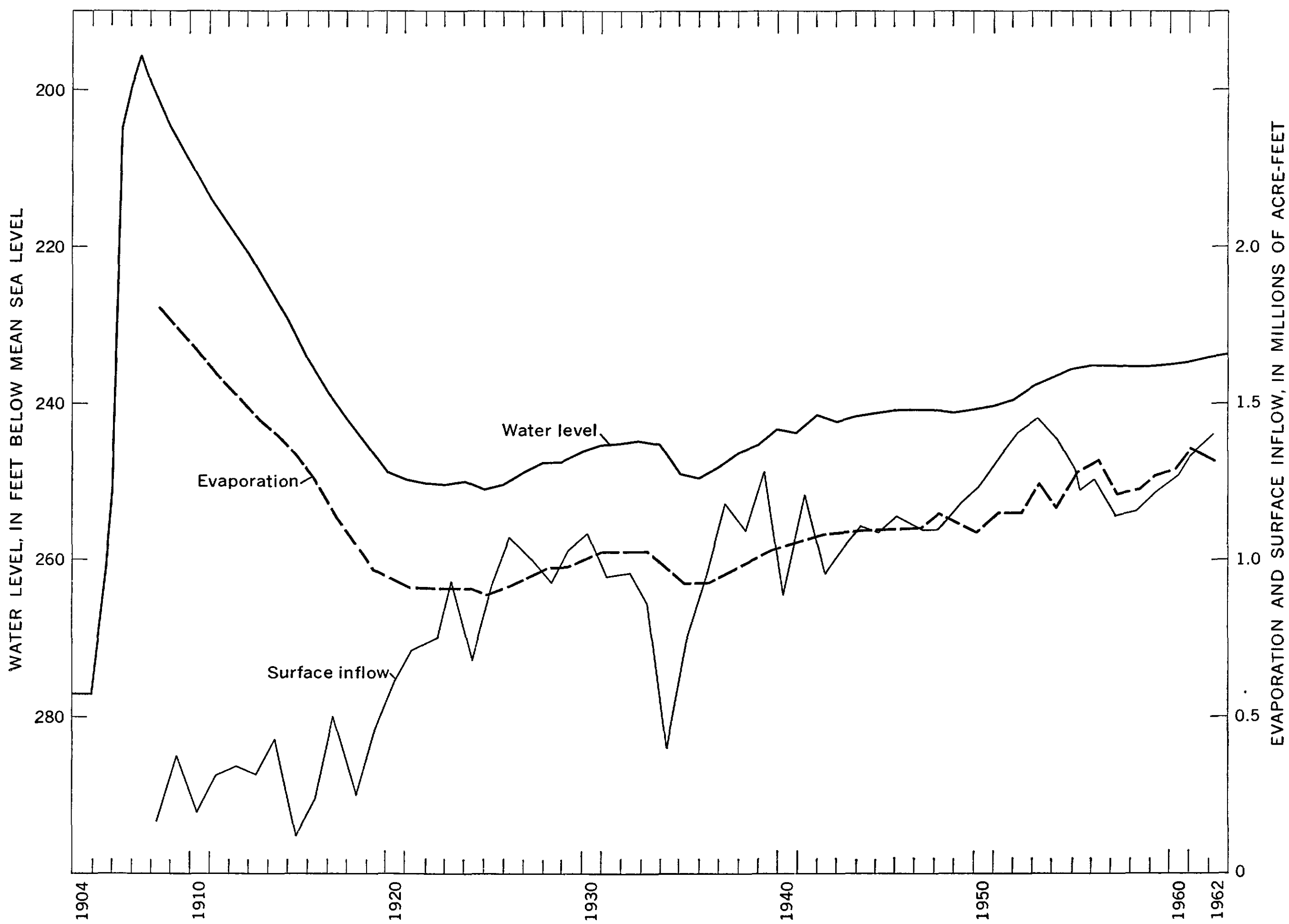

FIGURE 9.—Annual fluctuations of water level (datum of 1929), surface inflow, and evaporation.

surface and were redissolved when water again collected in the sink. Because of the presence of these soluble minerals, Salton Sea has been saline since its formation (1904–07), even though it was formed by a flood of fresh water from the Colorado River.

Common salt (NaCl) was extracted from surficial deposits in Salton Sink prior to the flooding of 1904–07; evaporative saltworks on the shore of the Salton Sea were operated from 1936 to 1945 and were then flooded by the rising water. As the water becomes more saline it becomes more attractive for salt recovery; consequently, the salt industry may again become a major factor in the economic exploitation of the sea.

Chemical analyses of Salton Sea water have been made at irregular intervals since 1907. Analyses were made at least annually during 1907–16 and 1945–47, and at least twice a year during 1948–64, but only one reasonably reliable chemical analysis and one determination of dissolved solids by evaporation were found for the intervening period 1917–44. The analyses are summarized in table 10.

The data listed in table 10 were derived by several analysts using different analytical procedures; hence, these data probably differ in reliability. The analytical values originally reported were made as consistent as possible by rounding to the same number of significant figures, by replacing a few inconsistent sodium and potassium values by calculated values, and by calculating the salinity as the sum of concentrations of the ionic constituents using only half the bicarbonate. For 1929, however, salinity determined by evaporation of a sample is listed. The calculated sum represents more than 99 percent of the dissolved solids including minor undetermined constituents and is therefore nearly synonymous with the total content of dissolved minerals.

All early analyses and some recent ones were of single samples of water collected some distance from the shore. Other data represent the averages of several samples or represent the analyses of composite samples. Since 1944 the Imperial Irrigation District has collected samples, in sets of five, from widely separated points on Salton Sea and has had each sample analyzed. However, comparison of concentrations of constituents and their changes indicated that one sample in each of several sets may have been unduly influenced by fresh water from the Alamo River or the New River. Consequently, the average results of only four of the analyses in each set were listed in table 10. Most of the recent Geological Survey analyses were of composite samples collected from about 35 points.

The temperature data gathered for the evaporation studies previously described indicate that the Salton Sea is generally well mixed. A study by Arnal (1961) of the areal variations in chlorinity (concentration of chloride and other halides) supports this conclusion. Consequently, the single samples should have been fairly representative of the entire sea, provided that they were collected sufficiently distant from the mouths of tributaries—particularly the Alamo and New Rivers.

SALINITY AND MINERAL CONTENT

Changes of salinity in a body of water that has no surface outflow are most effectively described in conjunction with changes of volume of water and of mineral content[3] because the salinity at a particular time depends on both the amount of water and the quantity of dissolved minerals. The annual values of volume of water (table 9) and those of mineral content and salinity of Salton Sea, derived from analyses in table 10, are shown together in figure 10.

The volume of Salton Sea at any time is derived as explained in the discussion of the water budget. Salinity at the time of sampling is determined by chemical analysis of a water sample. The sample is assumed to be representative of the entire sea. Mineral content is computed from salinity and volume in accordance with the following relation:

$$M = 0.00136VS, \tag{9}$$

where

M=mineral content, in tons,
V=volume of water, in acre-feet,
S=salinity, in parts per million.

