

The Salton Sea. Physical and Chemical Characteristics¹

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ABSTRACT

The Salton Sea of California lying below sea level in a desert basin, serves as a sump for irrigation water diverted from the Colorado River. The present Sea reached its maximum size and highest surface elevation at the time of its formation in 1907. Due to evaporation at the rate of six feet per year the surface elevation fell from -195 feet to its minimum of -240 feet in 1948, the surface area decreased from about 500 square miles to about 320, and the salt content (salinity) increased from 3.6‰ to about 40‰. Since 1948 increased "wastage" of water into the Sea has raised the surface to -235 feet (1956) and diluted the waters to a salinity of about 33‰. Although the total salinity is approximately the same as that of the oceans the waters of the Sea contain a different proportion of ions, and the pH is slightly higher.

The annual range of water temperature is from 10° to 36°C. In spring the surface may become as much as 5° warmer than the bottom, but since the maximum depth of the Sea is about 12 meters, mixing by winds rapidly removes differences between surface and bottom; during most of the year (August to May) there is less than 1°C difference between surface and bottom. Concentrations of dissolved oxygen ranged up to 11.8 mg/L at the surface and 9.3 mg/L at the bottom during winter. During calm periods in summer, however, the water at depths below 8-9 meters became anoxic for periods as long as 1-3 days; the surface waters, too, became depleted of oxygen, but for only an hour or so at about dawn. Concentrations of sulfide as high as 85 μg-at./L, and of ammonia as high as 50 μg-at./L were found during the anoxic periods in summer.

INTRODUCTION

The present Salton Sea covers an area of about 340 square miles in southern Riverside County and northern Imperial County, California. (The center is about 33° 20' N and 115° 50' W. See Fig. 1.) The Sea lies in the Salton Basin, which is a depression with a maximum depth of 273 feet (83 meters) below mean sea level, north of the delta of the Colorado River. The delta

separates the basin from the Gulf of California. According to Buwalda and Stanton (1930) the trough sank from above to below sea level during or since the formation of the delta. The Sea is therefore not a cut off arm of the ocean. The salts present in the Salton Sea are the result of evaporation of Colorado River water.

An old shore line, at an elevation approximately 30 feet above mean sea level (at which height the lake would spill into the Gulf), records a previous lake which covered 2200 square miles and extended from the Mexican border to the Indio Hills. This previous lake, which is judged to have been of fresh water from such evidence as the species of mollusk shells present, was called Lake Cahuilla according to Indian legends. It existed during a "pluvial" period in the late Pleistocene according to Cockerell (1946), and is referred to as Lake LeConte by Hubbs and Miller (1948) whose paper includes an excellent list of references to geological studies of the region. Since the days of Lake Cahuilla there have been numerous but less extensive lakes formed by

¹ With the objective of establishing a sport fishery in the Salton Sea, the Wildlife Conservation Board, State of California Department of Fish and Game, contracted with Fisheries, Department of Zoology, University of California, Los Angeles, to conduct a survey of the Sea. A complete report will be published elsewhere; this report summarizes some of the physical and chemical findings. The help of Dr. Boyd W. Walker, who supervised the project, is gratefully acknowledged, as is the assistance of an Advisory Committee of the Department of Fish and Game, which consisted of Frances Clarke, Phil Douglas, John Fitch, Scott Soule, and John Radovich. Acknowledgments are also due the following for making data available: H. F. Blaney, A. J. Boles, M. R. Huberty, J. S. Reger, T. A. Sprink, H. C. Troxell, Lowell Weeks, and L. V. Wilcox.

inflows from the Colorado River whenever it shifted its course through the delta and drained into the basin rather than into the Gulf. One such filling was recorded in 1891. Then, as on previous similar occasions, the limited amount of water soon evaporated

leaving a desert basin playa with a sufficient deposit of salt to allow salt mining to be carried on prior to 1905.

The present Salton Sea dates from the spring of 1905 when the main flow of the Colorado River was accidentally diverted into the Salton Basin by way of irrigation canals in the newly reclaimed Imperial Valley. The break was not repaired until February of 1907. During the two-year period the basin was filled to the -195 foot level, creating a lake with a maximum depth of 79 feet (24 meters) and covering 515 square miles.

IONIC COMPOSITION

Records from the period of the formation of the Sea (MacDougal 1914) reveal that in 1907 the salinity was about 3.6‰, which was approximately five times greater than the salt content of the Colorado River which was 0.7‰ at Yuma, the inlet to the irrigation canal. The difference in salinity is believed due to the salts leached from the previous bottom deposit.

The ionic composition of the Sea has changed somewhat since 1907. Table 1 shows that the proportion of Ca has decreased slightly from the value in the original Sea, and greatly relative to the proportion present in the River. The proportions of

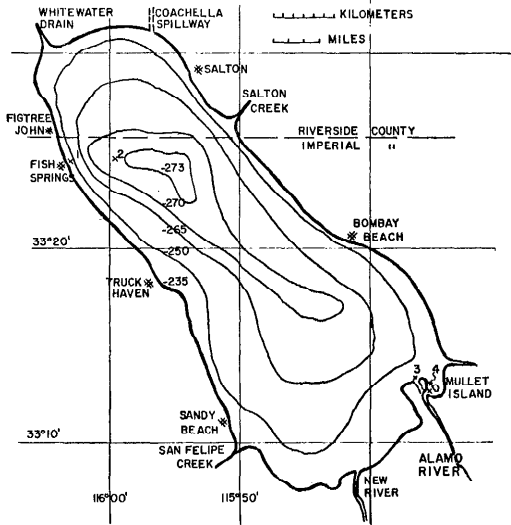


FIG. 1. Sketch of Salton Sea. Contours above -250 feet from U. S. Geological Survey, 1925. Contours below -250 approximate only, based on soundings by R. Arnal and U. C. L. A. Salton Sea Laboratory, 1954-1956. The four numbers show the location of stations mentioned in the section on chlorinity.

