Salinity of Surface Water in The Lower Colorado River–Salton Sea Area

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March 3, 1849

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By BURDGE IRELAN

WATER RESOURCES OF LOWER COLORADO RIVER—SALTON SEA AREA

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SALINITY OF SURFACE WATER IN THE LOWER COLORADO RIVER–SALTON SEA AREA

By BURDGE IRELAN

ABSTRACT

This report summarizes records of salinity and computations of the mineral burden of the Colorado River and tributary surface inflow from Lees Ferry to the Mexican border and of streams in the adjacent Salton Sea basin.

The virgin salinity regimen of the Colorado River (that prior to upstream irrigation) is unknown, but was probably similar to the regimen observed during earlier years of sampling. Before closure of Hoover Dam, the salinity at points of record on the river varied rather substantially daily, seasonally, and annually and also varied moderately (generally increasing) with distance downstream. Observed dissolved-solids concentrations, which ranged between 200 and 1,800 mg/l (milligrams per liter) consisted mainly of calcium bicarbonate at lower concentration levels and mixed sulfate and chloride salts at higher concentration levels.

The chemical-quality record for the Colorado River at Grand Canyon indicates that the 40-year weighted-average concentration is about 600 mg/l. The long-time average at Lees Ferry has been moderately less. Recent storage and diversion projects above Lees Ferry have apparently caused small increases in annual weighted-average mineral concentrations, but these increases have been less than the differences between 10-year weighted averages.

Since Lake Mead was formed, dissolved-solids concentrations in Colorado River water between Hoover and Imperial Dams have generally ranged between 600 and 900 mg/l, with calcium sulfate always the dominant dissolved salt. Concentrations below Hoover Dam have been higher, on the average, than those at Grand Canyon mainly as a result of evaporation from the surface of Lake Mead and solution from its bed. The higher concentrations, however, have been partially offset by precipitation of calcium carbonate in the lake. Solution of minerals from the bed of the lake, although still considerable, appears to be substantially less than during the first years after its formation.

The annual mineral burden of the river varies markedly, but average burdens for periods of 5 or more years are fairly stable. Although most of this burden originates above Lees Ferry, rather large increments originate in the discharge of Blue Springs, which are on the Little Colorado River a short distance above its mouth, and in the Virgin River. Other Lower Basin tributaries add much smaller increments to th river's mineral burden.

Low releases from Lake Powell during the first 2 years of impoundment caused a temporary rise in average salinity at Grand Canyon and contributed to later increases in the salinity of water in Lake Mead and in the Colorado River downstream from Hoover Dam.

Diversions to the California aqueduct increased substantially during 1961–65. This reduced the amount of river water available downstream from the diversion for dilution of slightly to moderately saline irrigation return flows from the Parker and Palo Verde Valleys and thereby caused higher average concentrations at Imperial Dam. Somewhat saline drain water from expanded irrigation in the Parker and Palo Verde Valleys also has contributed to the increased concentration at Imperial Dam.

Computations of gains and losses indicate that during recent years more mineral salts were removed from the Parker and Palo Verde Valleys in return flows than were brought into them in the irrigation water.

Dissolved-solids concentrations are now relatively constant at Imperial Dam because of upstream storage, but both the flow and the mineral burden of the Colorado River below the dam are greatly reduced by diversions to the All-American and Gila Gravity Canals. Thereafter, the salinity and mineral burden progressively increase as surface irrigation return flows and pumped ground water are discharged into the river.

During the last 30 years, flow of the Gila River above the Wellton-Mohawk area has usually been too small to affect materially the salinity and mineral burden of the Colorado River, although during the exceptional year 1966 it added some water of excellent quality to the irrigation supply. Ground water pumped to control water levels in the Wellton-Mohawk area and South Gila Valley has been much more saline than the applied irrigation water and has added substantially to the mineral burden of the lower Gila and Colorado Rivers, particularly since 1960. A salinity problem in Mexico caused by expanded pumping of saline ground water in 1961 has been brought under control by drilling new wells, constructing a concrete-lined conveyance channel with controlled outlets, and management of the pumping according to the salinity of the individual well waters and irrigation requirements.

Colorado River water flows through the All-American Canal from Imperial Dam to Imperial and Coachella Valleys in the Salton Sea basin without material change in salinity. Both valleys contained areas with saline soils before they were irrigated, and early salinity problems developed, mainly because of inadequate drainage. Present drainage systems have been developed to the point where more dissolved minerals are removed from irrigated areas than are brought in by irrigation water.

The Alamo, New, and Whitewater Rivers, which drain to the Salton Sea, have differing water-quality characteristics. Some water suitable for irrigation appears to enter each stream as a result of present irrigation practices, and part of their flows possibly could be salvaged.

INTRODUCTION

The Colorado River is a major continental stream draining one-twelfth of the conterminous United States. The equitable division of its water among the seven basin states and Mexico has long been and remains difficult. The Colorado's flow is subject to provisions of an international treaty, interstate compacts, congressional acts, and court decrees. Today the river is a source of water for small cities within its basin, for great cities outside its basin, and for irrigation of large areas in and near its basin. The natural salinity (concentration of dissolved solids) of its water ranks among the highest of the great rivers of North America. Increasing salinity in the lower reaches has long been recognized as an almost inevitable result of increasing use of water from rivers flowing through arid lands. Yet, strangely, none of the legal documents dividing the flow of the Colorado River is concerned with its salinity.

The Colorado River is a mammoth transport system in which both water and dissolved-mineral salts continuously move downstream. The river flow is derived from many sources, each with individual chemical characteristics which blend in the river. The resulting changeable pattern of interrelated variations in concentration, composition, and mineral load [1] constitutes the chemical regimen of the river, which has been investigated for this report.

Records of streamflow had been obtained at numerous points in the Colorado River basin for many years before the Geological Survey began an extended systematic sampling of the variations in mineral concentrations in the river water at Grand Canyon in August, 1925. Since then the Geological Survey has systematically sampled the lower river at one or more points every year. Some of the earlier quality-of-water records, however, have never been summarized in the published reports of the Geological Survey. Other organizations also have sampled the river, some occasionally and some for extended periods.

Foreseeing the time when water in the Colorado River and the local ground water, which is largely derived from the river, together will not be sufficient to meet projected needs without careful management, the Geological Survey in 1960 began a comprehensive investigation of factors affecting the development and use of water in and adjacent to the lower Colorado River including the Salton Sea basin, which depends primarily on the Colorado River for water. This report, describing the quality of the surface water, is one of a series that constitutes an appraisal of the water resources of the lower Colorado River–Salton Sea area. It examines all available chemical-quality records of surface water in the study area to determine the chemical regimen of the river as related both to variations in ionic concentrations in the water and to mineral loads transported by the river.

A companion report by Hely (1969) describes the area considered in this report and the availability of its surface water, explains the division of the Colorado River drainage at compact point into Upper and Lower Basins, and also explains the reasons for making a hydrological appraisal of the area primarily served by the Colorado River water rather than appraising a limited part of the Colorado River basin by itself. Ground-water quality in the area is to be separately covered in several reports describing the occurrence and availability of ground water.