The last two columns of table 10 show the volume and mineral content at the time each sample was taken. These computed values of mineral content are the principal basis for the mineral-content graph in figure 10. A useful guide to the shape of the 1916–45 graph, which is mostly unsupported by chemical data, was obtained by plotting a cumulative graph (not shown) of the inflow during that period (table 9).

Average annual values of salinity computed from the corresponding values of volume and mineral content were then used to define the salinity graph in figure 10.

At the time of the first chemical analysis, June 3, 1907, the mineral content of Salton Sea was approximately 77 million tons, of which only a small part could have been contained in the Colorado River water that formed the sea. The weighted-average concentration of dissolved solids in the Colorado River water was probably less than the 513 ppm (parts per million) determined for Colorado River at Yuma, Ariz., during October 1927–September 1928 (Howard, 1955). If

[3] Mineral content is the total quantity of dissolved minerals in the water body. It is synonymous with the term "salt content," as used in many reports, but "salt content" is also used sometimes in reference to the content of a specific salt, such as sodium chloride.

TABLE 10.—*Chemical analyses of water from Salton Sea*

[Concentrations in parts per million]

	Agency [1]	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na+K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Salinity (calculated)[2]	Volume of water (millions of acre-ft)	Mineral content (millions of tons)
June 3, 1907	CI	100	64	1,140	134	476	1,700	3,550	16	77
Nov. 12, 1907	USGS	107	68	1,260	165	559	1,830	3,910	15	80
Feb. 28, 1908	USGS	142	77	1,280	182	562	1,920	4,070	15	83
May 25, 1908	CI	119	76	1,370	156	567	2,040	4,250	14	81
June 8, 1909	CI	127	90	1,620	149	659	2,410	4,980	13	88
May 22, 1910	CI	137	98	1,900	129	764	2,810	5,770	12	94
June 3, 1911	CI	156	117	2,280	117	917	3,390	6,920	10	94
June 10, 1912	CI	173	136	2,710	246	1,070	3,950	8,160	9.3	100
June 18, 1913	CI	198	162	3,220	229	1,250	4,740	9,680	8.2	110
June 12, 1914	CI	222	190	3,810	223	1,480	5,600	11,400	7.2	110
June 8, 1915	CI	253	226	4,430	242	1,740	6,510	13,300	6.3	110
June 10, 1916	CI	299	272	5,330	232	2,080	7,880	16,000	5.3	120
June 10, 1923	CI	684	659	12,500	169	5,380	18,300	37,600	2.5	130
Mar. 21, 1929	Cal							33,200	3.1	140
Dec. 22, 1945	IID	766	880	11,100	207	6,780	16,000	35,600	4.05	196
Dec. 20, 1946	IID	831	921	11,000	207	6,900	15,900	35,700	4.05	197
Dec. 17, 1947	IID	742	942	11,100	210	6,990	16,000	35,900	4.01	196
Sept. 20, 1948	IID	780	1,050	12,100	198	7,490	17,400	38,900	3.94	208
Dec. 15, 1948	IID	869	996	11,300	213	7,150	16,500	36,900	3.97	199
Sept. 19, 1949	IID	918	1,020	11,900	206	7,580	17,200	38,700	4.02	211
Dec. 15, 1949	IID	970	953	11,200	217	7,160	16,400	36,800	4.08	204
Sept. 20, 1950	IID	909	1,120	11,700	202	7,350	17,100	38,200	4.11	214
Dec. 20, 1950	IID	782	963	11,200	221	7,120	16,200	36,400	4.20	208
May 19, 1951	IID	850	990	10,800	204	6,950	15,800	35,500	4.40	212
Sept. 25, 1951	IID	836	985	12,100	209	7,210	17,600	38,800	4.34	229
June 4, 1952	IID	818	909	10,400	213	6,820	14,900	34,000	4.72	218
Nov. 19, 1952	IID	812	939	10,600	192	7,120	15,200	34,800	4.67	221
May 18, 1953	IID	808	899	10,200	212	6,780	14,600	33,400	4.94	224
Nov. 23, 1953	IID	964	891	10,000	212	6,690	14,700	33,400	4.92	223
May 24, 1954	IID	912	878	9,830	226	6,500	14,400	32,600	5.24	232
Nov. 15, 1954	IID	872	822	9,940	215	6,560	14,300	32,600	5.16	228
June 13, 1955	IID	742	936	9,620	208	6,520	13,900	31,800	5.30	229
Nov. 21, 1955	IID	721	889	10,000	204	6,810	14,200	32,700	5.24	233
May 21, 1956	IID	708	889	9,980	204	6,830	14,100	32,600	5.42	240
Dec. 10, 1956	IID	756	905	10,200	200	7,160	14,300	33,400	5.26	239
May 27, 1957	IID	738	910	9,980	200	7,050	14,100	32,900	5.40	241
Nov. 25, 1957	IID	774	946	10,200	200	7,300	14,300	33,600	5.23	239
May 12, 1958	IID	759	939	10,100	189	7,170	14,300	33,400	5.45	247
Nov. 10, 1958	IID	762	951	10,300	179	7,330	14,500	33,900	5.23	241
May 25, 1959	IID	803	886	10,100	208	7,100	14,300	33,300	5.40	245
Nov. 9, 1959	IID	840	893	10,800	204	7,360	15,200	35,200	5.26	252
May 27, 1960	IID	807	877	10,400	191	7,130	14,600	33,900	5.48	253
Nov. 14, 1960	IID	813	950	10,400	199	7,290	14,800	34,400	5.40	253
Apr. 4, 1961	USGS	821	929	9,830	182	7,060	14,000	32,700	5.60	249
May 22, 1961	IID	813	967	10,100	197	7,230	14,400	33,600	5.60	256
Sept. 22, 1961	USGS	850	1,020	10,100	174	7,260	14,600	34,000	5.48	253
Nov. 20, 1961	IID	811	991	10,100	188	7,260	14,400	33,700	5.47	251
Jan. 29, 1962	USGS	889	905	10,000	183	7,250	14,200	33,300	5.58	253
Mar. 19, 1962	USGS	831	938	9,910	174	7,140	14,100	33,000	5.67	255
May 21, 1962	IID	796	957	10,100	196	7,280	14,300	33,500	5.72	261
Sept. 10, 1962	USGS	801	985	10,100	177	7,320	14,400	33,700	5.63	258
Nov. 12, 1962	IID	802	1,010	10,100	192	7,260	14,400	33,700	5.65	259
May 8, 1963	USGS	775	928	9,590	167	6,980	13,600	32,000	5.92	258
Oct. 10, 1963	USGS	792	964	9,740	178	7,210	13,800	32,600	5.92	262
Nov. 4, 1963	IID	820	968	9,380	198	5,900	14,400	31,600	5.97	257
May 18, 1964	IID	905	1,010	9,700	175	7,410	13,900	33,000	6.15	276
May 28, 1964	USGS	776	928	9,540	180	7,010	13,500	31,800	6.13	265

[1] Agencies responsible for publication or file data: CI, Carnegie Institution of Washington; Cal, state of California; IID, Imperial Irrigation District; USGS, U.S. Geological Survey. Data were obtained from the following publications or files:

Years	*Symbol*	*Source*
1907–16	CI	Sykes (1937).
1907–08	USGS	Van Winkle and Eaton (1910).
1923	CI	Carnegie Institution of Washington (1924).
1929	Cal	Coleman (1929).
1945–64	IID	Files of the Imperial Irrigation District.
1961–64	USGS	Files of the U.S. Geological Survey.

