Evaporation and Radiation Measurements at Salton Sea, California

By ALEX M. STURROCK, JR.

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2053

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1978

UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, *Secretary*

GEOLOGICAL SURVEY

W.A. Radlinski, *Acting Director*

Library of Congress Cataloging in Publication Data

Sturrock, Alex M.
Evaporation and radiation measurements at Salton Sea, California.
Water-Supply Paper 2053
Bibliography: p. 26
Supt. of Docs. No. : I 19.13: 2053
1. Evaporation (Meteorology)--California--Salton Sea. 2. Atmospheric radiation--California--Salton Sea--Observations. 3. Mass transfer. I. Title. II. Series: United States. Geological Survey. Water Supply Paper 2053.
QC915.7.U5S78 551.5'72'0979499 77-608153

For sale by the Superintendent of Documents, U. S. Government Printing Office

Washington, D. C. 20402

Stock Number 024-001-03056-0

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SYMBOLS

c =Specific heat of water.
E =Total evaporation in acre-feet.
E_{EB} =Evaporation computed by the energy-budget method.
E_{MT} =Evaporation computed by the mass-transfer method.
E_{WB} =Evaporation computed by the water-budget method.
E_T =Total energy-budget evaporation expressed in inches.
e_a =Vapor pressure of the air.
e_o =Vapor pressure of saturated air at the temperature of the water surface.
G =Ground water inflow.
I =Surface inflow.
L =Latent heat of vaporization of water.
N =Mass-transfer coefficient.
n =Number of energy-budget periods.
P =Precipitation over the Salton Sea.
p =Density of the evaporated water.
Q_a =Incoming long-wave radiation.
Q_{ar} =Reflected long-wave radiation.
Q_b =Heat transfer to and from bottom sediments.
Q_{bs} =Long-wave radiation emitted from the body of water.
Q_e =Energy used for evaporation.
Q_h =Energy conducted from the water as sensible heat.
Q_r =Reflected short-wave radiation.
Q_s =Incoming short-wave radiation.
Q_T =Net incoming radiation at the water surface.
Q_v =Net energy advected to the body of water.
Q_W =Energy advected from the body of water by the evaporated water.
Q_x =Increase in energy content of the body of water.
R =Bowen ratio.
S =Change in storage.
SE =Standard error of estimate.
T_b =Arbitrary base temperature.
TE =Correction for thermal expansion.
T_e =Temperature of the evaporated water.
T_o =Water-surface temperature.
u =Windspeed at some height above the water surface.

CONVERSION TABLE

For use of those readers who may prefer to use metric units rather than English units, the conversion factors for the terms used in this report are listed below:

Multiplying English Unit	*By*	*To Obtain Metric Unit*
acre-feet (acre-ft)	1.233×10^{-3}	cubic hectometers (hm^3)
cubic foot (ft^3)	2.832×10^{-2}	cubic meters (m^3)
feet (ft)	3.048×10^{-1}	cubic meters (m^3)
gallon (gal)	3.7854×10^{-3}	cubic centimeters (cm^3)
inch (in.)	25.4	millimeters (mm)
miles per hours (mi/hr)	0.447	meters per second (m/s)

EVAPORATION AND RADIATION MEASUREMENTS AT SALTON SEA, CALIFORNIA

By Alex M. Sturrock, Jr.

ABSTRACT

Evaporation from Salton Sea, Calif. was computed for a 539-day period between July 14, 1967, and January 2, 1969, by use of energy-budget, mass-transfer, and water-budget methods. The total evaporation computed by the three methods agreed within 5 percent. For computing evaporation by the mass-transfer method, vapor pressure measured at raft stations on the sea was considered to be more representative of the conditions over the sea than vapor pressure measured at land stations. The values of heat transfer to and from the bed were used in energy-budget computations. The inclusion of these heat transfer values improved the correlation of evaporation computed by the energy-budget and water-budget methods.

Monthly evaporation computed by the energy budget method for 1968 showed that the Salton Sea exhibited a double-wave evaporation similar to that of oceans in the same latitude.

Weekly and monthly comparisons were made to determine if radiation measured by the flat-plate radiometer is seasonally biased. Weekly totals of radiation from three flat-plate radiometers were compared to values of a Cummings Radiation Integrator. Monthly totals of radiation for each of the two types of instruments were compared to an empirical method for determining radiation. These comparisons indicate that the measurements of radiation by the flat-plate radiometer are not seasonally biased, and that the Cummings Radiation Integrator gives reliable measurements of radiation for periods as short as 1 week.

The net incoming radiation was measured at three stations around the Salton Sea. The areal variation was less than 1 percent on an annual basis and the largest weekly variation was less than 6 percent.

An empirical mass-transfer coefficient, N, was determined from energy-budget measurements. The value of this coefficient to give evaporation in inches per day is 0.00245 when the windspeed is expressed in miles per hour and vapor pressure is expressed in millibars. The coefficient is valid only when data are obtained at the raft stations.

INTRODUCTION

The Salton Sea is maintained by inflow drainage water from the Imperial, Coachella, and Mexicali Valleys. The sea, which has no outlet, serves as a natural sump to which these inflows must drain. The sea has become an important recreational resource in recent years and a number of proposals at the local, State, and Federal levels have been made to control the water level and the salinity.

A cooperative study to determine the rate of evaporation from the Salton Sea as well as to determine if existing mass-transfer and pan relationships can be used to estimate evaporation from large lakes was initiated in July 1967 by the U.S. Geological Survey and the National Weather Service. The results of the pan investigation will be reported by the National Weather Service elsewhere. This report is concerned with the evaporation and the mass-transfer relationship for the Salton Sea.

In an analysis of techniques used in a study conducted in 1961–62, Hughes (1967) determined that the computed values of evaporation by the energy-budget method indicated a seasonal bias. This bias was attributed to error in the measurements of radiation by the flat-plate radiometer. However, the annual evaporation rates computed by the energy-budget, mass-transfer, and water-budget methods were in close agreement and averaged about 72 in. annually over the 2-year period.

The purpose of this report is two-fold: (1) to determine the mass-transfer coefficient for the sea using the energy-budget method as a primary control with the water-budget method as a secondary control, and (2) to compare the measured values of the net incoming radiation obtained by the flat-plate radiometer to those obtained by a CRI (Cummings Radiation Integrator). The latter test was made to determine if radiation measured by the flat-plate radiometer was seasonally biased.

The values of net incoming radiation measured by three flat-plate radiometers and a CRI were compared for monthly and weekly periods. The areal variation of the net incoming radiation was determined from measurements by CRI's at three sites located around the Salton Sea. Measurements of the shortwave radiation component were made at four locations to determine the area variation of that parameter.

In this study, vapor pressure of the air was measured at six raft stations on the sea and three land stations around the sea to determine the effect of location on measurements of vapor pressure for the mass-transfer investigations.

Evaporation was computed by the energy-budget and water-budget methods for energy-budget periods as well as monthly periods. A mass-transfer coefficient was derived, and evaporation also was computed using the mass-transfer method.

INSTRUMENTATION

The Salton Sea was instrumented for evaporation measurement by the energy-budget, mass-transfer, and water-budget methods. The outputs of certain instruments were used in computations made by more than one method.

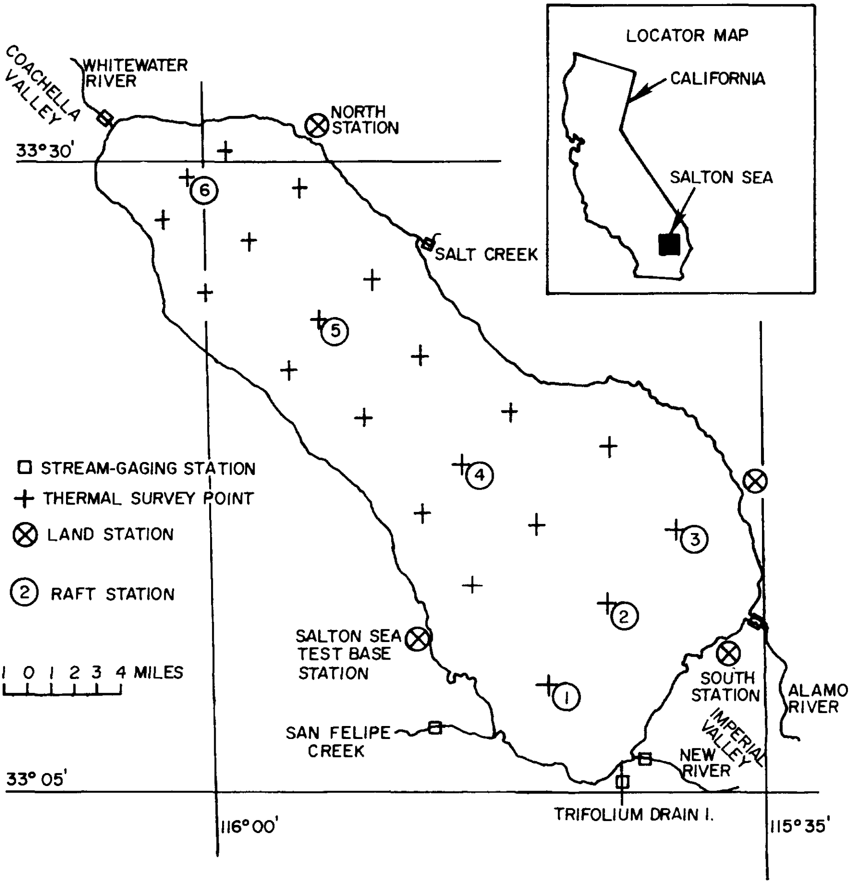

FIGURE 1.—Salton Sea data collection points.