An earlier investigation by the Geological Survey (Iorns and others, 1965) describes the water resources of the Upper Colorado River Basin in detail and serves as a background for the Lower Basin study.

Figure 1 shows the location of the area considered by this study, indicates its principal subdivision, and shows the sites of the major dams and principal sampling points discussed in the report.

GENERAL CHEMICAL CHARACTERISTICS OF COLORADO RIVER WATER FROM LEES FERRY TO IMPERIAL DAM

The salinity of Colorado River water commonly has been described in terms of its dissolved-solids concentrations, or the concentrations of dominant ionic constituents, stated either separately or combined as salts. A single dominant combination of ions, however, has rarely been adequate to define the river-water composition. The natural (virgin)

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[1] Mineral load, as used in this report, refers to the total quantity of dissolved-mineral salts and silica transported by the river past a particular point in a specified time. The term is synonymous with "salt load" as used in many reports, but is preferred because "salt load" sometimes refers only to a single salt—sodium chloride.

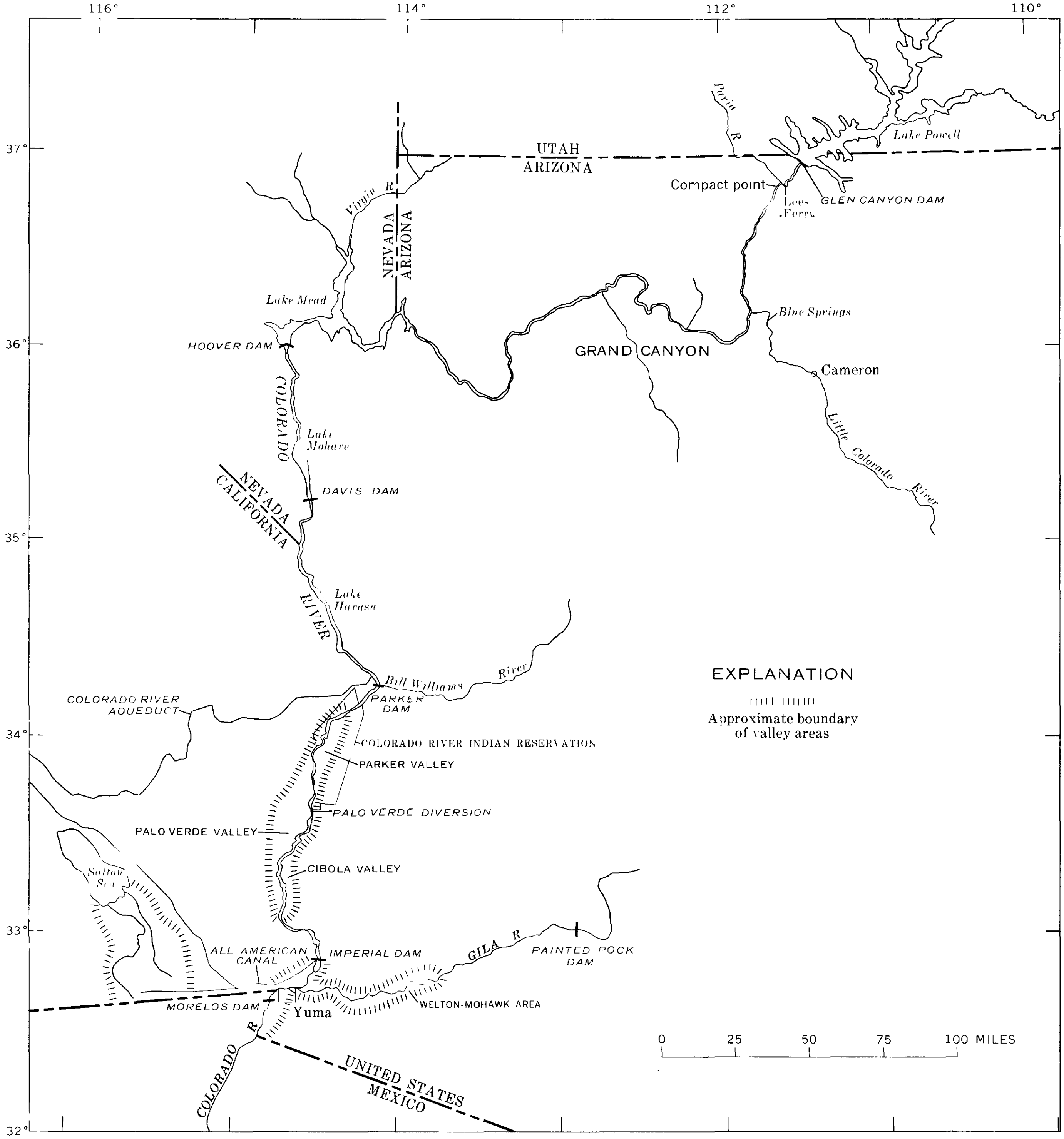

FIGURE 1.—Principal features of the lower Colorado River–Salton Sea area.

chemical regimen of the river, although not represented by chemical-quality records and therefore unknown, was undoubtedly one of large daily and seasonal variation in both salinity and composition.

Systematic records obtained for various points on the river since 1925 show that the chemical characteristics of the water in the lower river have varied both from point to point and from year to year. Long-term records obtained upstream from Lake Mead, encompassing a period that began after most of the Upper Basin irrigation had been developed and before the construction of the Glen Canyon Dam, represent a comparatively stable condition and a regimen that probably differs only slightly from the natural regimen. Data resulting from sampling below Hoover Dam and below Glen Canyon Dam show how the average concentrations have been increased and variations decreased as a result of man's control of the river.

The long-term records show that during larger spring floods above Lake Mead, the river water generally contains 200–350 mg/l (milligrams per liter) [2] of dissolved solids, consisting mainly of calcium bicarbonate. The sulfate concentration always exceeds the chloride concentration. During smaller spring floods the floodwater usually contains 350–500 mg/l of dissolved solids with sulfate concentrations about the same as bicarbonate concentrations. During low-flow periods, in fall and winter, the dissolved-solids concentrations have reached 1,500 mg/l nearly every year and occasionally have reached 1,800 mg/l. During these periods sodium nearly always has been the principal cation, but the mixture of anions has been such that no single salt predominates in the dissolved solids. Short records obtained prior to formation of Lake Mead indicate that the same chemical characteristics then prevailed at Yuma, Ariz.

Because concentrations of dissolved solids generally vary with stream discharge, comparison of water quality at different sites is best made by use of weighted-average concentrations for a particular period, usually a water year in this report. These weighted averages approximate the concentration that would be obtained by analysis of a sample from the streamflow for the entire year if it were well mixed. Weighted-average concentrations are computed from the available chemical analyses and the streamflow records by assigning the volumes of flow occurring during designated time intervals to the chemical analyses of water samples taken during those flow periods and by assigning estimates of analyses for any unsampled periods. The weighted averages are the quantities obtained by adding the products of the concentrations and the corresponding flow volumes and dividing by the total flow for the period averaged.