[2] Calculated as the sum of constituents shown using half the bicarbonate concentration, except that for 1929, which was determined by evaporation.

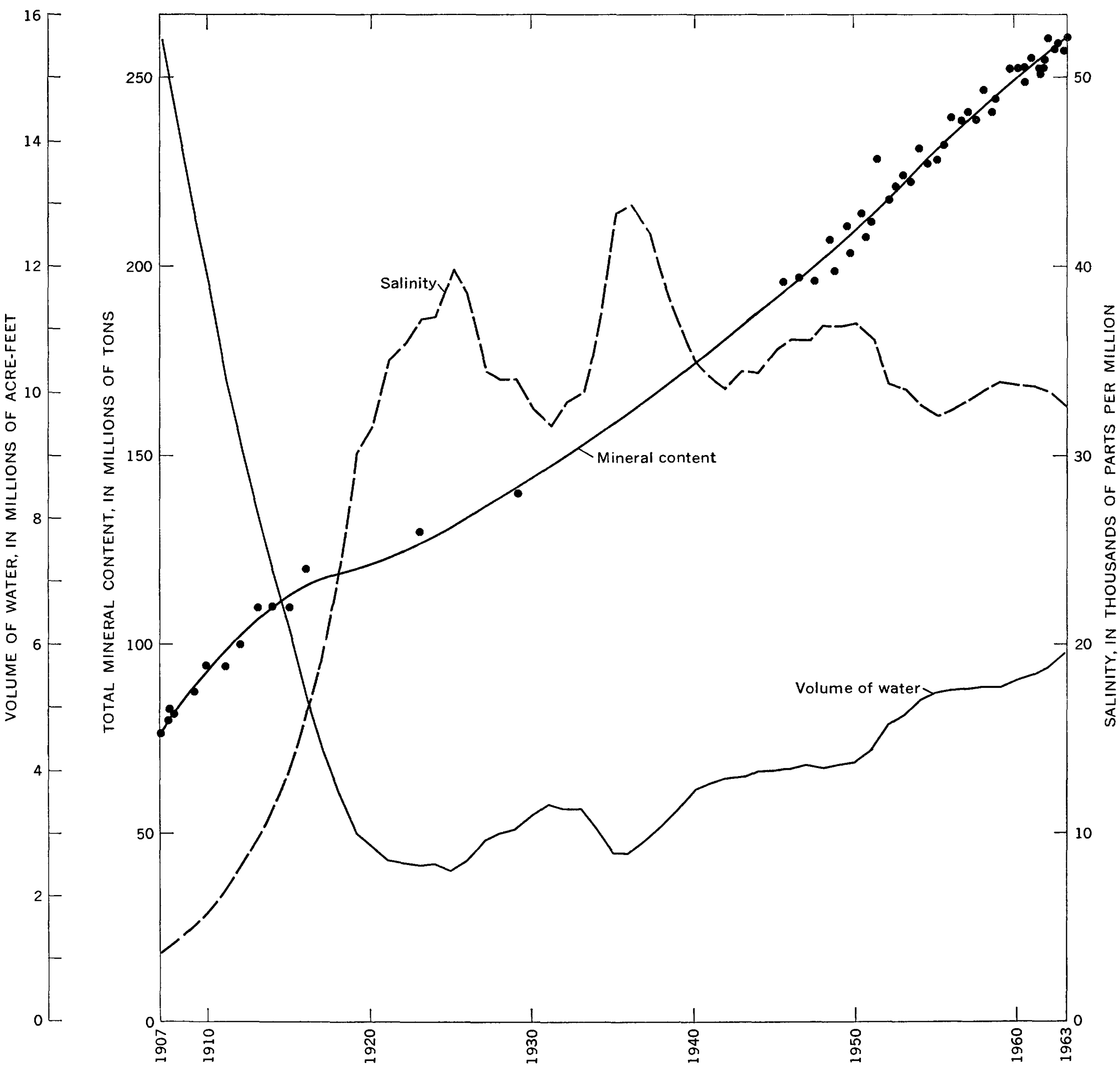

FIGURE 10.—Annual fluctuations of salinity, mineral content, and volume of Salton Sea, 1907–63.

this is true, the quantity of minerals contributed to Salton Sea by the Colorado River between November 1904 and June 1907 was less than one-seventh of the mineral content on June 3, 1907. The floodwater may have dissolved additional minerals as it came from Yuma to Salton Sea, but most of the balance of the mineral content on that date must have been dissolved from the bed of the sea.

The solution of minerals from the bed apparently continued for several years. By 1914 the mineral content had increased to about 110 million tons, although the relatively small inflow from 1907 to 1914 (fig. 9) could have contributed only minor quantities of minerals. The rate of increase in mineral content slowed gradually as the quantity of soluble minerals on the bed decreased and probably ceased or became negligible within a few years after 1914.

The annual increments of mineral content tended to increase gradually after 1920 because of the increasing inflow and the development of drainage systems for irrigated tracts. However, since 1945 the annual increments apparently have varied only slightly from the 1945–63 average increment of about 4 million tons.

Annual increments of mineral content may differ slightly from the corresponding annual loads of minerals in the inflow because of attrition resulting from chemical reactions and precipitation of salts, biological activities, and wind and wave action. Precipitation of slightly soluble salts is an important cause of change in the chemical composition of the water, but since 1907 the combined effect on salinity of all attrition processes in Salton Sea has been small. The effect of precipitation will increase in importance as salinity increases. Computation of the approximate amount of minerals in the inflow for 1961–62, based on numerous analyses of samples from the principal tributaries, indicated that the annual loads of minerals were approximately the same as the annual increments of mineral content; however, the computations were not precise enough to define the amount of attrition.

The salinity graph (fig. 10) shows a rapid rise in mineral concentration from about 3,600 ppm in 1907 to about 40,000 ppm in 1925, caused chiefly by the solution of minerals from the bed of Salton Sea and the rapid decline in volume of the sea. Salinity doubled about every 4 years during its steepest rate of rise. It reached a second, and higher, peak of about 43,000 ppm in 1936, as a result of a decline in volume of the sea caused by a shortage of irrigation water in 1931–35. A subsequent increase in volume counteracted the continuing increase in mineral content and caused salinity to decline to about 34,000 ppm in 1942. Salinity fluctuated within a relatively narrow range of between 32,000 and 37,000 ppm during 1942–63.

