Analysis of Techniques Used to Measure Evaporation From Salton Sea, California

By G. H. HUGHES

STUDIES OF EVAPORATION

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Comparison of results obtained by energy-budget,
mass-transfer, and water-budget methods
and examination of possible sources of error

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STUDIES OF EVAPORATION

ANALYSIS OF TECHNIQUES USED TO MEASURE EVAPORATION FROM SALTON SEA, CALIFORNIA

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ABSTRACT

During 1961–62 the evaporation from Salton Sea, Calif., was determined by three different methods. Determinations for 1- and 2-year periods by the practically independent water- and energy-budget methods differ by less than 5 percent. The average evaporation determined by these two methods establishes an empirical coefficient for the simplified mass-transfer equation, which is a basis for a third independent determination of the distribution of the yearly evaporation among the months or shorter periods. Comparison of the three determinations for periods of 10–29 days indicates a marked seasonal bias in the energy-budget evaporation, computed values being as much as 60 percent lower than water-budget evaporation during the winter and as much as 25 percent higher during the summer. Determinations by the water-budget and mass-transfer methods differ by smaller amounts that vary in a nearly random, rather than seasonal, pattern.

The principal cause of the seasonal bias in evaporation determined by the energy-budget method apparently is inadequate measurement of the total incoming radiation by the flat-plate radiometer. The seasonal interchange of heat between water and the underlying sediments, which has been disregarded in this and most previous applications of the energy-budget method, is a less important but significant factor in shallow-water bodies such as Salton Sea.

INTRODUCTION

Investigation of the hydrologic regimen of the Salton Sea by the U.S. Geological Survey in 1961–62 (Hely and others, 1966) included the determination of evaporation by the energy-budget, water-budget, and mass-transfer methods. The energy-budget and the water-budget methods provide basically independent measurements of evaporation. Because conditions at Salton Sea were in many ways favorable for application of both these methods, it was expected that results of the two would agree generally within 10 percent. Yearly evaporation rates by the two methods did agree exceptionally well, but rates for periods of 10–29 days commonly differed by much more than 10 percent. Furthermore, these differences tended to vary seasonally. Application of the mass-transfer method indicated that the seasonal distribution of yearly evaporation shown by the water-budget method was more nearly correct than that shown by the energy-budget method.

Prior to the studies at Salton Sea, the application of energy-budget and mass-transfer theory to the field measurement of evaporation had been investigated by the Geological Survey (1954) and other Federal agencies at Lake Hefner, Okla., and at Lake Mead, Ariz.–Nev. (Harbeck and others, 1958). From the study at Lake Hefner, Anderson (1954, p. 117) concluded that for periods greater than 7 days accuracy approaching 5 percent was attainable by use of the energy-budget method, provided that all terms of the budget were carefully evaluated. This suggested accuracy applies to evaporation rates corresponding to the warmer rather than the cooler months of the year. It may be presumed, further, that for a determination of such accuracy, overall conditions should be reasonably favorable.

The instruments used at Salton Sea were equivalent to those used at Lake Hefner and at Lake Mead. Procedures perfected during those studies were closely followed. The yield of usable data by the instruments was at least as good for Salton Sea as for either of the other two studies; consequently, the appearance of seasonal bias in the energy-budget results for Salton Sea caused considerable concern.

This report reviews the fundamental equations used in each of the three methods of determining evaporation from Salton Sea. Data for Salton Sea and nearby places are examined to determine the cause of the seasonal bias in the energy-budget results. The adequacy of the data for each method is considered with regard to the relative importance of individual terms in which particular data were used. Much of the discussion centers around the energy-budget method because the error resulting from the use of this method is the chief concern of the report.

The investigations covered by this report were under the general supervision of C. C. McDonald, project hydrologist, and the water-budget study was conducted by Allen G. Hely. Basic data required for the water-budget study were obtained under the direction of Walter Hofmann, district engineer, Menlo Park, Calif., or were furnished by the Imperial Irrigation District, (R. F. Carter, general manager) and Coachella Valley County Water District (Lowell Weeks, general manager). Other records, materials, and assistance were supplied by the Imperial Irrigation District.

Water-level recorders at Imperial Salt Farm and Desert Beach (North Shore Yacht Club) were installed by Coachella Valley County Water District. The North Shore Yacht Club granted permission to use its marina for a recording gage site.

The Sandia Corporation of Albuquerque, N. Mex., granted the use of its facilities at Salton Sea Base (Sandy Beach) and provided additional services, including the installation of two buoys in the sea. Personnel of the U.S. Navy stationed at Salton Sea Base participated by removing the buoys at the end of the study.

ENERGY-BUDGET METHOD

The energy-budget method of determining evaporation from a water body has been described elsewhere (Anderson, 1954), and only a review of the fundamental relations is given here. The method is based on the principle of conservation of energy. As applied to a water body, this principle requires that the net influx of energy be balanced by an increase of energy stored in the water. The energy budget for a water body may be expressed as follows:

$$Q_s-Q_r+Q_a-Q_{ar}-Q_{bs}+Q_v-Q_e-Q_w-Q_h=Q_\theta, \quad (1)$$

in which,

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

Terms representing amounts of energy derived from or used by chemical and biological processes, transformation of kinetic energy to heat, or conduction of heat through the bed of the water body are not included in equation 1. These terms generally have been considered negligible. For shallow-water bodies, however, heat conduction through the bed may be significant at certain times of the year. In a later section of the report the effect of such a possibility is considered for Salton Sea.

Energy used in the evaporation process and the sensible-heat exchange between air and a water surface are difficult to measure directly but their sum may be determined by the energy-budget equation as follows:

$$Q_s-Q_r+Q_a-Q_{ar}-Q_{bs}+Q_v-Q_\theta=Q_e+Q_h+Q_w. \quad (2)$$

The terms on the left side of equation 2 can be measured or can be computed by known theoretical and empirical relations. The net energy represented by these terms can be distributed among the terms on the right according to the following relations:

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

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, and
T_b=arbitrary base temperature.

If these relations are substituted in equation 2 and E is isolated, the following equation results:

$$E=\frac{Q_s-Q_r+Q_a-Q_{ar}-Q_{bs}+Q_v-Q_\theta}{\rho[L(1+R)+c(T_e-T_b)]}. \quad (3)$$

Equation 3 is applicable to any period for which all terms are evaluated. If quantities are expressed in terms of unit area and unit time, E is equivalent to the depth (volume per unit area) of water evaporated per unit time.

The water-surface temperature generally is used for T_e. The base temperature, T_b, may be selected arbitrarily provided the same value is used to evaluate Q_v and Q_θ. Generally 0°C is used for convenience. The methods of determining other terms of equation 3 are described in sections that follow. Table 1 lists average values for each term of the energy-budget for Salton Sea (eq. 1).

TABLE 1.—*Average values, by periods, of terms of the energy-budget equation for Salton Sea*

[Values in calories per square centimeter per day except as indicated]

Period	Number of days	Q_s	Q_r	Q_a	Q_{ar}	Q_{bs}	Q_v	Q_e	Q_h	Q_w	Q_θ
1961–62											
Jan. 9 to 23	14	299	30	595	18	769	6	45	−6	1	43
Jan. 24 to Feb. 6	13.5	312	29	615	18	778	6	72	−5	2	39
Feb. 6 to 21	15	403	35	621	19	789	7	146	−10	4	48
Feb. 21 to Mar. 8	15	462	39	603	18	795	8	180	−9	5	45
Mar. 8 to 20	12	495	38	621	19	817	10	167	−8	5	88
Mar. 20 to Apr. 4	15	529	40	678	20	822	11	269	−27	8	86
Apr. 4 to 17	13	624	45	705	21	844	12	337	−28	12	110
Apr. 17 to May 1	14	664	46	673	20	852	12	404	−16	15	28
May 1 to 15	14	656	41	686	21	860	12	421	−26	16	21
May 15 to June 12	28	694	44	770	23	883	12	450	−28	18	86
June 12 to 26	14	673	42	925	28	964	16	379	−39	20	220
June 26 to July 10	14	665	43	898	27	965	15	509	−31	27	38
July 10 to 24	14	607	38	954	29	990	15	444	−12	25	62
July 24 to Aug. 8	15	610	40	970	29	987	16	518	−20	29	13
Aug. 8 to 21	13	540	37	952	29	982	16	450	−21	25	6
Aug. 21 to Sept. 11	21	573	41	853	26	963	18	540	−14	28	−140
Sept. 11 to 22	11	528	38	839	25	938	15	483	5	24	−131
Sept. 22 to Oct. 2	10	505	38	764	23	923	17	272	−5	13	22
Oct. 2 to 31	29	403	33	705	21	884	11	328	2	13	−162
Oct. 31 to Nov. 14	14	341	32	641	19	822	8	252	−4	8	−139
Nov. 14 to 28	14	289	29	611	18	795	6	131	10	4	−81
Nov. 28 to Dec. 11	13	267	28	595	18	780	6	112	−1	3	−72
Dec. 11 to Jan. 2	22	242	25	585	18	765	4	51	8	1	−37
Total	357.5										
Average		495	37	731	22	868	11	308	−12	13	1
1962–63											
Jan. 2 to 15	13	294	31	563	17	767	3	104	−1	3	−61
Jan. 15 to 29	14	275	27	591	18	754	6	72	1	2	−2
Jan. 29 to Feb. 12	14	312	29	640	19	776	6	36	−7	1	104
Feb. 12 to Mar. 2	18	389	33	598	18	777	6	177	11	4	−27
Mar. 2 to 19	17	456	35	617	18	777	7	185	−1	5	61
Mar. 19 to Apr. 2	14	514	38	667	20	804	10	201	−19	6	141
Apr. 2 to 16	14	571	39	772	23	853	15	256	−38	9	216
Apr. 16 to 30	14	583	40	758	23	869	13	431	−29	17	3
Apr. 30 to May 17	17	624	41	739	22	877	13	471	−15	19	−39
May 17 to June 4	18	657	42	764	23	864	12	419	−25	16	94
June 4 to 18	14	674	42	807	24	893	13	497	−34	21	51
June 18 to July 2	14	665	42	875	26	941	16	383	−43	19	188
July 2 to 16	14	659	42	904	27	946	15	529	−43	27	50
July 16 to 30	14	591	38	953	29	970	17	428	−29	23	102
July 30 to Aug. 13	14	612	41	904	27	967	17	510	−38	27	−1
Aug. 13 to 27	14	538	37	939	28	982	18	403	−29	22	52
Aug. 27 to Sept. 10	14	536	38	867	26	972	17	465	−12	25	−94
Sept. 10 to 24	14	483	35	895	27	959	20	364	−18	19	12
Sept. 24 to Oct. 7	13	442	33	794	24	946	19	419	22	21	−210
Oct. 7 to 22	15	400	32	731	22	902	13	289	14	13	−128
Oct. 22 to Nov. 5	14	340	30	711	21	889	11	133	−3	6	−14
Nov. 5 to 20	15	303	30	648	19	869	9	223	20	9	−210
Nov. 20 to Dec. 3	13	271	28	633	19	823	7	75	10	2	−46
Dec. 3 to 17	14	257	28	599	18	814	7	37	3	1	−38
Dec. 17 to Jan. 8	22	222	24	580	17	791	6	59	8	2	−93
Total Jan. 2, 1962, to Jan. 8, 1963	371										
Total Jan. 9, 1961, to Jan. 8, 1963	728.5										
Average Jan. 2, 1962, to Jan. 8, 1963		464	35	736	22	868	12	283	−11	12	3
Average Jan. 9, 1961, to Jan. 8, 1963		479	36	734	22	868	11	295	−12	13	2

INCOMING RADIATION (Q_s+Q_a)

The total incoming radiation—solar radiation (Q_s) plus long-wave atmospheric radiation (Q_a)—supplies nearly all of the energy involved in the energy-budget equation; hence, accurate determination of incoming radiation is critical. Solar and atmospheric radiation generally are derived as individual components so that reflected solar radiation (Q_r) and reflected atmospheric radiation (Q_a) may be computed rather than actually measured over the water surface.

Radiation was measured at Sandy Beach on the shore of the Salton Sea (fig. 48). Total incoming radiation was measured by a flat-plate radiometer; solar radiation, by an Eppley pyrheliometer. The output of each instrument was recorded alternately, in sequence at 3-minute intervals, by a Minneapolis-Honeywell recording potentiometer. Hourly values of total incoming radiation and of solar radiation were determined from the recorded data. Atmospheric radiation was computed as the difference between these measured values.

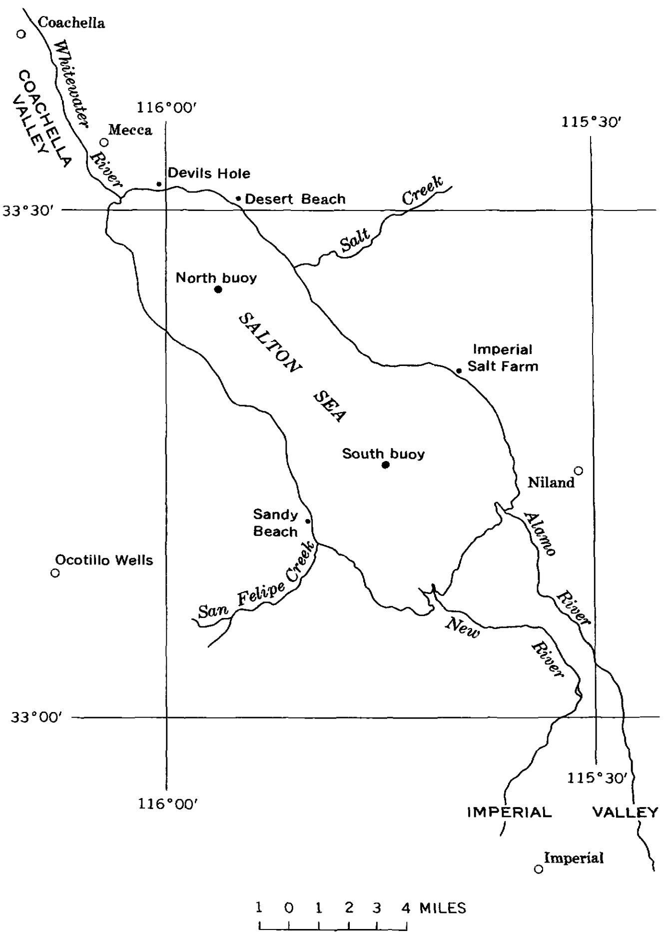

FIGURE 48.—Map of Salton Sea area, showing principal tributaries and sites where data were collected.

The assumptions that incoming radiation at Sandy Beach equalled the average rate for Salton Sea and that intermittently recorded intensities were representative of those during the intervening periods should be valid for periods lasting several days.

The recording instrument performed satisfactorily except during one period of about a month when the chart-drive mechanism failed intermittently. Periods of no record due to power failures, commonly during thunderstorms, seldom involved more than a few hours. Records of radiation were complete for 96 percent of the total study period.

For the short periods of no record, both solar radiation and atmospheric radiation were estimated from trends for the preceding and following periods. For the longer periods of no record, solar radiation was estimated from measurements by the U.S. Army Meteorological Team at Yuma Proving Ground (formerly Yuma Test Station), near Yuma Ariz. Also, for the longer periods of no record, atmospheric radiation was estimated from an empirical relationship formulated by Koberg (1964) involving solar radiation, air temperature, and the vapor pressure of air. Atmospheric radiation could have been estimated from measurements of total incoming radiation at Yuma Proving Ground made by the U.S. Army Meteorological Team using a flat-plate radiometer identical with that used at Sandy Beach; however, the correlation of radiation data for the two stations was not as consistent for total incoming radiation as it was for solar radiation. As the temperature and vapor pressure of air at Sandy Beach often were recorded during periods when radiation data were lacking, use of Koberg's method probably provided the most reliable estimates of atmospheric radiation.