TABLE 1. Ionic composition (‰) of Salton Sea water 1907 to 1955 and comparison with river waters, ocean, and Caspian Sea

Date	Ca	Mg	Na	K	CO ₂	HCO ₃	SO ₄	Cl	Analyzed	Total
1907 ¹	0.099	0.064	1.110	0.023	0.066	—	0.476	1.697	3.55	3.65
1910 ¹	0.137	0.098	1.893	0.035	0.064	—	0.764	2.809	5.6	6.04
1913 ²	0.197	0.161	3.231	0.035	0.113	—	1.246	4.739	9.72	10.025
1916 ²	0.298	0.272	5.289	0.057	0.114	—	2.079	7.876	15.98	16.47
1929 ³	0.196	0.588	3.921	as Na	0.102	—	1.37	6.39	12.47	14.43
1945 ⁴	0.850	0.920	11.345	—	0.207	—	6.924	16.241	36.48	37.37
1948 ⁵	0.804	0.992	11.824	0.192	0.021	0.171	7.55	16.99	38.55	40.425
1955 ⁵	0.764	0.951	9.938	0.224	0.021	0.159	6.806	14.422	33.29	33.68
Colo. R. (1907) ¹	0.072	0.022	0.138	0.015	0.091	—	0.20	0.138	0.68	0.696
Alamo R. (1951) ⁶	0.157	0.113	0.410	0.011	—	0.199	0.529	0.66	2.08	2.256
New R. (1951) ⁶	0.141	0.066	0.435	0.01	—	0.209	0.444	0.605	1.91	1.93
Ocean ⁷	0.413	1.27	10.55	0.38	—	0.014	2.649	19.15*	34.22	34.48
Caspian Sea ¹	0.29	0.77	3.17	0.07	0.047	—	3.10	5.46	12.9	12.94

Sources of data:

¹ Ross 1914

² Sykes 1937

³ Coleman 1929

⁴ Imperial Irrigation District Lab.

⁵ USDA Salinity Lab., Riverside, Cal.

⁶ California Division Water Resources Survey 1953

⁷ Table 35, Sverdrup *et al.* 1942

* Chloride plus bromide

Mg and of SO_4 , on the other hand, have increased gradually during the years since 1907. Na and K are now present in about the same proportions as in 1907; Cl has decreased slightly in proportion to total, and HCO_3 decreased from 13% of the total salts in river water to 1.9% in the original Sea and since then to the current value of about 0.5%.

At present the salinity of the Salton Sea (about 33‰) is only slightly below that of the oceans, but the waters contain relatively less Mg, K, and Cl; about the same proportion of Na; and more SO_4 , Ca, HCO_3 , and CO_3 than are present in ocean water. Although the present salinity of the Salton Sea is about three times greater than that of the Caspian Sea, the ionic composition of the two are fairly comparable. (Table 1). Apparently, evaporation of Volga River and Colorado River waters resulted in similar proportions of Ca, K, SO_4 , and Cl, but with a greater proportion of Mg and less of Na in the Caspian.

With the exception of the aberrant analysis for 1929, the data of Table 1 indicate that the total salt content of the present Salton Sea increased gradually from 1907 to a high in 1948 when the salinity was 14

times greater than the original value. The increased salt content resulted from excess of evaporation over inflow. (The annual rate of evaporation is six feet or about 1.8 meters according to Blaney 1954.)

SURFACE ELEVATION

There have been fluctuations in the surface elevation of the Sea, due to variations in the amount of water inflow, as well as to the high rate of evaporation. Although the drainage area of the Salton Basin is quite extensive—about 7500 square miles—it is a desert region, so that the Whitewater, Salton, and San Felipe drainages are minor sources compared to the amount of water that enters the basin from the Colorado River. Inflow from the Colorado has depended on irrigation practice. When the diversion of the full flow of the Colorado into the Salton Sea ended in 1907, relatively little land was under cultivation in the Imperial and Coachella Valleys, and little water entered the Sea. Records of the U. S. Department of the Interior, Geological Survey, show that the surface fell from -195 feet in 1907 to -250 feet in 1925. The level fluctuated between -250 and -243 feet during the next ten years. After com

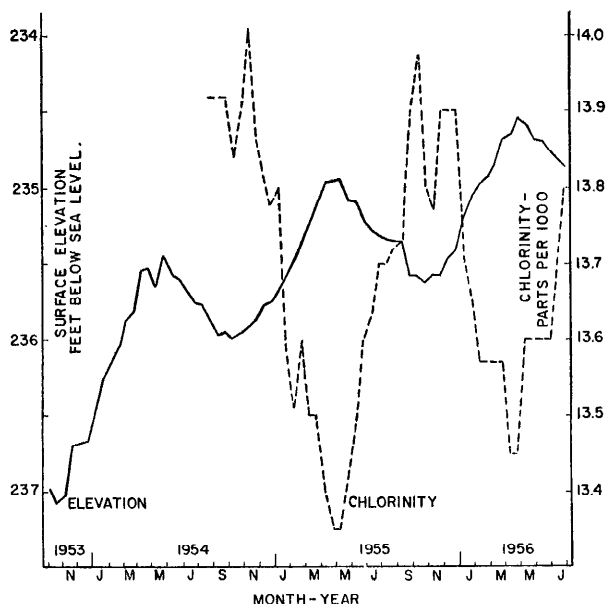


FIG. 2. Surface elevation at Fig Tree John (solid line) and chlorinity off Fish Springs (dotted line).

pletion of Boulder Dam more water was available, more land was put under irrigation, and more water entered the Sea whose level rose to -240 feet by 1948. It rose even more rapidly after 1948, due to land reclamation after World War II. By 1956 the surface elevation reached -234.4 feet, at which level the maximum depth is about 40 feet (12 meters).

