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EVAPORATION FROM AND STABILIZATION OF SALTON SEA WATER SURFACE

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Abstract--Salton Sea was formed as the result of a break of the Colorado River in 1905 when practically the entire flow of the river discharged into the Salton Basin for nearly two years. At that time this body of water covered about 350,000 acres and reached a maximum elevation of 195 ft below sea level. For many years the excess of evaporation over inflow caused the elevation of the water surface to drop some 55 ft to minus 250 ft by 1923. Since 1935, the water level in Salton Sea has been rising. In recent years this has resulted in encroachment and damage on adjoining lands, causing concern to Federal, State, and local agencies and land owners. Therefore, three evaporation stations bordering the sea were established to study the problem. An analysis of pan evaporation, gage heights, and inflow measurements indicates that the annual evaporation from Salton Sea ranges from about 70 to 76 inches. The Federal Government has withdrawn from entry all public land in the area below the elevation minus 220 ft. Salton Sea, in January, 1954, had risen to an elevation of minus 235.8 ft and thus has leeway of 15.8 ft before reaching the minus 220-ft contour. A review of this study and other reports indicates that the water surface will continue to rise for a number of years but will eventually stabilize below an elevation of minus 220 ft prior to the year 1980.

Introduction--Salton Sea is located in northern Imperial County and southern Riverside County, California, and it occupies the lower portion of Salton Basin, which is an enclosed basin. A large part of this basin is below Pacific sea level, the lowest point being at a minus elevation of about 273 ft. The drainage area of this basin comprises some 7500 sq mi of which about 1000 sq mi are in Baja California, Mexico. Salton Sea receives not only the storm runoff from this basin, but also the drainage from some 550,000 acres of irrigated land in Imperial and Coachella Valleys, California, and 150,000 acres in the Mexicali Valley of Mexico. It provides the only outlet for surface runoff, drainage water, and ground-water seepage originating in these valleys (see Fig. 1).

During geological time, the Colorado River has flowed alternately north into the basin and south in the Gulf of California, forming a large delta with elevation of some 40 ft above Pacific sea level. In past ages, the basin has been filled to various depths over long periods by overflow from the river. During these periods, sediments, originating in those portions of the states of Arizona, California, Colorado, Nevada, New Mexico, Utah and Wyoming within the Colorado River Basin, were deposited to depths of more than 1000 ft, forming the fertile land area now known as Imperial Valley. A shore line, now visible, indicates an ancient lake - called Lake Cahuilla by the Indians - reached an elevation of over 30 ft above sea level (this is the height at which the water would be before overflowing back into the Gulf of California).

Throughout Imperial and Coachella Valleys, there is evidence of other shorelines at lower elevations, indicating shorter periods of overflow of the river into the basin before a change in conditions in the delta forced the river to discharge back into the Gulf again.

The overflow of the Colorado River created a large lake in the Salton Basin in the 1880's and again in 1891 when over 100,000 acres of the bottom of the Salton Sink were covered with flood waters to a depth of six feet. However, dry years followed, the water in the Lake evaporated and the basin was dry when the development of Imperial Valley was commenced in 1900.

Salton Sea was formed in 1905 as the result of a break of the Colorado River which poured into the Imperial Valley for nearly two years. After that, the water level in the Sea dropped for many years, as the evaporation exceeded the inflow.

In recent years the rising water level in Salton Sea has resulted in encroachment and damage on adjoining lands, causing some concern to Federal, State, and local agencies. Therefore, in 1947, at the request of the Imperial Irrigation District of the State of California, the Division of Irrigation and Water Conservation of the Soil Conservation Service (since January 1, 1954, part of the newly