Measurements of total incoming radiation at Sandy Beach and at Yuma Proving Ground should be equally reliable as identical instruments were used. Comparison of measurements for the two stations may suggest the probable reliability of such measurements in general. The two stations are about 100 miles apart, but similarly exposed and they are commonly affected by the same air-mass systems. Some differences in solar radiaton might occur because of the local variation of absorption properties of the lower atmosphere. It was expected, however, that total incoming radiation would be about the same at each location.

Measured total incoming radiation was greater at Sandy Beach than at Yuma Proving Ground during most of 1961, but the two were about equal during most of 1962. Throughout both years, however, solar radiation at Sandy Beach was substantially less than that at Yuma Proving Ground (see fig. 49). At Sandy Beach total incoming radiation was neither significantly greater nor significantly less in 1961 than in 1962, but solar radiation was generally less in 1962. In contrast, at Yuma Proving Ground total incoming radiation was consistently less in 1961 than in 1962, whereas solar radiation was about the same in both years. The monthly average temperature and vapor pressure at the two places suggests that total incoming radiation should be about the same (fig. 50). Also, solar radiation at each of two U.S. Weather Bureau stations—Las Vegas, Nev., and Phoenix, Ariz.—was about the same for both years.

As measured in 1961–62, monthly total incoming radiation at Sandy Beach and at Yuma Proving Ground differed by as much as 12 percent and, in 12 of the 24 months, differed by as much as 3 percent or more. If such differences indicate errors in measurement, they are large enough to affect seriously the accuracy of evaporation computed by the energy-budget method. Specifically, an error of only 1 percent in the measurement of total incoming radiation would result in an error of about 4–10 percent in computed evaporation, depending on the season considered.

REFLECTED RADIATION (Q_r+Q_{ar})

Incident radiation is reflected by a water surface according to the angle of incidence and the reflective properties of the water. Short-wave radiation from the sun that reaches the earth's surface is partly diffuse but largely directional. Long-wave radiation from the atmosphere, on the other hand, is entirely diffuse. Consequently, the proportion of long-wave atmospheric radiation that is reflected by the water surface is constant, but the proportion of solar radiation that is reflected varies according to the hour of the day and the season of the year.

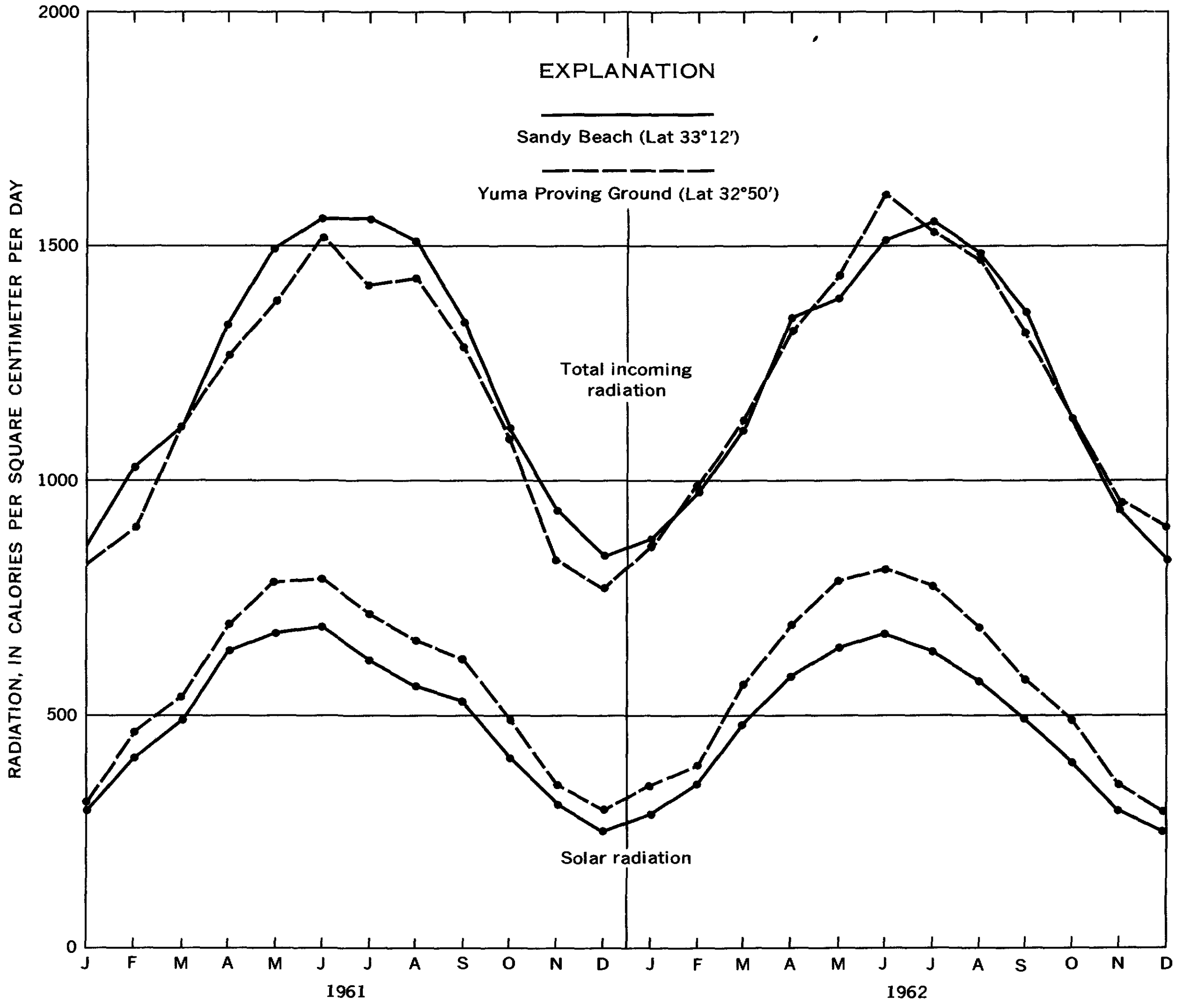

FIGURE 49.—Monthly radiation at Sandy Beach, Calif., and at Yuma Proving Ground, Ariz., 1961–62.

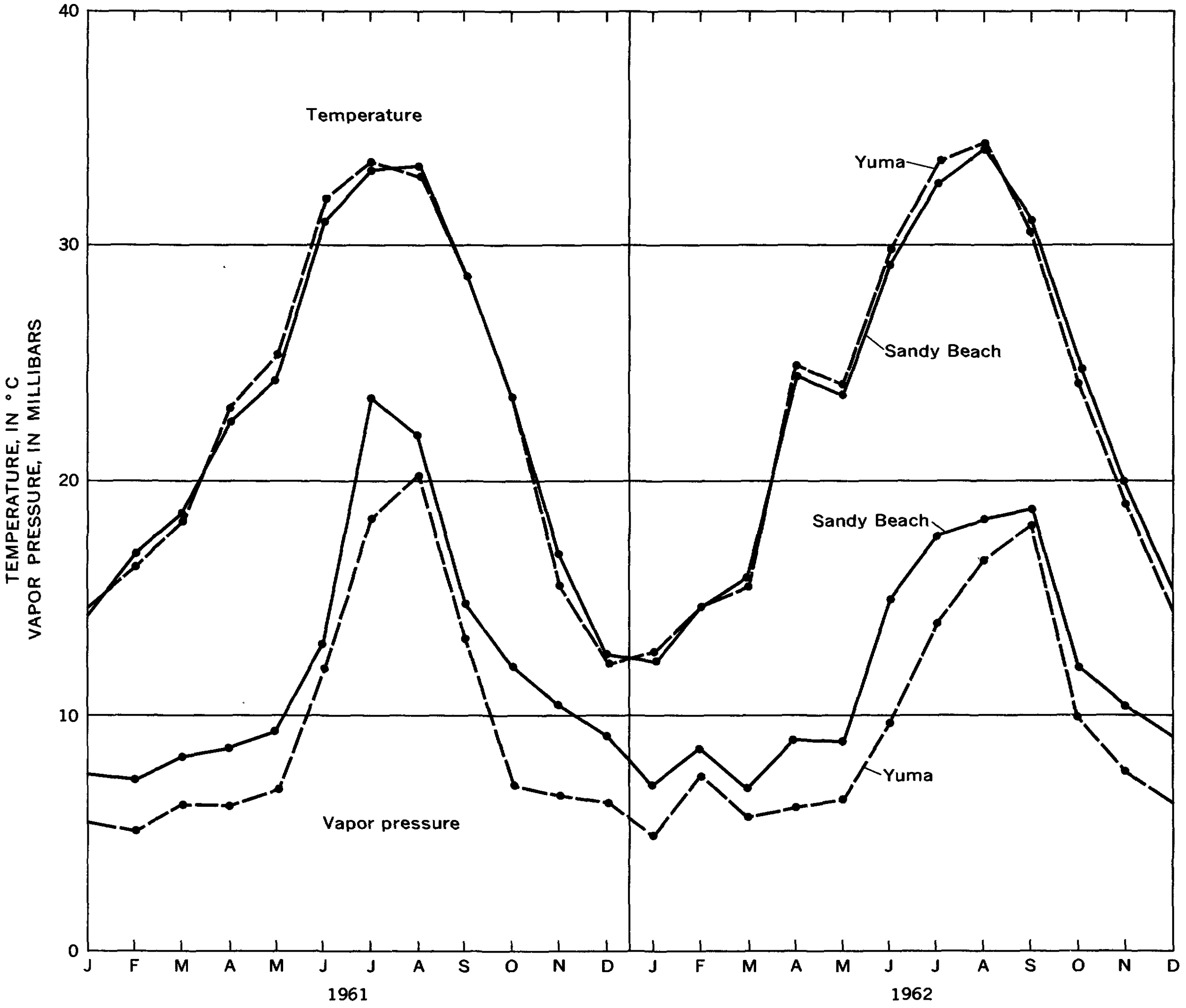

FIGURE 50.—Monthly temperature and vapor pressure of air at Sandy Beach, Calif., and at Yuma, Ariz. (U.S. Weather Bureau station, about 18 miles southwest of Yuma Proving Ground), 1961–62.

Reflected solar radiation was computed by applying hourly reflectivity coefficients to corresponding values of incident solar radiation. Coefficients were derived from an empirical relation between reflectivity and the sun's altitude (Anderson, 1954). As clear-sky conditions were predominant, especially during periods of highest evaporation, clear-sky reflectivities were applied in all computations. Any error in reflected solar radiation caused by disregarding cloud cover would be small (Koberg, 1964, fig. 36), probably less than 5 percent for any budget period. Reflected solar radiation was equal to about 6 percent of the incident solar radiation during the summer and about 10 percent during the winter.

Reflected long-wave atmospheric radiation was computed as the product of values of incoming atmospheric radiation and a reflectivity coefficient of 0.030. This coefficient was shown by J. T. Gier and R. V. Dunkle (in U.S. Geological Survey, 1954, p. 96–98) to be applicable to ocean water (and, consequently, to the Salton Sea) as well as to fresh water.

RADIATION EMITTED (Q_{bs}) BY SALTON SEA

Long-wave radiation emitted by Salton Sea depends on the temperature and emissivity of the water at the surface and was computed in accordance with the Stefan-Boltzman law using an emissivity of 0.970 as determined by J. T. Gier and R. V. Dunkle (in U.S. Geological Survey, 1954, p. 96–98).

Temperature of the water surface was recorded continuously at two buoys anchored at the positions shown in fig. 48. The recorded temperatures were verified by readings of a mercury thermometer when the recorder charts were changed. These readings generally agreed within 0.5°C. The recorder was adjusted when the discrepancy exceeded this value. Instrument failure at the north buoy resulted in loss of record for one period of about a month. Losses of record from other causes were infrequent and usually were for periods of only a few days. The record of water-surface temperature for the entire study was 91 percent complete for the north buoy and 97 percent complete for the south buoy.

The average of the water-surface temperatures at the two buoys was assumed to represent the entire water surface. The record for one buoy was used for both when data for the other buoy were missing. When data for both buoys were missing, the water-surface temperature was estimated from trends of the preceding and following periods.

The term Q_{bs} was the largest single term of the energy-budget equation; among the several budget periods it was from 2- to 20-fold greater than the energy used for evaporation (see table 1). Consequently, a relatively small error in the term Q_{bs} has an appreciable affect on the accuracy of the computed evaporation. For example, the deviation in long-wave radiation from the Salton Sea corresponding to a 1°C change in average yearly water-surface temperature is equivalent to about 4 percent of the energy used for evaporation. Thus, the extent to which the average of water-surface temperatures at the two buoys represented the mean temperature for the entire surface of the Salton Sea is critical.

The daily water-surface temperatures at the two buoys commonly differed but seldom by more than 1° C; the temperature differences tended to balance over a period of several days. The diurnal variation of the water-surface temperature usually was greater at the south buoy but seldom exceeded 5° C at either buoy. The range of water-surface temperatures observed during individual thermal surveys (described in the following section) was about the same as the daily range recorded at the buoys. The average range for all surveys was 3.3° C; the maximum range was 5.8° C.

Figure 51 shows that for corresponding periods the difference between water-surface temperatures recorded at the two buoys and those observed during thermal surveys seldom exceeded 1° C and never exceeded 2° C. The data indicate that during periods of relative calm, when thermal surveys could be made, the water-surface temperatures recorded at the two buoys represented the mean temperature of the entire surface of Salton Sea within 1° or 2° C. Representation probably was as good or better at other times because the water frequently was well mixed by high winds. Accordingly, it is presumed that error in the emitted long-wave radiation, Q_{bs}, generally does not exceed 2 percent.

CHANGE IN ENERGY STORAGE (Q_θ)

The thermal energy content of Salton Sea was based mainly on the temperature readings made during thermal surveys at intervals of 10–29 days. These readings were taken at specific depths at 35 stations that were spaced to provide representative sampling.

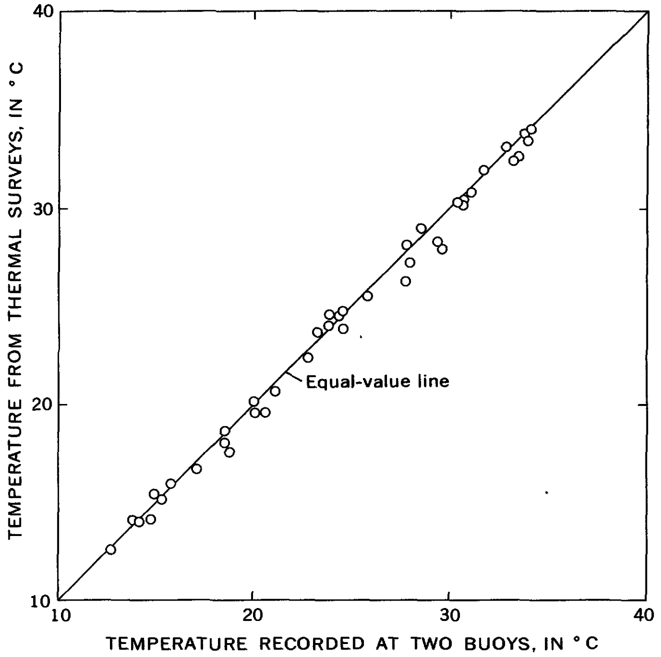

FIGURE 51.—Relation between water-surface temperatures of Salton Sea as recorded at two buoys and as measured during thermal surveys.