Weighted-average concentrations have been published previously for some, but not all, of the Colorado River sampling records. The reliability of weighted-average analyses representing the individual yearly flows at the specified sampling points depends on the number and distribution of samples analyzed, the accuracy of the individual analytical determinations, and the accuracy of the streamflow record. For the years of published weighted averages there have been numerous sampling schedules, variable completeness of the individual chemical analyses, and many different analytical procedures. Therefore, the published weighted averages have not been equally representative of water quality. Consequently, evaluating the long-term variations in Colorado River salinity and the changes caused by man's activities has necessarily involved reviewing the records of chemical analyses for completeness of sampling and representativeness of reported analytical values. It has also involved estimating values when none were available, recomputation of some previously computed weighted-average concentrations, and estimating weighted averages for unsampled years by using sampling records at other river points as guides. As a result of this reappraisal, the tables of weighted-average concentrations in this report differ in some respect from previously published weighted averages. The tables also include weighted averages of individual constituents not previously published.

Annual weighted-average concentrations for the five long-term sampling points most useful in evaluating water-quality variation in the lower Colorado River are given in tables 1–5. The tables include only years of actual sampling for the years prior to 1941, but to provide a 25-year record to use in tracing mineral movement down the river they include estimates for all unsampled years from 1941 on.

Comparison of the ionic and dissolved-solids concentrations at different points for the same year shows generally increasing concentrations downstream and more variation in the annual weighted averages of most constituents above Lake Mead than below it. To understand the variation of salinity in the river it is therefore necessary to consider each sampling record in turn.

LEES FERRY

The Colorado River at Lees Ferry, which is above the confluence of the Paria River, contributes considerably more than 99 percent of the average surface flow at compact point, the division between the upper and lower Colorado River. Hence, records for Lees Ferry (table 1) provide accurate indices of streamflow and water-quality variation at compact

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[2] The original analytical data summarized in this report generally state concentrations in parts per million. Recently, however, the Geological Survey has adopted the policy of reporting concentrations as milligrams per liter and this report follows that system. Except for concentrations above about 7,000 ppm, the two systems are numerically equal.

TABLE 1.—*Annual weighted-average concentration for Colorado River at Lees Ferry, Ariz.*

[Results in milligrams per liter unless otherwise indicated. ^{e} (estimated) signifies concentrations determined indirectly instead of by weighting individual analyses]

Water year	Total flow (acre-ft)	Mean discharge (cfs)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids			Hardness as $CaCO_3$		Specific conductance (micromhos at 25°C)
														Sum				
													Residue at 180°C	Milligrams per liter	Tons per acre-ft	Calcium, magnesium	Noncarbonate	
1929	19,190,000	26,500	17	72	22	62	6.5	161	222	35	-------	2.2	518	518	0.70	270	^{e}138	^{e}773
1930	13,050,000	18,030	15	76	25	74	4.4	168	248	44	-------	2.5	572	570	.78	292	154	^{e}856
1941	16,020,000	22,140	^{e}15	^{e}67	^{e}21	^{e}68		^{e}154	^{e}210	^{e}39	-------	^{e}2.2	-------	^{e}498	.68	^{e}254	^{e}128	^{e}758
1942	17,010,000	23,490	^{e}13	^{e}63	^{e}22	^{e}63		^{e}146	^{e}204	^{e}36	-------	^{e}2.6	-------	^{e}476	.65	^{e}248	^{e}128	^{e}726
1943	11,240,000	15,530	18	66	26	75		153	229	48	0.3	4.5	540	542	.74	272	146	810
1944	13,200,000	18,180	14	60	23	65	3.3	144	200	42	^{e}.3	^{e}3.7	482	484	.66	244	126	733
1945	11,530,000	15,920	16	69	24	70	4.5	162	213	49	-------	3.4	-------	529	.72	270	138	803
1946	8,722,000	12,050	^{e}13	^{e}79	^{e}28	^{e}83		^{e}190	^{e}247	^{e}55	-------	^{e}2.5	-------	^{e}601	.82	^{e}311	^{e}156	^{e}912
1947	13,490,000	18,640	^{e}12	^{e}69	^{e}24	^{e}62		^{e}151	^{e}215	^{e}41	-------	^{e}2.1	-------	^{e}500	.68	^{e}271	^{e}135	^{e}760
1948	13,670,000	18,830	14	70	22	61	2.8	167	194	40	.4	2.4	489	490	.67	265	128	744
1949	14,340,000	19,810	14	71	23	62	3.0	175	195	41	.3	2.6	498	499	.68	272	128	764
1950	11,040,000	15,250	12	75	28	70	4.0	179	230	49	.3	2.2	559	560	.76	302	156	850
1951	9,817,000	13,560	14	79	27	72	4.9	185	235	52	.4	2.2	578	579	.79	308	156	877
1952	17,960,000	24,740	13	74	21	57	4.2	198	181	34	.3	1.9	483	484	.66	271	108	750
1953	8,787,000	12,140	13	81	30	83	4.3	185	262	59	.3	2.9	627	628	.85	325	174	940
1954	6,101,000	8,427	13	98	33	109	5.7	201	337	75	.4	3.7	774	775	1.05	380	216	1,150
1955	7,290,000	10,070	15	97	29	91	5.3	211	283	64	.4	4.6	694	695	.94	361	188	1,030
1956	8,740,000	12,040	15	81	24	70	4.6	192	212	53	.5	4.0	558	560	.76	300	143	846
1957	17,320,000	23,930	15	76	20	50	3.8	198	159	34	.4	5.2	472	462	.63	272	109	722
1958	14,220,000	19,640	18	86	20	62	4.1	201	199	43	.6	4.0	536	537	.73	296	132	822
1959	6,742,000	9,311	^{e}14	92	29	95	^{e}5.5	183	^{e}304	^{e}65	^{e}.4	^{e}4.0	722	700	.95	348	198	1,030
1960	9,182,000	12,650	^{e}16	84	20	72	^{e}5.1	185	^{e}225	^{e}50	^{e}.4	^{e}3.7	595	^{e}569	.77	292	140	848
1961	6,643,000	9,177	^{e}16	106	27	93	^{e}5.5	186	^{e}319	^{e}68	^{e}.4	^{e}4.2	752	^{e}731	.99	376	223	1,070
1962	14,770,000	20,400	^{e}18	76	19	57	^{e}4.0	189	^{e}180	^{e}38	^{e}.3	^{e}2.7	508	^{e}488	.66	266	111	740
1963	2,500,000	3,453	^{e}15	115	39	142	^{e}5.8	200	^{e}440	^{e}98	^{e}.5	^{e}5.0	1,000	^{e}959	1.30	448	284	1,450
1964	2,414,000	3,325	^{e}12	116	33	119	^{e}6.5	185	^{e}400	^{e}85	^{e}.4	^{e}3.5	890	^{e}866	1.18	425	274	1,310
1965	10,820,000	14,950	^{e}11	81	23	79	^{e}5.0	161	254	56	^{e}.3	^{e}3.0	607	592	.81	296	164	918

point, about a mile downstream. The concentrations of dissolved solids in table 1 generally tend to decrease with increase in streamflow. Most of the major ionic constituents correlate with streamflow in much the same way as dissolved solids, but the minor constituents do not show the same consistency between concentration and flow.