To determine if measurements of radiation by the flat-plate radiometer were seasonally biased, a new CRI was designed to measure radiation. Three of these units were fabricated and installed at sites around the sea (fig. 1). At the Salton Sea Test Base Station (fig. 1) three flat-plate radiometers, a shortwave pyrheliometer, and one of the CRI's were used to measure radiation.

The temperature of the water in the Salton Sea was measured at preselected sites (fig. 1) during thermal surveys made at approximately monthly intervals over the 539-day study period beginning July 14, 1967, and ending January 2, 1969. A portable battery powered underwater thermometer was used to measure the variation of temperature with depth at 20 points on the Salton Sea. This instrument used a thermistor to sense the change in temperature. Measurements of temperature were obtained at 2 ft intervals for depths up to 10 ft and at 4 ft intervals for depths from 10 ft to the bottom. The maximum depth measured at the 20 sites was 46 ft.

LAND STATIONS

The NWS (National Weather Service) established Class A weather stations at the four sites shown in figure 1. Class A pan evaporation, Class A pan maximum and minimum water temperature, maximum and minimum air temperature and windspeed at the 1.64 ft and 3.28 ft levels, and precipitation were measured daily at these stations. Continuous recordings were made of air temperature and relative humidity at 5 ft above the ground surface.

The U.S. Geological Survey installed CRI's at Salton Sea Test Base Station, North Station, and South Station. At the North and South stations, the CRI's were sited inside the standard NWS 4-foot chain link enclosure with the NWS instruments (fig. 2). A daily inspection of the CRI at the North station was made by personnel of the California State Parks, at the South station by personnel of the National Wildlife Refuge, and at the Salton Sea Test Base Station by personnel of the U.S. Geological Survey.

The headquarters for the study was established at Salton Sea Test Base. At the Test Base, the CRI and NWS instruments were positioned approximately 100 ft north of the headquarters building on an abandoned parking ramp for amphibious aircraft. Three ventilated flat-plate radiometers and a 10-junction Eppley pyrheliometer[1] were mounted to a platform on the roof of the headquarters building to measure the radiation. Supplementary wet- and dry-bulb temperature measurements were obtained by a nonventilated thermocouple psychrometer 50 ft north of the building at a 6.56 ft height.

Continuous recording thermometers with 7-day charts were installed at the Imperial Irrigation District's stream gaging stations on the New and Alamo Rivers to determine the temperature of the inflow waters to the Salton Sea (fig. 1). Inspections were made weekly at these stations to check the recorded temperatures against calibrated thermometers and to change the recorder charts.

Inflow from the Imperial and Mexicali Valleys to the Salton Sea was measured by recording gages at the Alamo River, New River, San Felipe Creek, and Trifolium drain 1. Inflow from the Coachella Valley to the sea was measured by recording gages at the Whitewater River and Salt Creek. The Salton Sea elevation was determined by use of a water level recorder mounted from a pier approximately 200 ft from the shoreline and 300 ft south of the headquarters building.

[1]The use of brand names in this report is for identification purposes only and does not imply endorsement by the U.S. Geological Survey.

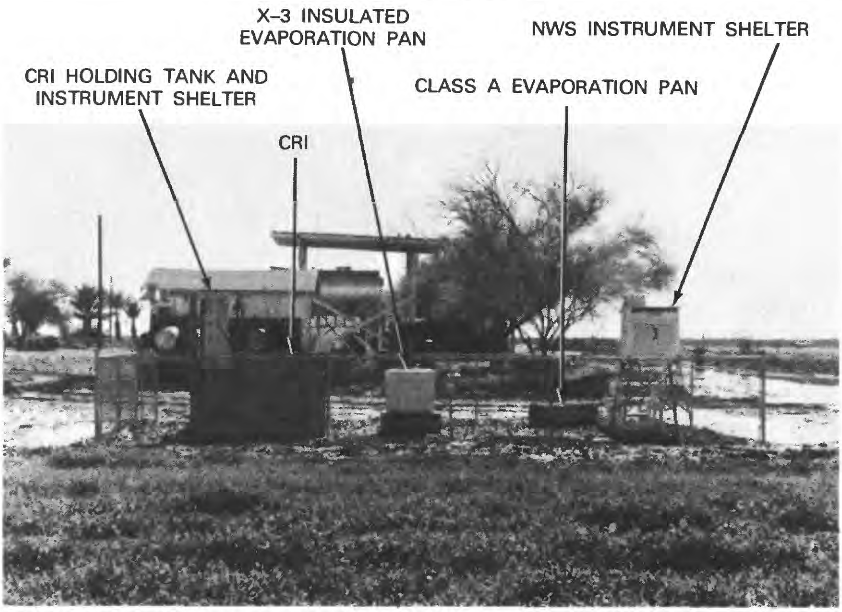

FIGURE 2.—South Station enclosure with Cummings Radiation Integrator and National Weather Service instruments.

RAFT STATIONS

Water-surface temperature, windspeed, and wet- and dry-bulb temperatures at the 6.56 ft level were measured at the six raft stations shown in figure 1. Windspeed measurements were also obtained at the 13.12 ft level for rafts 1, 3, 4, and 6. The total wind movement in miles was noted at each visit to the stations. Temperatures were recorded hourly by a Fischer-Porter Digital Recorder interfaced with a servo-programmer unit developed by the Survey research instrumentation laboratory at Reston, Va.

The rafts were constructed using six standard 55-gal steel drums for floatation and angle steel for a frame. The four end drums were filled with styrofoam to insure floatation in case of damage. A wooden platform 6 ft × 12 ft was joined to the frame to serve as a base for the instrument shelter and to give added rigidity to the raft. An instrument shelter, approximately 2.5 ft × 2.5 ft × 4 ft, was attached to the platform at the center of the raft. The instrument shelter housed the Fischer-Porter recorder and servo programmer, a Chelsa timer, a backup analog thermometer for measuring the water-surface temperature, and the necessary batteries for operation of the instruments. A standard 55-gal steel drum filled with concrete attached to one end of the raft frame by a steel cable anchored the raft.

A mast mounted at the anchored end of the raft supported the anemometer at the 6.56 ft level. Mounting the anemometer at this position insured that it would be on the upwind side of the raft and that no blockage would occur from the instrument shelter. The anemometer located at the 13.12 ft level was mounted on a telescoping mast near the center of the raft. The mast was secured to the top of the instrument shelter to give added support against swaying during rough seas.

The ventilated psychrometer was mounted to a wooden support arm extending beyond the edge of the raft so that the psychrometer was positioned at 6.56 ft above the water surface. This psychrometer used thermistors to sense the wet- and dry-bulb temperatures. Water was supplied by capillary action to the wick of the wet-bulb sensor from a reservoir attached to the underside of the psychrometer. A battery powered suction fan produced an airflow over the sensors.

A thermistor to measure water-surface temperature was mounted on a vertical support that extended into the water from the center of the raft. The sensor was fastened to the support at a point approximately 1 in. below the surface of the water. A backup record of water-surface temperature was recorded by an analog recorder. This recorder used a filled-system temperature sensor connected by a capillary to a Bourdon tube and was mounted on the vertical support at the same level as the thermistor.