In addition to the long-term changes in surface level, there is an annual cycle with highest elevation in spring and lowest in fall. Based on records from Figtree John's gauging station (maintained by the Coachella Valley County Water District), Figure 2 shows the cycle from 1953 to 1956. The cycle occurs because evaporation is low in winter, and exceeds water inflow only during the hottest part of the year. In addition, since 1935 the total annual inflow has exceeded the amount evaporated, resulting in a net increase in quantity of water in the Sea. Figure 2 indicates a net rise of one foot from November 1953 to October 1954, and a 0.4-foot rise from the fall of 1954 to the fall of 1955. These recent rises of level are less than the maximum yearly rise of 1.5 foot from 1951 to 1952, indicating that the rise of the Sea is slowing. The shape of the basin is such that with a rise in surface elevation the area of the Sea increases more rapidly than its volume (Holbrook 1927). Because of the increased area now available for evaporation, it is estimated, by the irrigation districts concerned, that, from the known rates of inflow of water and of evaporation, the level of the Sea may be stabilized at about the current surface elevation.

CHLORINITY

The salt content of the Sea shows an annual cycle with highest and lowest chlorinity occurring, respectively, at the lowest and highest surface elevations. Superimposed on Figure 2 is a plot of the chlorinity determinations made during the present study of the Sea. (Determinations were by titration of halides with silver nitrate.) From the data presented in Table 1, it is apparent that the weight ratio of Cl to total salinity (S) is not the same as in the oceans. Analyses since 1949 indicate that the ratio of Cl to S has ranged from 2.42 to

2.31, with an average value of 2.36. During the years of this study (1954-1956) the chlorinity in the main body of the Sea has ranged from 13.3 to 14‰, corresponding to a salinity range of from 31.4 to 33.0‰.

The main body of the Sea refers to the deeper portion and to the northern and western halves. As mentioned previously, most of the fresh water entering the Sea comes from the New and Alamo Rivers, which enter at the south (Fig. 1). The relatively uniform chlorinity of the main body of the Sea is illustrated by the following data. The chlorinity gradient from the north shore (outlet of Whitewater) to Fish Spring, a distance of about 7 miles, was from 13.6 to 13.9‰ on November 3, 1954. The previous week (October 26, 1954) samples from an east-west transect showed the chlorinity to be 13.7‰ on the east shore (Bombay Beach) and 13.8‰ on the west shore (off Truckhaven) with values of 13.9 and 13.8 in mid-sea. At a station on the south shore away from influence of stream discharge the average chlorinity of monthly samples from May 1955 to May 1956 was 12.9‰ with a range from 12.3 to 13.5. Chlorinity at this station (#3, Fig. 1, off the former mouth of the Alamo River) seems fairly typical of most of the southern and southwestern parts of the Sea.

In contrast to the relative uniformity and the small annual range of chlorinity in the main portion of the Sea, there are wide variations in chlorinity in the southeastern part where most of the freshwater enters. For example, data obtained November 8 and 10, 1954, illustrate the effect of freshwater entry at the southeast corner of the Sea, where the discharge of the Alamo River is eastward toward Mullet Island. A mile to the west of the river outlet the chlorinity was 13.9‰ at the bottom and 13.5 at the surface. A quarter of a mile east from the outlet, however, the chlorinity was 4.1‰, and at the west shore of Mullet Island it was 9.6. Two and one-half miles north of the island, along the shore of the Sea, surface chlorinity was 10.2, and 2 miles further north (about 4 miles from the mouth of the river) the surface value was 12.5 at shore, 12.9 a mile offshore, and 13.3 at the bottom (four meters). At Mullet Island (Station 4, Fig.

1) the average annual chlorinity was 10.8‰ with a range from 1.5 to 13.6 (a chlorinity of 1.5 is only twice that of the water in the Alamo River prior to entry into the Sea). The influence of fresh water has been noted as far north as Bombay Beach which is 9–10 miles from the river mouth. In general, the lower chlorinity is noticeable only along the southeast shore, and there is considerable delay before the effect of dilution is noticed in the main body of the Sea. Perhaps evaporation of the fresher water, which tends to float on the surface, modifies the dilution which then spreads slowly throughout the Sea by diffusion and a generally counterclockwise current.

Lowest chlorinity in the main body of the Sea during 1955 was only slightly below the lowest observed in 1956. It may be that the decrease in chlorinity, which has gone on since the peak of about 17.6‰ was reached in 1948–1949, has ended as the result of a new balance between evaporation and rate of inflow. If the surface elevation should stabilize at the current level, and if the amount of salt now entering remains the same, it can be calculated that the salinity of the Sea might be expected to increase again at a rate of about 0.4‰ per year.

TEMPERATURE

Although high temperatures are attained in summer, winter water temperatures are relatively low. The extreme range of tem-

perature during a two-year period from August 1954 to August 1956 was from 10° to 36°C. Temperatures at the surface and at a depth of 3 meters were recorded by a dual-recording thermometer located on a dock at Sandy Beach where the maximum depth within reach was 3 meters. From these data were plotted the mean water temperatures shown in Figure 3. The figure includes mean air temperatures recorded at Fish Springs. No records were obtained for the energy of solar radiation, but the annual variation in the intensity of sunlight is shown by the increase in both air and water temperatures from a low in winter to a high in summer. From May to August the air is warmed more rapidly than the water: the mean air temperature consistently exceeds the mean water temperature. In June and July the water surface may be warmed so rapidly by solar energy that there is a significant difference between temperatures at surface and bottom, although the maximum depth of the Sea is only about 40 feet (12 meters). Table 2 shows subsurface temperatures taken with a reversing thermometer on selected days in 1955. From September to May temperatures were quite the same throughout the water column. At the end of May there was still only 0.7° difference between surface and bottom. On June 8, however, the difference was 5.3°, but this large difference was temporary and decreased to 2.2° by

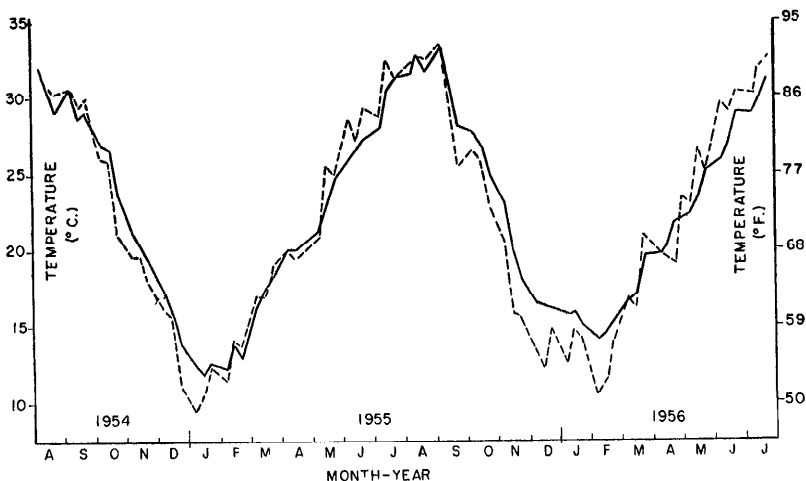


FIG. 3. Mean water temperature (solid line) at Sandy Beach and mean air temperature (dotted line) at Fish Springs.