Prior to construction of Glen Canyon Dam (16 miles upstream) the averages of the daily concentrations of dissolved solids at Lees Ferry were substantially larger than the computed annual weighted-average concentrations. This is no longer true. Iorns, Hembree, and Oakland (1965) prepared a dissolved-solids duration table for the period 1914–57 which included the values listed below.

Percentage of time concentration equaled or exceeded that indicated	*Concentration (mg/l)*
60	730
70	580
80	420
93	295

They estimated the weighted average for 1914–57 to be 499 mg/l, corresponding to an average annual discharge of 12,710,000 acre-feet. They also estimated that the weighted-average concentrations of dissolved solids at Lees Ferry increase about 3.4 mg/l for each 100,000 acre-feet diverted out of the basin in headwater areas and about 13.3 mg/l for each 100,000 acres of newly irrigated land above compact point. An increase of not more than 400,000 acre-feet for out-of-basin diversion and about 50,000 acres of newly irrigated land is a reasonable estimate of the maximum extent of these factors since 1957. Thus, the 1965 weighted average of dissolved solids at Lees Ferry has been increased by no more than 20 mg/l since Iorn's study period.

Storage of water in Lake Powell began in March 1963, and Colorado River flows immediately downstream were extremely low in 1963 and 1964 because of retention of water in the reservoir. During the 2 years, the weighted-average concentrations of dissolved solids, sulfate, and chloride at Lees Ferry were higher than those for any previous year of record. Then in 1965, when releases, from Lake Powell were increased to near median annual river flows, the concentrations were only slightly above the previous range for similar volumes of flow. The 1965 concentration (592 mg/l for an annual flow of 10,820,000 acre-ft) was only slightly larger than the 5-year average concentration for 1958–62 (575 mg/l for an average annual flow of 10,311,000 acre-ft).

The small apparent increase in concentration for 1965 over that for 1958–62 may be partly due to the combined effects of solution from the bed of Lake Powell and evaporation of pure water from its surface, but it is probably mainly due to errors in the sampling and changes in streamflow.

GRAND CANYON

A program of systematic (mostly daily) water sampling for chemical analysis has been in operation longer and with fewer unsampled periods at Grand Canyon than at any other point on the Colorado River. The Grand Canyon record (table 2) is based on sampling during every year except 1943, for which year the concentration was estimated from records at Lees Ferry. Because of its greater length, more comprehensive character, and closer proximity to the major areas of water use, this record provides a better index of natural variability of lower Colorado River salinity than the shorter and less complete Lees Ferry record, which has been considered as the reference record in some other studies.

Comparisons between the annual concentrations given for Grand Canyon in table 2 with those given for Lees Ferry in table 1 indicate that the water at the lower station regularly has moderately higher concentrations of several constituents.

Although table 2 gives both the annual streamflows and corresponding annual weighted-average analyses for Colorado River water at Grand Canyon, the relation between streamflows and concentrations is not readily apparent. To make the relation clearer, the annual streamflows and annual weighted average of dissolved-solids concentrations are plotted as paired bars in figure 2. No significant change in the relation between annual discharge and average con-

TABLE 2.—*Annual weighted-average concentration for Colorado River at Grand Canyon, Ariz.*

[Results in milligrams per liter unless otherwise indicated. [e] (estimated) signifies concentrations determined indirectly instead of by weighting individual analyses]