CHEMICAL COMPOSITION

Chemical composition of water in Salton Sea changes with time, not only because of changes in volume and mineral content but also because the proportions of the various constituents in the inflow differ from those in the sea, and because the least soluble minerals that can form by combination of the available ions precipitate from the solution when concentrations are above certain levels. Although precipitation of minerals has been relatively minor compared to the total mineral content, it will probably increase markedly as concentrations increase.

Bar graphs showing the concentrations, in chemical equivalents, of dissolved solids in Salton Sea on selected dates are shown in figure 11. Similar graphs for Colorado River water, inflow to Salton Sea, and typical ocean water are included for comparison.

Most inflow to Salton Sea consists of Colorado River water, which is modified by evapotranspiration in the irrigated areas, by deposition of some constituents in the soils, and by solution of minerals from the soils (leaching). The first bar shown in figure 11 represents the unaltered Colorado River water. Although available records are not adequate to enable precise determination of the average chemical quality of the inflow, the second bar may be fairly representative of this average. It is based on typical water samples of the New and Alamo Rivers, collected at different times during 1962 when streamflow was near average.

Comparisons of the concentrations and proportions of constituents in the inflow to the sea with those for Colorado River water indicate a large increase in the concentration of all ions except bicarbonate (HCO_3). Apparently carbonate was deposited in the soils or removed by biological activity. Concentration by evapotranspiration can account for only part of the increase in sodium plus potassium ($Na+K$) and chloride (Cl). Large amounts of these constituents have probably been leached from soils irrigated with Colorado River water.

The quantity of minerals leached from soils undoubtedly varies from year to year but cannot be accurately determined from available records. If the area involved does not increase, a long-term downward trend in the quantities of leached minerals reaching the sea can be expected.

The chemical composition of water in Salton Sea prior to 1923 was governed mainly by the solution of minerals from the bed. A comparison of the graphs of composition for the early years with those for later years shows the gradual change in proportions of constituents resulting from the additions of minerals in the inflowing water.

Graphs of the cumulative content of the individual constituents (similar to the mineral-content graph in figure 10) are more useful than the graphs in figure 11 for predicting future chemical characteristics. Accordingly, cumulative-content graphs are shown in figure 12.

At any particular time the chemical composition of Salton Sea water depends on its earlier composition, the relative accretions of the various ionic constituents since that earlier time, and the individual solubilities of the various possible ionic combinations.

Sodium and chloride have been the dominant dissolved constituents in Salton Sea and will undoubtedly remain so indefinitely because of the high solubilities of sodium and chloride minerals which could form by ionic combination. Sulfate (SO_4) has been the next most abundant ion. During most of the life of the sea its content ratio of sulfate to chloride has increased and is still increasing.

Concentrations of calcium (Ca) and sulfate are apparently at or near levels which will cause combination to form a gypsum ($CaSO_4 \cdot 2H_2O$) precipitate. In an effort to determine whether the water was saturated with gypsum in 1965 a portion of a sample of the water was analyzed; another portion was agitated overnight

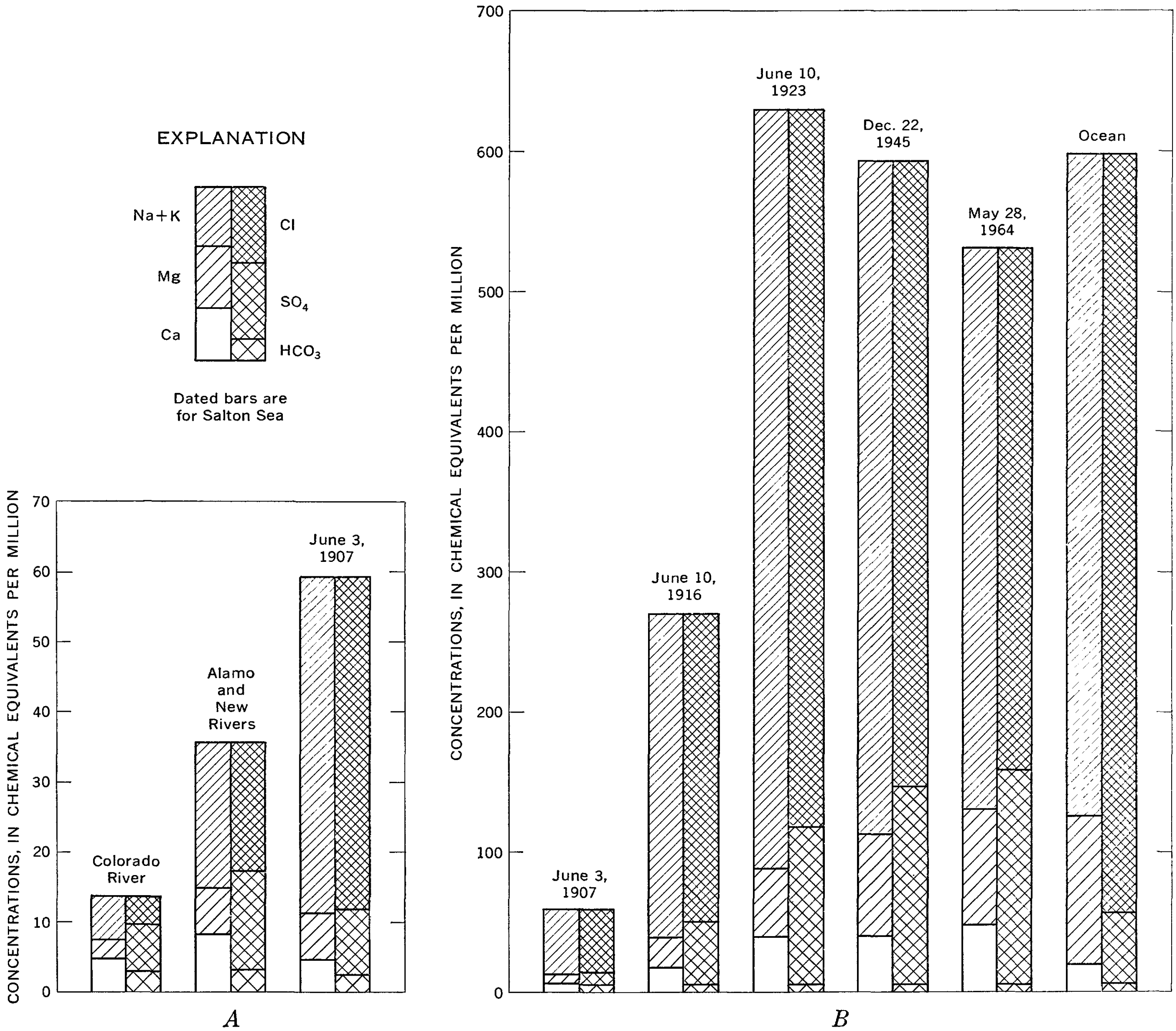

FIGURE 11.—Comparisons of chemical composition, in equivalents. *A*, Weighted average for the Colorado River at Imperial Dam during 1962; weighted average of typical analyses for the Alamo and New Rivers, which contributed about three fourths of the inflow to Salton Sea; and Salton Sea on June 3, 1907. *B*, Salton Sea, on selected dates, and typical ocean water.

with some powdered gypsum, then filtered and analyzed. The results of the experiment indicated that the water was near saturation with gypsum, as only slight increases of calcium and sulfate (probably within the range of analytical errors) were obtained. Whether or not the calcium and sulfate concentrations are now partly controlled by the precipitation of gypsum, they no doubt will be in the future—increasingly so, as the salinity increases. This control may result in a nearly constant sulfate concentration after the sea has become saturated with gypsum.