The temperature readings were obtained by a Whitney underwater thermometer having a small thermistor for a sensing element. Accuracy was verified at the end of the study period by means of simultaneous temperature readings obtained in a common medium by both the Whitney thermometer and a precision-grade mercury thermometer. Differences between readings averaged 0.2° C and ranged from 0° to 0.3° C over the operating temperature range of 11–37° C. Similar, but less comprehensive, temperature checks made in the field during the study period provided assurance that the calibration of the Whitney thermometer did not change. This consistency was more important than the absolute accuracy of the calibration because the change in energy storage rather than the total storage was required.

Energy storage was computed for successive 2-foot-thick layers of water from the surface to a depth of 10 feet and for successive 4-foot-thick layers below that depth. Temperatures observed at midlayer were averaged to obtain a mean temperature of water in each layer, except for the top layer in which temperatures observed at the surface and at 1- and 2-foot depths were averaged. The energy content of the layer, relative to a base temperature of 0° C, was the product of the volume of water and its mean temperature, density, and specific heat. The difference between successive determinations of energy content was divided by the product of the average surface area of the Salton Sea for the period and the number of days in the period to obtain the change in energy storage (Q_θ) in the units used for the energy-budget computations.

The time required to make the thermal surveys varied with the condition of the power boat and the roughness of the water surface but averaged about 8 hours per survey. All except the first two of the 49 thermal surveys made during the study period were completed in one day, and all were begun between 9 and 11 a.m.

The water temperature varied considerably more with depth than with area during any individual thermal survey. The average variation with depth for all surveys was 6.0° C; the maximum variation was 12.8° C.

Figure 52 shows typical variations of temperature with depth. In all but a few of the several thermal surveys made, most of the temperature variation occurred in the uppermost 10 feet of water. If the trend of the water temperature below a depth of 10 feet is projected upward, the surface temperature so indicated ordinarily is a close approximation of the predawn water-surface temperature at the two buoys on the day of the thermal survey. This observation suggests that most of the thermal stratification that might have existed the preceding day was dispersed during the night and that much of the observed stratification was created after sunrise on the day of the thermal survey. During sustained periods of calm, however, stratification extended to greater depths and undoubtedly persisted through the night.

Changes in volume of Salton Sea during periods between thermal surveys were small relative to the total volume; therefore, the energy content of the sea varied mainly with the temperature of the water. As there are no pronounced irregularities in the configuration of the sea to retard mixing by wind- or thermal-induced currents, temperature readings taken at each sampling station should represent a relatively large part of the sea. Consequently, the changes in energy storage that are dependent on the definition of the thermal structure of the sea are believed to be accurately determined. Changes in energy storage were small relative to the energy used by evaporation except during a few periods in the spring and autumn when the temperature was changing rapidly and in the winter when evaporation rates were low.

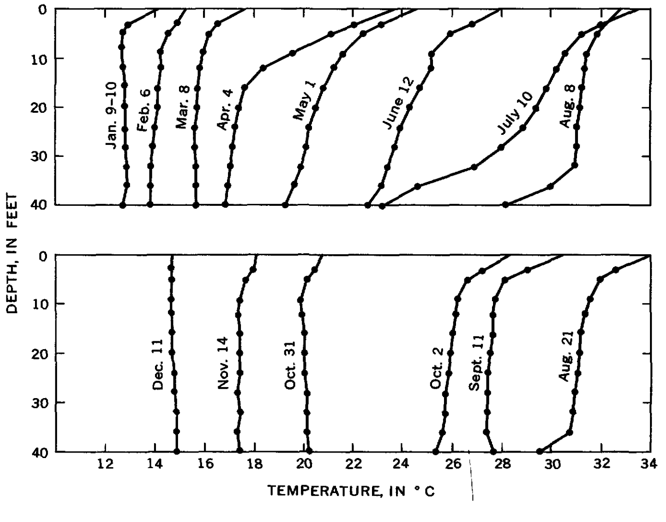

FIGURE 52.—Selected temperature profiles of Salton Sea illustrating seasonal changes of water temperature, 1961.

NET ENERGY ADVECTED (Q_V) INTO SALTON SEA

As there was neither surface-water nor ground-water outflow from Salton Sea, the advected energy term, Q_v, consisted only of heat added by inflowing water. Inflow to the sea consisted of drainage from irrigated lands, runoff from nonirrigated lands, rainfall on the water surface, and ground-water seepage. Methods of measuring or estimating each of these inflow components are described in the section on water budget. Although the volume of inflow was substantial, the advected energy per unit area was relatively small because the surface area was large.

In principle, the temperature as well as the volume of each inflow component is needed to determine the advected-energy term. Actually, however, a mean temperature representing inflow from only the principal sources was used for the total inflow, even though the temperature of inflow from other sources may have differed by several degrees. The mean temperature selected was that of the New and Alamo Rivers, which together contributed more than 80 percent of the total inflow. The resulting error in computed evaporation is negligible because the advected-energy term is relatively insignificant in the overall energy budget for the sea.

Temperature of the water in each river was measured once weekly during the first 8 months of the study and twice weekly thereafter, generally during daylight hours. For a complete year, the average of all these temperature measurements probably would be close to the average for all inflow because seasonal temperature fluctuations were adequately sampled. However, the average temperature for the relatively short energy-budget periods could not be reliably determined with only one or two measurements a week because of diurnal and other short-term temperature fluctuations. Consequently, a parameter that was measured continuously and that correlated well with the water temperatures was sought as the basis of more reliable temperatures for the budget periods.

The average of water temperatures obtained periodically during energy-budget periods were found to correlate reasonably well with the average air temperature recorded at Sandy Beach during the same periods (fig. 53). The apparent linear relation between the two temperatures is approximated by the equation:

$$T_w = 1.5 + 0.83T_a, \qquad (4)$$

where T_w and T_a are the temperatures of water and air, respectively, in degrees centigrade.

Hence, the temperatures applied to the total volume of inflow to compute advected energy were estimated from the air temperatures at Sandy Beach according to equation 4. The specific heat and density values for pure water were applied in these computations, and they were considered to be constant.

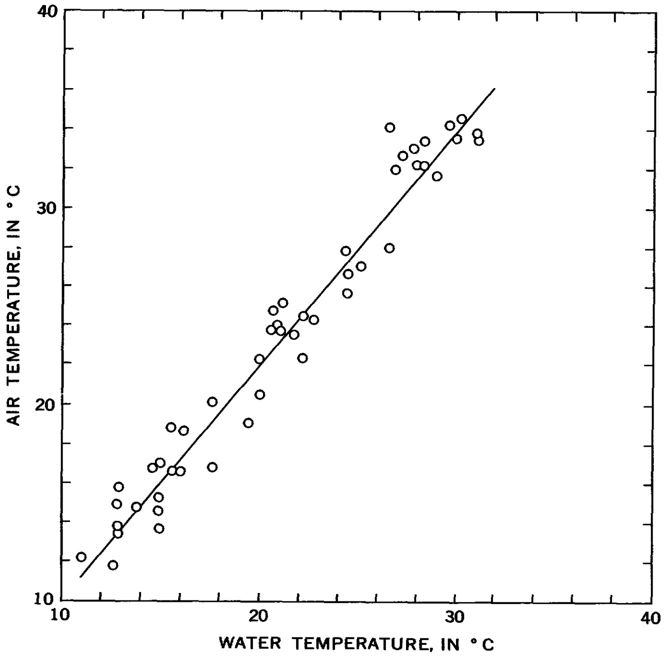

FIGURE 53.—Relation between the average of water temperatures measured periodically at New and Alamo Rivers and the average air temperature recorded continuously at Sandy Beach, for energy-budget periods.

SENSIBLE-HEAT TRANSFER BETWEEN AIR AND WATER (Q_h)

The solution of the energy-budget equation depends on a determination of the ratio of the sensible-heat exchange between air and water to the energy used by evaporation from the water surface. Bowen's (1926) expression of this ratio, shown by the Lake Hefner studies to be satisfactory for use in evaporation computations, is as follows:

$$R = 0.61\left(\frac{T_0 - T_a}{e_0 - e_a}\right)\frac{P}{1000}, \qquad (5)$$

in which

T_0 = temperature of the water surface, in degrees centigrade,
T_a = temperature of the air, in degrees centigrade,
P = atmospheric pressure, in millibars,
e_0 = vapor pressure of saturated air at the temperature of the water surface, in millibars, and
e_a = vapor pressure of the air, in millibars.

Values of e_0 for Salton Sea were obtained from standard vapor pressure tables for a sodium chloride solution approximately equal in concentration to the water of Salton Sea (Harbeck, 1955). The values of T_0 were the same as those used to compute long-wave radiation emitted by the water surface (p. 156). Daily values of T_a and e_a were determined for air at Sandy Beach from dry- and wet-bulb temperatures measured about 6 meters above land surface (about 8 m above the surface of the Salton Sea). The Bowen ratio was computed for each energy-budget period by using average values of temperature and vapor pressure and the standard atmospheric pressure corresponding to the altitude of the Salton Sea.

Dry- and wet-bulb temperatures were obtained by means of thermocouple psychrometers similar to those used at Lake Mead and Lake Hefner, except that small suction fans were added to assure sufficient air movement past the wick-covered wet-bulb thermocouple during calm periods. Amplified thermocouple outputs were recorded by a recording milliammeter. An ice bath, replenished twice weekly, provided a constant reference temperature of 0° C for the thermocouple outputs. Twice-weekly servicing also maintained sufficient distilled water in the wet-bulb reservoirs and kept the wet-bulb wicks free of dust.

Comparison of recorded air temperatures with readings by a conventional mercury thermometer revealed that the values indicated by the recording milliammeter were substantially in error—the error increasing nonlinearly with temperature. The temperature-error relation was reasonably consistent, however, and satisfactory corrections based on this relation were made until April 18, 1961, when the recording of dry- and wet-bulb temperatures was switched to the Honeywell recorder to eliminate the need for such corrections.

The recorded dry- and wet-bulb temperatures were verified twice weekly by means of a small portable psychrometer aspirated by an electrically powered suction fan. These verification readings commonly agreed with corresponding values from the Honeywell recorder within 0.5°C. The records of dry- and wet-bulb temperatures were complete for 96 percent of the total study period.

The precision required in determining the ratio of sensible-heat transfer to the energy used by the evaporation depends to a large extent on the magnitude of the ratio. When the ratio is small relative to unity, an error in its determination results in a much smaller error (percentagewise) in the computed evaporation, as noted by Anderson (1954, p. 106). Hence, whether or not all of the assumptions underlying Bowen's expression for this ratio are entirely correct matters little so long as the ratio remains small.

Because the temperature of the Salton Sea responded rather quickly to seasonal changes in air temperature, the temperature difference between the air and the water surface ordinarily was small, commonly less than 2°C (fig. 54). Because of the warm climate, the vapor pressure of saturated air at the temperature of the water surface was large in relation to the vapor pressure of the ambient air during the entire year (fig. 55). As a consequence of these two relationships, the Bowen ratio tended to be small throughout the study period. Mean values ranged from -0.10 to $+0.10$ for 80 percent of the energy-budget periods; the extremes among all periods were -0.15 and $+0.20$. Daily values were larger, as would be expected, but ordinarily they were between -0.3 and $+0.3$; most of the exceptions occurred during the winter. If the measured parameters used to derive these values truly represented conditions at Salton Sea, any error in the computed evaporation that might be attributed to the use of Bowen's ratio presumably would not be appreciable.

In the preceding discussion of long-wave radiation emitted by Salton Sea, it has been inferred that the water-surface temperatures at the two buoys adequately represented the temperature of the total water surface, T_0; hence, values of e_0 also may be assumed to be representative. However, before the same assumption may be made regarding T_a and e_a, the temperature and humidity of air at Sandy Beach must be considered. Koberg (1958) showed that the energy budget for Lake Mead was little affected when values representing the temperature and humidity of air at different places were used in the Bowen ratio. Data applied were those for the barge anchored near the center of Boulder Basin (2- and 8-meter levels) and for the Las Vegas Airport. Temperature and humidity at Las Vegas Airport were considered to represent unmodified air in the vicinity of Lake Mead, after appropriate adjustment was made for difference in altitude. Air at the barge was modified to a different degree at each level, but its representativeness did not vary with wind direction.

At Sandy Beach, however, air may or may not be modified by the Salton Sea, depending on the direction

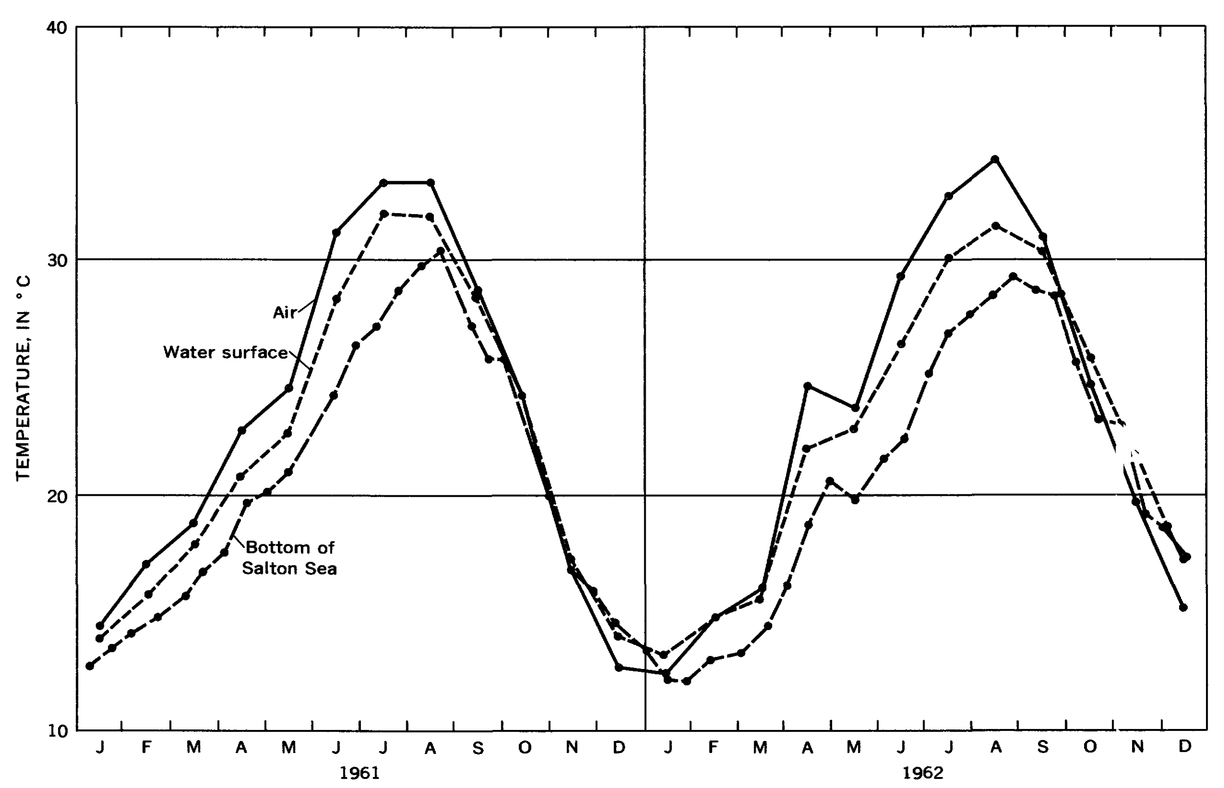

FIGURE 54.—Monthly mean air temperature at Sandy Beach, monthly mean water-surface temperature of Salton Sea, and mean temperature of water at the bottom of the sea during thermal surveys.