Water year	Total flow (acre-ft)	Mean discharge (cfs)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids			Hardness as $CaCO_3$		Specific conductance (micromhos at 25°C)
													Residue at 180°C	Sum				
														Milligrams per liter	Tons per acre-ft	Calcium, magnesium	Noncarbonate	
1926	14,420,000	19,920	19	66	21	75	5.7	159	201	56	-------	1.6	523	525	0.71	251	121	[e]800
1927	17,260,000	23,840	17	77	22	77	5.5	162	235	53	-------	2.4	569	570	.77	282	150	[e]869
1928	15,630,000	21,530	17	66	22	65	4.3	162	187	48	-------	2.4	491	493	.67	255	122	[e]752
1929	19,430,000	26,840	18	74	23	73	6.2	164	229	48	-------	2.5	555	556	.75	279	144	[e]848
1930	13,420,000	18,540	16	81	26	85	5.0	184	252	62	-------	3.4	622	622	.85	309	158	[e]948
1931	6,721,000	9,283	13	93	34	131	4.7	201	325	107	-------	7.5	813	815	1.11	372	208	[e]1,240
1932	15,970,000	21,990	13	73	21	74	4.1	176	202	54	-------	3.3	531	532	.72	268	124	[e]811
1933	10,010,000	13,820	13	82	26	93	4.9	181	249	74	-------	4.0	635	636	.86	312	163	[e]970
1934	4,656,000	6,431	15	105	39	159	6.1	206	392	136	-------	5.1	960	960	1.31	422	254	[e]1,460
1935	10,220,000	14,110	14	74	22	81	3.9	177	204	69	0.3	3.5	559	560	.76	275	130	[e]854
1936	12,320,000	16,970	16	83	23	79	6.0	186	228	61	.3	2.4	591	591	.80	302	149	[e]901
1937	12,410,000	17,140	12	83	25	85	6.1	193	238	64	-------	1.9	610	612	.83	310	152	[e]933
1938	15,630,000	21,590	14	76	22	73	4.6	189	199	53	-------	1.9	538	538	.73	280	125	[e]814
1939	9,618,000	13,290	17	85	28	96	5.3	198	254	77	.4	2.7	662	664	.90	327	164	[e]1,010
1940	7,435,000	10,240	15	92	31	115	4.6	200	296	95	.4	2.5	750	751	1.02	357	193	[e]1,130
1941	16,940,000	23,400	15	79	22	76	5.1	193	214	53	.3	1.6	561	562	.76	288	130	856
1942	17,260,000	23,840	13	69	23	69	5.3	160	212	50	.4	2.2	523	524	.71	266	136	799
1943	11,430,000	15,790	[e]18	[e]80	[e]27	[e]85	[e]4.6	[e]202	[e]232	[e]67	[e].3	[e]4.0	[e]620	[e]619	[e].84	[e]310	[e]135	[e]946
1944	13,530,000	18,630	13	77	24	73	4.6	204	200	56	.3	3.1	552	553	.75	290	124	861
1945	11,870,000	16,400	15	80	26	82	7.2	207	220	65	.3	2.1	601	601	.82	306	137	919
1946	9,089,000	12,550	14	93	29	97	7.0	235	248	81	.5	2.1	688	689	.94	351	158	[e]1,040
1947	13,740,000	18,970	12	82	25	76	6.0	211	217	58	.4	1.7	583	584	.79	308	134	882
1948	13,870,000	19,100	14	81	23	73	4.1	212	195	59	.4	1.8	556	557	.76	296	123	862
1949	14,370,000	19,840	15	84	24	75	4.1	220	201	57	.3	2.6	572	573	.78	308	128	880
1950	11,080,000	15,300	14	91	28	84	5.8	235	231	70	.3	1.9	642	644	.87	342	150	996
1951	9,839,000	13,590	14	87	29	90	[e]6.0	219	241	76	.4	2.2	673	655	.92	336	156	987
1952	18,160,000	25,020	15	84	23	66	5.3	233	184	48	.3	2.9	558	543	.76	304	113	831
1953	8,879,000	12,260	15	95	31	101	6.8	243	262	86	.4	2.7	719	722	.98	364	166	1,100
1954	6,229,000	8,604	14	105	34	132	6.3	231	335	111	.3	4.2	856	858	1.16	402	212	1,300
1955	7,580,000	10,470	16	99	30	111	6.2	228	281	93	.4	4.5	753	755	1,02	370	184	1,140
1956	8,860,000	12,210	15	82	25	85	5.1	201	215	78	.5	3.9	600	609	.82	308	143	927
1957	17,500,000	24,170	16	75	19	60	4.5	184	168	49	.5	2.9	486	486	.66	265	114	746
1958	14,550,000	20,100	18	85	22	74	4.7	199	210	60	.5	2.8	576	576	.78	302	140	877
1959	6,935,000	9,579	[e]16	98	29	116	[e]7.0	207	[e]303	[e]97	[e].5	[e]4.5	779	[e]775	1.05	364	194	1,170
1960	9,584,000	13,200	[e]16	84	21	86	[e]6.1	192	[e]227	[e]70	[e].4	[e]1.9	624	[e]608	.85	296	138	930
1961	7,050,000	9,739	[e]15	108	29	115	[e]6.0	195	[e]323	[e]102	[e].4	[e]4.5	814	[e]792	1.11	388	228	1,190
1962	15,250,000	21,060	[e]18	77	20	68	[e]5.0	195	[e]181	[e]54	[e].3	[e]2.5	531	[e]522	.72	272	112	803
1963	2,742,000	3,788	[e]15	114	38	171	[e]8.5	234	[e]396	[e]153	[e].4	[e]6.3	1,050	[e]1020	1.43	440	248	1,570
1964	2,727,000	3,756	[e]14	115	35	170	[e]7.0	219	[e]399	[e]149	[e].5	[e]5.5	1,030	[e]1000	1.40	431	252	1,540
1965	10,980,000	15,170	[e]12	83	24	92	[e]5.0	175	251	76	[e].3	[e]2.5	652	632	.89	306	162	987

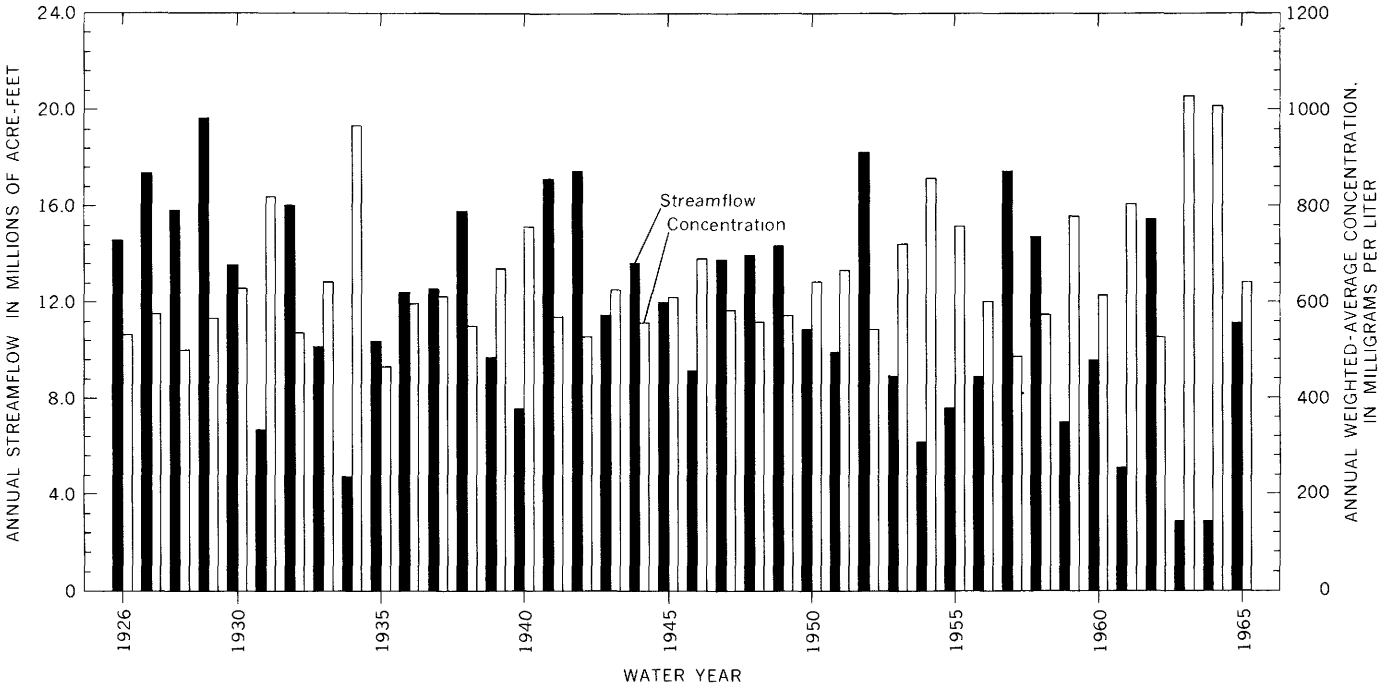

FIGURE 2.—Annual streamflow and annual weighted-average concentration of dissolved solids, Colorado River at Grand Canyon, 1926–65.

centration is suggested by the figure, except the temporary one caused by closure of Glen Canyon Dam in 1963. The figure clearly shows that the years with the greatest streamflow have had among the lowest dissolved-solids concentrations and that years of approximately equal streamflow have had only moderate variations in average concentrations. Thus, so far as can be determined from the parallel plotting, the Colorado River had a nearly stable chemical regimen during the years 1926–62. The great change in regimen caused by closure of Glen Canyon Dam in 1963 seems to have been limited to 2 years, as the relation between salinity and streamflow for 1965 is within the range that might have been expected for the volume of flow.