Calcium, magnesium (Mg), and bicarbonate (HCO_3) have been relatively minor constituents. Since the formation of Salton Sea, the concentration of bicarbonate has, to a small degree, fluctuated about an apparently quasi-stable level. Although calcium and bicarbonate can exist together in low concentrations, higher concentrations cause the formation of calcium carbonate ($CaCO_3$), which is nearly insoluble. Although magnesium carbonate ($MgCO_3$) may be precipitated under some conditions, it is much more soluble than calcium carbonate. Gypsum may precipitate if concentrations of its ions are only moderately high. Magnesium sulfate ($MgSO_4$), in contrast, is highly soluble. These solubility relationships have resulted in nearly stable bicarbonate concentration and slowly rising calcium concentration,

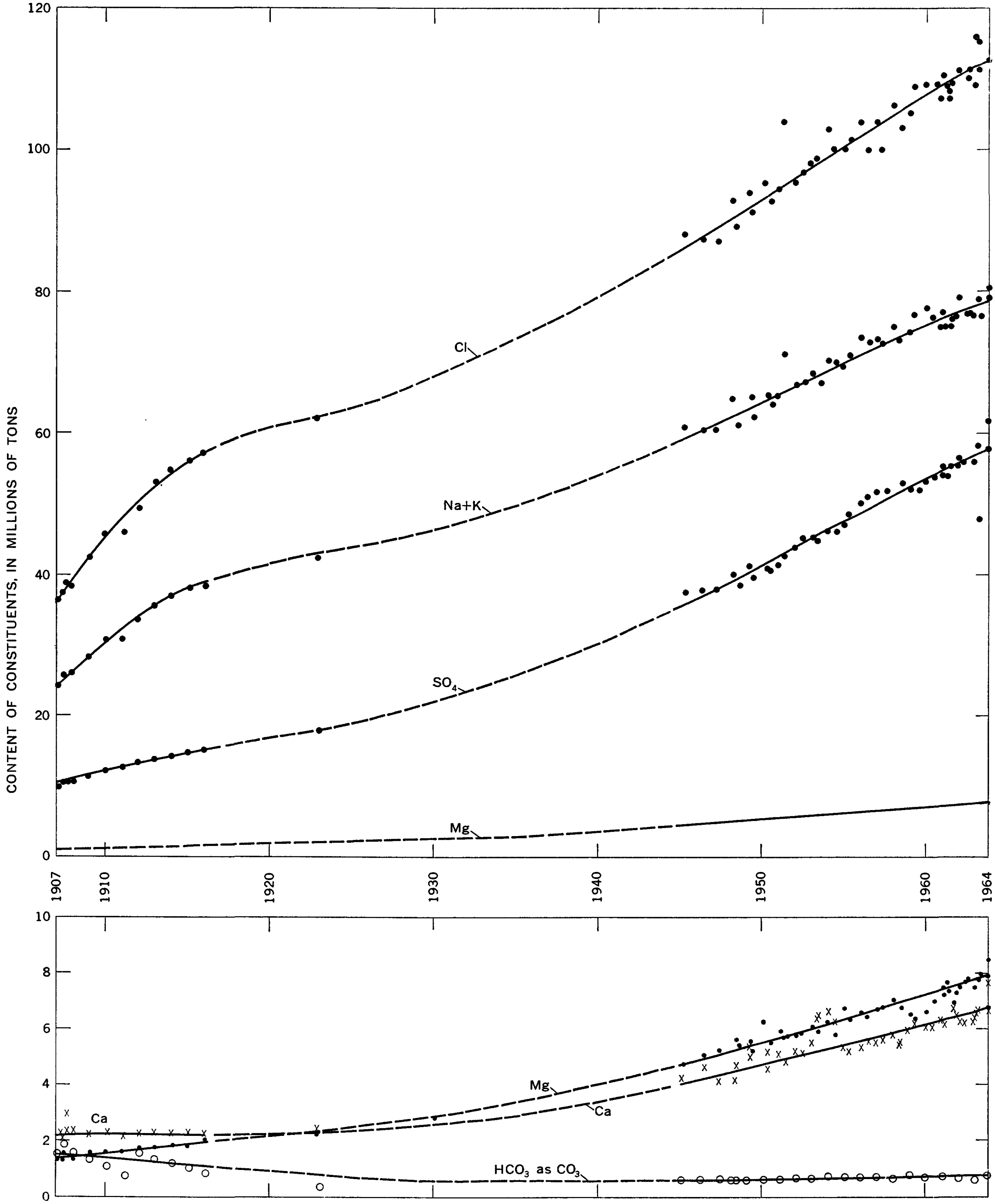

FIGURE 12.—Trends of the content of individual constituents in Salton Sea. Magnesium (Mg) is shown in both parts of the diagram to help indicate the relation between the parts.

which may be at or near peak level, and in continual increases in magnesium concentration. The magnesium concentration will probably increase to several times that of the calcium concentration, as in ocean water.

TEMPERATURE OF THE WATER

Water temperatures exert great influence on aquatic life and on most uses of the Salton Sea. Although no long-term records of water temperature are available, the data gathered for the evaporation studies exemplify the variations to be expected.

Figure 13 shows the variations during 1961–62 of the monthly air temperature at Sandy Beach, the monthly temperature of the water surface as measured at the two buoys (fig. 2), and the monthly temperatures of water at the bottom of the sea. The bottom temperatures were determined by averaging all measurements observed in the bottom layer for each thermal survey; monthly temperatures were estimated from a graph of the individual determinations.

Although the period of record is much too short for a significant determination of mean monthly water temperatures, the relations between seasonal patterns of water temperature and of air temperature should enable estimation of water temperatures within a few degrees if the air temperature is known.

Average-temperature profiles were computed from the 35 profiles obtained during each thermal survey. Selected profiles (fig. 14) determined during 1961 illustrate a variety of shapes that occur during an annual cycle of warming and cooling.

Early morning temperatures of the water surface at the two buoys (fig. 2) indicate that the sharp bend to the right near the top of many profiles was caused by warming of the surface during the day of the thermal survey. When air temperature is higher than water temperature during long periods of calm, pronounced thermal stratification tends to occur, as illustrated by the profiles for April 4 and July 10. In contrast with this tendency for stratification, water in the sea is mixed to various depths by wind and by convection currents during periods when air temperatures are lower than water temperatures.