The raft stations were visited at approximately 10-day intervals for service and maintenance. The ventilated psychrometer was checked against a portable psychrometer and the wick cleaned or changed depending on its condition. The water-surface temperature sensors were checked against a calibrated mercury in glass thermometer. The battery voltages for the servo-programmer unit and the ventilated psychrometers were checked, and batteries were replaced if voltages were low. The anemometer bearings were oiled, and the anemometers were periodically interchanged with spares so that they could be returned to the headquarters shop for minor overhaul and testing.

Corrosion was a major problem at the Salton Sea raft stations. The lower anemometers and psychrometers were frequently covered with a salt crust from the salt-water spray. The upper and lower anemometer bearings were changed frequently, and capillary lines for the analog surface-water temperature probe were frequently replaced. The 55-gal steel drums, which were painted with a corrosive resistant paint, had to be replaced periodically.

CUMMINGS RADIATION INTEGRATOR

The CRI (Cummings Radiation Integrator) is an open container of water insulated so that heat losses through the bottom and sides are minimized. It is assumed that the radiation received by the CRI at a point near a reservoir is the same as that received by the reservoir itself.

FABRICATION

The CRI was fabricated from three 4 ft × 4 ft × 1 ft white styrofoam billets which had been glued together to form a 4 ft × 4 ft × 3 ft block. A 2.33 ft diameter hole was cut in the upper two billets to form the tank of approximately 8.53 ft^3 capacity. The tank's circumference was sealed with three coats of white silicone rubber and its base with two coats of white and a final coat of black silicone rubber to absorb penetrating radiation. The CRI was placed on a 6 ft × 6 ft × 0.5 ft wooden base for stability.

A galvanized sheet metal radiation shield with a ratio slope of 0.042:1.0 was mounted atop the CRI. A 2.5 ft diameter hole was cut from the center of the shield and a 0.21 ft vertical rim attached to the circumference to prevent driving rain from entering the CRI. The framework for the shield allowed air to pass freely over the CRI. It was found shortly after the study began that high winds caused water to splash out of the tank, so in early August, a 4 ft high solid wind barrier was added to the perimeter of each wooden base platform. The design of the CRI is shown in figure 3.

OPERATION

The water-surface temperature, wet- and dry-bulb temperatures, and temperature of inflow water used by the CRI were measured and recorded hourly on the Fischer-Porter Digital Recorder interfaced with a servo programmer. The digital recorder and servo programmer were housed in the instrument stand which served to support the water supply tank and float unit. The water-surface temperature probe was attached to the underside of a 1 in. × 2 in. × ½ in. styrofoam float. The float was tied to the point gage with string which allowed the surface-water temperature probe to remain approximately ½ in. below the water surface as small changes in the elevation occurred. The inflow-water temperature was measured by a probe in the inflow-water line just inside the wind barrier on the north side of the CRI. A ventilated psychrometer, the same type as used on the rafts, was mounted from one of the instrument stand legs at a height of 6.56 ft.

The CRI's were serviced weekly. When servicing, the water in the CRI was stirred thoroughly before the temperature was taken with a calibrated thermometer. The psychrometer was checked against a

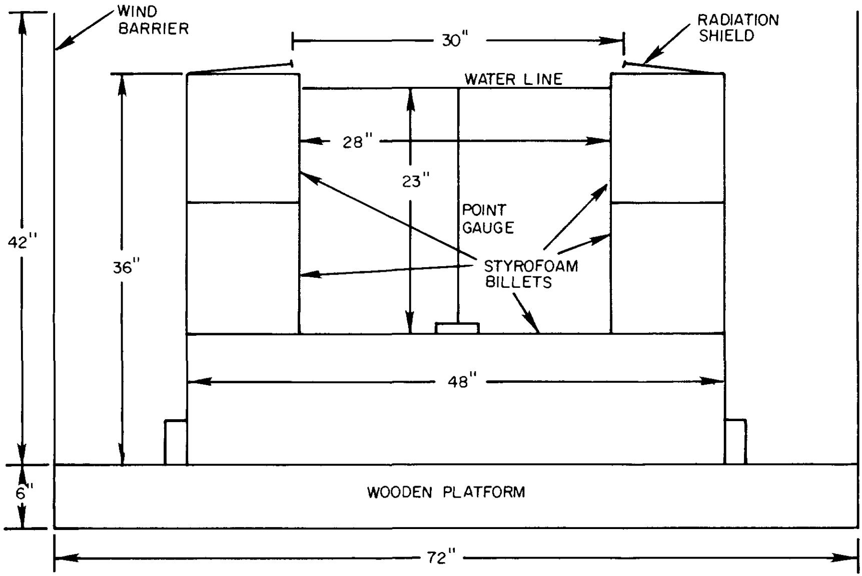

FIGURE 3.—Cross section of Cummings Radiation Integrator.

portable ventilated psychrometer and the wick cleaned or changed if needed. The battery voltage for the ventilating psychrometer motor was checked and the battery replaced when the voltage was less than 5½ volts. The total amount of water in the system was determined before and after filling so that total evaporation from the CRI could be determined. The weekly service visits to each of the CRI's were made at approximately the same time of day so as to minimize the net change in energy storage between visits. The digital-recorder-punch tapes were removed at each service visit.

As evaporation occurred, water from a supply tank through a valve-actuated float unit was added at the base of the CRI to maintain a constant water-surface elevation at 1 in. below the rim.

MEASUREMENT OF RADIATION

The net incoming radiation at the water surface, $Q_{T'}$ of the CRI is computed by the equation

$$Q_T = Q_x + Q_e + Q_h + Q_w - Q_v - Q_I + Q_{bs} - Q_{p'}, \qquad (1)$$

where all the above quantities are expressed in calories per square centimeter per day (cal cm^{-2} day^{-1}) and where;

Q_T =the net incoming radiation at the water surface,
Q_x =the increase in energy stored in the CRI,
Q_e =the energy utilized in evaporation,
Q_h =the energy conducted from the CRI as sensible heat,

Q_w =the energy advected from the CRI by the evaporated water,
Q_v =the energy advected to the CRI by the influx of water,
Q_I =the energy conducted to the CRI through the insulation,
Q_{bs} =the long-wave radiation emitted from the CRI, and
Q_p =the energy added to the CRI from rainfall.

The value of Q_T was determined for weekly periods that coincided with the CRI service visits. To determine the value of Q_T for periods longer than 1 week, the values for weekly periods were averaged.

RADIATION MEASUREMENTS

Previous studies of the Salton Sea (Hely and others, 1966; Hughes, 1967) indicated some difficulties in measurement of radiation. These difficulties are discussed in the following sections.

SHORT-WAVE RADIATION

Within the conterminous United States, the southwestern section receives the greatest amount of short-wave radiation on an annual basis. The measured monthly values of short-wave radiation at Salton Sea were compared to measurements from Las Vegas, Nev. (National Weather Service), Phoenix, Ariz. (National Weather Service), Yuma, Ariz. (U.S. Army Meteorological Team at Yuma Proving Ground), and Brawley, Calif. (Agricultural Research Service Experimental Station).

The results of this comparison are shown in table 1. The areal variation of short-wave radiation among the measurements is very small; therefore, it was assumed that the measurements of short-wave radiation at the Test Base were representative for the Salton Sea, at least on a monthly basis. The annual averages are also shown in table 1.

NET INCOMING RADIATION

To determine if the net incoming radiation measured by the flat-plate radiometer was seasonally biased, measurements from the three flat-plate radiometers were compared to measurements obtained by the CRI at the Salton Sea Test Base Station for 76 weekly periods. The results of the comparison are shown in table 2. Also shown in table 2 are the weekly values for the CRI's at the north and south stations. The last two columns show the net incoming radiation averaged for the three flat-plate radiometers and the three CRI stations.