June 14 and to 1° on June 30 (not shown). The difference in temperature remained slight through July 7, but on July 18 the surface was 3.9° warmer than the bottom. By the end of July the bottom temperature was up to nearly 30°, and surface and bottom differed by only 1.1°. During August the maximum observed difference was 0.8°, and at times surface and bottom temperatures were equal (as on August 24). Then from September on (until May) the usual difference in temperature between surface and bottom was 1° or less.

The temperature gradients that appeared during June and July were associated with changes in the weather. The warming of the surface on June 8 followed the appearance of the first protracted period without winds and with air temperatures above 38°. The warming recorded on July 18 followed four days without wind and with a mean air temperature of 40°. The appearance of a marked vertical temperature gradient seemed dependent on both rapid increase in surface warming by solar radiation and on lack of wind. Wind action mixes the shallow waters of the Sea rather thoroughly, as will be brought out in the next section dealing with concentrations of dissolved oxygen.

From Table 2 it should be evident that there is no thermocline of any duration. During the brief periods when surface and bottom temperatures are relatively far apart there may be a sharp transition between layers of water, but this may occur near the surface (between 2 and 3 meters on June 8), or at greater depth (between 7 and 9 meters on July 18), or there may be a uniform gradient (July 7). There is thus no permanent

layering, but only temporary stratification following windless periods during early summer when the water temperatures are rising to their annual maximum. Once attained, the high water temperatures were maintained until mid-September. During this period (August and early September) the insolation of the water was consistently high as judged by air temperatures: the mean maximum air temperature for the entire month of August was 37.5°, and for the first 10 days of September the mean maximum was 40°.

During autumn the water cooled slowly: the bottom temperature did not fall below 30° until after mid-September; it then decreased to 25° in mid-October, and to 20° in mid-November. During this period of decreasing water temperatures the entire water column seemed to cool uniformly, without any great differences between surface and bottom comparable to the relatively large differences found during the period of increasing water temperatures during June and July.

DISSOLVED OXYGEN

Concentrations of dissolved oxygen were determined by the unmodified Winkler method. The application of this technique to sea water is discussed by Jacobsen *et al.* (1950).

Near shore there are great diurnal changes in oxygen concentration. For example, in water with a depth of about 3 meters approximately 100 meters off shore on September 11, 1954, surface concentrations ranged from 4.0 mg/L at 6:40 A. M. to 8.7 mg/L at 6:20 P. M. Bottom concentrations at these hours were 3.3 and 8.8 mg/L, respectively. Water temperatures which ranged from 29.2° at dawn to 31.4° at sunset were then at about their yearly maximum. The evening concentration of 8.7 mg/L is well above the saturation value for the high temperature concerned.

During the colder part of the year the surface water may become even more supersaturated with oxygen. Thus on February 17, 1955, when the water temperatures were 15–16°, the evolution of oxygen by an early bloom of phytoplankton at a station approx-

TABLE 2. Vertical distribution of water temperatures (°C) in 1955

Depth m	May 27	June 8	June 14	July 7	July 18	July 27	Aug. 24	Sept. 15	Sept. 20	Oct. 19	Nov. 15
0	23.0	28.2	26.4	28.0	30.9	30.9	31.2	32.7	29.0	25.8	20.0
1		28.0		27.6							
2		27.5		27.0							
3		24.8	25.5	26.8	30.4						
5	22.4	24.0	25.0	26.6	30.0	30.2	31.3	31.8	28.2	25.5	19.8
7					29.7						
9		23.5			27.9						
11	22.3	22.0	24.2	26.6	27.0	29.8	31.2	31.6	28.2	25.6	19.9

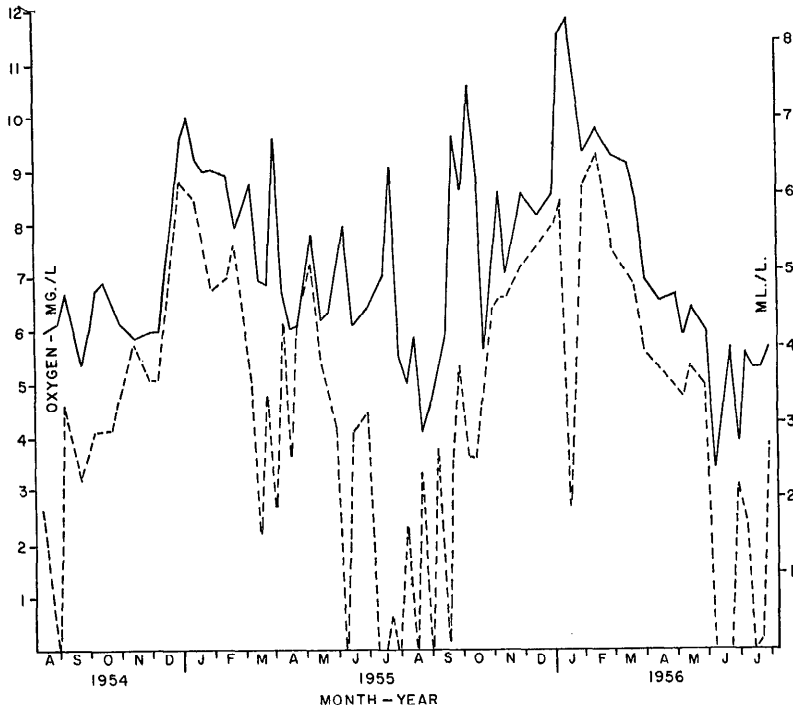


FIG. 4. Dissolved oxygen at mid-day: surface (solid line) and bottom (dotted line) three miles off shore from Fish Springs.

imately one mile offshore above a depth of seven meters raised the concentration of dissolved oxygen from 8.8 mg/L at dawn to 11.5 mg/L at noon. The bottom concentrations (seven meters) ranged from 5.3 to 5.7 mg/L.