FUTURE REGIMEN

Man's influence on the hydrologic regimen of Salton Sea has been almost entirely through the effects of irrigation. Because of the rapidly increasing use of the sea for recreation, however, proposals for controlling both water level and salinity by works in or near the sea are being considered.

If no works are constructed to accomplish direct control of Salton Sea or that add significant amounts

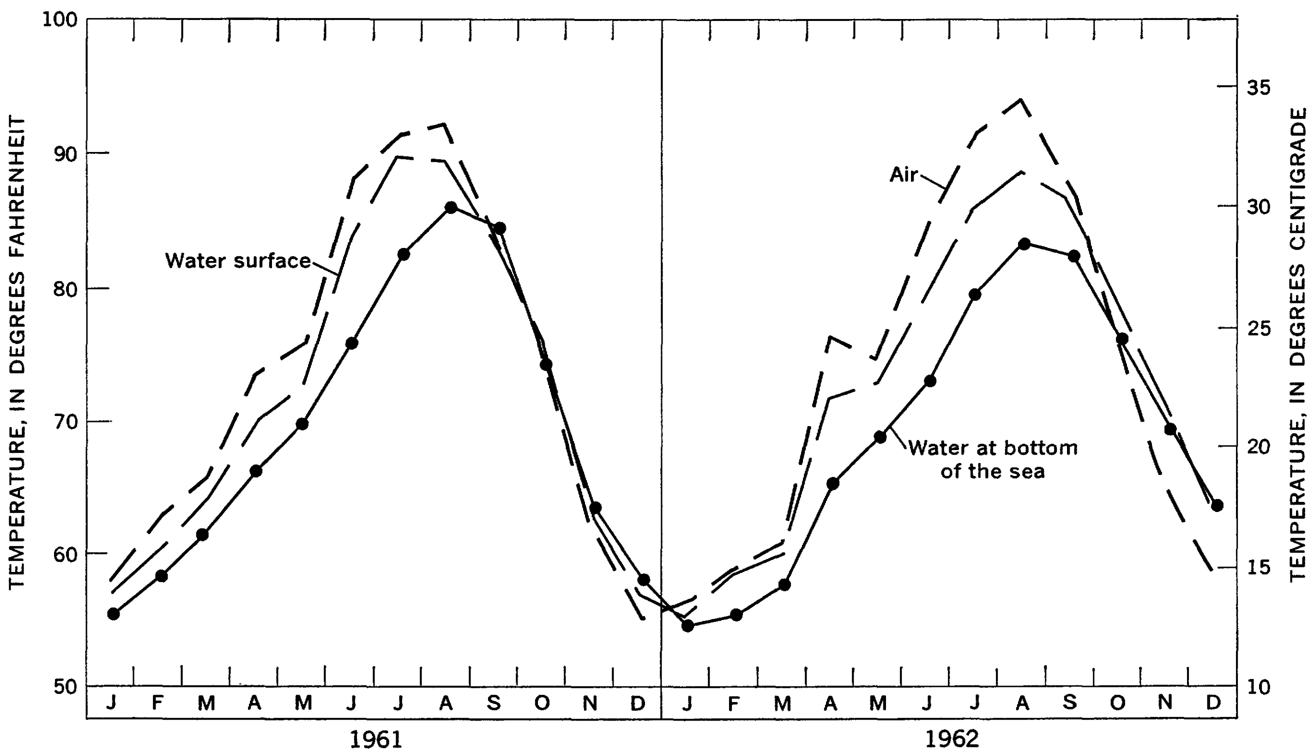

FIGURE 13.—Monthly temperatures of water at the surface and at the bottom of Salton Sea and of air at Sandy Beach. 1961–62.

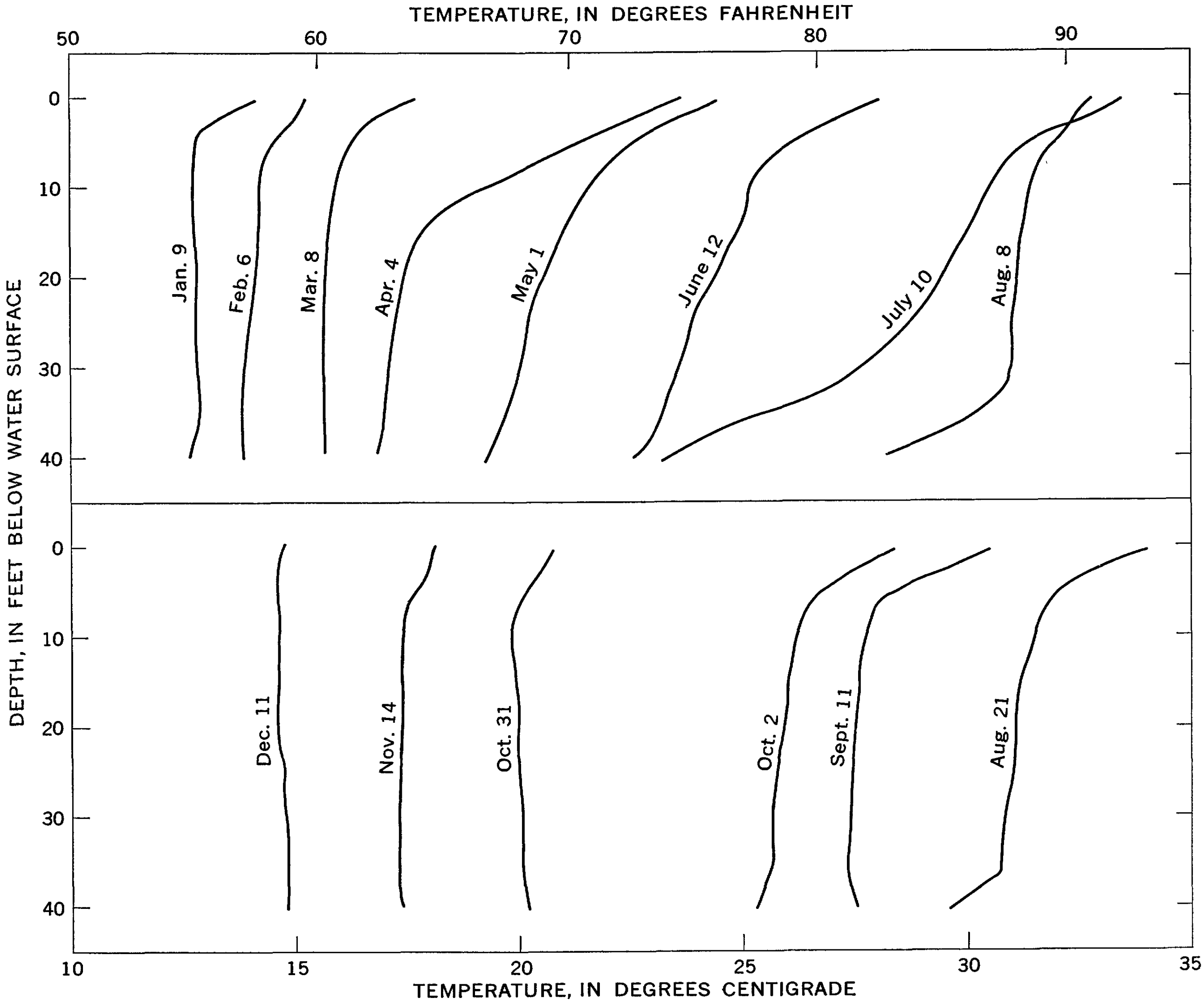

FIGURE 14.—Selected 1961 temperature profiles of Salton Sea.