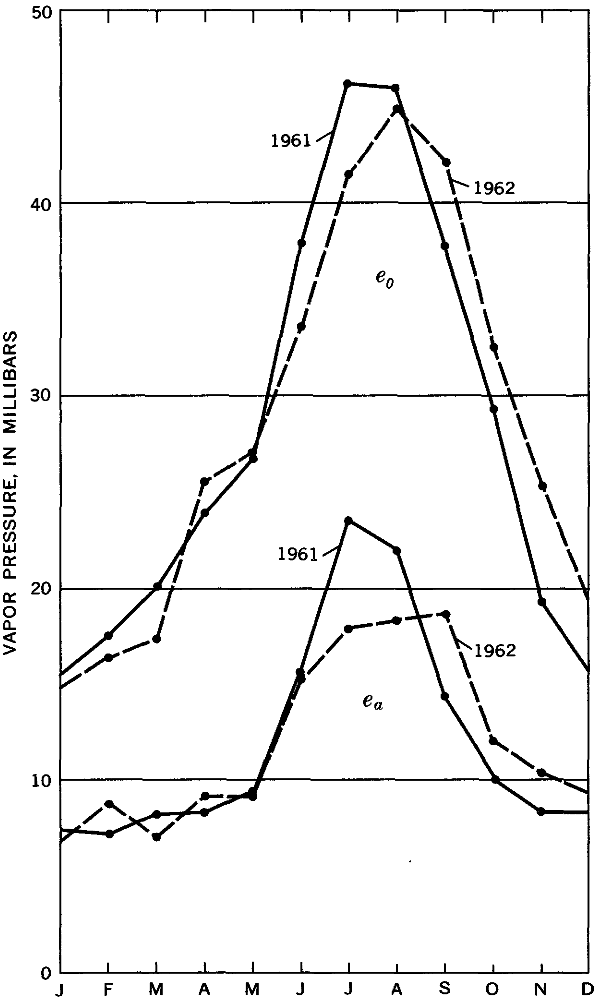

FIGURE 55.—Monthly average vapor pressures of air at Sandy Beach (e_a) and of saturated air at the temperature of the surface of Salton Sea (e_0).

of the wind. Although wind direction and velocity varied appreciably during periods lasting several days, the pattern of such variations differed seasonally. Hence, energy-budget evaporation rates based on measurements of the air at Sandy Beach might be expected to be biased seasonally.

Because the environments are similar and the two places are relatively close to each other, the temperature and humidity of air at Yuma, Ariz., may be assumed to represent unmodified air at Salton Sea. Thus, the degree of possible bias due to using data for Sandy Beach in energy-budget computations for the sea can be evaluated by substituting, in equation 5, values of T_a and e_a derived from data published by the U.S. Weather Bureau for Yuma. With Bowen ratios so revised, the evaporation rates computed for the 48 energy-budget periods differed from those in table 1 by an average of only 2 percent. The difference was greater than 2 percent in 11 of the periods, but it did not exceed 6 percent in any period. Seasonal bias of the differences was not evident. Thus, for periods lasting several days, the seasonal variation in the influence of the sea on the average temperature and humidity of air at Sandy Beach presumably was not great enough to be reflected as seasonal bias in the energy-budget evaporation rates.

TRANSFER OF HEAT THROUGH THE BOTTOM OF SALTON SEA

The transfer of heat through the bottom of the water body has been considered to be negligible in other studies of evaporation and was not included in computations of evaporation from Salton Sea. However, comparisons of evaporation from the sea computed by different methods suggest a seasonal bias in some of the data. As heat transfer through the bed could contribute to such bias, the probable rates of heat transfer (heat flux) were investigated.

The amount of energy conducted through the bed owing to the ordinary geothermal gradient of the earth's crust would be negligibly small in energy-budget determinations of evaporation. On the other hand, for periods lasting several days, heat flux through the bed due to the seasonal variation in water temperature may be significant in the energy budget of a water body, even though net flux for a year is negligible.

Heat flux through the bed may be assumed to vary with the deviation of the bottom water temperature from its mean value and with the thermal conductivity and heat-storage capacity of the bed materials in which changes of heat storage take place. Fluctuations of bottom water temperature would tend to diminish with increasing depth of the water body; ordinarily, the fluctuation is small for water bodies 100 feet or more deep. Shallow water bodies, however, may be mixed almost completely by wind- or thermal-induced currents and, as a result, the range of temperature variation at the bottom may approach that of the monthly mean air temperature at the surface.

The seasonal variation of water temperature at the bottom of Salton Sea is shown in figure 54. As the graph of bottom water temperature is approximated by a sine curve having an amplitude of about 8° C and a period of one year, simple heat-flow theory as described by Pearce and Gold (1959), may be applied to estimate the heat flux through the bed of the sea.

Where periodic heating at the surface of a semi-infinite homogeneous medium is sinusoidal, the heat-flux distribution is defined by the following equation:

$$q=akT_se^{-ax}\sin\left(\omega t+\phi+\frac{\pi}{4}-xa\right), \qquad (6)$$

in which

q=heat flux at distance x at time t, in cal cm^{-2} sec^{-1},
$a=\sqrt{\frac{\pi C_v}{Pk}}$,
C_v=volumetric heat capacity, in cal cm^{-3} °C^{-1},
k=thermal conductivity, in cal cm^{-1} sec^{-1} °C^{-1},
P=period of the temperature variation, in seconds,
$\omega=\frac{2\pi}{P}$, in radians sec^{-1},
T_s=amplitude of the temperature variation at the surface, in degrees centigrade, and
ϕ=phase angle of the temperature variation at the surface, depending on choice of zero time, in radians.

For the condition of maximum heat flux at the surface ($x=0$), equation 6 simplifies to

$$q\,\max=T_s k\sqrt{\frac{2\pi C_v}{Pk}}. \tag{7}$$

As deduced from heat-flow theory and the known fluctuation of the bottom temperature of Salton Sea (fig. 54), maximum heat flux from the water into the bed of the sea occurred about the first of July and the maximum flux from the bed into the water occurred about mid-December. Each date is about 45 days before the bottom water of the sea reached its maximum or minimum temperature, respectively. Similarly, there was no heat flux at the bed near mid-April and mid-September.

Values of k and C_v for the bottom material of Salton Sea are not available from direct measurements; however, values for ocean floor sediments and sandy-silt or clay soil having a high water content should be applicable. Pearce and Gold (1959, p. 1296) computed values of 0.00235 cal cm^{-1} sec^{-1} °C^{-1} and 0.77 cal cm^{-3} °C^{-1} for k and C_v, respectively, from measurement of temperature and heat flux in a "Leda Clay" soil of relatively high water content. These values agree closely with corresponding values for "wet marshy soil" by Geiger (1959, p. 28) and values of k alone given for ocean floor sediments by several investigators (Gerard and others, 1962, p. 785–802; Von Herzen and Uyeda, 1963, p. 4226; Uyeda and others, 1962, p. 1186). A maximum of 13 cal cm^{-2} day^{-1} was computed for heat flux at the bottom of Salton Sea by substituting, in equation 7, values given by Pearce and Gold for k and C_v and a value of 8° C for T_s.

Including a heat-flux term having such a maximum value in the energy budget of Salton Sea would have decreased computed evaporation (table 1) for the period mid-June to mid-July by an average of almost 3 percent and would have increased that for December by almost 20 percent. Accordingly, the precision of energy-budget evaporation rates for shallow water bodies can be improved for weekly or monthly periods by including a term for heat flux at the bed.

MASS-TRANSFER METHOD

Evaporation from a water surface can be treated as the turbulent transport of water vapor in the overlying boundary layer in accordance with mass-transfer theory. A simplified empirical equation that retains the fundamental principles of this concept was formulated by Marciano and Harbeck (1954) in the Lake Hefner studies. An equation of the same type was used in the Salton Sea study, as follows:

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

where

E=rate of evaporation, in inches per day,
N=an empirical coefficient,
u=average wind speed, in miles per hour,
e_0=average vapor pressure of saturated air at the temperature of the water surface, in millibars, and
e_a=average vapor pressure of the air, in millibars.

Equation 8 relates evaporation to measured parameters that reflect the movement of air over a water surface and the capacity of the air to take up moisture from the water surface. The coefficient, N, represents the combined effect of all other factors that may influence evaporation. At present, an accurate determination of N for a specific water body depends on independent measurement of the evaporation. However, experience suggests that future studies employing standardized measuring techniques may lead to empirical relations from which an approximate coefficient can be determined without resort to other measurements of evaporation.

The coefficient, N, for Salton Sea was determined to be 0.00156 from the average results of the energy- and water-budget determinations for the 2-year study divided by the average value of the product, $u(e_0-e_a)$, for the same period. The coefficient thus derived applies with certainty only to Salton Sea and only when base data are obtained at points essentially the same as those used during the study.

The wind speed used in equation 8 was measured 2 meters above the water surface by anemometers mounted on the two buoys located as shown in figure 48. The anemometer bearings were cleaned and oiled biweekly and apparently remained in good condition. The mechanical counter of the anemometer at the south buoy jammed twice, resulting in loss of record for two periods of about 1 month each. There was no loss of record at the north buoy. Estimates of wind speed at the south buoy for periods of no record were based on the wind speed data for Sandy Beach.

Anemometer counters usually were read only on days when thermal surveys were made; therefore, the average wind speed at the buoys could be determined precisely only for the energy-budget periods previously described. Average values of e_0 and e_a, from which the vapor-pressure difference was computed, also were determined for energy-budget periods as described in the section on the sensible-heat transfer (p. 159). Consequently, it was most convenient, as well as desirable, to compute evaporation by equation 8 for the same periods so that results for the two methods would be directly comparable.

APPLICATION TO PERIODS OTHER THAN THE CALIBRATION PERIOD

As the mean mass-transfer coefficient, N, was determined from data for the 2-year period, it should apply to any year-long period. For periods shorter than a year, however, its use would produce consistent results only if the parameters, as measured, represented conditions for Salton Sea with equal faithfulness during all periods. This restrictive requirement might not have been satisfied by data for periods lasting only a few days, because of inadequate sampling of variable meteorologic conditions provided by the relatively small number of instruments used; however it may have been satisfied by data for periods as long as those used for the evaporation computations.

The average wind speed at each of the two buoys undoubtedly represented wind movement over a large part of Salton Sea. Consequently, the mean wind speed for the two buoys probably always represented the entire Salton Sea even though speeds at the two buoys at times differed appreciably (fig. 56). Similarly, the temperature measurements at the two buoys, from which values of e_0 were derived, probably were representative (p. 157). The same is not necessarily true of values for e_a, however, because the influence of the Salton Sea on the temperature and humidity of air at Sandy Beach varied with wind direction, which tends to vary with the season.

The discussion of the energy-budget method arrived at the conclusion that the representativeness of the vapor-pressure difference (e_0-e_a) was about the same during most energy-budget periods. However, in the energy-budget method the vapor-pressure difference appeared only in the Bowen ratio, which functioned as a small corrective term. In the mass-transfer method, to the contrary, evaporation is directly pro-

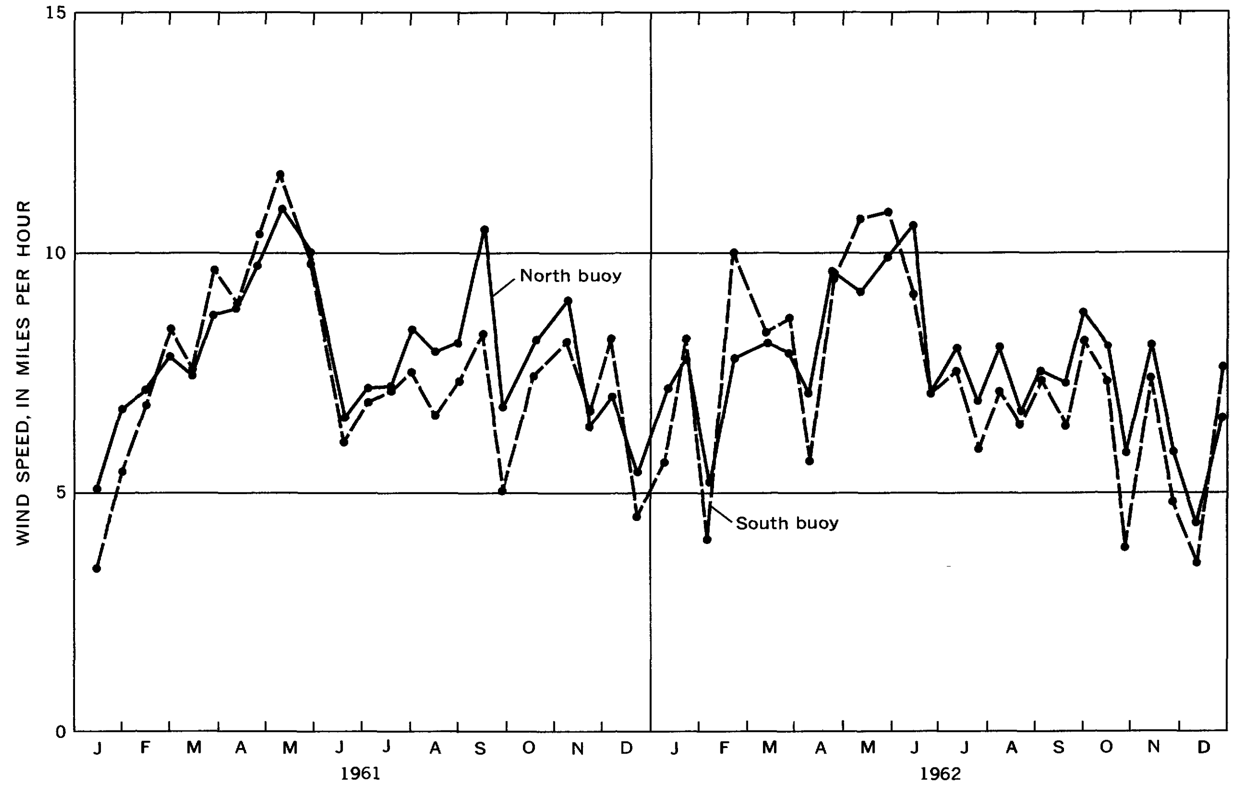

FIGURE 56.—Average wind speeds for energy-budget periods as measured at two buoys in Salton Sea, 1961-62.

portional to vapor-pressure difference (eq 8). Accordingly, pronounced seasonal bias might be introduced through the e_a term.

As a means of appraising how large such seasonal bias might be, values of e_a for Yuma, Ariz. (fig. 50), were substituted in equation 8 for those observed at Sandy Beach. Leaving u and e_0 unchanged, a new coefficient (N) was computed, and the evaporation for energy-budget periods was redetermined accordingly. Figure 57 compares these results with those derived from values of e_a at Sandy Beach. Slight seasonal bias is apparent. However, the difference for individual budget periods averaged less than 6 percent and exceeded 10 percent in only eight periods.