For each of the 76 periods the individual flat-plate radiometers agreed within 3 percent of the averaged value for the three radiometers. For all but 7 of the 76 periods, the net incoming radiation measured at the Salton Sea Test Base CRI agreed to within 5 percent of the average value for the three flat-plate radiometers. A maximum dif-

TABLE 1.—*Monthly solar radiation values for stations near the Salton Sea*
[In calories per square centimeter per day]

Location	Yuma (U.S. Army)	Brawley (ARS)	Salton Sea (USGS)	Phoenix (NWS)	Las Vegas (NWS)
1967:					
January	--	328	--	287	278
February	--	422	--	422	409
March	--	496	--	476	489
April	608	600	634	663	625
May	677	678	703	682	707
June	744	711	755	691	752
July	645	622	644	612	652
August	592	566	596	571	588
September	509	503	502	522	498
October	453	454	449	464	448
November	324	329	305	342	283
December	255	287	264	257	245
April–December average	534	528	539	534	533
Annual average	--	500	--	499	498
1968:					
January	294	324	311	303	291
February	344	374	365	369	356
March	461	498	504	466	519
April	613	650	633	646	658
May	681	700	688	723	721
June	697	719	714	743	737
July	632	644	639	659	656
August	587	616	618	615	612
September	550	558	548	568	568
October	431	458	427	438	420
November	316	362	319	331	331
December	267	303	265	273	258
Annual average	490	517	503	510	511

ference of 9 percent was found in period 36. The differences between the Salton Sea Test Base CRI and the average flat-plate values do not appear to have a seasonal bias.

Values of the net incoming radiation by months are shown in table 3. Column two of the table is the average daily value by months from the three flat-plates. Column three of the table is the average daily value by months from the CRI at the Salton Sea Test Base Station. Column four shows daily values by months of Q_T determined from an empirical method developed by Koberg (1964). In Koberg's method, the value of the magnitude of the long-wave radiation component is computed from measurements of air temperature, air-vapor pressure, and the ratio of measured short-wave radiation to clear sky radiation. Using the flat-plate values as a standard, the maximum error for any month in either the CRI or the Koberg value is 4 percent. The annual 1968 values for the three methods agree within 1 percent. For the period August to December, the average daily values by month for 1968 averaged 2 percent less than these same values for 1967.

An inspection of the results in table 3 indicates that there is no seasonal bias in the flat-plate radiometer values. The flat-plate values are assumed accurate and were used in the energy-budget computations.

EVAPORATION COMPUTATIONS

ENERGY-BUDGET METHOD

The energy budget for a body of water, accounting for all the major energy terms, may be expressed as follows:

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

where

Q_s =incoming short-wave radiation,
Q_r =reflected short-wave radiation,
Q_a =incoming long-wave radiation,
Q_{ar} =reflected long-wave radiation,
Q_{bs} =long-wave radiation emitted from the body of water,
Q_v =net energy advected to the body of water,
Q_e =energy used for evaporation,
Q_h =energy conducted from the water as sensible heat,
Q_w =energy advected from the body of water by the evaporated water,
Q_b =heat transfer to the water from the bottom sediments, and
Q_x =increase in energy content of the body of water.

The above equation equates the net transfer of energy into and out of the body of water to changes in energy storage. All the terms of equation 2 are expressed in calories per square centimeter per day (cal cm^{-2} day^{-1}).

The short-wave radiation, Q_s, was measured at the Test Base. The reflected short-wave component, Q_r, was computed as a percentage of Q_s, the percentage ranging from 6 to 10 according to the sun angle.

The long-wave radiation Q_a, was determined from average measurements of the three flat-plate radiometers. The flat-plate radiometer measures total radiation received from the sun and sky, and the long-wave radiation is determined by subtracting the short-wave component from this total. The reflected long-wave radiation, Q_{ar}, was computed as the product of the incoming long-wave radiation value and the reflectivity coefficient of 0.03. This coefficient was determined from measurements made by Gier and Dunkle (U.S. Geol. Survey, 1954, p. 96–98).

The net incoming radiation at the water surface, Q_T, is the sum of the individual radiation components ($Q_s - Q_r + Q_a - Q_{ar}$).

The radiation emitted by the water surface, Q_{bs}, is computed from the average surface-water temperature using the Stefan-Boltzman law for black-body radiation with an emissivity for water of 0.97 as determined by Gier and Dunkle (U.S. Geol. Survey, 1954, p. 96–98).

TABLE 2.—*Average values, by periods, of net incoming radiation at the water surface, Q_T, for Salton Sea*

[In calories per square centimeter per day]

Period number	Period	Number of days	FP[1] 240	FP 137	FP 320	Salton Sea Test Base CRI	North Station CRI	South Station CRI	FP average	CRI average
	1967									
1	July 13–July 19	7	1,472	1,471	1,487	1,495	1,505	1,513	1,477	1,504
2	July 20–July 26	7	1,421	1,411	1,436	1,414	1,443	1,441	1,423	1,433
3	July 27–Aug. 2	7	1,527	1,515	1,518	1,518	1,528	1,537	1,520	1,528
4	Aug. 3–Aug. 9	7	1,473	1,476	1,479	1,542	1,489	1,508	1,476	1,513
5	Aug 10–Aug 16	7	1,471	1,492	1,502	1,511	1,510	1,517	1,488	1,513
6	Aug. 17–Aug. 23	7	1,425	1,433	1,441	1,393	1,487	1,405	1,433	1,428
7	Aug. 24–Aug. 30	7	1,387	1,386	1,421	1,358	1,448	1,402	1,398	1,403
8	Aug. 31–Sept. 6	7	1,283	1,289	1,280	1,285	1,267	1,284	1,284	1,279
9	Sept. 7–Sept. 13	7	1,344	1,365	1,342	1,340	1,351	1,389	1,350	1,360
10	Sept. 14–Sept. 20	7	1,279	1,263	1,263	1,249	1,266	1,295	1,268	1,270
11	Sept. 21–Sept. 30	7	1,273	1,260	1,270	1,339	1,225	1,269	1,268	1,278
12	Sept. 28–Oct. 4	7	1,242	1,241	1,236	1,226	1,308	1,250	1,240	1,261
13	Oct. 5–Oct. 11	7	1,134	1,141	1,145	1,181	1,112	1,199	1,140	1,164
14	Oct. 12–Oct. 18	7	1,104	1,103	1,107	1,110	1,071	1,118	1,105	1,100
15	Oct. 19–Oct. 25	7	1,099	1,081	1,089	1,086	1,028	1,066	1,090	1,060
16	Oct. 26–Nov. 1	7	1,035	1,011	1,033	1,092	1,075	1,025	1,026	1,064
17	Nov. 2–Nov. 8	7	1,021	1,005	1,020	993	989	968	1,015	983
18	Nov. 9–Nov. 15	7	1,004	995	995	1,021	978	988	998	996
19	Nov. 16–Nov. 21	6	927	910	913	884	918	881	917	894
20	Nov. 22–Nov. 29	8	911	896	908	906	925	891	905	907
21	Nov. 30–Dec 6	7	866	861	870	847	853	825	866	842
22	Dec. 7–Dec. 13	7	811	804	800	799	845	758	805	801
23	Dec. 14–Dec. 21	8	788	754	755	805	845	840	766	830
24	Dec. 22–Dec. 27	6	869	852	875	824	840	829	865	831
25	Dec. 28–Jan. 3	7	837	841	855	827	843	843	844	838
	1968									
26	Jan. 4–Jan. 10	7	836	827	839	890	859	844	834	864
27	Jan. 11–Jan. 17	7	868	855	846	846	847	816	856	836
28	Jan. 18–Jan. 24	7	903	899	895	883	872	856	899	870
29	Jan. 25–Jan. 31	7	892	896	889	900	909	887	892	899
30	Feb. 1–Feb. 7	7	939	935	925	902	898	857	933	886
31	Feb. 8–Feb. 14	7	970	959	965	917	933	890	965	913
32	Feb 15–Feb. 22	8	1,036	1,037	1,049	976	1,017	1,018	1,041	1,004
33	Feb. 23–Feb. 28	6	1,093	1,101	1,104	1,070	1,078	1,047	1,099	1,065
34	Feb. 29–Mar. 6	7	1,073	1,081	1,068	1,058	1,045	1,086	1,074	1,063