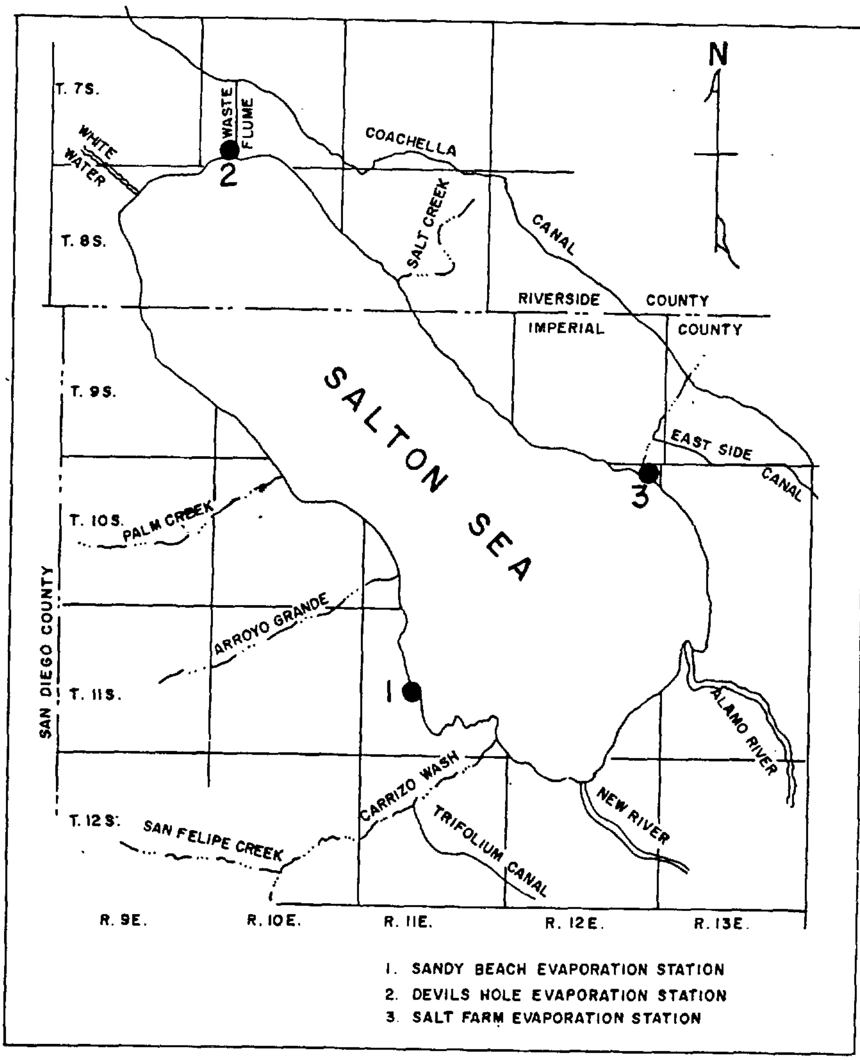

Fig. 1--Map of Salton sea showing evaporation stations

organized Soil and Water Conservation Research Branch of the Agricultural Research Service, U. S. Department of Agriculture) established three evaporation stations along the shores of the sea for the purpose of obtaining data to estimate future elevations of Salton Sea surface and at what level it might be stabilized. This study was under the supervision of the author until July, 1951, when the stations were taken over and continued by the Imperial Irrigation District [BRADSHAW and Others, 1951].

Formation of Salton Sea--As a result of a break of the Colorado River in the spring of 1905, practiclaly the entire flow of the river discharged into the Salton Basin for nearly two years creating Salton Sea. At the time of the closure of the break in February 1907, the Sea covered about 350,000 acres and had reached a maximum elevation of 195 ft below sea level. For the next twelve or thirteen years an excess of evaporation over inflow caused the elevation of the sea to drop rapidly. However, by 1920, irrigation development in the Imperial and Mexicali Valleys had reached a point where return flow to the Sea equalled the evaporation. For the next few years the rate of lowering slowed down with elevations leveling off until in 1925, when the low point of about 250 ft below sea level was reached. From then until 1931 there was a rise in the Sea of about seven feet due in part to a plentiful water supply for irrigation and in part to several severe local winter storms.

However, water shortages, particularly in 1931 and 1934, which caused large crop losses in Imperial Valley, resulted in a drop of several feet in the Sea to another minimum elevation of minus 248 ft in 1935 (see Fig. 2).