Comparison of the annual analyses in table 2 shows that all the major ions contribute to the variation in dissolved solids at Grand Canyon. Most of the salinity changes, however, result from changes in the concentrations of the anions, so the general nature of the chemical regimen of the river can be determined by considering only the major anions. Thus, the line connecting yearly dissolved-solids concentrations in figure 3 is roughly parallel to lines formed from yearly weighted-average concentrations of sulfate, bicarbonate, and chloride; this indicates fairly consistent inter-ionic relationships. Figure 3 shows that the annual chloride concentration at Grand Canyon has always been much less than the annual bicarbonate and sulfate concentrations, that in most years the sulfate concentration has exceeded the bicarbonate concentration, but that for those years with low dissolved-solids concentrations the sulfate was nearly equal to or less than the bicarbonate.

Most of the annual bicarbonate concentrations at Grand Canyon prior to 1943 were lower and changed less from year to year than the later ones. A possible explanation for this apparent change in regimen is that during the first years of sampling long delays occurred between sample collection and analysis. Consequently, there may have been considerable calcium carbonate precipitation in the more concentrated samples prior to chemical analysis that would have resulted in low values for the yearly bicarbonate concentrations. If during the early years the individually determined bicarbonate concentrations averaged 20–30 mg/l lower than the true values—a reduction which appears possible from a study of figure 3 and of the original data—the long-time dissolved-solids concentration reported as 598 mg/l in table 6 may be 10–15 mg/l less than the true value.

Records of water quality obtained at Grand Canyon after the formation of Lake Powell in 1963 are of too short duration to determine the probable future effect of this lake on downstream river-water quality. Chemical analyses of samples obtained through 1965, however, suggest that some solution of calcium

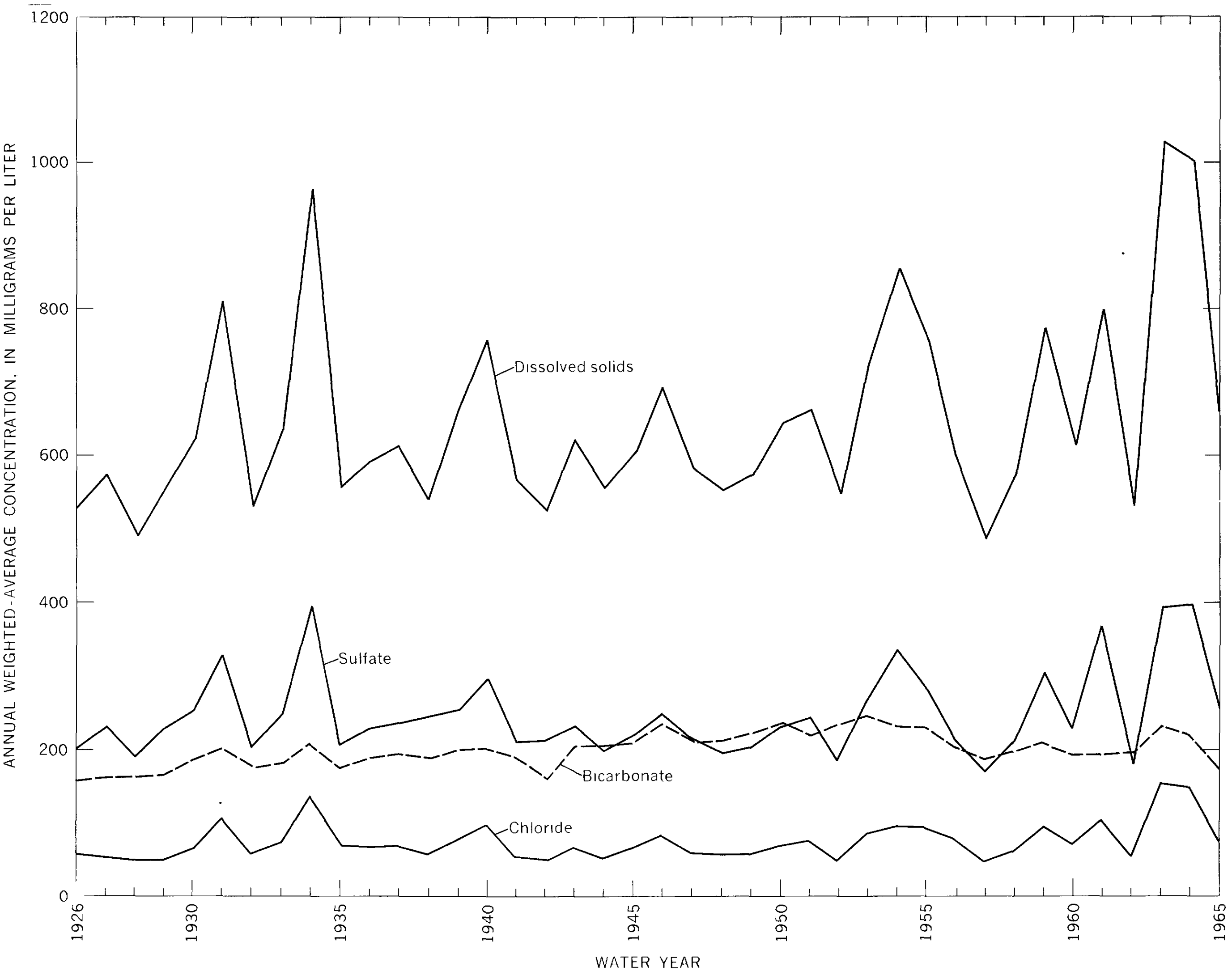

FIGURE 3.—Annual weighted-average concentration of dissolved solids, sulfate, bicarbonate, and chloride, Colorado River at Grand Canyon, 1926–65.

sulfate and sodium chloride from the lakebed has occurred and that there may have been some precipitation of calcium carbonate in the lake.

As annual river flows are known to have a small degree of dependence on immediately preceding annual flows with either high or low flow years tending to come together, it is possible that there is a similar sequential dependence of annual weighted-average concentrations. Study of the record for Colorado River at Grand Canyon, however, suggests that any such dependence is small and that annual concentrations are mostly related to annual discharge. Treating the annual concentrations as entirely random is helpful in a statistical summary of their variation (table 3). As most of the flow at Grand Canyon is now regulated by Lake Powell, future fluctuations in annual dissolved-solids concentrations will no doubt be less than those during 1926–62. Nevertheless, table 3 is of interest because it provides a summary of actual variations during a period of nearly stable irrigation development in the tributary area. The table shows that annual concentrations differ markedly but that averages for periods of 10 or more years usually differ only slightly.

In table 3, concentrations are given in tons per acre foot as well as milligrams per liter because irrigators in the lower Colorado River service area generally are familiar with dissolved-solids concentrations so expressed. Load data, described later, are also given either in tons or tons-equivalent because such expressions have been customary in reports about the Colorado River.