As representative of the concentrations of dissolved oxygen in the main body of the Sea, Figure 4 shows values obtained from mid-day samples taken at approximately weekly intervals during 1955 and semi-monthly during 1956 at a station about three miles east of Fish Springs in the deepest part of the Sea (about 12 meters). Mid-day surface concentrations ranged from a maximum of 11.8 mg/L on January 16, 1956, to a minimum of 3.4 mg/L on June 6, 1956. Bottom values ranged from such high winter concentrations as 8.9 mg/L on January 4, 1955 and 9.3 mg/L on February 14, 1956, to the low of zero, which was recorded on several occasions in summer.

In general, during winter there are high concentrations of dissolved oxygen throughout the water column. However, as early

as January, 1956, and during March and April of 1955 there were times when concentrations were much lower at the bottom. In early June of both 1955 and 1956 the bottom became anoxic, but the condition did not last long. Figure 4 indicates the temporary nature of the bottom oxygen depletion. In July of 1955, however, only one of six determinations showed any oxygen present, and that one (on July 27) showed only 0.65 mg/L. Periods when oxygen is absent at the bottom are periods without wind. The surface of the sea becomes glassy and so smooth it mirrors the surrounding hills. One such windless period occurred in mid-July of 1955. Records of samples taken at 9:30 A. M. on July 12, at noon on July 18, and at 6 A. M. and 6 P. M. on July 19 are quite similar in showing no oxygen present at depths below 9 meters. Morning and evening temperatures and pH, as well as the concentrations of dissolved oxygen found on July 19 are shown in Table 3.

In contrast to these records from the

TABLE 3. *Early morning and evening concentrations of dissolved oxygen, temperature, and pH, 3 miles offshore from Fish Springs on July 19, 1955*

Depth m	6 A. M.			6 P. M.		
	Diss. O ₂ mg/L	Temp. °C	pH	Diss. O ₂ mg/L	Temp. °C	pH
0	7.4	30.6	8.69	9.3	31.4	8.73
7	6.4	29.4	8.55	5.6	30.3	8.58
9	0	28.0	8.34	0		8.37
11	0	27.4	8.34	0	27.5	8.26

TABLE 4. *Evening and early morning concentrations of dissolved oxygen, temperature, and pH, 3 miles offshore from Fish Springs, mid-September and mid-October, 1955*

Depth m	September 15, 5 P. M.			September 16, 5:45 A. M.		
	Diss. O ₂ mg/L	Temp. °C	pH	Diss. O ₂ mg/L	Temp. °C	pH
0	10.1	32.7	8.74	0.8	30.4	8.28
5	3.4	31.8	8.56	0.7	30.4	8.26
11	0.5	31.6	8.52	0.6	30.6	8.3
Depth m	October 18, 4 P. M.			October 19, 6 A. M.		
	Diss. O ₂ mg/L	Temp. °C	pH	Diss. O ₂ mg/L	Temp. °C	pH
0	8.9	25.5	8.7	3.1	25.0	8.48
5	3.7	25.6	8.52	3.1	25.2	8.48
11	2.6	25.6	8.48	3.1	25.3	8.44

windless period in mid-July where there was little difference between morning and evening concentrations, records for mid-September and mid-October (Table 4) show the disappearance of surface to bottom differences in concentrations of dissolved oxygen (as well as in pH and temperature) during the 12-hour period between samplings. The uniformity of the water column in the early morning seems to indicate that, in addition to the effect of overnight respiration by plankton, there was mixing due to wind action. During 1956 the bottom anoxia again appeared during June, but was absent in early July. Then, after a windless period, by July 16 the condition was as indicated in Table 5 with data from samples taken at 10 A. M. Ammonia, sulfide, and pH, included in the table, will be discussed later. Of interest here is the absence of oxygen below 8 meters, and the three-degree difference in temperature between surface and bottom. On July 18, two days later and

after a day with strong south wind, the data in Table 6 were obtained in the same location, again at 10 A. M. The thorough mixing is indicated by the similarity of surface and bottom temperatures, the oxygen at the bottom, the small difference in pH, etc.

Following a period of oxygen depletion at the bottom, oxygen concentrations at the surface may be lowered temporarily, as at dawn on September 16, 1955, when the concentration at the surface three miles from shore was only 0.8 mg/L (at the bottom it was 0.55 and at mid depth 0.7 mg/L). The biological effect of another period of oxygen depletion (data shown in Table 5) is indicated by a field note made July 16, 1956: "Fish 'kill' general throughout the north end of the Sea. A few dead *Bairdiella* floating at surface about a mile offshore from Fish Springs. Many dead on beaches July 13 to July 16." (The *Bairdiella* referred to is a croaker, the most prevalent fish in the Sea.) Another example of the biological effect of the anoxia is the disappearance of *Neanthes succinea*, a bottom-dwelling worm, from the bottom at depths below about 8 meters during summer.