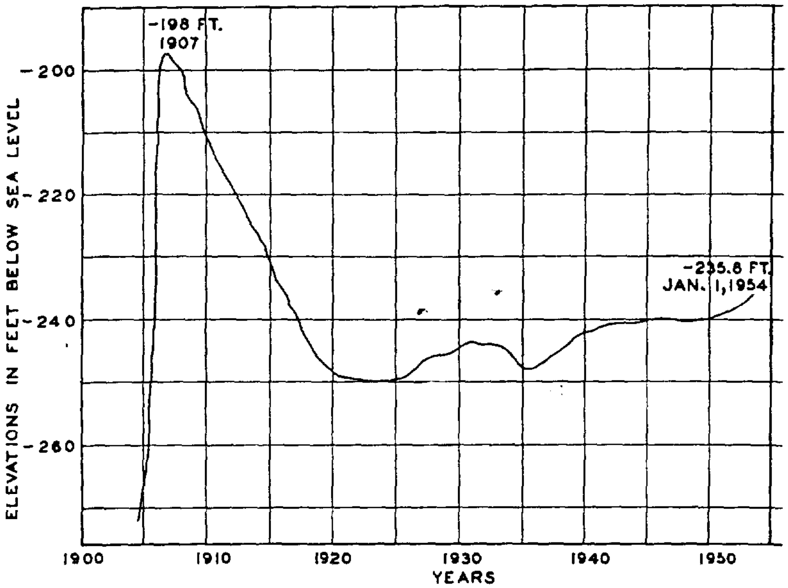

Fig. 2--Water surface fluctuations, 1904-1954, Salton Sea, California

Since the commencement of storage behind Hoover Dam in February, 1935, there has been an ample water supply available to the lower Colorado River and the Sea has been rising, although at varying rates. The elevation on January 1, 1954 was 235.8 ft below sea level and had a surface area of approximately 218,000 acres. The storage capacity of the Sea at this elevation is around 5,300,000 acre feet. For several years the level of Salton Sea has been rising more rapidly than for some time past-about 1.5 ft during 1951.

Factors involved in sea rise

There is nothing mysterious about the rapid rise of Salton Sea in the past five years. Several writers have implied that the rise was unaccountable and that little is known about the Sea. They make no mention of investigations that have been made or of monthly gage readings of the elevation since 1904. They imply that the rise threatens the existence of Imperial and Coachella Valleys. One writer attributes the rise to seepage from the Gulf of California through cracks in the delta. Another writer advances the theory that the building processes in the delta might become reversed, thus permitting the tidal bore at the mouth of the Colorado River in Mexico to erode its way through the delta and inundate these highly-developed areas in the United States. Investigations show the fallacy of these theories as they are not based on facts [DOWD, 1952; SIKES, 1937]. Recent surveys show that 50 miles from the mouth of the river the basal cone of the delta forms a barrier over 40 ft high in Mexico and from sea level on the Gulf side to sea level on the United States side, this barrier is about 65 miles wide [LAWSON, 1950]. A comparison of the early United States Navy survey in 1873 and a recent survey shows that the Gulf of California has not encroached upon this distance since that time and there has been no perceptible retrogressive changes at the mouth of the river for some eight years. Taking these factors into account, plus the fact that nature's dam has remained intact for centuries, it would seem that Imperial Valley has little to fear from the possibility of seepage from the Gulf.

There is nothing unprecedented about the rapid rise in the last several years. Whenever inflow from local rain storms and return flow from irrigation exceed evaporation, the Sea rises. Runoff from single storms has raised the elevation as much as 1.5 ft. Summer storms followed by a cool, wet fall and winter were a decided factor in the 1.5-ft rise of 1951. Other factors are the

100,000 acres increase in irrigated area, and the increase in efficienty of drainage in Imperial Valley, with consequent increase in return flow from irrigation to Salton Sea [DONNAN and Others, 1954]. In 1948, diversions from the Colorado River to Imperial and Coachella Valleys totalled 2,900,000 acre feet; in 1951 the total was over 3,500,000. Another factor was a change in the crops grown. The year 1951 saw a return of cotton to Imperial Valley for the first time in twenty years-28,000 acres in 1951 and 88,000 in 1952. Cotton required considerable water and results in greater return-flow than some other crops. Seepage and waste water from the Coachella Branch of the All American Canal and the increased use of Colorado River water for irrigation in Coachella Valley have also contributed to the recent rise in Salton Sea level. These factors combined explain the rise of Salton Sea. No doubt as the irrigated area increases, there will be a further rise in the sea level.