35	Mar. 7–Mar 13	7	1,052	1,052	1,037	1,021	1,065	1,037	1,047	1,041
36	Mar 14–Mar. 20	7	1,091	1,099	1,099	1,200	1,129	1,135	1,096	1,155
37	Mar. 21–Mar. 27	7	1,156	1,151	1,164	1,154	1,125	1,122	1,157	1,134
38	Mar. 28–Apr. 3	7	1,160	1,174	1,174	1,182	1,156	1,151	1,169	1,163
39	Apr. 4–Apr. 10	7	1,222	1,203	1,235	1,206	1,209	1,229	1,220	1,215
40	Apr. 11–Apr. 17	7	1,208	1,196	1,230	1,227	1,231	1,258	1,211	1,239
41	Apr. 18–Apr. 24	7	1,192	1,169	1,220	1,250	1,259	1,256	1,194	1,255
42	Apr. 25–May 1	7	1,322	1,297	1,338	1,298	1,274	1,252	1,319	1,275
43	May 2–May 8	7	1,285	1,258	1,286	1,334	1,288	1,350	1,276	1,324
44	May 9–May 15	7	1,301	1,287	1,320	1,340	1,337	1,305	1,303	1,327
45	May 16–May 22	7	1,384	1,385	1,397	1,406	1,362	1,338	1,389	1,369
46	May 23–May 30	8	1,421	1,410	1,421	1,435	1,440	1,449	1,417	1,441
47	May 31–June 5	6	1,407	1,406	1,418	1,473	1,440	1,449	1,410	1,454
48	June 6–June 12	7	1,359	1,360	1,397	1,398	1,383	1,439	1,372	1,423
49	June 13–June 19	7	1,458	1,450	1,462	1,386	1,436	1,520	1,457	1,447
50	June 20–June 26	7	1,471	1,445	1,463	1,430	1,414	1,456	1,460	1,433
51	June 27–July 3	7	1,448	1,435	1,451	1,449	1,460	1,459	1,445	1,456
52	July 4–July 10	7	1,507	1,507	1,514	1,408	1,406	1,451	1,509	1,422
53	July 11–July 17	7	1,442	1,444	1,443	1,481	1,457	1,429	1,443	1,456
54	July 18–July 31	14	1,513	1,497	1,456	1,463	1,474	1,437	1,489	1,458
55	Aug. 1–Aug. 7	7	1,487	1,485	1,483	1,487	1,489	1,472	1,485	1,483
56	Aug. 8–Aug. 14	7	1,397	1,392	1,397	1,371	1,424	1,387	1,395	1,394
57	Aug. 15–Aug. 21	7	1,350	1,343	1,353	1,380	1,305	1,385	1,349	1,357
58	Aug. 22–Aug. 28	7	1,341	1,320	1,329	1,333	1,357	1,375	1,330	1,355
59	Aug. 29–Sept. 4	7	1,390	1,373	1,367	1,388	1,368	1,374	1,377	1,377
60	Sept. 5–Sept. 11	7	1,353	1,336	1,353	1,359	1,326	1,339	1,347	1,341
61	Sept. 12–Sept. 18	7	1,291	1,268	1,276	1,310	1,262	1,267	1,278	1,280
62	Sept. 19–Sept. 25	7	1,189	1,172	1,201	1,251	1,253	1,225	1,187	1,243
63	Sept. 26–Oct. 2	7	1,223	1,196	1,212	1,163	1,147	1,167	1,210	1,157
64	Oct. 3–Oct. 9	7	1,170	1,144	1,146	1,119	1,132	1,140	1,153	1,130
65	Oct. 10–Oct. 16	7	1,114	1,095	1,103	1,148	1,097	1,137	1,104	1,127
66	Oct. 17–Oct. 23	7	1,071	1,059	1,083	1,038	1,031	1,038	1,071	1,036
67	Oct. 24–Oct. 30	7	1,078	1,048	1,070	1,068	1,037	1,038	1,065	1,048
68	Oct. 31–Nov. 6	7	1,006	986	996	999	973	989	996	987
69	Nov. 7–Nov. 13	7	975	952	973	1,030	957	950	967	979
70	Nov. 14–Nov. 20	7	979	965	961	939	957	925	968	940
71	Nov. 21–Nov. 26	6	924	922	915	899	897	917	920	904
72	Nov. 27–Dec. 4	8	832	837	845	862	861	854	838	859
73	Dec. 5–Dec. 11	7	835	824	843	817	803	799	834	806
74	Dec. 12–Dec. 18	7	816	809	814	810	782	774	813	789
75	Dec. 19–Dec. 25	7	796	785	793	811	769	773	791	784
76	Dec. 26–Jan. 1	7	827	818	825	785	787	764	823	799
Average for 76 periods			1,164	1,155	1,164	1,163	1,157	1,158	1,161	1,160

[1]FP = flat-plate radiometer.

TABLE 3.—*Average daily value by months of net incoming radiation at the water surface, Q_T, at Salton Sea*

[In calories per square centimeter per day]

Month	Average of three flat-plate radiometers	Salton Sea Test Base Cummings Radiation Integrator	Koberg's equation
1967			
August	1,452	1,450	1,425
September	1,286	1,296	1,296
October	1,113	1,132	1,166
November	959	953	970
December	822	818	831
August–December average	1,126	1,130	1,138
1968			
January	867	875	866
February	1,009	966	977
March	1,107	1,119	1,124
April	1,223	1,237	1,272
May	1,351	1,381	1,373
June	1,429	1,422	1,463
July	1,471	1,453	1,447
August	1,392	1,392	1,409
September	1,280	1,294	1,319
October	1,100	1,095	1,123
November	947	954	963
December	818	814	825
August–December average	1,107	1,109	1,128
Annual Average	1,166	1,167	1,180

The energy advected to the sea, Q_v, was computed using the measured temperature and volume products of surface inflow, rainfall, and ground water inflow.

The change in energy content of the body of water, Q_x, was determined from the difference between the computed energy content for each thermal survey.

The three terms of equation 2, Q_e, Q_h, Q_w, were determined as functions of the evaporation rate (E_{EB}) using the following relations:

$$Q_e = p\,E_{EB}L;\ Q_h = R\ Q_e;\ \text{and}\ Q_w = pc\,E_{EB}\,(T_e - T_b)$$

where

p =density of the evaporated water,
L =latent heat of vaporization of water,
R =the Bowen ratio,
c =specific heat of water,
T_e =temperature of the evaporated water, and
T_b =arbitrary base temperature.

In the above relationship T_e is presumed to be equal to the water-surface temperature (T_o) and T_b is assumed to be 0°C.

To compute the evaporation rate using the energy-budget method for a specific interval of time, equation 2 takes the following form:

$$E_{EB} = \frac{Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} + Q_v - Q_x + Q_b}{L\,(1 + R) + T_o} \qquad (3)$$

where E_{EB} is the energy-budget evaporation rate, L is the latent heat of vaporization, R is the Bowen ratio, and T_o is the water-surface temperature. For a more detailed explanation of each of the energy-budget terms, the reader is referred to Anderson (1954).

The specific interval of time to which equation 3 is applied is the interval over which the change in energy content of the reservoir is measured: this interval is called an energy-budget period. The energy content of the reservoir was estimated by a thermal survey consisting of temperature profiles at 20 preselected sites (fig. 1). During the 539-day study, 18 thermal surveys were made giving 17 energy-budget periods. The average length of these periods was 32 days, with maximum and minimum periods of 42 and 19 days respectively.

The heat transfer through the bottom of the Salton Sea (Q_b) was computed for the 17 energy-budget periods using an equation described by Pearce and Gold (1959). The magnitude of the bed conduction term ranged from -14 cal cm^{-2} day^{-1} in midsummer and zero in the early spring and fall to $+13$ cal cm^{-2} day^{-1} in midwinter. Including the bed conduction term in the energy-budget of Salton Sea decreased the (computed) high evaporation rates during June and July by approximately 3 percent and increased the low evaporation rates during December and January by approximately 15 percent. The average values for each term of equation 2 during each of the 17 energy-budget periods are listed in table 4.

Exclusion of the bed conduction term Q_b in the energy budget decreased the agreement between the evaporation values determined by the water-budget and energy-budget methods. This term is included, therefore, in the results presented herein.

WATER-BUDGET METHOD

The Salton Sea has no surface outflow. The only manner in which water leaves the Sea is by way of evaporation. The evaporation for the Salton Sea was estimated by use of the water-budget method which applies for a specific time period. The water-budget equation is:

$$E = I + P + G - S + TE \qquad (4)$$

where

E =total evaporation loss from the Salton Sea,
I =surface inflow,
P =precipitation over the Salton Sea,

G =ground-water inflow,
S =change in storage, and
TE =correction for thermal expansion.

During the study, surface inflow to the Salton Sea was derived from drainage from irrigated land in the Imperial, Mexicali, and Coachella Valleys. Inflow from the Imperial and Mexicali Valley was derived as the sum of flows in the Alamo River, New River, 21 drains and wasteways, and San Felipe Creek. Inflow from the Coachella Valley was derived as the sum of flows in the Whitewater River, 20 drains, and Salt Creek. The inflow was measured by recording gages at the Alamo River, New River, Whitewater River, Trifolium drain, and after September 1967 Salt Creek and San Felipe Creek. Inflow from the 41 drains and wasteways were estimated from periodic measurements. An unknown, but small amount of inflow occurred from drains that were not measured. The flows from the New and Alamo Rivers represented 91 percent of the total measured inflow.