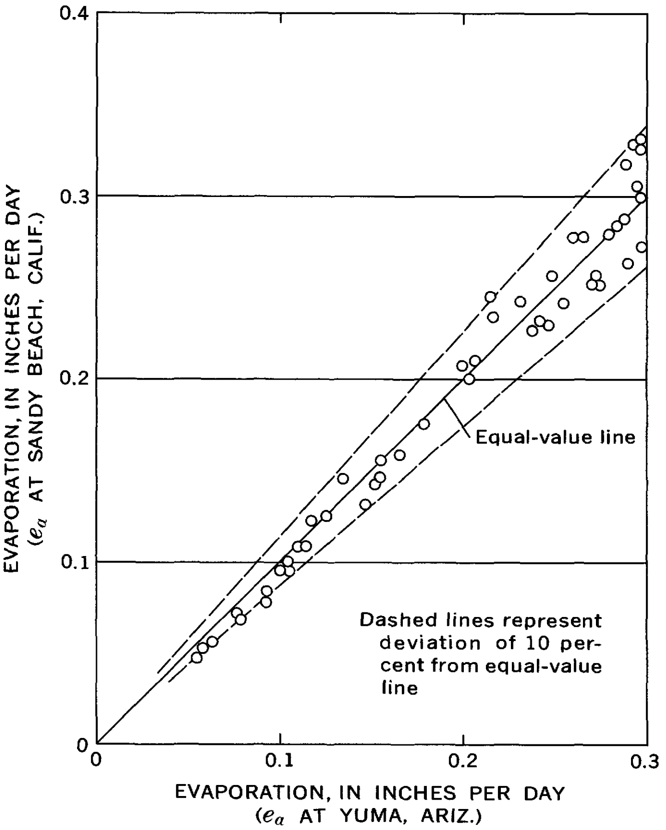

FIGURE 57.—Relation between evaporation from Salton Sea by the mass-transfer method based on the vapor pressure of air at Sandy Beach and that based on the vapor pressure of air at Yuma, for energy-budget periods.

WATER-BUDGET METHOD

As Salton Sea has no outflow except by evaporation, the water-budget equation can be written as follows:

$$I-E=\Delta C, \tag{9}$$

where

I=inflow from all sources,
E=evaporation, and
ΔC=increase in stored water.

Hence, evaporation can be determined by an evaluation of the other two terms. Successful application of this method depends on the relative magnitudes of the individual terms, as well as on the relative accuracy of the measured terms, because the computed evaporation term contains the residual of errors in all other terms. Fortunately, several conditions at the Salton Sea were favorable for a reasonably accurate determination of evaporation by the water-budget method. Evaporation was nearly equal to total inflow; the principal sources of the inflow were adequately measured; changes in volume, which were relatively small, were adequately determined; and rainfall occurred infrequently and was of small consequence.

Water enters Salton Sea from three sources: surface inflow from irrigation drains and natural streams, subsurface seepage, and precipitation on the water surface.

SURFACE INFLOW

Drainage from irrigated land in Imperial and Coachella Valleys was by far the largest source of inflow. Most of the drainage from Imperial Valley entered Salton Sea through New and Alamo Rivers (fig. 48) but substantial amounts entered the sea directly from more than 30 minor channels. Whitewater River contributed more than half the surface drainage from Coachella Valley, 18 minor channels contributed the remainder. San Felipe Creek and Salt Creek, the principal tributaries from nonirrigated land, contributed small amounts of surface inflow to Salton Sea.

The instrumentation and procedures used to measure or estimate surface-inflow items are described in another report (Hely and others, 1966). Amounts of surface inflow shown in table 2 were taken from that report. Of the total amount shown, 91.5 percent was measured at recording gages, 6.5 percent was estimated from periodic measurements, and only 2 percent was ungaged. Table 3 shows the annual contributions of the principal tributaries.

TABLE 2.—*Yearly surface inflow to Salton Sea, in acre-feet, 1961–62*

Contributing area	1961	1962
Imperial Valley	1, 242, 000	1, 280, 000
Coachella Valley	83, 890	112, 700
Other	10, 200	9, 850
Total	1, 336, 000	1, 403, 000

For this report, computations of evaporation by the water-budget method are for periods defined by the dates of thermal surveys (p. 157), rather than months, so that results by all three methods can be compared directly. The assumptions required to estimate the

TABLE 3.—*Yearly surface inflow to Salton Sea from tributary streams with continuous streamflow records, in acre-feet, 1961–62*

Stream	1961	1962
Alamo River	675, 500	681, 300
New River	437, 000	455, 300
Whitewater River	53, 390	69, 590
Salt Creek	3, 470	4, 420
San Felipe Creek	1, 130	374
Five minor channels	30, 350	31, 480
Total	1, 201, 000	1, 242, 000

9.5 percent of the surface inflow that was not continuously recorded probably were about as valid for energy-budget periods as for the monthly periods used in making the estimates. Consequently, little reliability was sacrificed by the choice of periods used for the water-budget computations.

SUBSURFACE INFLOW

On the basis of estimates of subsurface inflow from Coachella Valley, made by the California Department of Water Resources (1964), and of preliminary estimates of subsurface inflow from other contributing areas, made by the U.S. Geological Survey, Hely, Hughes, and Irelan (1966) concluded that the total ground-water inflow to Salton Sea was about 50,000 acre-feet yearly. As this inflow is less than 4 percent of the surface inflow, a large percentage error in the estimate would have little effect on the computed evaporation. Subsurface inflow was assumed to occur at a uniform rate during the year.

RAINFALL ON THE WATER SURFACE

The average rainfall on Salton Sea was assumed to be equal to the average rainfall at three recording rain gages located on the shore at Sandy Beach, Imperial Salt Farm, and Devils Hole. The average of rainfall measured at three U.S. Weather Bureau stations near the sea (Niland, Mecca, and Ocotilla Wells) was about the same as that of the three stations on the shore.

Table 4 shows that rainfall on the water surface was an insignificant item of the water budget for Salton Sea, amounting to only 32,700 acre-feet in 1961 and 23,200 acre-feet in 1962. As the total rainfall for a month commonly occurred in a single storm period lasting only 1 or 2 days, only a few budget periods were affected by rainfall.

TABLE 4.—*Recorded monthly rainfall of three gages at Salton Sea, in inches, 1961–62*

[Records furnished by Imperial Irrigation District. No rain recorded in January 1963]

Month	1961				1962			
	Sandy Beach	Devils Hole	Salt Farm	Average	Sandy Beach	Devils Hole	Salt Farm	Average
Jan	0. 25	0. 05	0. 26	0. 19	0. 70	0. 05	0. 74	0. 50
Feb	0	0	0	0	. 11	. 10	. 07	. 09
Mar	. 04	. 06	0	. 03	. 05	. 05	0	. 03
Apr	0	0	0	0	0	0	0	0
May	0	0	0	0	0	0	0	0
June	0	0	0	0	0	0	0	0
July	0	0	0	0	0	0	0	0
Aug	1. 75	. 15	. 65	. 85	0	0	0	0
Sept	0	0	. 20	. 07	. 20	0	0	. 07
Oct	0	0	0	0	0	. 15	0	. 05
Nov	0	. 03	0	. 01	0	0	0	0
Dec	. 65	. 57	. 60	. 61	. 61	. 40	. 48	. 50
Total	2. 69	. 86	1. 71	1. 76	1. 67	. 75	1. 29	1. 24

WATER LEVEL

A record of water level and a relation between water level and the volume of Salton Sea were required to determine the change in volume during each budget period.

Continuous records of water level were obtained at three points on Salton Sea—Sandy Beach, Desert Beach, and Imperial Salt Farm (fig. 48). The recording gages at Desert Beach and Imperial Salt Farm were adjusted to the datum of the previously existing gage at Sandy Beach by reference to the water level during a period of sustained calm. After this adjustment, the average daily water-level readings at the three gages usually were within 0.01 foot of a mean value during periods of relative calm and within 0.10 foot during windy periods. Instantaneous values sometimes differed appreciably, however, because wind-induced surface oscillations (seiches) were not in phase at the three places. The period of the seiches was about 3.2 hours and the amplitudes commonly were less than 0.05 foot but were as large as 0.50 foot following high winds. Definition of the water level at the beginning and the end of energy-

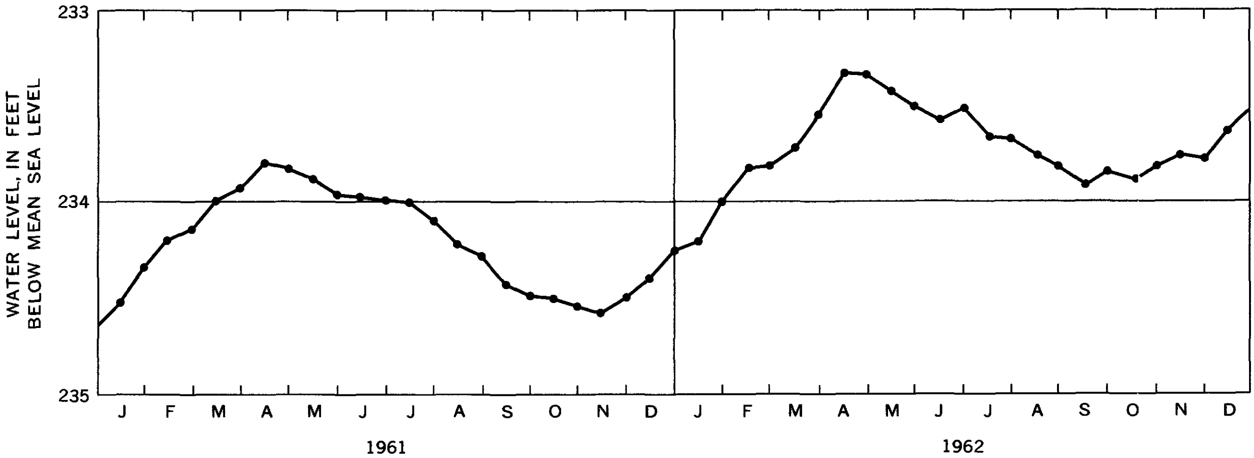

FIGURE 58.—Water level of Salton Sea at midmonth and at end of month, 1961–62.

budget periods was unaffected by inaccuracies due to winds because all energy-budget periods necessarily began and ended on days of relative calm.

The water level of the sea changed slowly and varied within a range of about 1 foot, as indicated in figure 58. Daily changes of the average water level usually were less than 0.02 foot; thus, for energy-budget periods the average water levels for the beginning and ending days were considered to be satisfactory for determining changes in volume of the sea.

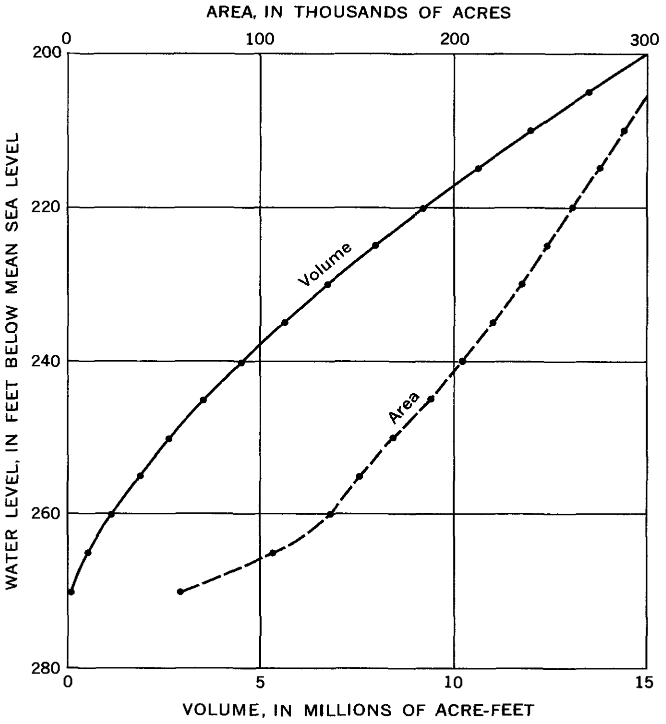

FIGURE 59.—Relations of area and volume to water level of Salton Sea. (From relations dated February 1958 and used prior to 1965.)

CHANGE IN VOLUME

Relations of area and volume to the water level of Salton Sea (fig. 59) applied in this report were derived from U.S. Geological Survey photogrammetric maps for altitudes above −240 feet. For lower altitudes, the relations probably were based on surveys made prior to 1905, but the source of the data used could not be ascertained. However, the general reliability of the relations in this range was confirmed from soundings made in 1962 by Shawn Beihler of California Institute of Technology (in Hely and others, 1966).

CORRECTION FOR THERMAL EXPANSION

The computed change in volume of the Salton Sea was adjusted for effects of thermal expansion of water by a method similar to that described in the Lake Hefner report (U.S. Geological Survey, 1954, p. 19). The average adjustment for all periods was only 4 percent of the computed evaporation, but adjustments were as large as 13 percent during the spring and autumn when temperature changes were relatively large. The net adjustment for a year was negligible.

COMPARISON OF EVAPORATION DETERMINED BY THE THREE METHODS

Table 5 gives the evaporation determined for Salton Sea by the energy-budget, mass-transfer, and water-budget methods. The yearly evaporation for the study period averaged 72.81 inches computed by the energy-budget method and 70.52 inches by the water-budget method. The mean evaporation for the total study period, as determined by these two methods, was used to compute the mass-transfer coefficient, *N*; hence, a corresponding figure of mean yearly evaporation for the mass-transfer method would not be independently determined. Nevertheless, the distribution of the total evaporation among individual periods

TABLE 5.—*Evaporation from Salton Sea computed by energy-budget, water-budget, and mass-transfer methods, and evaporation from class A pan at Sandy Beach*

Period	Number of days in period	Evaporation (inches)			
		Energy budget	Water budget	Mass transfer	Class A pan
1961–62					
Jan. 9 to 23	14	0.42	0.67	0.78	----------
Jan. 24 to Feb. 6	13.5	.65	.88	.97	----------
Feb. 6 to 21	15	1.47	1.44	1.62	----------
Feb. 21 to Mar. 8	15	1.81	1.84	2.20	----------
Mar. 8 to 20	12	1.35	1.42	1.73	4.24
Mar. 20 to Apr. 4	15	2.70	2.34	2.62	6.12
Apr. 4 to 17	13	2.95	2.30	2.60	6.04
Apr. 17 to May 1	14	3.82	3.60	3.89	7.96
May 1 to 15	14	3.98	4.03	4.28	8.70
May 15 to June 12	28	8.51	7.20	7.64	16.16
June 12 to 26	14	3.60	3.00	3.16	7.61
June 26 to July 10	14	4.86	3.81	3.89	8.71
July 10 to 24	14	4.23	3.67	3.56	7.21
July 24 to Aug. 8	15	5.28	4.36	4.30	8.08
Aug. 8 to 21	13	3.99	3.28	3.33	6.58
Aug. 21 to Sept. 11	21	7.70	7.71	6.97	12.12
Sept. 11 to 22	11	3.61	3.43	3.07	4.81
Sept. 22 to Oct. 2	10	1.86	1.85	2.07	4.09
Oct. 2 to 31	29	6.40	7.10	6.79	10.44
Oct. 31 to Nov. 14	14	2.37	3.01	2.23	3.45
Nov. 14 to 28	14	1.23	1.37	1.53	2.47
Nov. 28 to Dec. 11	13	.97	1.36	1.31	2.39
Dec. 11 to Jan. 2	22	.75	1.08	1.17	1.85
Total	357.5	74.51	70.75	71.71	----------
1962–63					
Jan. 2 to 15	13	.90	1.40	1.22	2.05
Jan. 15 to 29	14	.67	.77	1.09	2.08
Jan. 29 to Feb. 12	14	.34	.57	.66	1.74
Feb. 12 to Mar. 2	18	2.13	2.36	2.21	4.59
Mar. 2 to 19	17	2.11	2.11	2.12	4.65
Mar. 19 to Apr. 2	14	1.89	1.50	2.03	4.82
Apr. 2 to 16	14	2.42	1.71	2.18	6.26
Apr. 16 to 30	14	4.07	3.53	3.63	7.28
Apr. 30 to May 17	17	5.42	5.07	5.10	9.85
May 17 to June 4	18	5.09	4.57	4.52	10.42
June 4 to 18	14	4.69	3.75	3.71	8.40
June 18 to July 2	14	3.65	3.08	3.39	9.32
July 2 to 16	14	5.04	4.30	3.98	9.56
July 16 to 30	14	4.06	3.44	3.23	7.77
July 30 to Aug. 13	14	4.87	4.38	4.63	9.29
Aug. 13 to 27	14	3.83	3.44	3.39	7.97
Aug. 27 to Sept. 10	14	4.43	4.17	4.24	7.31
Sept. 10 to 24	14	3.47	3.26	3.44	6.81
Sept. 24 to Oct. 7	13	3.71	4.22	4.12	5.29
Oct. 7 to 22	15	2.94	3.58	3.54	4.97
Oct. 22 to Nov. 5	14	1.25	1.47	1.83	3.50
Nov. 5 to 20	15	2.26	3.09	3.16	3.73
Nov. 20 to Dec. 3	13	.65	1.40	1.08	1.89
Dec. 3 to 17	14	.35	.92	.97	1.67
Dec. 17 to Jan. 8	22	.87	2.20	2.09	2.59
Total	372	71.11	70.29	71.56	143.81

within the study period that is provided by the mass-transfer method is entirely independent of that for the water-budget method and is nearly independent of that for the energy-budget method because factors common to both the energy-budget and mass-transfer equations do not affect the computed evaporation to the same degree.