Evaporation investigations--Evaporation studies have been carried on at various times by the Division of Irrigation Engineering and Water Conservation of the Soil Conservation Service (activites transferred to Western Soil and Water Management Section, Soil and Water Conservation Research Branch, Agricultural Research Service, U. S. Department of Agriculture, January 1, 1954) and its predecessors for a number of years in California, Colorado and other areas [ROBSON, 1913; YOUNG and BLANEY, 1941; YOUNG, 1947]. In Southern California studies and measurements of evaporation have been made under arid conditions such as Silver Lake [YOUNG and BLANEY, 1941], Bard [YOUNG and BLANEY, 1945], and Salton Sea [BRADSHAW and Others, 1951] as well as several semi-arid coastal areas at the request of the State Engineer of California and local agencies.

The difficulty of direct determination of evaporation from large water areas results from the general impossibility of obtaining a complete inventory of all the waters entering and leaving a reservoir. Occasionally, opportunities exist for computing evaporation from records of inflow, outflow, bank storage, precipitation on the water surface, and changes in water surface levels.

Usually, evaporation is measured from small water surfaces in standard evaporation pans such as U. S. Weather Bureau or screen pans [YOUNG, 1947]. Such measurements may be reduced to lake or reservoir equivalents through use of conversion factors or coefficients derived experimentally for the type and size of pan.

In 1909-10, after preliminary investigation, the U. S. Weather Bureau conducted some evaporation studies with pans suspended from towers off-shore above Salton Sea. However, as far as can be determined from the fragmentary published reports, the results were inconclusive.

Early estimates of evaporation from Salton Sea were based primarily on gage heights, rainfall, and estimates of inflow. Being below sea level, there is no outflow and since the bottom of the sea is composed of tight materials, seepage losses have been considered negligible.

Using such data, a few engineers have estimated evaporation for Salton Sea, the results being in general agreement. Unpublished figures prepared by the Salton Sea investigators show the average computed evaporation for the ten-year period, 1909-10 to 1918-19 to be 68.76 inches per year as shown in Table 1 [YOUNG, 1947]. In estimating these values, the inflow from Alamo and New Rivers was arbitrarily taken as 277,000 acre feet annually. The records do not show that any inflow was considered from such streams as San Felipe Creek, Whitewater River, or the numerous flood washes that enter the Sea.

Robson estimated average annual evaporation for the six-year period, April 1, 1907, to April 1, 1913, to be 65.84 inches on basis of inflow, rainfall, and gage heights [ROBSON, 1913]. Since the discharge from Alamo and New Rivers had to be estimated and there was no record of inflow from Whitewater River and San Felipe Creek, it is probable that this estimate is too low.

Probable evaporation shown in Table 2 was computed by Grunsky for the year April 1, 1907, to March 31, 1908, in the same manner, as 73.68 inches [YOUNG, 1947]. In 1927, Holbrook of the U. S. Geological Survey, in a study of probable future stages of the Salton Sea, estimated the average annual evaporation from Salton Sea based on available data as 5.8 ft [HOLBROOK, 1927].

Recent evaporation studies--The Salton Sea is located in a closed basin and provides the only outlet for surface runoff, drainage water and ground-water seepage originating in the Imperial Valley, Mexicali Valley (Mexico), Coachella Valley, and the adjoining mesa lands.

Table 1--Average computed lake evaporation from Salton Sea, California, 1909-10 to 1918-19[a]

Year	Evaporation
	inch
1909-10	72.76
1910-11	66.57
1911-12	64.22
1912-13	65.99
1913-14	68.27
1914-15	84.69
1915-16	65.23
1916-17	53.17
1917-18	69.73
1918-19	76.96
Average	68.76

[a]Source: Unpublished estimates by Salton Sea investigators, U. S. Weather Bureau.