It seems that only the water below about

TABLE 5. *Dissolved oxygen, temperature, pH, ammonia, and sulfide, 3 miles offshore from Fish Springs, 10 A. M., July 16, 1956*

Depth m	Diss. O ₂ mg/L	Temp. °C	pH	NH ₃ -N µg-at./L	Sulfide-S µg-at./L
0	5.4	30.0	8.51	10	0.35
6	4.3	29.0	8.42	11	0.7
8	0.5	28.4	8.35	22	1
9	0		8.19	35	15
10	0	27.2	8.16	40	38
11	0		8.08	48	64
12	0	27.0	8.02	36	85

TABLE 6. *Dissolved oxygen, temperature, pH, ammonia, and sulfide 3 miles offshore from Fish Springs, 10 A. M., July 18, 1956*

Depth m	Diss. O ₂ mg/L	Temp. °C	pH	NH ₃ -N µg-at./L	Sulfide-S µg-at./L
0	5.0	29.5	8.50	17	0.1
6	4.5	29	8.49	15	0.1
8	4.4	29	8.47	12	0.1
10	3.7	29	8.42	14	0.1
12	3.4	29	8.40	17	0.1

8 or 9 meters becomes strongly anoxic. The region concerned thus includes the central, deepest part of the Sea, in approximately the area below the -265 foot contour shown in Figure 1. Regions near shore with depths less than 8 or 9 meters do not seem to be affected. Thus, at dawn on September 16, 1955, when the surface concentration 3 miles from shore was only 0.8 mg/L, the concentration 100 meters from shore was 5.5 mg/L both at the surface and at the bottom (3m).

HYDROGEN ION CONCENTRATION

Determinations in the field with a Beckman Model G portable pH meter showed pH to range from 8.3 to 8.6 in winter and from 8.5 to 8.8 in summer. The water of the Salton Sea contains a different ratio of carbonate to bicarbonate than the oceans, and the pH is higher. As in the oceans, photosynthetic uptake of carbon from the buffer system causes a diurnal cycle of pH. An example (Table 7) of the diurnal range of pH near shore and one mile offshore on April 12, 1955, illustrates the daily trend during a time of year when water temperatures were below 20°C.

Data from the same locations on July 19, 1955, (shown in Table 8) illustrate the pH values found during the hottest time of the year, on a day when surface water temperatures at shore were 31.4° at dawn and 31.6° at sunset.

Data for vertical distribution of pH and the diurnal range observed in the deeper part of the Sea on the same date (July 19, 1955) are included in Table 3. Tables 4 and 6 also include data for pII values in deeper water.

The pII of the bottom mud is more acid

TABLE 7. *Diurnal changes in pH and temperature, April 12, 1955*

	Near shore				One mile offshore			
	Surface		Bottom (3 m)		Surface		Bottom (7 m)	
	pH	temp.	pII	temp.	pII	temp.	pH	temp.
6 A. M.	8.32	19.2	8.39	19.0	8.41	18.8	8.39	18.6
12 M.	8.50	21.0	8.40	19.8	8.56	21.0	8.51	19.2
6 P. M.	8.62	21.2	8.60	20.5	8.58	20.0	8.51	18.8
Midnight	8.47	19.4	8.47	19.2	8.46	18.9	8.40	18.2

TABLE 8. *Diurnal changes in pH and temperature, July 19, 1955*

	Near shore				One mile offshore			
	Surface		Bottom (3 m)		Surface		Bottom (7 m)	
	pH	temp.	pH	temp.	pII	temp.	pII	temp.
5 A. M.	8.67	31.4	8.63	31.4	8.62	31.2	8.52	29.7
11 A. M.	8.74	31.4	8.72	31.4	8.7	31.0	8.62	29.2
6 P. M.	8.81	31.6	8.81	31.6	8.75	31.5	8.63	30.3

than that of the water. During anoxic periods in 1956, pII and redox potentials of the mud were measured. The pH of the bottom mud was 7.5 on July 6 and 7.4 on June 22. The oxidation and reduction potential of the mud recorded on these days was -474 mV and -480 mV, respectively.

SULFIDE

The depletion of oxygen at the bottom seems to be due to bacterial decomposition of a thick layer of plankton that accumulates by early summer. On the surface of this organic layer the sulfur bacterium *Beggiatoa* was noted in September and October 1955. The presence of sulfur bacteria and of periods of bottom anoxia during the summer and fall of 1955 led to interest in the possibility that high concentrations of sulfide might occur when oxygen was absent. A method of determining sulfide in sea water was obtained from Dr. N. W. Rakestraw of the Scripps Institution of Oceanography. The method, which is a modification of the Standard Methods colorimetric technique utilizing para-amino-dimethyl aniline and ferric chloride to produce methylene blue in the presence of sulfide ion, proved satisfactory in the Sea.

Beginning in January 1956 and continuing through June determinations were made at approximately semi-monthly intervals; six samples were analyzed during July. The average value of 12 bottom samples (from a 12-meter depth) taken from January through May was 0.25 $\mu\text{g-at./L}$ with a range from 0 to 0.5. On June 6, the day of the first appearance of oxygen depletion at the bottom, the concentration of sulfide rose to 1.5 $\mu\text{g-at./L}$ at the bottom, and on June 22 the concentration was 50 $\mu\text{g-at./L}$. In early

July concentrations were low: 0.5 $\mu\text{g-at./L}$ on both July 2 and 9. Then on July 16 the bottom concentration of sulfide rose to 85 $\mu\text{g-at./L}$. The bottom values for the last three determinations made in July were 0.1, 1.0, and 0.6 $\mu\text{g-at./L}$ on July 18, 24, and 31, respectively. In contrast to the high values and the great variation in concentrations at the bottom, the average sulfide concentration in 20 surface samples analyzed during the 7 months from January through July was 0.3 $\mu\text{g-at./L}$ with a range from 0 to 0.6 $\mu\text{g-at./L}$. Data on vertical distribution of sulfide on July 16 and 18 are included in Tables 5 and 6.

AMMONIA, NITRATE, AND PHOSPHATE

Ammonia was determined by direct Nesslerization after precipitation of interfering ions by the Witting-Buch technique (Wirth and Robinson 1933), nitrate by the diphenylbenzidine method (Atkins 1932), and phosphate by the molybdate-stannous chloride method (Wooster and Rakestraw 1951). It should be pointed out that, of these colorimetric methods used for analysis, only the one for phosphate is well-established. The method used for ammonia proved satisfactory because of the high concentrations present, but the method for nitrate was inconsistent, and the nitrate concentrations given below are of questionable value.

TABLE 9. Average concentration and range of concentration of ammonia, nitrate, and phosphate in $\mu\text{g-at./L}$.