of minerals, the future hydrologic regimen will depend mainly on the amount of water imported to the Salton Sea basin and on how efficiently the water is used. The trends of annual inflow and water level (fig. 9) should not be expected to continue when there is no surplus water in the Colorado River, because those trends were established when a surplus for all actual uses existed. Although some future events may tend to increase inflow, the competition for available water and the high cost of new supplies will probably tend to reduce inflow.

Increased inflow might result from installation of drains in Mexicali Valley, where continued successful irrigation will probably be dependent on the provision for drainage by either drains or wells, or an increase in inflow might result from the conversion from irrigation to municipal and industrial uses, which generally consume a relatively small part of the total water withdrawn.

An average annual seepage loss of more than one-third of a million acre-feet from the Coachella Canal and the part of the All American Canal that is within the Salton Sea basin could possibly be reduced sharply by use of canal linings or sealants. The net effect of such seepage reduction on inflow to Salton Sea cannot be evaluated or predicted with confidence because the effect would depend on the disposition of the salvaged water and, also, because the amount of seepage that now reaches the sea is unknown. Reduction of seepage probably would not markedly reduce inflow unless it were to be accompanied by a reduction in the amount of water imported to the Salton Sea basin.

A significant reduction in inflow to Salton Sea might be caused by reduction of operational losses (unused water discharged to Salton Sea) and, also, by reuse of drainage water. A curtailment of imports, enforced during 1964, resulted in the significant reduction of operational losses and of inflow to the sea.

If the annual inflow to Salton Sea from both surface and underground sources were to stabilize, the water level would also tend to stabilize after it had risen (or fallen) to the level at which mean annual values of gain and loss are equal. The water level would then continue to fluctuate within a range of a few feet in response to seasonal changes in evaporation and inflow (fig. 4) and the effects of occasional storms, but it would have no upward or downward trend. For this condition the long-term water budget (eq 1) reduces to

$$I_s+I_g=E-P, \tag{10}$$

because the change in volume (ΔV) is zero. Evaporation (E) and precipitation (P) are placed together on the right side of equation 10 because both are atmospheric phenomena and the quantities of water involved vary with the surface area. Thus instead of treating precipitation as an increment of the inflow, it is subtracted from the evaporation to obtain the net loss to the atmosphere, commonly called net evaporation.

The normal annual net evaporation per unit of surface area is 5.57 feet, computed from the previously determined values of evaporation (5.78 ft) and precipitation (0.21 ft). The corresponding mean annual volumes of net evaporation equal this rate multipled by the surface area, which varies with water level (fig. 3). Although the relation between water level and net evaporation is merely a replica of the relation in figure 3, it is shown in figure 15 with a different horizontal scale for the convenience of readers who wish to estimate the probable stable water level corresponding to assumed future inflows. The two dashed lines indicate the position of the relation if the actual evaporation per unit area is either 5 percent more or 5 percent less than the value derived in this report.

When conditions of long-term stability are being considered, inflow may be substituted for net evaporation (eq 10) in figure 15.

To illustrate the application of figure 15, assume that the annual surface inflow during some future period will vary only slightly from 1,350,000 acre-feet. Then the sum of surface- and ground-water inflow will be 1,400,000 acre-feet, and the water level will stabilize at about 224 feet below mean sea level. Similarly, if the surface- and ground-water inflow should be 800,000 acre-feet, the stable water level would be about 254 feet below mean sea level.

Increasing salinity of Salton Sea may cause a gradual decrease in the average rate of evaporation. Although Harbeck (1955) stated that "It is impossible to define a simple relationship between salinity and the decrease in evaporation," his data indicated that evaporation of ocean water (salinity, about 35,000 ppm) is about 2 percent less than that from fresh water in the same environment. The corresponding reduction would be about 3 percent for a salinity of 60,000 ppm, and about 6–7 percent for a salinity of 100,000 ppm. Evaporation from a sample of brine from Great Salt Lake (salinity, 251,000 ppm) was about 20 percent less than that from fresh water.

Figure 15 is based on an evaporation rate that was applicable when the salinity was near 34,000 ppm and, consequently, will not be applicable when the salinity is increased to several times that amount, unless the relation line is adjusted accordingly. The effect of moderate changes in salinity, however, may be less than the effect of errors involved in the definition of the relationship.

The graph of total mineral content of Salton Sea (fig. 10) indicates a rather stable rate of increase for 1945–63 of about 4 million tons per year, which can probably be projected for a few years with relatively little error. Any decrease in the quantity of inflow resulting from an increase in the efficiency of water use will probably be at least partly offset by an increase in salinity of the inflow.

Future events, however, may cause changes in the average annual increment of mineral content. A proposed development to produce electric power from steam supplied by a geothermal well field near Niland, Calif., would contribute significant amounts of brine

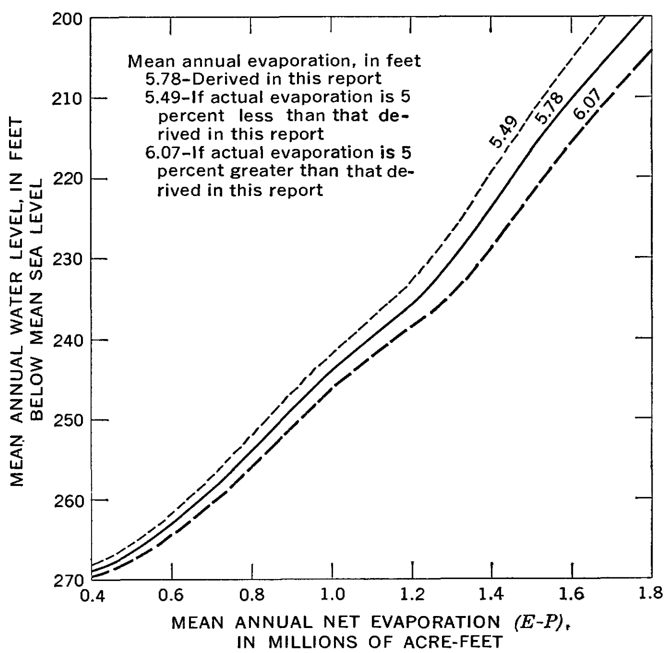

FIGURE 15.—Relation between mean annual values of water level and net evaporation, and between water level and inflow (of both surface water and ground water) when inflow and net evaporation are in equilibrium.

to the sea, unless other means of waste disposal are provided. Construction of an extensive drainage system in Mexicali Valley whereby effluent would be discharged to the Alamo and New Rivers would tend to increase the inflow of minerals to the sea. Precipitation of gypsum (as described in the section "Chemical Composition") or a gradual decrease in the amount of sodium chloride leached from soils however, may reduce the average increment. The annual increment of calcium content during 1945–63 (about 140,000 tons) is sufficient for removal of about 480,000 tons of calcium sulfate in the form of gypsum if concentrations become high enough.