Table 2--Computed lake evaporation from Salton Sea, California, 1907-08 [YOUNG, 1947]

Year and month		Evaporation
		inch
1907	Apr.	5.16
	May	8.52
	June	8.88
	July	8.28
	Aug.	6.36
	Sep.	11.16
	Oct.	6.84
	Nov.	6.48
	Dec.	4.20
1908	Jan.	2.16
	Feb.	2.64
	Mar.	3.00
Total		73.68

In recent years, the rising water level in Salton Sea has resulted in encroachment on adjoining lands, causing concern to the Imperial Irrigation District and land owners.

In connection with cooperative drainage investigations, the Imperial Irrigation District requested the Division of Irrigation Engineering and Water Conservation of the Soil Conservation Service, to make a study of evaporation from Salton Sea. In July, 1947, three evaporation stations bordering Salton Sea were established in locations shown in Figure 1 by Donnan and Bradshaw under the supervision of the writer. Annual unpublished progress reports [BRADSHAW and Others, 1951] for years 1947 to 1950 present the results of evaporation studies and describe the scope of the investigations. These stations were turned over to the Imperial Irrigation District in 1951. A summary of pan evaporation for the calendar years 1948, 1949, and 1950 is shown in Table 3.

Table 3--Measured evaporation of fresh water from screen pans at three stations bordering Salton Sea, 1948, 1949 and 1950

Station	Location	Evaporation		
		1948	1949	1950
		inch	inch	inch
1	Sandy Beach	121.57	114.44	112.44
2	Devil Hole	99.26	96.13	91.25
3	Salt Farm	94.73	90.02	88.60
Mean		105.18	100.20	97.43

Pan reduction coefficients--Coefficients for converting pan evaporation to lake evaporation have been used for many years [ROHWER, 1931; YOUNG, 1947]. Evaporation records at Yuma, Bard, Silver Lake, Salton Sea, and other stations in arid locations indicate that usual coefficients for converting pan records to evaporation from lake surfaces are too high [BRADSHAW and Others, 1951; YOUNG and BLANEY, 1941]. Also this is indicated by estimates of evaporation based on gage heights and inflow into Salton Sea [BRADSHAW and Others, 1951]. The coefficient for the screen pan under desert conditions has not been definitely determined. Coefficients for Weather Bureau pan range from 0.60 for arid conditions to 0.80 for humid areas.

In May, 1938, a gage was installed under the direction of the writer in Silver Lake, ten miles north of Baker, California, along with a Class A Evaporation Station for the purpose of determining pan coefficients under desert conditions. Measured evaporation for the period May 12, 1938, to April 1, 1939, was 68.96 inches from the lake and 113.10 inches from the Weather Bureau pan, which gives a pan coefficient of 0.61. Since evaporation records of the Weather Bureau pan are more numerous and usually used in estimating evaporation from lake surfaces, screen pan records have been reduced to Weather Bureau pan evaporation by establishing a ratio between the two pans by observations at

U. S. Yuma Field Station and Sandy Beach Station at Salton Sea. The ratios of the Weather Bureau pans to the screen pans at those stations are shown in Table 4.

Table 4--Ratios of evaporation from Weather Bureau pan to screen pan

Station and location	Year	Evaporation		
		Weather Bureau pan	Screen pan	WBP/SP
		inch	inch	inch
U. S. Yuma Field Station, Bard	1938	100.74	79.79	1.26
U. S. Yuma Field Station, Bard	1939	100.28	75.42	1.33
Salton Sea, Sandy Beach	1948	144.31	121.57	1.19
Mean				1.26

Estimated evaporation 1948-53--From available pan records at Salton Sea at stations shown in Figure 1 and other data, the annual evaporation from Salton Sea for the six-year period, 1948 to 1953 inclusive, is estimated to range from 70.5 to 76.4 inches as indicated in Table 5. The average annual evaporation for this six-year period is 73 inches.