Station Number	Depth m		Ammonia	Nitrate	Phosphate
1	0	Average	5.35	0.85	0.47
		Range	0.2-13.5	0.2-1.9	0.33-1.0
	6	Average	5.9	0.8	0.61
		Range	0.2-18.3	0.2-1.73	0.32-1.95
	12	Average	9.5	0.78	0.45
		Range	0.4-40.0	0.2-1.85	0.3-0.85
2	0	Average	5.5	0.91	0.47
		Range	0.1-12.3	0.4-2.0	0.3-0.6
	3	Average	5.9	0.99	0.51
		Range	0.2-13.3	0.4-2.2	0.2-0.85
	3	Average	4.8	0.93	0.71
		Range	0.1-10.0	0.4-1.4	0.45-1.1
4	Average	12.3	7.63	1.1	
	Range	0.2-30.0	0.8-30.0	0.55-4.2	

Table 9 summarizes data obtained at four stations. Data from Stations 1 and 2 are based on weekly samplings during a two-year period (Sept. 1954 to July 1956). Station 1 is representative of the deepest water in the Sea (depth 12 meters) located about 3 miles offshore from Fish Springs (see Fig. 1). Station 2 is representative of the conditions at shore in the main part of the Sea, located about 100 meters offshore from Fish Springs. Data from Stations 3 and 4 are based on monthly samplings during a one-year period (May 1955 to May 1956). Station 3 is on the south shore near the former mouth of the Alamo River (depth about 1.5 meters), a location relatively little influenced by present stream discharge. Station 4 is off Mullet Island (depth also about 1.5 meters), about a mile from the present mouth of the Alamo, a location where the effects of stream discharge are noticeable. Because the water was so shallow at Stations 3 and 4 only surface samples were taken.

In the main body of the Sea (Stations 1 and 2) the range of concentrations of nitrate-N was nearly the same at all depths; the average was slightly higher at the surface and near shore. The range and average concentration of phosphate-P was greatest at mid-depth, while ammonia concentrations were highest at the bottom.

Concentrations of ammonia showed a marked seasonal trend in the main body of the Sea. Figure 5 shows the trend at both surface and bottom at Station 1. Concentrations at the bottom rose from a low of 0.4 $\mu\text{g-at./L}$ in winter to about 10 $\mu\text{g-at./L}$ by May, and then reached a maximum above 30 $\mu\text{g-at./L}$ during summer. Concentrations fell to 10 $\mu\text{g-at./L}$ in September and October and then continued downward to the winter low. In contrast to ammonia, there were only slight differences between surface and bottom concentrations of nitrate and phosphate (only the bottom values are shown in Fig. 5), and no significant seasonal trends are indicated.

At Station 3 (the south shore of the Sea) there were only slightly higher concentrations of phosphate and nitrate, and slightly lower concentrations of ammonia than were found in the main body of the Sea. How-

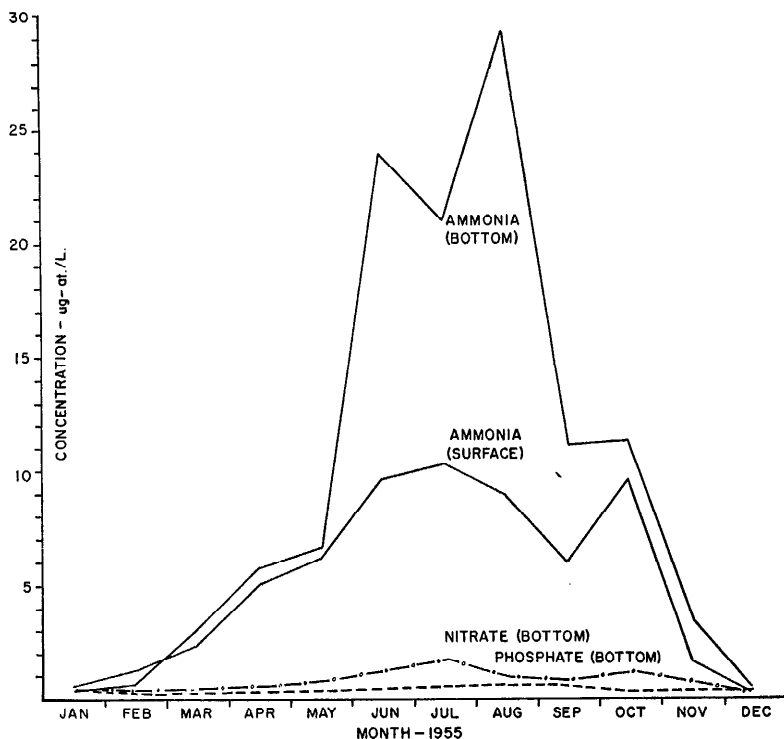


FIG. 5. Ammonia-N, nitrate-N, and phosphate-P three miles off shore from Fish Springs.

ever, at Station 4 (off Mullet Island and in line with the discharge of the Alamo River) there were significantly higher concentrations of nitrate and phosphate than at any of the other stations. The highest average concentration of ammonia also occurred at Station 4, although the maximum there was exceeded by the maximum found at the bottom in deeper water (at Station 1).

The concentrations of ammonia, nitrate, and phosphate at Station 4 depend on the quantity of water discharged into the Sea, which varied depending on seasonal differences in irrigation practice in the Imperial Valley. Most of the water "wasted" into the Sea has been used for irrigation, and it carries salts, fertilizer, and soil from the land. In the water of the New and Alamo Rivers near their points of entry into the Sea the average concentration of phosphate was $5 \mu\text{g-at./L.}$, and these rivers carried an average of $10 \mu\text{g-at.}$ of ammonia and $25 \mu\text{g-at.}$ of nitrate per liter. The concentra-

tions of these plant nutrients at the surface in the main body of the Sea are, of course, much lower. Thus, the amount of dissolved inorganic phosphate at the surface (Station 1) averaged $0.4 \mu\text{g-at./L.}$, which is about $1/10$ the concentration present in the river water. And the amount of nitrogen momentarily available at the surface (Station 1) averaged about $6 \mu\text{g-at./L.}$ (present largely as ammonia) in contrast to the average of $35 \mu\text{g-at.}$ of available nitrogen (mostly in the form of nitrate) present in the river waters. Most of the nitrogen and phosphate in the Sea are not, of course, in the dissolved inorganic form, but are assimilated by the organisms present and become incorporated in them and in the organic mud of the bottom. The Sea is highly productive and there seems to be an effective cycle of use and re-use of the nutrients that enter. The organisms in the Sea and their productivity will be discussed in detail elsewhere, but the following section summarizes some of the biological aspects of the Salton Sea.