The agreement among evaporation rates determined by different methods for periods ranging in length from 10 to 29 days is much less satisfactory than the agreement among annual rates. Figure 60 indicates the seasonal variation in evaporation rates by the three methods. Appreciable spread among rates for occasional periods might be expected because of random errors in the measurements or estimates utilized in each method, but some of the discrepancies shown tend to follow a seasonal pattern.

Figure 61 shows that energy-budget evaporation rates generally were less than water-budget rates during periods of low evaporation and greater during periods of high evaporation. Figure 62 shows the same relative bias by a comparison of energy-budget evaporation rates and corresponding values of the mass-transfer product, $u(e_0-e_a)$, used in equation 8. In contrast, figure 63, which plots the same mass-transfer products against water-budget rates, does not indicate seasonal bias.

As the water-budget and mass-transfer results were in satisfactory agreement for at least two-thirds of the periods involved, they were averaged to provide a basis for further study of the seasonal bias that seemingly is inherent in the energy-budget results.

Figure 64 shows the differences between the energy-budget rates and the average of the water-budget and mass-transfer rates, expressed as the energy required to evaporate an equivalent amount of water and as percentages. These differences, because they are so large, must be caused chiefly by errors in one or more of those energy-budget terms that consistently are relatively large, such as, solar radiation, Q_s, atmospheric radiation, Q_a, and long-wave radiation emitted by the water, Q_{bs}.

If the differences in figure 64 were to be ascribed entirely to the effect of error in the water-surface temperature on the computed long-wave radiation emitted by the water (Q_{bs}), that error would have to be as great as 8°C and, disregarding sign, would have to average 4°C. The average range of the water-surface temperatures taken during individual thermal surveys was only 3.3°C, and correlation between these readings and the temperatures recorded at the two buoys was reasonably close (fig. 51). It is doubtful, therefore, that error in the average surface temperature could have exceeded 1 or 2°C in any period.

J. T. Gier and R. V. Dunkle (in U.S. Geological Survey, 1954, p. 96–98) showed that for a range in temperature that applies to natural water bodies in the Southwest, the emissivity of water for long-wave radiation does not vary with temperature of the water. They also showed that the emissivity changes when the water surface is contaminated by an oil film. At Salton Sea, however, no such film was noted on the surface, and the surface of the sea did not appear abnormal in any way. Consequently, the apparent seasonal bias in the evaporation by the energy-budget method cannot reasonably be attributed to the emitted radiation term.

Owing to the manner in which the components of incoming radiation, Q_a and Q_s, were used in the energy-budget computations, a relatively large error in measured solar radiation, Q_s, has little effect on the accu-

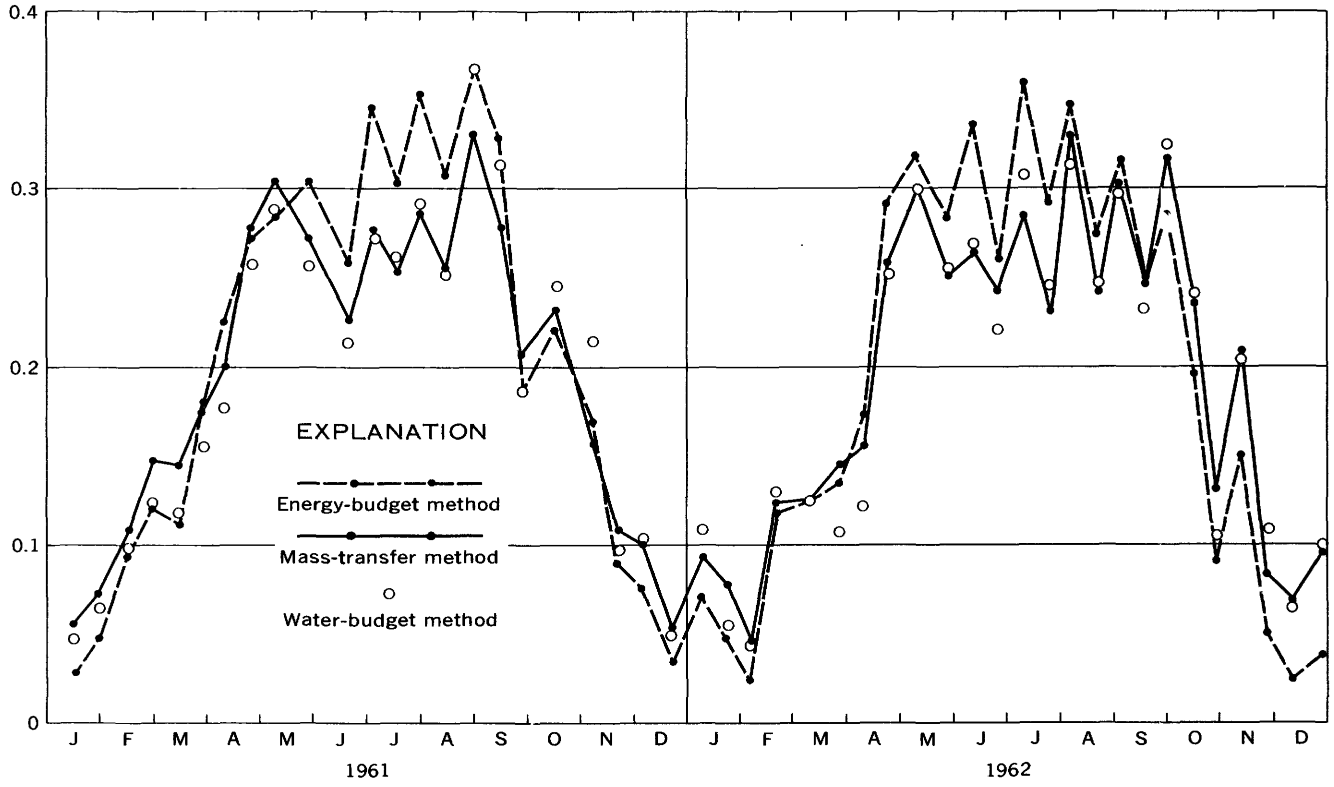

FIGURE 60.—Evaporation from Salton Sea by three methods for energy-budget periods.

racy of the computed evaporation. For insertion in equation 3, atmospheric radiation, Q_a, was computed as measured total incoming radiation minus measured solar radiation, Q_s. However, Q_s appears in the same equation as a plus term, and thereby eliminates almost all effect of any possible error in Q_s. Some slight effect remains, however, because any incorrect distribution of the total incoming radiation between Q_s and Q_a causes some error in the reflected-radiation terms, Q_r and Q_{ar}. These terms were computed from Q_s and Q_a, respectively, by means of small but slightly different reflectivity coefficients (p. 156). Error in the computed yearly evaporation due to an error of 15 percent in measured solar radiation (table 1), for example, would amount to only 1 percent. In conclusion, therefore, the seasonal bias of the energy-budget results must be attributed largely to the measurement of total incoming radiation.

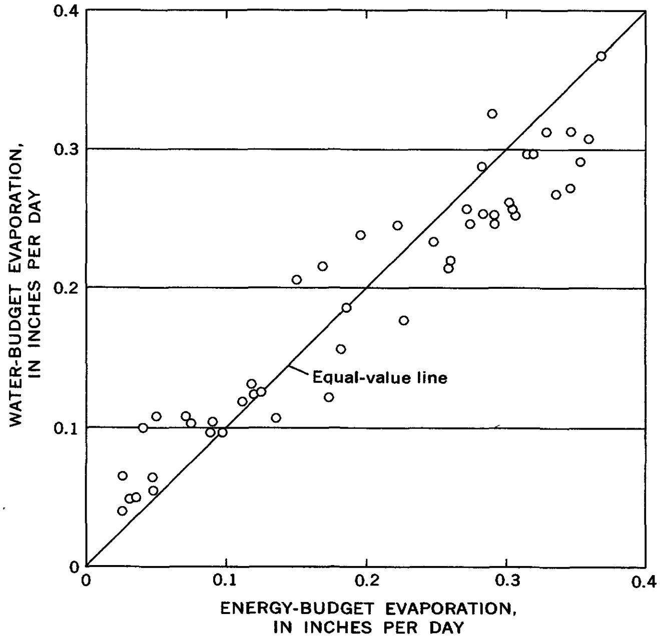

FIGURE 61.—Relation between evaporation (for energy-budget periods) by the energy-budget method and evaporation by the water-budget method.

In regard to the importance of error in measured solar radiation, however, a distinction must be made between methods by which atmospheric radiation is obtained. If, by any means, atmospheric radiation should be determined independently of solar radiation, any error in solar radiation would be fully reflected in the computed evaporation.

Measurements of total incoming radiation by the flat-plate radiometer have not always been reliable. Differences have been noted between measurements of total incoming radiation at Sandy Beach and at Yuma Proving Ground (fig. 49), but apparently these differences were not biased seasonally. Of course,

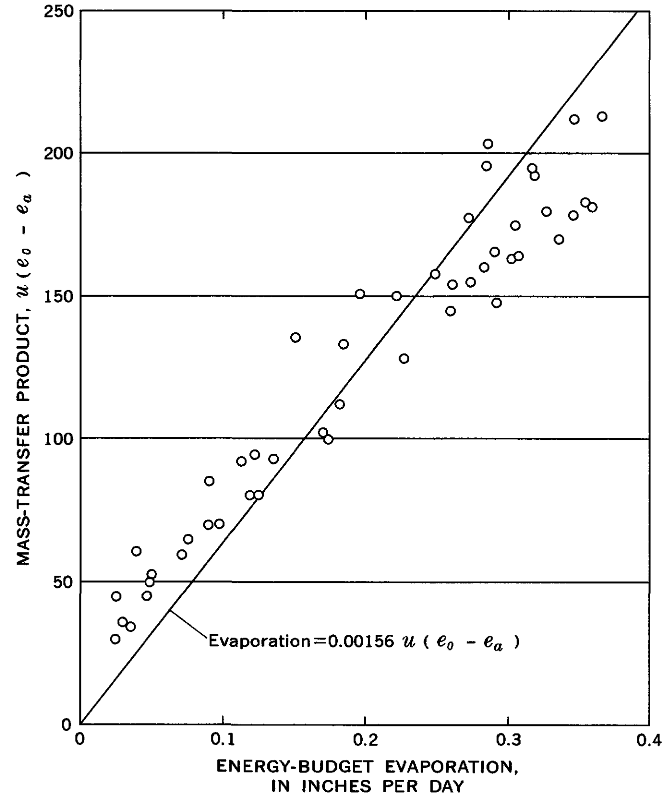

FIGURE 62.—Relation between evaporation (for energy-budget periods) by the energy-budget method and corresponding values of the mass-transfer product, $u(e_0-e_a)$.

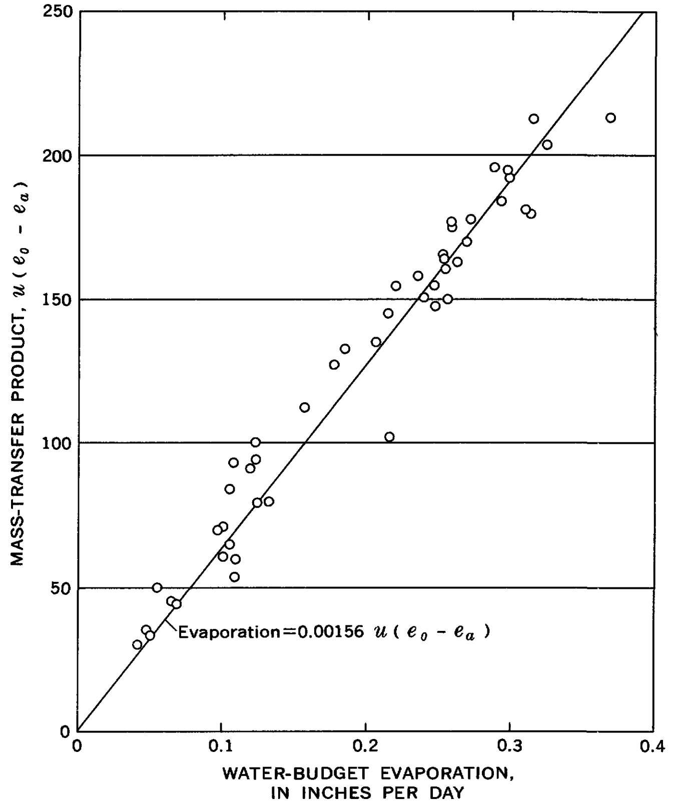

FIGURE 63.—Relation between evaporation (for energy-budget periods) by the water-budget method and corresponding values of the mass-transfer product, $u(e_0-e_a)$.