Table 5--Estimated annual evaporation from Salton Sea, California, based on average pan records from three stations[a]

Year	Evaporation (fresh water)			Evaporation Salton Sea (estimated)[e]
	Measured screen pan[b]	Weather Bureau pan[c]	Lake (estimated)[d]	
	inch	inch	inch	inch
1948	105.18	132.5	79.5	76.4
1949	100.20	126.3	75.8	72.9
1950	97.43	122.8	73.7	70.8
1951	101.51	127.9	76.7	73.7
1952	96.98	122.2	73.3	70.5
1953	101.82	128.3	77.0	74.0
Average	. . .	. . .	. . .	73.0

[a]Measurements in 1948, 1949, and 1950 by the Division of Irrigation Engineering and Water Conservation, Soil Conservation Service, U. S. Dept. of Agriculture in cooperation with the Imperial Irrigation District.

[b]Average of Sandy Beach, Devils Hole, and Salt Farm stations adjacent to Salton Sea.

[c]Based on average ratio of screen pan to Weather Bureau pan 1.26 established from measurements at Sandy Beach, and Bard, California.

[d]Pan reduction coefficient of 0.60 based on Silver Lake and other records [YOUNG and BLANEY, 1941].

[e]Corrected for measured salt content of Salton Sea (percentage by weight [YOUNG and BLANEY, 1945].

During the 1948-51 investigations the author considered determining evaporation from Salton Sea from measured monthly inflows from Alamo River and New River, change in sea elevations, rainfall, estimates of inflow into the sea from flood waters, through the channels of Whitewater River, San Felipe Creek and several washes, and from wasteway of the Coachella Valley branch of the All American Canal. Table 6 illustrates the results obtained for the years 1949 and 1950. The difference between the evaporation shown in Tables 5 and 6 may be attributed to the fact that the computations shown in the latter tabulations do not include corrections for ground-water seepage which is an unknown factor.

Future elevation and stabilization of Salton Sea--The question, 'At what elevation is it anticipated that the level of Salton Sea will be stabilized?' is one which deeply concerns Federal and State agencies, Imperial Irrigation District, Coachella Valley County Water District and owners of private land and resorts bordering the shores of the sea. A definite answer at this time is difficult to make since there are a number of unknown factors which will affect its future elevation. For instance, to

Table 6--Computed annual evaporation from Salton Sea based on measured gage heights, rainfall, and inflows from Alamo River and New River and estimated other unmeasured inflows

Year	Rain-fall	Salton Sea		Inflow		Calculated evaporation		
		Area (average)	Average elevation (minus)	Measured Alamo and New Rivers	Other sources (estimated)	From measured data[a]	From estimated inflow[b]	Total[c]
	inch	acre	ft	ac ft	ac ft	inch	inch	inch
1949	1.92	205,500	240	1,130,416	124,400	61.4	7.3	68.7
1950	0.21	206,800	239	1,199,291	100,000	62.5	5.8	68.3

[a] Based on measured monthly inflow from Alamo and New Rivers, rainfall on Salton Sea surface and change in sea elevation.
[b] Based estimated unmeasured surface inflows.
[c] Exclusive of ground-water seepage (estimated at 70,000 acre feet per year)

date there has been virtually no attempt to provide drainage for the 150,000 acres in Baja California, Mexico, which are part of the drainage area of Salton Sea. An extensive system of drains must be constructed to permit continue profitable farming of this area. What will these drains and waste water from Mexican canals contribute to Salton Sea?