TABLE 4.—*Average values of terms in the energy budget of Salton Sea for periods 19 to 42 days in length*
[In calories per square centimeter per day]

Period number	Period	Days	Q_T	Q_{bs}	Q_v	Q_e	Q_h	Q_w	Q_b	Q_x
	1967–68									
1	July 14–Aug. 10	28	1,477	985	13	457	−14	25	12	25
2	Aug. 11–Sept. 5	26	1,399	985	21	404	13	23	9	−14
3	Sept. 6–Oct. 10	35	1,266	958	13	394	6	20	3	−102
4	Oct. 11–Nov. 9	30	1,034	900	11	232	10	10	−5	−102
5	Nov. 10–Dec. 10	31	906	846	8	200	31	7	−10	−160
6	Dec. 11–Jan. 15	36	823	769	5	119	29	3	−13	−79
	1968–69									
7	Jan. 16–Feb. 18	34	934	782	7	87	0	2	−12	80
8	Feb. 19–Mar. 20	31	1,080	822	10	256	−16	8	−7	27
9	Mar. 21–Apr. 23	34	1,195	841	12	309	−7	11	0	53
10	Apr. 24–May 24	31	1,325	874	11	377	−24	15	8	86
11	May 25–June 25	32	1,430	932	12	369	−9	18	12	121
12	June 26–July 14	19	1,461	952	15	446	−15	23	14	57
13	July 15–Aug. 19	36	1,442	970	14	489	−16	26	12	−25
14	Aug. 20–Sept. 15	27	1,350	965	13	371	−5	20	7	6
15	Sept. 16–Oct. 22	37	1,156	904	12	377	−11	16	0	−118
16	Oct. 23–Dec. 3	42	965	855	7	227	22	8	−8	−132
17	Dec. 4–Jan. 2	30	821	780	4	119	26	3	−13	−90
1–17	July 14, 1967– Jan. 2, 1969	539	1,164	885	11	302	2	13	0	−27
1–12	July 14, 1967– July 14, 1968	367	1,175	881	11	294	1	13	0	−3
7–17	Jan. 16, 1968– Jan. 2, 1969	353	1,181	876	10	306	−4	13	0	−1

Precipitation was measured at the four land stations using National Weather Service rain gages. The average rainfall for the four stations was assumed to be representative of precipitation on the Salton Sea.

The ground-water inflow to the Salton Sea was estimated to be 50,000 acre-ft per year during the 1961-62 study (Hely and others, 1966). A value of 137 acre-ft per day was used for this study.

The change in storage was determined from water-level measurements and the relation of water level to volume. The relationship of water level to volume was determined from a topographic survey and soundings described in Hely, Hughes, and Ireland (1966). The water level during the study fluctuated from a maximum of 231.7 ft to a minimum of 232.7 ft below mean sea level. The elevation on December 31, 1967, as well as December 31, 1968, was 232.7 ft below mean sea level. Therefore, the net change in storage for 1968 was zero.

The coefficient of volume expansion for liquids is the ratio of the change in volume per Celsius degree to the volume at 0°C. The value of the coefficient varies with temperature. The changes in volume due to thermal expansion at Salton were determined from changes in temperature at successive thermal surveys and the average volume during the period. To determine the monthly values of thermal expansion, the average water temperature was assumed to vary uniformly with time between thermal surveys. A complete discussion of the computation of the thermal-expansion term is found in the Lake Hefner report (U.S. Geol. Survey, 1954, p. 19–20). In this study the term varied between zero (where there was no change in temperature between thermal surveys) to 8,200 acre-ft.

Table 5 shows the monthly values of the water-budget parameters in acre-ft.

MASS-TRANSFER METHOD

Computing evaporation by the mass-transfer method involves only the water-vapor transport from the body of water to the atmosphere; whereas, in the energy-budget method, evaporation is considered as only one item in the complete energy budget for the body of water. Most equations for estimating evaporation by the mass-transfer method take the form

$$E_{MT} = N\, u\, (e_o - e_a), \tag{5}$$

where

N = the mass-transfer coefficient,

u = the windspeed at some height above the water surface,

e_o = vapor pressure of saturated air at the temperature of the water surface, and

e_a = vapor pressure of the air at some height above the water surface.

TABLE 5.—*Average values of terms in the monthly water budget of Salton Sea from August 1967 through December 1968, in acre-feet*

Month	I	P	G	ΔS	TE	E
1967						
August	105,340	20,790	4,165	−71,000	0	201,295
September	109,530	15,544	4,165	0	−5,609	123,630
October	121,210	233	4,165	0	−8,247	117,361
November	98,740	17,960	4,165	23,000	−5,231	92,634
December	67,420	16,608	4,165	0	−5,956	82,237
Aug–Dec total	502,240	71,135	20,825	−48,000	−25,043	617,157
1968						
January	87,670	—	4,165	71,000	419	21,254
February	97,330	2,038	4,165	95,000	5,041	13,574
March	124,390	10,895	4,165	47,000	2,397	94,847
April	116,250	3,754	4,165	0	5,120	129,289
May	106,610	—	4,165	−47,000	4,548	162,323
June	95,090	—	4,165	−48,000	1,951	149,206
July	102,420	2,368	4,165	−23,000	5,759	137,712
August	97,280	—	4,165	−71,000	−2,828	169,617
September	113,790	—	4,165	−47,000	−6,373	158,582
October	113,770	233	4,165	0	−4,984	113,184
November	88,200	—	4,165	0	−6,074	86,291
December	89,920	2,094	4,165	23,000	−4,220	68,959
Annual total	1,232,720	21,382	49,980	0	− 756	1,303,326
Aug–Dec total	502,960	2,327	20,825	−95,000	−24,479	596,633

The units used in equation 5 have E_{MT} expressed in inches per day, u expressed in miles per hour, and e_o and e_a expressed in millibars. The empirical mass-transfer coefficient, N, accounts for parameters that affect evaporation from the body of water, including the surface area, surrounding topography, and others. The mass-transfer coefficient determined for one body of water is not transferable to another site. In this study windspeed and vapor pressure of the air were measured at 6.56 ft above the water surface.

To determine the mass-transfer coefficient for the Salton Sea, two sets of radiation data were available from the flat-plate radiometers and the CRI's. Vapor pressure data were available from the three land stations and the six raft stations. The windspeed was measured only at the raft stations. In order to determine which combination of data best represented the conditions for the sea, complete energy budgets and the corresponding mass-transfer coefficients were determined for eight separate combinations of data. The radiation as determined by the flat-plate and CRI were each used with four combinations of vapor pressure data. The first combination averaged all available (raft and land) data, the second used only the data obtained at the rafts, the third used only the data obtained at the three land

TABLE 6.—*Determination of the mass-transfer coefficient*, N

Vapor pressure measure at	E_{EB} (in inches/day)	$u(e_o-e_a)$ (mi/hr × mb)	E_T (in inches)	N (in inches/day mi/hr × mb)	SE (in inches/day)	SE (in percent of E_{EB})
Radiation data from FP						
All stations	0.206	96.39	111.30	0.00214	0.02921	14.2
Raft stations	.204	83.44	110.04	.00245	.03086	15.1
Land stations	.209	109.35	112.39	.00191	.03646	17.5
Test Base Station	.207	113.78	111.74	.00182	.03279	15.8
Radiation data from CRI						
All stations	0.205	96.39	110.73	0.00213	0.03169	15.5
Raft stations	.203	83.44	109.42	.00243	.03330	16.4
Land stations	.208	109.35	111.85	.00190	.03842	18.5
Test Base Station	.206	113.78	111.16	.00181	.03629	17.6

stations, and the final used only the data obtained at the Test Base. The results of these computations are shown in table 6. In table 6, E_{EB} is the average energy-budget evaporation rate for the study in inches per day; $u(e_o - e_a)$ is the mass-transfer product of the average windspeed and the average vapor pressure deficit in miles per hour times millibars; E_T is the total energy-budget evaporation expressed in inches; N is the mass-transfer coefficient determined from the ratio E_{EB} to $u(e_o - e_a)$ in units such that E_{EB} is given in inches per day when u is expressed in miles per hour and $(e_o - e_a)$ is expressed in millibars. SE is the standard error of estimate of evaporation expressed in inches per day, and was computed by the equation

$$SE = \sqrt{\frac{\Sigma\,[E_{EB} - Nu\,(e_o - e_a)]^2}{n - 1}} \qquad (6)$$

where the sum is performed over the 17 energy-budget periods represented by n in the equation (Spiegel, 1961). The standard error of estimate was also computed as a percentage of the average daily evaporation.