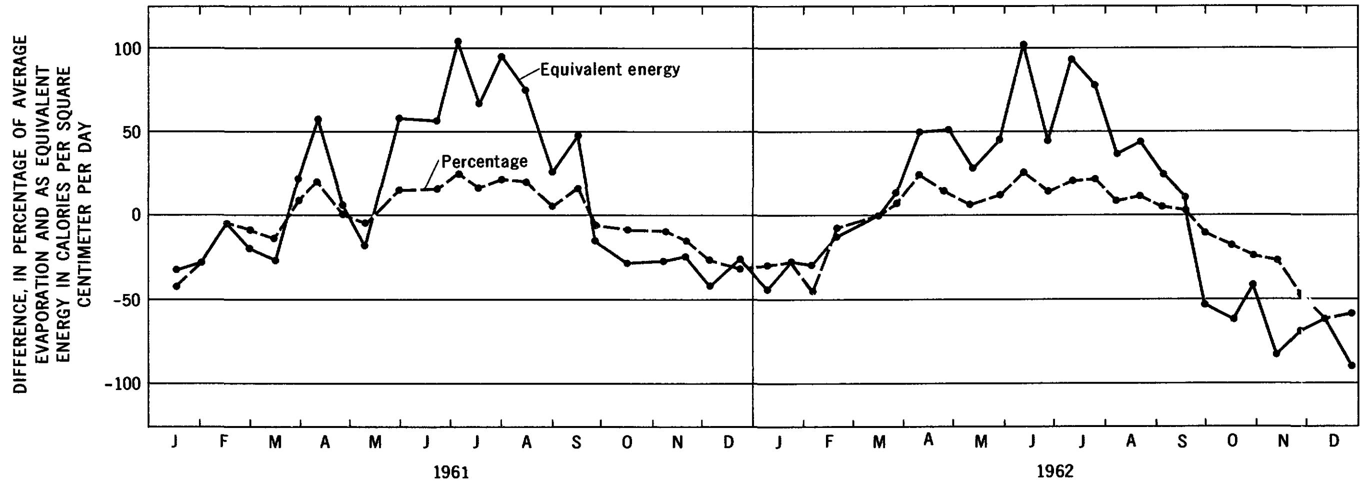

FIGURE 64.—Differences between evaporation (for energy-budget periods) by the energy-budget method and the average of evaporation by the mass-transfer and water-budget methods.

seasonal bias would not be detectable in measurements from identical instruments if the cause of bias were inherent in those instruments.

In the studies at Lake Hefner and at Lake Mead (Anderson, 1954; Koberg, 1958) the determination of atmsopheric radiation as the difference between measured total incoming radiation and measured solar radiation was concluded to be inaccurate. In those studies, therefore, estimates of atmospheric radiation based on nighttime measurements by the flat-plate radiometer were used instead, seemingly with success. In the energy budget for Salton Sea, however, similar use of nighttime measurements by the flat-plate radiometer resulted in winter evaporation rates that were unreasonably small.

Alternative values of the atmospheric-radiation term, Q_a, for Salton Sea were computed independently from measurements of air temperature, humidity, and solar radiation at Sandy Beach, according to the empirical method of Koberg (1964). In this method, measured solar radiation is used to establish an index of cloud cover; the effect of a specific percentage of cloud cover diminishes with increasing air temperature. The air temperatures at Sandy Beach ranked with the highest of those included by Koberg in the formulation of his method; hence, the accuracy of the atmospheric radiation so computed for Sandy Beach depends only slightly on the accuracy of the measured solar radiation.

Figure 65 shows the relation between measured atmospheric radiation (total incoming radiation minus solar radiation) and the corresponding computed values; the measured atmospheric radiation is greater during periods of high radiation and less during periods of low radiation. Differences between measured and computed values (fig. 66), expressed in units of energy, not only are similar in magnitude to equivalent differences between evaporation rates by the energy-budget method and the average of those by the water-budget and mass-transfer methods, but they also vary in a similar seasonal pattern.

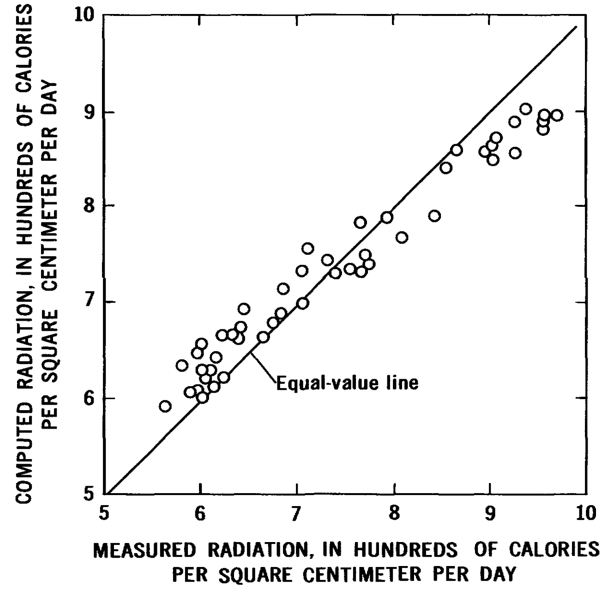

FIGURE 65.—Relation between long-wave atmospheric radiation as measured and that computed by Koberg's method.

Evaporation from Salton Sea was redetermined by the energy-budget method using the values of Q_a computed by the Koberg method. Figure 67 shows these redetermined results plotted against the average from the water-budget and mass-transfer methods and suggests only a slight seasonal bias. The redetermined yearly evaporation differs by less than half of one percent from that shown in table 5.

The better agreement obtained by use of the computed values of atmospheric radiation suggests, but does not prove, that the measured values are in error. Percentagewise, the differences between measured and computed values (fig. 65) were small. The average difference for all periods was less than 4 percent; the maximum less than 10 percent. These differences are no greater than those reported by Koberg (1964) for similar data used in the formulation of his empirical method. The only evidence implying greater reliability of the computed values for Sandy Beach is the reduction of apparent seasonal bias caused by their use. On the other hand, the field performance of the flat-plate radiometer has not been always satisfactory (Koberg, 1964, p. 108).

COMPARISON OF EVAPORATION FROM SALTON SEA WITH CLASS A PAN EVAPORATION

Evaporation from a U.S. Weather Bureau class A pan was measured at Sandy Beach beginning February 28, 1961, and pan evaporation for subsequent energy-budget periods is included in table 5. The annual pan coefficient (ratio of evaporation from the Salton Sea to pan evaporation) was 0.50, based on energy- and water-budget evaporation results for a period of about a year. Pan coefficients for energy-budget periods varied seasonally, those based on the average of mass-transfer and water-budget evaporation ranging from 0.31 to 0.83. No adjustments were made for heat transfer through the sides and bottom of the pan.

The seasonal variation of a pan coefficient may be attributed largely to the temperature lag in the water body that results from the difference in heat storage capacities of a pan and of a larger body of water (Kohler, 1954, p. 148). Hence, the pan coefficients for energy-budget periods should correlate well with corresponding changes in energy storage in Salton Sea that are due only to natural heating by the sun and atmosphere. These changes are the difference between the measured changes in energy storage and the net of advected energy, $Q_\vartheta-(Q_v-Q_w)$, including that associated with the evaporated water. Similar values for the pan might be considered also, but they are extremely small in comparison to the energy used for pan evaporation and may be neglected.

A plot of the term $Q_\vartheta-(Q_v-Q_w)$ versus class A pan coefficients (fig. 68) shows fair correlation when coefficients were determined from either water-budget or mass-transfer data but little correlation when pan coefficients were based on energy-budget data. This

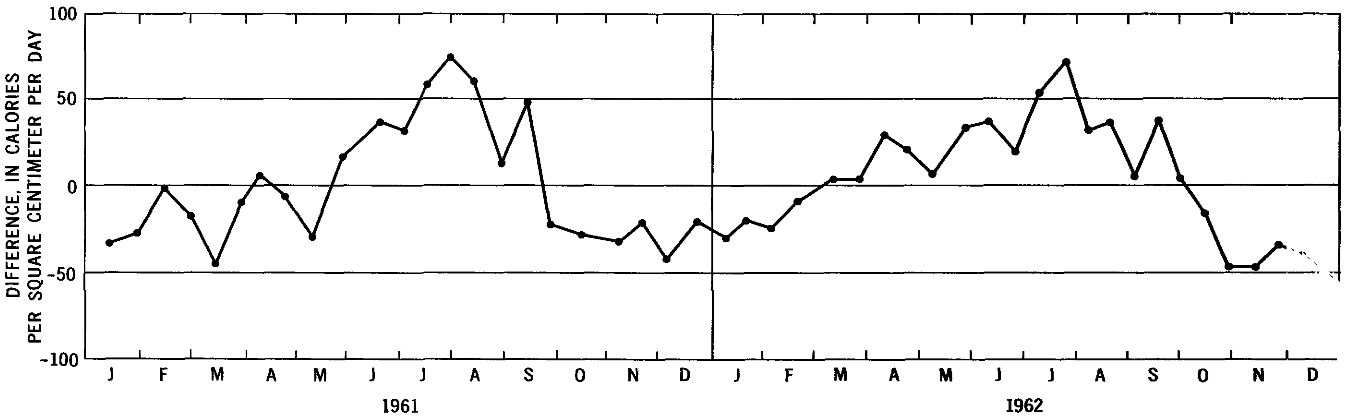

FIGURE 66.—Seasonal differences between measured and computed long-wave atmospheric radiation.

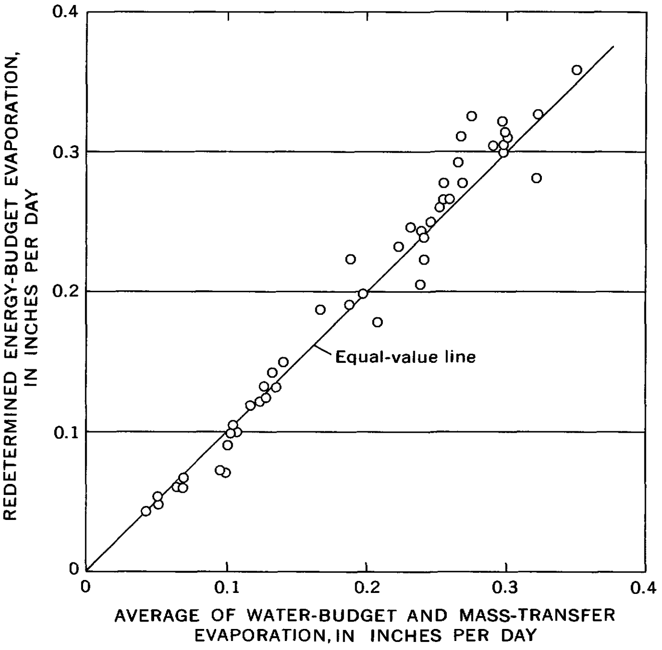

FIGURE 67.—Relation between redetermined energy-budget evaporation and the average of water-budget and mass-transfer evaporation. Q_a computed by Koberg's method was substituted for measured values in this redetermination.

lack of correlation with energy-budget data confirms the apparent seasonal bias in the energy-budget results.

COMPARISON OF EVAPORATION DATA FOR SALTON SEA AND LAKE MEAD

Lake Mead is about 200 miles north-northeast of Salton Sea and about 1,500 feet higher in altitude, but similarity of the desert environments of the two water bodies suggests that evaporation rates should be similar. Therefore, useful information may be obtained by comparing energy-budget and mass-transfer data for Salton Sea with corresponding data for Lake Mead (Harbeck and others, 1958).

Comparisons of evaporation data for the nonconcurrent studies should be valid for complete years, if evaporation during each study period was about average for the respective areas involved. Records of evaporation now available for Lake Mead (U.S. Geological Survey annual water-supply papers) indicate that during the 1952–53 study period evaporation from Lake Mead was nearly average. Similarly, records of pan evaporation measured at Salton Sea during the years 1948–62 (Hely and others, 1966) indicate that during 1961–62 evaporation from Salton Sea exceeded the 1948–62 average by only 3 percent. Hence, comparisons of the nonconcurrent data should be meaningful.

ENERGY-BUDGET DATA

The approximate yearly evaporation by the energy-budget method was 72.8 inches for Salton Sea during 1961–62 and was 85.0 inches for Lake Mead during 1952–53. The yearly value for each station represents the average for 2 complete years. However, the Lake Mead study covered only 18 months, so some of the data were used to derive values for both years. Corresponding average values of terms in the energy budget and of associated parameters for each water body are shown in tables 6–8; certain terms were combined to facilitate later comparisons. These values are based on data published in tables or graphs in the Lake Mead report. Consideration of these terms, and some of the factors that influence their magnitude, may help explain why the difference in evaporation was larger than expected.

Net incoming radiation from the sun and atmosphere, $Q_s - Q_r + Q_a - Q_{ar}$, was nearly the same at the two locations. This factor suggests that evaporation rates for each water body should be about the same; however, as Salton Sea is south of Lake Mead by about 2.5°

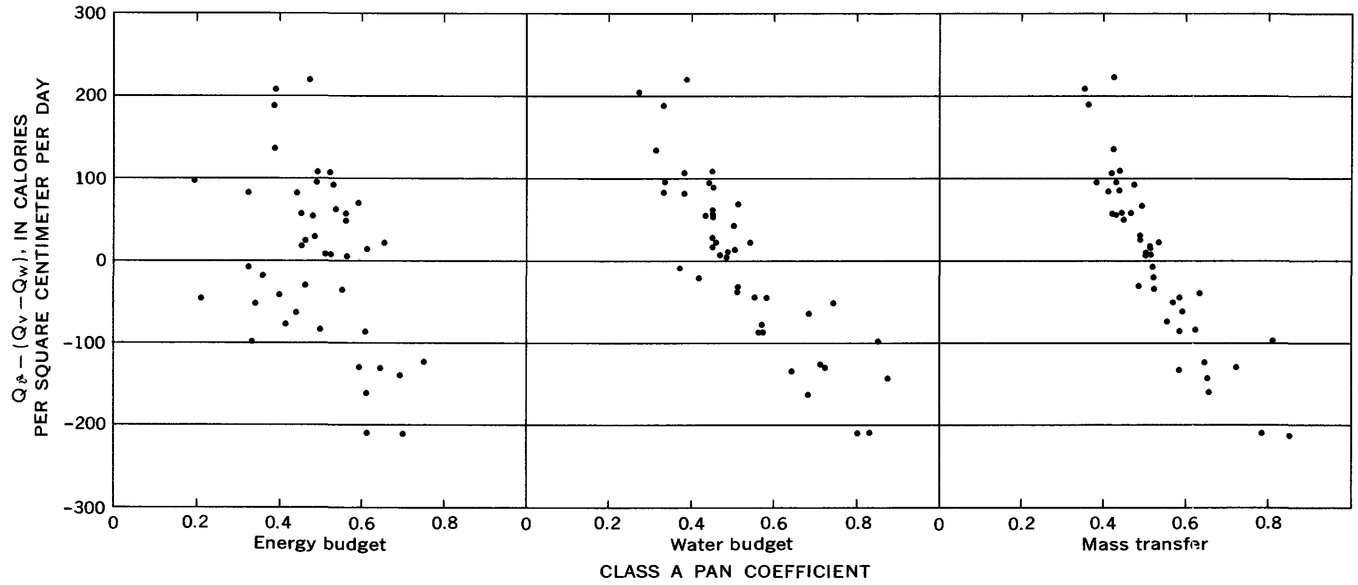

Figure 68.—Correlation between changes in energy storage in Salton Sea and coefficients for a class A pan at Sandy Beach.