The Colorado River water contains approximately one ton of salts per acre-foot [DONNAN and Others, 1954]. The average annual depth of irrigation water applied to crops in Imperial Valley ranges from about 1.6 ft for barley to 4.7 ft for alfalfa; thus, 4.7 tons of salt per acre is added to alfalfa land annually. Most of this salt is removed by drainage systems and passed on to the Salton Sea in order to maintain a salt balance; otherwise, the lands would become so waterlogged and impregnated with salts as to become unprofitable for agriculture. Thus, the rise of water in the Sea is linked closely to the problems of water quality and drainage in Imperial, Coachella, and Mexicali valleys. As new lands are put under irrigation, the installation of tile drainage systems on farms in these valleys will increase the flow into Salton Sea. Tile drains are being installed in Imperial Valley farms at the rate of about 20,000 acres per year. While drainage systems in 1953 included more than 150,000 acres of land, there are over 1400 miles of open drains and 4,000 miles of tile lines in the valley now. Drainage systems are now being installed on some farms in Coachella Valley.

The importance of Salton Sea as a drainage basin has been realized for a great many years and studies have been made from time to time as to its behavior and what might be expected in the future. In the year 1924, the Federal Government withdrew from all forms of entry all public lands of the United States in the Salton Sea area lying below an elevation of 244 ft below sea level, and created a Public Water Reserve. At that time the elevation of the sea was approaching 250 ft below sea level, and the free-board of six feet was thought to be sufficient. But this was without a proper consideration of future conditions. The United States Geological Survey undertook an investigation of the probable future stages of Salton Sea and, in a report issue in 1927, reached the conclusion that the stabilized elevation of the sea might be between elevations 223 ft and 226 ft below sea level, but that for safety the maximum elevation should be considered as 220 feet below sea level. This is 15.8 feet higher that the present elevation. Based on these conclusions, and by Executive Order in 1928, the Federal Government withdrew from entry all public lands of the United States in the Salton Sea area lying below this elevation of 220 ft below sea level, adding the withdrawn area to the Public Water Reserve.

An analysis of the available data for the nine-year period 1945-53 shown in Table 7 indicates that the total surface inflow exceeded the evaporation by 823,400 acre feet. During this period, the level of the sea rose from minus 240.5 to minus 236.2 ft elevation, while area of the sea surface increased from 204,000 acres in 1945 to 217,000 acres in 1953. This water balance study indicates that average annual evaporation from the sea is about 72 inches.

Unpublished estimates as to when the Salton Sea will reach the minus 220-foot contour vary from the year 1968 to the year 1985. In my opinion, this elevation will not be reached prior to 1980. A review of these facts and other reports indicates that the water surface of Salton Sea will continue to rise for a number of years, the rate depending upon various factors. It remains for the future to show whether the estimated stabilized elevation of minus 220 feet may or may not be too conservative.

Table 7--Analysis of available data on Salton Sea for period 1945-53

Year	Measured inflow		Other inflow	Total inflow	Mean elevation of sea	Mean surface area	Potential evaporation (72 inches per year)	Net change in storage[b]
	Imperial Valley	Coachella Valley						
			Ac ft	Ac ft	ft	Acre	Ac ft	Ac ft
1945	1,068,100	. . .	185,000	1,253,100	-240.5	204,000	1,224,000	++29,100
1946	1,116,900	. . .	120,000	1,236,900	-239.8	207,000	1,242,000	-5,100
1947	1,068,900	. . .	119,000	1,187,900	-240.0	206,000	1,236,000	-48,100
1948	1,054,900	10,000[a]	146,000	1,210,900	-240.2	205,000	1,230,000	-19,100
1949	1,130,400	12,000	177,000	1,319,400	-239.8	207,000	1,242,000	+77,400
1950	1,143,200	52,000	118,000	1,313,200	-239.4	208,000	1,248,000	+65,200
1951	1,206,000	79,000	215,000	1,500,000	-239.0	209,000	1,254,000	+246,000
1952	1,298,000	68,000	155,000	1,521,000	-237.3	213,000	1,278,000	+243,000
1953	1,350,000[a]	75,000[a]	112,000	1,537,000	-236.2	217,000	1,302,000	+235,000
Accumulated 9-year net								+823,400

[a]Estimated.

[b]Estimated capacity January 1, 1945 = 4,400,000 acre feet
Nine-year net = +823,400 acre feet
Estimated capacity Dec. 31, 1953 = 5,223,400 acre feet
(For capacity of 5,223,400 acre feet, the elevation should be 236.2)

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