HOOVER DAM

The record of annual weighted-average concentrations for Colorado River below Hoover Dam (table

TABLE 3.—*Summary of weighted-average concentrations of dissolved solids, Colorado River at Grand Canyon, during selected periods prior to closure of Glen Canyon Dam*

Period and type of weighted average	Streamflow (acre-ft)	Weighted-average concentration: Milligrams per liter	Weighted-average concentration: Tons per acre-foot
Weighted average for selected years during 1926–62:			
Year of median streamflow (1936)	12,320,000	591	0.804
Year of median weighted average (1956)	8,860,000	609	.828
Year of maximum streamflow (1929)	19,430,000	556	.756
Year of minimum streamflow and maximum weighted average (1934)	4,656,000	960	1.31
Year of minimum weighted average (1957)	17,500,000	486	.661
Mean of annual weighted averages	12,130,000	629	.855
Weighted averages for selected periods during 1926–62:			
Total period	12,130,000	598	.814
Current base period for hydrologic normals, 1931–60	11,543,000	607	.826
Period of inflow to Lake Meade, 1936–62	11,890,000	602	.819
1926–35	12,780,000	584	.794
1936–45	12,840,000	586	.797
1946–55	11,280,000	629	.856
1953–62	10,240,000	630	.857
1956–62	11,390,000	590	.803

4) includes years when samples were collected at Willow Beach, 10 miles downstream, immediately prior to and during the early part of the filling of Lake Mead. It also includes several years when analyses of samples obtained at various depths between the intake towers of Lake Mead were used as measures of the quality of the water in the river.

Lake Mead is comparable to a huge mixing bowl into which pour the widely variable flows of the Colorado River, the much smaller Virgin River flows, several small spring-fed streams, and the infrequent flows from several generally dry channels. The lake alters the chemical regimen of the river below the lake as well as the streamflow regimen. Thus, it has virtually eliminated the natural daily and seasonal variations of concentration and has much reduced the annual variation. It has brought about changes in the water resulting from precipitation of calcium carbonate and silica and by solution of gypsum and possibly common salt from its bed. Also, evaporation of pure water from the lake has constantly increased the salinity of released water.

Histograms of the annual weighted-average concentration of dissolved solids for 1935–62 (fig. 4) illustrate the increased concentrations and reduced annual variation of Colorado River water below Hoover Dam as compared with that near Grand Canyon.

The records show that the concentrations of Colorado River water below Hoover Dam are still responsive to changes in flow, although the response has been muted by Lake Mead. During wetter periods of a few years, more water has flowed into Lake Mead than could be stored, so more has been released than actually needed by users downstream. During such

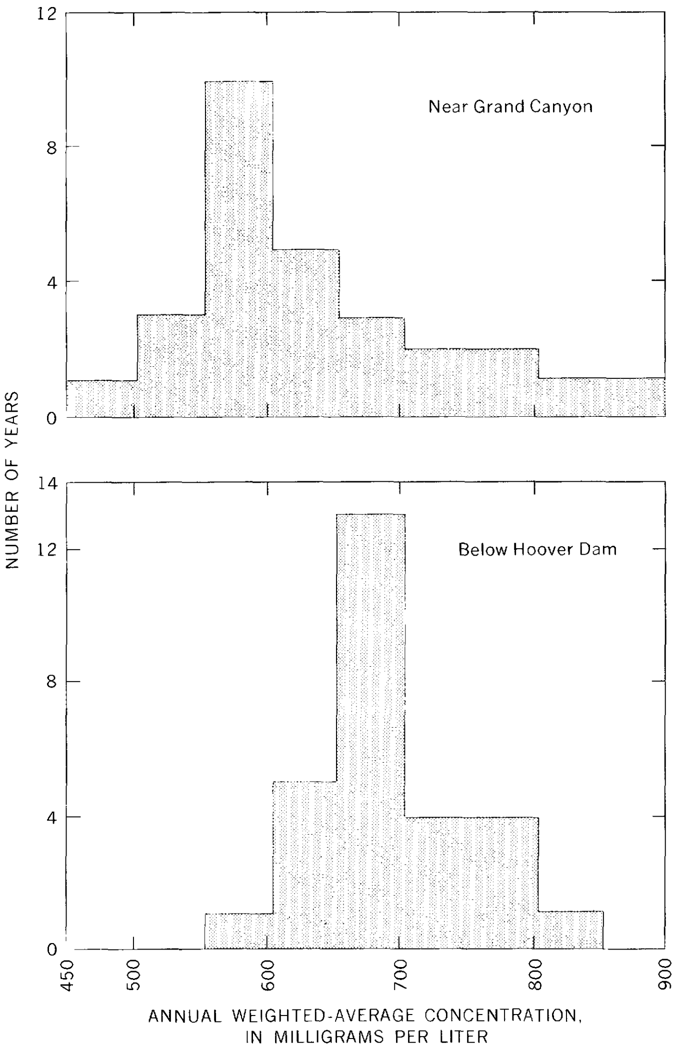

FIGURE 4.—Histograms of dissolved-solids concentration near Grand Canyon and below Hoover Dam, 1935–62.

TABLE 4.—*Annual weighted-average concentration for Colorado River below Hoover Dam, Ariz.-Nev.*

[Results in milligrams per liter unless otherwise indicated. ^{e} (estimated) signifies concentrations determined indirectly instead of by weighting individual analyses]