DISCUSSION

The Salton Sea is of fresh water origin but due to a high rate of evaporation its waters now have a total salt content comparable to that of the oceans. Although the difference in proportion of ions might be expected to make the Sea a difficult environment for marine organisms, the fauna of the Sea consists of hardy marine animals. The flora, too, is predominantly marine. The organisms living in the Sea must be able to tolerate a great range of temperature (great for a marine environment) and a high summer temperature; in addition they must also tolerate the relatively large diurnal fluctuations in pH and in concentrations of dissolved oxygen that result from photosynthesis and respiration. However, the diurnal changes would seem to be minor stresses compared to the greater stress occurring annually when decomposition of settled zoo- and phyto-plankton brings about periods of oxygen depletion at the bottom. The concurrent high concentrations of sulfide and ammonia also contribute toward making summer the most difficult season for many organisms to survive.

Marine plants and animals without wide ranges of tolerance from the normal marine environment do not survive in the Sea. Thus, there are no macroscopic red or brown algae, for example, and filamentous green algae are limited to the fresh water inlets. The only macroscopic plants in the Sea are blue-green algae which form conspicuous growths on pilings and on the bottom in shallow areas. The growths of blue-green algae occasionally break free from the bottom, and float at the surface. Although the blue-green algae are thus conspicuous at times, the predominant plants of the Sea are dinoflagellates, diatoms, and other single-celled algae which live suspended in the water.

The dinoflagellates include a species of *Exuviella*, similar to *baltica*, which was absent from collections only during August and September. It, and another dinoflagellate (a species of *Gymnodinium?*), were most numerous during sporadic local blooms near shore where they appeared at times in such numbers that they colored the water.

Of the diatoms of the Sea, *Cyclotella caspia* is perhaps the most representative, being present in all collections. Maximum numbers occurred in spring and fall. A pennate diatom, *Nitzschia longissima*, although absent (or present in small numbers) during summer, was the most abundant plant cell present in fall and winter.

Other dinoflagellates and diatoms, as well as silicoflagellates, coccolithophores, a euglenoid, etc., occur in the Sea, but none attain populations as great as the species mentioned above. One other plant cell deserves mention because it is the most prevalent plant of the phytoplankton in early summer. It is a small green alga, resembling *Westella botryoides*, whose identity has not been confirmed.

Plant cells of the types described above serve as food for the zooplankton which is limited to four invertebrate animals of numerical significance. The most abundant animal in the summer plankton is a rotifer, *Brachionus plicatilis* Müller, which is present from May-June to December-January. Maximum numbers occur in August. The taxonomic help of Dr. E. H. Ahlstrom, who has monographed the genus *Brachionus* (Ahlstrom 1940), is gratefully acknowledged.

Neanthes succinea (Frey and Leuckart), a nereid worm, was introduced into the Sea in 1930 and first reported prevalent in 1936 (Hartman 1936). The adults live in the bottom mud and spawn at the surface. The larvae have a planktonic period of about two weeks. Based on plankton sampling, it would seem that *Neanthes* has two peaks of spawning, March-June, and October-November, but that spawning occurs the year around, at least near shore where eggs were found every month of the year. In deeper water (below 8-9 meters) *Neanthes* disappears from the bottom during summer, and neither eggs nor larvae were found in the plankton collected above such depths during August and September. It seems that the adults at the bottom are killed by lack of oxygen (or by high sulfide or ammonia?) during anoxic periods. Only after oxygen becomes present continuously again in fall does the central, deepest part of the Sea become repopulated with *Neanthes*.

Barnacles find only limited space for attachment, because rocks occur only in the volcanic plugs at the southern shore of the Sea, but *Balanus amphitrite* Darwin covers submerged vegetation and debris, pilings, etc. The barnacle was probably introduced during the 1940s and was first reported from the Sea by Rogers (1949). Immature states of *Balanus* appeared in all plankton collections with the exception of a few collections in January-February and some in July. Peaks of spawning occurred March-June and August-September. Greatest numbers were found in April.

The life cycle of *Neanthes*, and the rate of growth and of settling of *B. amphitrite* in the Sea have been studied by Richard H. Linsley, whose results will be reported elsewhere.

A copepod, *Cyclops dimorphus* Kiefer, was redescribed from the Sea by Johnson (1953). It is present in the plankton only during the warmest months of the year. It disappears from the plankton in December-January and reappears in June-July. Maximum numbers occur in autumn.

Most of the plankton animals are not eaten directly; the fish present in the Sea do not include any species which, as adults, feed by screening the plankton. Some of the plankton animals are eaten by young stages of fish, but the majority accumulate, together with the settled phytoplankton, to form the rich bottom mud on which *Neanthes* feed. Studies by Jay C. Quast indicate that the adult worms are the principal fish food of the Sea.

Fish are the final link in the food chain within the Sea. There are three species of minor importance that live along the shores; one, *Cyprinodon macularius*, is native, the other two, *Gambusia affinis* and *Gillichthys mirabilis*, were introduced. The two principal species present, *Bairdiella icistius* and *Cynoscion* sp., have been studied by Richard R. Whitney. The Gulf Croaker, *Bairdiella*, was introduced in 1950-51 from the Gulf of California. Although many species of fish have been introduced, only *Bairdiella* has built up great numbers: it was able to establish itself because of the presence of *Neanthes*, which had been introduced 20 years before.

(The situation seems similar to the introduction of *Neanthes* as a fish food in the Caspian Sea, reported by Zenkevich 1951.) With *Bairdiella* established there is food for a predatory fish, and one of the species of *Cynoscion* (white sea bass) that were introduced almost yearly from 1950 to 1955 has spawned in the Sea. It may be that *Cynoscion* will establish itself and thus add another link to the food chain.

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