Estimates of the future salinity of the unregulated Salton Sea involve estimates or assumptions of the corresponding values of both mineral content and volume of water (eq 9). The following examples are based on the values used in previous examples of stable water levels, where applicable, and are illustrative only.

Assume that the annual inflow stabilizes at 1,400,000 acre-feet before 1980 and that the average annual increment of mineral content for the 17-year period 1964–80 will be 4,500,000 tons. The mineral content in 1980 would then be about 340 million tons, the volume (corresponding to the stable water level of 224 ft below mean sea level), about 8 million acre-feet (fig. 3), and the salinity, about 31,000 ppm.

Similarly, assuming 800,000 acre-feet for the stable inflow and 3,600,000 tons for the average annual increment of mineral content, the corresponding stable water level would then be 254 feet below mean sea level, and the volume, about 2 million acre-feet; the mineral content and salinity in 1980 would be calculated as 320 million tons and 120,000 ppm, respectively.

SCHEMES FOR REGULATION

A progressive increase in the salinity of Salton Sea would inevitably cause gradual deterioration of its value for recreation. Moreover, any large changes in water level, particularly when associated with large lateral changes in shorelines, would hinder the utilization of the sea and operation of marinas and other shore installations. Because of these menaces to the rapidly increasing recreational uses of the sea, agencies and consultants of the State of California began an investigation in 1964 of the feasibility of limiting the salinity and of regulating the water level.

In the following discussion of hydrologic and chemical aspects of regulation, the amount of drainage from irrigated tracts will assumedly be determined by the available water supply and irrigation economics, not by requirements for regulation of the sea. Also assumed is the fact that evaporation suppression by use of chemical films will not be practical on large windswept water bodies, although such suppression has been achieved experimentally on small water bodies.

The most practical procedures for control of salinity and water level of Salton Sea include (a) removal of water and minerals by pumping, and (b) the use of dikes to limit the surface area and reduce the quantity of water evaporated.

A long-term increase in salinity of Salton Sea can be avoided only by removing minerals at a rate sufficient to compensate for the inflowing minerals and the effects of any changes in volume of the sea. Hence, removal of water is an essential part of any plan for long-term control of the sea. The removal of water to control salinity would be compatible with its removal for control of water level if inflow were relatively high, but it would aggravate the problem of controlling water level if inflow were relatively low. If inflow were insufficient to maintain the desired water level in the entire sea, a system of dikes could be constructed so that net evaporation from the surface of the principal regulated basin would be in equilibrium with the net inflow (total inflow less water removed by pumping).

Limiting values of salinity and water level for use in designing and operating regulating works would depend on the values considered to be desirable or tolerable and on the costs of maintaining various values. Although no specific standards for such values have been set (1965), some of the hydrologic problems involved in regulating Salton Sea are hereby illustrated by use of assumed values, as in preceding examples.

1. Assume that inflow stabilizes at the relatively high annual value of 1,400,000 acre-feet, that the average annual addition to the mineral content of the sea after 1963 is 4,500,000 tons, and that the average annual salinity is to be limited to 40,000 ppm. With no regulation, the corresponding stable water level and volume would be 224 feet below mean sea level (fig. 15) and 8 million acre-feet (fig. 3), respectively. At the specified salinity, the mineral content would be about 430 million tons (eq 9)—that is about 170 million tons more than the mineral content in 1963. This quantity of minerals would accumulate in 38 years after 1963, and the salinity would reach 40,000 ppm by about the year 2001. Prevention of later increases in mineral content and salinity, however, would require the annual removal of 83,000 acre-feet of water with a salinity of 40,000 ppm. Hence, the final stable water level would be about 230 feet below mean sea level (corresponding to an average net inflow of 1,320,000 acre-ft). Prevention of a large rise and later decline of water level would accordingly require regulation by pumping several years earlier.

2. Assume that the values of inflow and addition of minerals are the same as those in example 1 but that the regulated water level is at 234 feet below mean sea level. At that level the annual net evaporation from Salton Sea would be 1,250,000 acre-feet, and the removal of an additional 150,000 acre-feet would be required for regulation. The annual removal of this quantity of water at a salinity of 25,000 ppm would be sufficient to prevent an increase of mineral content. Thus, the salinity of the sea would gradually approach 25,000 ppm as a limit.
3. Assume that inflow stabilizes at the relatively low annual value of 800,000 acre-feet, that the average annual addition of minerals is 3,600,000 tons, and that the limiting average annual salinity is to be 40,000 ppm (as in example 1). Removal of a quantity of minerals equal to the annual additions would require removal of 66,000 acre-feet of water per year at the specified salinity. Subtracting this from the assumed inflow leaves 734,000 acre-feet per year to be dissipated as net evaporation, which requires a surface area of about 130,000 acres (less than 60 percent of the natural surface area of the sea in 1962). For any actual system of dikes that would provide such a small area for the principal regulated basin, an appreciable part of the inflow would probably enter auxiliary basins rather than the principal basin, and appropriate adjustments of the computations would be required.

The ultimate disposal of minerals or brine is an important part of any scheme for regulating Salton Sea. Water could be evaporated from separate basins or from diked-off parts of the sea. Saline residues left at altitudes above the surface of Salton Sea, however, might involve a serious danger of contaminating usable ground-water supplies. Moreover, because of the great quantities of minerals involved, long-term operation of any regulating works would require removal of minerals from auxiliary evaporating basins.

Disposal of concentrated brine by pipeline to the Gulf of California or to Laguna Salada (fig. 1), a dry salt playa that is slightly below mean sea (ocean) level, would avoid most of the danger of contamination but would require an international agreement.

Because of similar brine-disposal problems, the feasibility of regulating Salton Sea and feasibility of commercial development of power from the geothermal well field near Niland may be interrelated. Wells drilled in this area and tested in 1962 yielded steam and concentrated brine. Except for disposal of the brine, the feasibility of developing power from the steam has been demonstrated. Actual development, however, may depend on a satisfactory plan for brine disposal that would accommodate brines from both the well field and Salton Sea.

The average rate of evaporation from Salton Sea derived in this report would apply with little error to a relatively large regulated water body but would not apply to auxiliary basins because evaporation from brines is as much as 20 percent less than that from fresh water. Also, the evaporation from small basins would be affected by their location with respect to the principal water body and the direction of prevailing winds.

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