Table 6.—*Yearly values of terms of the energy-budget equation for Lake Mead and Salton Sea*

[Values in calories per square centimeter per day except as indicated; values for Lake Mead based on data by Harbeck, Kohler, Koberg, and others (1958, p. 28, table 7)]

Water body	$Q_s - Q_r + Q_a - Q_{ar}$	Q_{bs}	Q_h	Q_w	$Q_v - Q_\vartheta$	Q_e	Evaporation (inches)
Lake Mead	1,150	846	−5	13	56	352	85.0
Salton Sea	1,155	868	−12	13	9	295	72.8
Difference	5	22	7	0	47	57	12.2

Table 7.—*Average yearly water-surface temperature,* T_0 *and air temperature (8-meter level),* T_8, *for Lake Mead and Salton Sea, in degrees centigrade*

[Values for Lake Mead based on data by Harbeck, Kohler, Koberg, and others (1958): T_0 derived from data for Q_{bs} given in table, T_8 from graph in fig. 4]

Water body	T_0	T_8	$T_0 - T_8$
Lake Mead	20.6	20.9 (Boulder Basin)	−0.3
Salton Sea	22.4	23.2 (Sandy Beach)	−0.8

Table 8.—*Average yearly values of parameters used in mass-transfer equation, for Lake Mead (Boulder Basin) and Salton Sea*

[Values for Lake Mead based on data by Harbeck, Kohler, Koberg, and others (1958): e_0 derived from temperature data for Boulder Basin barge in table 18; e_a from graph for Las Vegas Airport in fig. 6; u_2 from data for Boulder Basin in table 16]

Water body	Vapor pressure, (millibars)			Wind speed, u_2, (mph)	Product, $u_2(e_0 - e_a)$
	e_0	e_a	$e_0 - e_a$		
Boulder Basin	24.8	6.0 (Las Vegas)	18.8	7.5	137
Salton Sea	38.3	9.5 (Yuma)	18.8	7.6	145

latitude, slightly greater net incoming radiation might be expected at Salton Sea.

The long-wave radiation emitted by the water body Q_{bs}, was substantially greater for Salton Sea than for Lake Mead. As might be expected, the difference corresponded almost exactly with the difference in water-surface temperatures for the two water bodies (table 7). The higher water-surface temperature for Salton Sea appears reasonable in view of the fact that the air temperatures were higher at Salton Sea than at Lake Mead (table 7).

Owing to the effect of salinity on evaporation, the water-surface temperature of Salton Sea was 0.1°–0.2° C higher than it would have been for a comparable fresh-water body (Harbeck, 1955). As a result of reservoir operation, on the other hand, the water-surface temperature of Lake Mead may have been as much as 0.7° C higher than it would have been for a comparable water body from which only the uppermost water was released (Harbeck and others, 1958). The relatively smaller temperature difference between air and the water surface at Lake Mead is consistent with these facts.

Although the yearly evaporation rate was greater for Lake Mead than for Salton Sea, the temperature at which evaporation took place was less. Consequently, the energy per unit area that was advected by the evaporated water, Q_w, was the same for each water body.

The energy conducted from the water as sensible heat, Q_h, varies with the temperature gradient of the air above the water surface and the eddy diffusivity of the air for heat. As the diffusivity factors for Lake Mead and Salton Sea probably are the same, the Q_h terms (table 6) should be proportional to the corresponding differences between air and water-surface temperatures (table 7). The rough proportionality between Q_h terms and the temperature differences, however, is partly coincidental. Air temperatures used in the energy-budget computations for Lake Mead were those for the 2-meter level at Boulder Basin barge rather than those for the 8-meter level; temperatures at the 2-meter level averaged about 0.3° C lower than those at the 8-meter level. There is little doubt, however, that the sensible-heat exchange between the air and the water was a small item in the energy-budget of each water body. Net transfer of sensible heat was from the air to the water in each case, as indicated by the negative sign shown with values of Q_h in table 6.

If, during any period, the net energy advected into a water body, Q_v, is balanced by a change in energy storage, Q_ϑ, evaporation during the period is not affected. Therefore, comparisons involving Q_v and Q_ϑ are most effective when the difference, $Q_v—Q_\vartheta$, is used rather than the separate terms.

The large value of the Q_v-Q_ϑ term for Lake Mead (table 6) resulted chiefly from the large volume of water that moved through the lake each year and the fact that the average temperature of the outflowing water was less than the temperature of the inflowing water (Koberg, 1958). Both inflow and outflow of Lake Mead averaged about 14 million acre-feet per year during the study period, and the weighted-average temperature of the inflow exceeded that of the outflow by about 5° C. (Koberg, 1958, figs. 3 and 16). In contrast, during the study period, inflow to Salton Sea averaged about 1.4 million acre-feet per year, with no surface outflow, and the average temperature of the inflow was about 21° C. From these values the total energy advected by flowing water was 2.4 times greater for Lake Mead than for Salton Sea. Moreover, the average surface area of Salton Sea was about 1.8 times that of Lake Mead during the respective study periods. Hence, on a unit-area basis, the Q_v term for Lake Mead was more than 4 times that for the Salton Sea.

The advected energy might have been stored temporarily but eventually had to be dissipated by conductive, radiative, or evaporative processes—just as energy from all other sources was dissipated.

The foregoing comparisons indicate that the difference in the yearly evaporation rates that were determined for Lake Mead and Salton Sea by the energy-budget method may be attributed chiefly to two factors: (1) The energy emitted by long-wave radiation from Salton Sea was substantially greater than that for Lake Mead, and (2) the net energy advected by inflowing and outflowing water was much greater for Lake Mead than for Salton Sea. Minor differences in other energy-budget terms influenced the difference in computed evaporation; the effect of these differences alone, however, was not significant.

MASS-TRANSFER DATA

The parameters of the empirical mass-transfer equation are comparable for different water bodies only when measured in the same way. According to Harbeck (1962), comparison should be valid if both the wind speed at a low altitude above the water surface and the water surface temperature are measured near the center of the water surface area and if the vapor pressure of air is the same as that of the approaching (unmodified) air.

The water-surface temperatures and the 2-meter level-wind speeds used in the studies at Lake Mead and at Salton Sea fulfill the requirements for reliable comparison. However, in each case the vapor pressure determined was that of air partly modified by passage over parts of the two water bodies. As the degree of modification varied with wind direction at Salton Sea (Sandy Beach) but was independent of wind direction at Lake Mead (Boulder Basin barge), a meaningful comparison would not result from use of these modified vapor-pressures values. Consequently, vapor pressures corresponding to air at Las Vegas, Nev., and Yuma, Ariz., which may be considered about equally representative of unmodified air at Lake Mead and at Salton Sea, respectively, were used in this comparison. The product, $u_2(e_0-e_a)$ given in table 8 was computed as the average product of monthly values of u_2 and of (e_0-e_a) rather than as the product of the average yearly values. Effects of the seasonal variation of both the wind-speed and the vapor-pressure difference are more accurately accounted for by this method.

In the mass-transfer studies at Lake Mead (Harbeck and others, 1958, p. 34, 35), because alternatives were lacking, the wind speed for Boulder Basin was considered to represent all basins of Lake Mead. On the other hand, the data showed that the vapor-pressure difference for Boulder Basin generally was slightly less than for other parts of the lake, chiefly because the water-surface temperature usually was slightly less in Boulder Basin. Allowance was made for these differences in the Lake Mead study.

Data for Boulder Basin were used for the comparison in table 8 because values for all parameters could be conveniently obtained from the Lake Mead report only for that location. Hence, the product, $u_2(e_0-e_a)$ that applies to the entire lake would exceed by a slight amount the product shown in table 8 for Boulder Basin. Fortunately, this difference can be approximated from data that are available. The average value of e_0 for Lake Mead exceeded the corresponding value for Boulder Basin by 0.8 millibars. As the humidity in the various basins was not appreciably different, the vapor-pressure difference averaged about 19.6 millibars for the entire lake compared to 18.8 millibars for Boulder Basin alone. As the same wind speed must be used in either case, the mass-transfer product for Lake Mead should be larger than that for Boulder Basin by the ratio of 19.6 to 18.8. On this basis, the mass-transfer product for Lake Mead was roughly equal to the corresponding product for Salton Sea, a fact which indicates that evaporation from Lake Mead and Salton Sea would be about the same if the same mass-transfer coefficient is applicable to each body.

If the mass-transfer parameters are measured as described, however, the mass-transfer coefficient apparently decreases with increasing surface area (Harbeck, 1962, fig. 31). Figure 69 shows the relation between the coefficient and surface area, as presented by Harbeck, but modified to accommodate data for Salton Sea. Accordingly, if the mass-transfer products were the same, evaporation from Lake Mead would exceed that from Salton Sea, but not by the amount indicated by the energy-budget results of the respective studies.

The relation in figure 69 was intended to apply only when the vapor pressure of unmodified air was used in determining the mass-transfer coefficient; the coefficients shown for most lakes are based on unmodified air measured some distance from the respective lakes. In contrast, however, the vapor pressure of air used in determining the indicated coefficients for Boulder Basin and Salton Sea was for partly modified air at the 8-meter level measured near the center of Boulder Basin and at Sandy Beach, respectively.

Coefficients for Boulder Basin and Salton Sea (table 9), based on vapor pressure of unmodified air at Las Vegas and Yuma, respectively, are plotted as crosses in figure 69. A relation line drawn near these points would be in reasonable agreement with data for all water bodies except those having surface areas of only 1 acre. Some such shift is warranted, at least in the upper part of the relation line, because the vapor pressure of air at Las Vegas and Yuma probably more nearly represents that of unmodified air at Boulder Basin and Salton Sea, respectively, than the vapor pressure of air as measured at the 8-meter level in either study.

Harbeck (1962, p. 105) concluded that the apparent relation between the mass-transfer coefficient and the

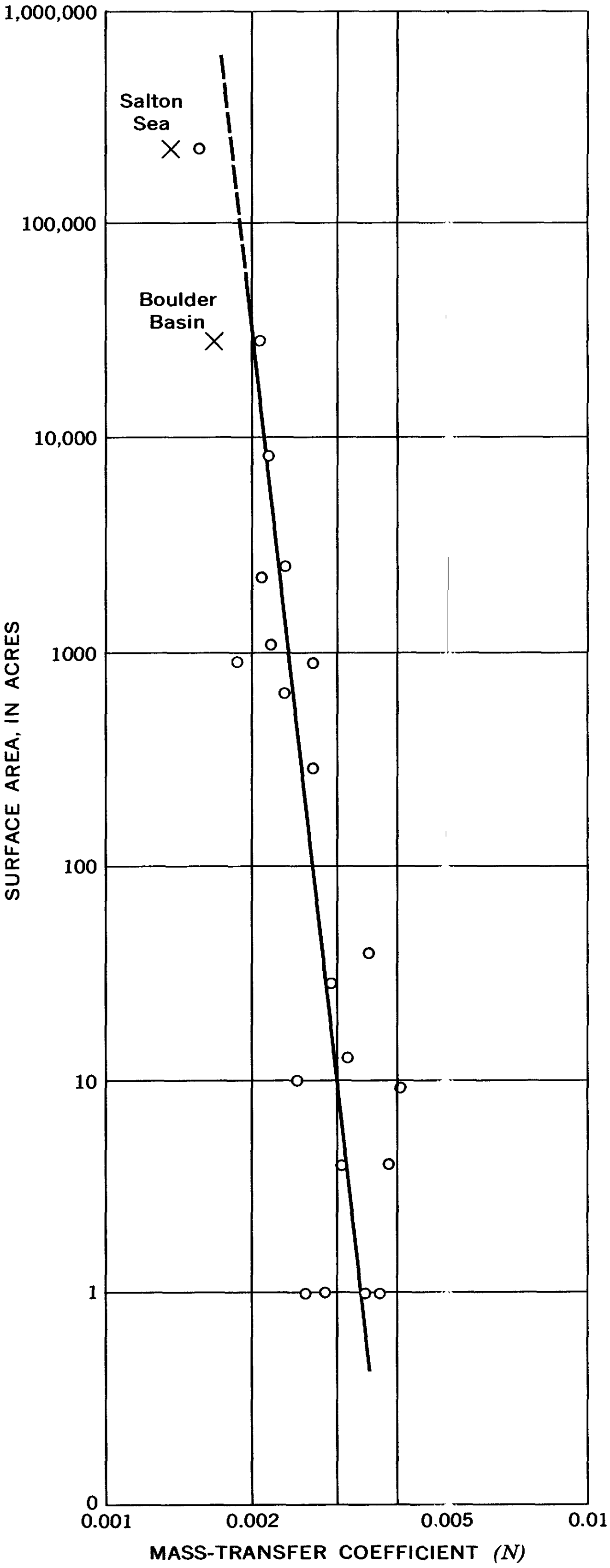

FIGURE 69.—Relation between mass-transfer coefficient, *N*, and surface area of water body. Values indicated for Boulder Basin and Salton Sea by circles are based on vapor pressures of air measured locally at the respective water bodies; values indicated by crosses for the same water bodies are based on vapor pressures of air at Las Vegas, Nev., and Yuma, Ariz., respectively. (Adapted from Harbeck, 1962 fig. 31.)

TABLE 9.—*Mass-transfer coefficient,* N, *corresponding to the vapor pressure of air at different locations, for Boulder Basin and Salton Sea*

Water body	Location of instruments	*N*
Boulder Basin	Boulder Basin barge, 8-meter level.	0.00208
	Las Vegas, Nev	.00167
Salton Sea	Sandy Beach, 8-meter level	.00156
	Yuma, Ariz	.00136

water-surface area was due in part to the effect of surface roughness on the slope of the wind profile near the surface and in part to the tendency for evaporation to decrease downwind. If this relation is valid, the total surface area of the water body is not an adequate index of either of these effects unless the water bodies are compact and of similar shape. Thus, the configuration of the water bodies may account for much of the scatter of the data plotted in figure 69. Scatter may also result from errors in the basic determinations of evaporation from which the coefficients for the respective water bodies were derived or from nonhomogeneity of the meteorological data. Because of the complexity of the many variables involved, such a relation may never be satisfactorily defined.

This analysis of mass-transfer data for the two studies confirms that average evaporation from Salton Sea is less than that from Lake Mead. However, the analysis does not conclusively establish that the difference was a great as indicated by the energy-budget data for the two studies.

CONCLUSIONS

The application of each of the methods used to evaluate evaporation from Salton Sea is subject to practical limitations. Both the energy-budget and water-budget methods determine evaporation as a residual of several measured terms. Evaporation so determined contains the residual of measurement errors in all other terms. Application of the water-budget method is limited to water bodies where inflow and outflow can be measured with adequate precision—the required degree of precision depending generally on the magnitude of inflow and outflow in relation to that of the evaporated water.

The energy-budget method can be used for water bodies where inflow and outflow cannot be measured with sufficient precision for a water-budget determination if the thermal energy content of the inflow and outflow is small in relation to the energy used for evaporation. For successful application of this method, however, all other important terms of the energy-budget equation must be precisely evaluated.

The mass-transfer method conveniently provides the relative seasonal distribution of evaporation from a water body, but the determination of absolute amounts by this method requires use of the mass-transfer coefficient, which first must be defined by some independent measurement of evaporation.

Conditions at Salton Sea were relatively favorable for application of both the energy- and water-budget methods, but, for periods lasting 10–29 days, evaporation results by these two methods tended to differ seasonally by substantial amounts. The seasonal distribution of yearly evaporation given by the mass-transfer method generally agreed better with that by the water-budget method; hence, it was concluded that the energy-budget evaporation was seasonally biased.

Examination of energy-budget and other data for Salton Sea indicated that the techniques used provided satisfactory measures of all terms of the energy-budget equation except the total incoming radiation. The seasonal bias of the energy-budget evaporation was attributed chiefly to inadequacies of the flat-plate radiometer which was used to measure total incoming radiation. Neglect of the seasonal interchange of heat by conduction at the bed of the sea contributed to the bias.

Experiences at Salton Sea, Lake Hefner, and Lake Mead all indicate that total incoming radiation as measured by the flat-plate radiometer may be appreciably in error. Research leading to increased accuracy in the determination of this important parameter will be required to develop the potential usefulness of the energy-budget method.

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