The mass-transfer coefficient, N, for a reservoir is the slope of the line relating the mass-transfer product, $u(e_o - e_a)$, as the independent variable and an independent measurement of the evaporation rate as the dependent variable. In this study, the independent measurement of the rate of evaporation was obtained by the energy-budget method. The plot of this relationship, for the 17 energy-budget periods at Salton Sea is shown in figure 4.

Values of the mass-transfer product for each of the 17 periods were obtained as follows. The anemometers at each of the rafts were read on days when thermal surveys were made and the average windspeed was determined by dividing the difference in the dial reading by the time interval. The vapor pressure of the air was determined from the average wet- and dry-bulb temperatures measured at the raft stations. The saturation vapor pressure of the water surface was determined using the average temperature measured at the raft station and standard vapor pressure tables for sea water (Harbeck, 1955).

The evaporation, as determined by the energy-budget method, is not very sensitive to variations in the measured vapor pressures because this term is only used in the determination of the Bowen ratio. Using either estimate of the radiation, the variations in the energy-budget evaporation (E_{EB}) was less than 2 percent, while the value of the mass-transfer product varied by over 30 percent. The total variation in the energy-budget evaporation among the eight cases was 3 percent.

One of the purposes of this study was to determine the value of the empirical mass-transfer coefficient for the Salton Sea. The value of this coefficient accounts for many physiographic factors of the Salton Sea, and of course, its value is dependent on the location at which the data are collected. The data that produced the smallest standard error of estimate in the average daily evaporation rate are assumed to be the most representative for use with the mass-transfer method.

In both radiation categories, the mass-transfer coefficient determined using the vapor pressure data at the raft stations or the raft and land stations combined appears to be more representative of conditions at Salton Sea than data obtained at the Test Base or the land stations. A comparison of the 17 energy-budget evaporation values, computed using each of the eight combinations of data with the corresponding water-budget values, also indicates that the radiation from the flat-plate radiometers and vapor pressure measured at the rafts are most representative of conditions at the Salton Sea.

The N value (0.00245 expressed in $\dfrac{\text{in/day}}{\text{mph} \times \text{mb}}$ derived from this combination was used as the mass-transfer coefficient to determine evaporation by the mass-transfer method. These results are shown in figure 4. A smaller standard error was obtained by use of the flat plate for every combination of vapor pressure. This infers that the flat-plate radiation values are slightly more accurate.

When the water budget was used as the independent evaporation measurement, the resulting mass-transfer coefficient was 0.00233, expressed in the same units, and the standard error was 0.0459 in.-day. The larger standard error of the water budget indicates the energy budget more accurately predicts monthly evaporation.

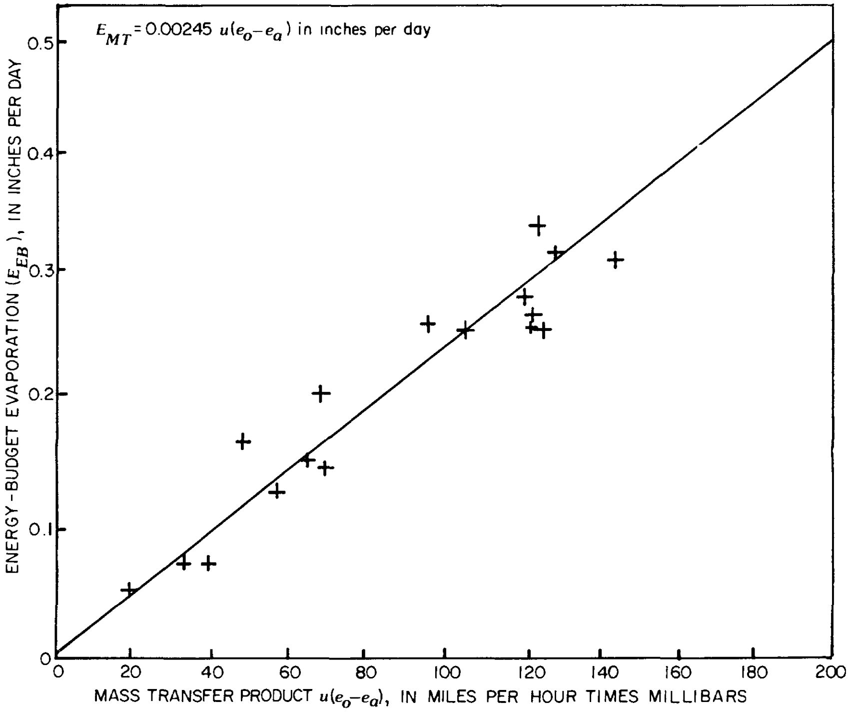

FIGURE 4.—Relationship of the mass-transfer product to evaporation measured by the energy-budget method.

DISCUSSION OF RESULTS

Values of evaporation from the Salton Sea were determined by the energy-budget, mass-transfer, and water-budget methods for each of the 17 energy-budget periods, and the results are shown in table 7. The total evaporation computed by the three methods for the 539-day study period agree within 5 percent. The comparison of evaporation totals for the three methods for periods 1 through 12 and 7 through 17 (approximately yearly evaporation totals) differ by 7 and 6 percent respectively. A comparison of values of evaporation for individual periods, however, show a wider range of differences. No seasonal bias in any of the methods is apparent.

The values for monthly evaporation from the Salton Sea were computed by the mass-transfer, energy-budget, and water-budget methods.

The monthly values of evaporation were computed using the mass-transfer coefficient and measurements of u $(e_o - e_a)$ at the raft stations. Daily values of the windspeed were not recorded but determined from anemometer readings at the time of thermal surveys and

TABLE 7.—*Total evaporation from Salton Sea computed by energy-budget, mass-transfer, and water-budget methods for periods 19 to 42 days in length*

Number	Period	Number of days in period	Evaporation (in inches) Energy budget	Mass transfer	Water budget
	1967–68				
1	July 14–Aug. 10	28	8.72	8.64	7.47
2	Aug. 11–Sept. 5	26	7.16	7.52	7.07
3	Sept. 6–Oct. 10	35	9.36	10.29	8.95
4	Oct. 11–Nov. 9	30	4.71	4.78	5.67
5	Nov. 10–Dec. 10	31	4.17	4.33	4.20
6	Dec. 11–Jan. 15	36	2.87	3.00	2.90
	1968–69				
7	Jan. 16–Feb. 18	34	1.99	1.58	2.56
8	Feb. 19–Mar. 20	31	5.33	3.57	2.56
9	Mar. 21–Apr. 23	34	7.08	5.50	8.11
10	Apr. 24–May 24	31	7.89	7.06	6.05
11	May 25–June 25	32	7.99	9.33	8.28
12	June 26–July 14	19	5.75	6.61	4.00
13	July 15–Aug. 19	36	11.97	10.58	12.59
14	Aug. 20–Sept. 15	27	6.81	8.14	6.22
15	Sept. 16–Oct. 22	37	9.44	9.25	8.43
16	Oct. 23–Dec. 3	42	6.42	7.00	7.74
17	Dec. 4–Jan. 2	30	2.38	2.87	2.22
1–17	July 14, 1967–Jan. 2, 1969	539	110.04	110.05	105.02
1–12	July 14, 1967–July 14, 1968	367	73.02	72.21	67.82
7–17	Jan. 16, 1968–Jan. 2, 1969	353	73.05	71.49	68.76

maintenance visits to the rafts. To determine the windspeed for monthly periods, the value was assumed constant between readings. The values of e_o and e_a were computed daily, and these values summed to give average monthly values.

Thermal surveys were not made on a calendar-month basis so the energy-budget method could not be used directly to compute evaporation on a monthly basis because of the possible error in determining the energy storage term. Evaporation computed by energy budget must be prorated over periods that would contain parts of two months. The mass-transfer product was used to prorate energy-budget evaporation between months because it reflected the change in the rate of evaporation within the energy-budget period. The equation used to compute monthly energy-budget evaporation is:

$$\begin{matrix}E_{EB}\text{ depth for}\\ \text{part period}\end{matrix} = \frac{E_{MT}\text{ depth for part period}}{E_{MT}\text{ depth for full period}} \times \begin{matrix}E_{EB}\text{ depth for}\\ \text{full period}\end{matrix} \qquad (7)$$

TABLE 8.—*Monthly evaporation from Salton Sea, August 1, 1967, to December 31, 1968*

Month	Evaporation (inches)		
	Energy budget	Mass transfer	Water budget
1967			
August	9.06	9.85	10.64
September	7.78	8.33	6.55
October	6.38	6.20	6.22
November	3.63	3.94	4.90
December	4.00	4.04	4.35
1968			
January	1.65	1.54	1.12
February	1.97	1.42	0.71
March	5.94	4.50	4.96
April	6.87	7.18	6.75
May	8.61	8.29	8.49
June	7.60	8.20	7.83
July	9.06	8.16	7.24
August	10.09	10.93	8.94
September	8.69	9.39	8.39
October	5.73	5.00	5.99
November	4.67	4.68	4.57
December	2.60	3.01	3.65
Total 1968	73.48	72.30	68.64
Total 17-month period	104.33	104.66	101.30

in which E_{EB} is the evaporation for the energy-budget period, and E_{MT} is the mass-transfer evaporation. Evaporation computed for parts of a month were totaled to obtain the individual monthly values.

The monthly values of the water budget were computed directly from summations of the daily values of the parameters over each month. The results for the three methods are shown in table 8. The three methods agree within 3 percent for the 17-month period. The annual totals for 1968 agree within 7 percent.

Neumann (1954) concluded from heat budget considerations that the annual variation of evaporation from lakes in the middle latitudes resembles a double wave and is similar to evaporation from the oceans, in similar latitudes, except for a phase shift. Besides the accepted winter minimum of evaporation, a second minimum occurs in the spring or in the early summer. The totals for monthly evaporation computed by the energy-budget method shown in table 8 support Neumann's conclusion. The winter minimum occurs in January or February and a second minimum occurs in June or July. The two maxima occur in May and August.

The monthly totals of evaporation computed by the energy-budget method in a 1961–62 study (Hely and others, 1966) also show the double wave evaporation. Like the results of this study, the 1961 data show the evaporation maximums occurring in May and August and evaporation minimums occurring in January and June. The 1962 data, however, show the maximums occurring in May and July and the minimums occurring in December and June.

It is indicated from the monthly energy-budget data for both studies that the annual variation of evaporation for the Salton Sea does exhibit the double wave postulated by Neumann. It is also indicated from the data that the occurrence of the double wave will vary in accordance with the weather conditions.

The accuracy of the water budget increases with length of period considered because changes in storage become relatively insignificant. Therefore, the water-budget total for the 539-day period should be accurate. Furthermore, the evaporation totals computed by the energy-budget method are very sensitive to the accuracy of the net incoming radiation values. Arbitrarily increasing the net incoming radiation by 5 percent resulted in an 18.2 percent increase in the total energy-budget evaporation for the 539-day period. Therefore, the agreement between the energy-budget and water-budget totals for the entire period indicates that both the flat-plate and CRI give accurate long term values of net incoming radiation. When the entire period is considered, the energy-budget evaporation was within 1 percent of the value obtained by use of the CRI. Likewise, the period total for either the flat-plate or CRI agreed within 5 percent of the water-budget evaporation. If one assumes the water-budget total for the 17-month period is exact, the measured net incoming radiation values of either the flat-plate or CRI should be in error by less than 1.5 percent.

On a monthly basis the agreement between the flat-plate and CRI radiation values is generally good. The root-mean-square difference was 1.4 percent. On a weekly basis, the agreement was also good, the root-mean-square difference being 3.3 percent. The agreement between the CRI and the average of the flat plates is good for periods of a week or longer.

The areal variation of the net incoming radiation measured at the three stations was only about 1 percent on an annual basis. On a weekly basis the variation is greater. The average annual net incoming radiation values measured at each CRI station during 1968 was 1163 cal cm^{-2} day^{-1} at the Test Base, 1157 cal cm^{-2} day^{-1} at the North Station, and 1158 cal cm^{-2} day^{-1} at the South Station. Using the average of the three flat-plates at the Test Base as a basis for comparison, the root-mean-square difference between the net incoming radiation measured at the North Station was 4.0 percent, with a maximum of 10.4 percent in period 23, while that at the South Station was 3.6 percent with a maximum difference of 9.7 percent in period 23.

Previous investigations, using an earlier model of the CRI, have shown it to have a slight seasonal bias when used to compute monthly values; (Koberg, 1958; Harbeck and others, 1959). It is believed that neither the flat-plate radiometer nor the CRI values in this study contain a seasonal bias. A comparison of the monthly water-budget evaporation values with the energy-budget values determined by use of the flat-plate radiometers shows no seasonal bias. Since radiation values determined by use of the flat-plate and the CRI are completely independent, one would not expect a seasonal bias in the flat plate to correspond to any seasonal bias in the CRI. The data in table 3 show no seasonal bias between monthly flat plate and CRI or the flat plate and the empirical values.

CONCLUSIONS

Evaporation totals measured by the energy-budget, mass-transfer, and water-budget methods for the 539-day period agree within 5 percent. It was determined in this study that vapor pressure measured at the raft stations is more representative of conditions over the Salton Sea for evaporation computations than vapor pressure measured at land stations. The annual variation of monthly evaporation computed by the energy-budget method showed that the Salton Sea exhibits a double-wave evaporation similar to that of oceans in the same latitude.

The empirical mass-transfer coefficient, N, was determined from energy-budget measurements. The value of the coefficient is 0.00245, which gives the evaporation in inches per day when the windspeed is expressed in miles per hour and vapor pressure is expressed in millibars. The coefficient is only valid when data are obtained at the raft stations. Coefficients for use when data are collected elsewhere are given in this report.

To determine if radiation measured by the flat-plate radiometer is seasonally biased, 76 weekly measurements from a Cummings Radiation Integrator were compared with the flat-plate values. The results of this comparison and a comparison on a monthly basis indicate that the measurements of radiation by the flat-plate radiometer are not seasonally biased. The CRI gives reliable measurements of radiation periods as short as 1 week.

The areal variation of the net incoming radiation measured at the three CRI stations was very small on an annual basis and it is not large on a weekly basis.

REFERENCES

Anderson, E. R., 1954, Energy-budget studies, in water-loss investigations—Lake Hefner studies, Technical report: U.S. Geol. Survey Prof. Paper 269, p. 71–119.

Harbeck, G. E., Jr., 1955, The effect of salinity on evaporation: U.S. Geol. Survey Prof. Paper 272–A, 6 p.

Harbeck, G. E., Jr., Koberg, G. E., and Hughes, G. H., 1959, The effect of the addition of heat from a powerplant on the thermal structure and evaporation of Lake Colorado City, Texas: U.S. Geol. Survey Prof. Paper 272–B, 49 p.

Hely, A. G., Hughes, G. H., and Ireland, Burdge, 1966, Hydrologic regimen of Salton Sea, California: U.S. Geol. Survey Prof. Paper 486–C, 32 p.

Hughes, G. H., 1967, Analysis of techniques used to measure evaporation from Salton Sea, California: U.S. Geol. Survey Prof. Paper 272–H, 25 p.

Koberg, G. E., 1958, Energy-budget studies, *in* Harbeck, G. E., Jr., Kohler, M. A., Koberg, G. E., and others, Water-Loss Investigations: Lake Mead Studies, U.S. Geol. Survey Prof. Paper 298, p. 20–29.

———1964, Methods to compute long-wave radiation from the atmosphere and reflected solar radiation from a water surface: U.S. Geol. Survey Prof. Paper 272–F, 29 p.

Neumann, J., 1954, On the annual variation of evaporation from Lakes in middle latitudes: Archiv f. meteorologie, geophysik and bioklimatologie, Ser. B., Bd. 5, H. 3/4.

Pearce, D. C., and Gold, L. W., 1959, Observations of ground temperature and heat flow at Ottawa, Canada: Jour. Geophys. Research, v. 64, no. 9, p. 1,293–1,298.

Spiegel, M. R., 1961, Theory and problems of statistics: New York, McGraw-Hill, 359 p.

U.S. Geological Survey, 1954, Water-loss investigation—Lake Hefner studies, Technical report: U.S. Geol. Survey Prof. Paper 269, 158 p. [previously pub. as U.S. Geol. Survey Circ. 229 (1952) and as U.S. Navy Electronics Lab. rept. 327].

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