Water year	Total flow (acre-ft)	Mean discharge (cfs)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids: Residue at 180°C	Dissolved solids: Sum: Milligrams per liter	Dissolved solids: Sum: Tons per acre-ft	Hardness as $CaCO_3$: Calcium, magnesium	Hardness as $CaCO_3$: Noncarbonate	Specific conductance (micromhos at 25°C)
1935	5,556,000	7,674	13	82	29	108	5.8	169	268	101	0.3	3.3	693	694	0.94	324	185	^{e}1,070
1936	6,282,000	8,653	13	78	24	85	5.7	152	242	72	.3	2.7	596	599	.81	293	168	^{e}907
1937	5,826,000	8,048	10	102	25	93	5.4	157	314	74	-------	3.1	703	704	.96	358	229	^{e}1,060
1938	6,168,000	8,519	11	103	25	90	5.7	153	314	69	-------	2.8	696	696	.95	360	234	^{e}1,040
1939	8,473,000	11,700	13	102	26	93	6.1	158	321	72	.3	3.2	712	716	.97	362	232	^{e}1,070
1940	7,694,000	10,600	13	110	28	98	5.2	159	348	77	.3	3.0	761	762	1.03	390	259	1,140
1941	11,730,000	16,200	11	110	28	98	6.4	153	355	79	.3	3.0	766	767	1.04	390	264	1,140
1942	17,880,000	24,690	12	103	27	98		156	329	72	.4	2.6	719	722	.98	367	239	1,080
1943	12,500,000	17,260	13	95	26	89		158	303	64	.3	3.2	673	673	.92	344	214	1,010
1944	14,450,000	19,910	12	92	28	90	5.9	159	299	70	.4	3.4	679	677	.92	344	214	1,030
1945	12,940,000	17,870	^{e}12	^{e}93	^{e}30	95		^{e}166	^{e}302	^{e}77	-------	^{e}3.0	^{e}696	^{e}695	.95	^{e}356	^{e}220	^{e}1,060
1946	11,290,000	15,600	^{e}10	^{e}89	^{e}30	90		^{e}162	^{e}288	^{e}75	-------	^{e}2.5	^{e}664	^{e}662	.90	^{e}346	^{e}212	^{e}1,030
1947	10,660,000	14,730	^{e}12	^{e}90	^{e}29	96		^{e}161	^{e}294	^{e}78	-------	^{e}1.8	^{e}688	^{e}680	.92	^{e}344	^{e}212	^{e}1,040
1948	12,750,000	17,570	^{e}11	^{e}88	^{e}27	89		^{e}157	^{e}281	^{e}71	-------	^{e}1.8	^{e}649	^{e}646	.88	^{e}330	^{e}202	^{e}985
1949	13,200,000	18,230	^{e}11	^{e}85	^{e}25	84		^{e}156	^{e}263	^{e}67	-------	^{e}1.8	^{e}615	^{e}615	.84	^{e}315	^{e}187	^{e}939
1950	12,940,000	17,870	^{e}11	^{e}84	^{e}26	81		^{e}158	^{e}257	^{e}66	-------	^{e}1.9	^{e}606	^{e}606	.82	^{e}316	^{e}187	^{e}927
1951	9,981,000	13,790	13	84	28	90		167	267	72	-------	2.0	663	639	.90	324	188	977
1952	14,370,000	19,800	^{e}13	83	27	^{e}90	^{e}4.5	^{e}160	^{e}273	^{e}72	-------	^{e}2.1	652	^{e}645	.89	318	187	974
1953	12,780,000	17,650	^{e}13	83	23	82	^{e}4.2	^{e}162	^{e}253	^{e}62	-------	^{e}2.0	632	^{e}604	.86	302	168	938
1954	10,690,000	14,760	^{e}13	88	25	90	^{e}5.0	^{e}164	^{e}274	^{e}73	-------	^{e}2.1	677	^{e}652	.92	322	188	1,010
1955	9,276,000	12,810	^{e}13	102	27	106	^{e}5.0	^{e}167	^{e}320	^{e}94	-------	^{e}2.2	778	^{e}753	1.06	366	228	1,150
1956	7,818,000	10,770	^{e}13	104	32	117	^{e}5.3	170	^{e}350	^{e}103	-------	^{e}3.7	837	^{e}813	1.14	391	252	1,230
1957	8,088,000	11,170	^{e}12	96	31	110	^{e}5.3	171	^{e}320	^{e}98	-------	^{e}2.2	791	^{e}760	1.08	367	227	1,170
1958	12,270,000	16,940	11	87	24	86	4.2	158	269	71	.3	2.9	661	634	.90	316	186	985
1959	9,757,000	13,480	11	84	24	81	4.0	158	261	67	.3	3.2	622	614	.85	308	178	944
1960	9,251,000	12,740	11	88	25	87	3.9	158	^{e}270	^{e}72	-------	^{e}2.5	656	^{e}639	.89	322	193	983
1961	8,661,000	11,960	10	92	27	92	4.6	160	288	^{e}82	.4	3.5	694	680	.94	340	210	1,040
1962	8,304,000	11,470	12	101	26	98	4.3	162	^{e}311	^{e}87	.3	3.5	725	727	.99	359	226	1,090
1963	8,810,000	12,170	10	98	24	96	4.3	160	290	86	.3	2.7	700	691	.95	343	212	1,050
1964	8,234,000	11,340	10	93	27	97	4.3	154	292	90	-------	1.2	703	691	.96	328	202	1,030
1965	7,917,000	10,940	10	101	29	115	5.4	156	335	108	.4	1.6	814	782	1.11	371	243	1,210

periods the concentrations have generally decreased from year to year. During some dry periods inflow concentrations have been relatively high, and the outflow has been more nearly restricted to downstream water needs; so outflow has exceeded inflow for 2 or 3 consecutive years. The salinity of released water has always risen during such periods.

Because the changes in chemical characteristics of water released from Lake Mead have been of public concern, a brief statement of explanation is in order. Lake Mead began to form in 1935; during the years 1936–41 its contents increased every year except 1940, the maximum levels yet attained were reached in 1941. In 1936, the chemical character of water released from Lake Mead was similar to the weighted-average flow of the Colorado River at Grand Canyon, but was rarely like it thereafter. Solution from the newly flooded bottom of Lake Mead was probably greater during the years of the rising lake level than at any time since. As a result of bed solution and the more concentrated inflows of 1939 and 1940, the weighted-average concentrations of dissolved solids and sulfate below Hoover Dam trended upward from 1936 to a maximum in 1940.

During the years 1942–52 the flow at Grand Canyon averaged 13,430,000 acre-feet, and only 1946 and 1951 had flows of less than 10 million acre-feet. As a result of this long period of comparatively high streamflow, the concentration of dissolved solids, sulfate, and chloride generally declined, reached the lowest on record in 1950, rose slightly in 1951, and again declined to almost the previous lows in 1953.

The years 1953 to 56, inclusive, had the four lowest consecutive annual flows ever recorded at Grand Canyon and correspondingly high concentrations. Consequently during this 4-year period the concentrations of dissolved solids, sulfate, and chloride below Hoover Dam rose each year, with the highest annual averages yet experienced occurring in 1956. Rather high inflow to Lake Mead occurred in 1957–58, and in 1959 the concentrations of the water released from Lake Mead were nearly as low as the minimums of 1953. Three successive years of below-average inflow during 1959–61 then resulted in increased concentrations below Hoover Dam each following year. High inflow to Lake Mead in 1963 was followed by reduced salinity below Hoover Dam in both 1963 and 1964.

The regulated low flows at Grand Canyon in 1963 and 1964, each of which was less than two-thirds the unregulated minimum of 1934, were followed in 1965 by markedly higher concentrations below Hoover Dam, with the chloride concentrations reaching an all-time maximum.

This pattern of low inflow at Grand Canyon being followed by rising concentration levels below Hoover Dam, together with the demonstrated effects of Lake Mead on water quality below Hoover Dam, suggest what will happen as Lake Powell rises to higher operating levels. Lake Powell will decrease the variability of concentrations downstream and may cause a slight increase in average concentrations. The resulting more uniform concentrations in the inflow to Lake Mead will further reduce the variability of the concentrations below Hoover Dam, possibly by half.

LAKE HAVASU

Lakes Mohave and Havasu have only minor effects on the quality of Colorado River water because of their relatively small storage capacity is equal to only a few months of river flow. The inflow between Hoover and Parker Dams is generally so small that its effect on the quality of river water is also negligible.

The first major diversion of water from the lower Colorado River is the water pumped into the Colorado River aqueduct of the Metropolitan Water District of Southern California from Lake Havasu. Hill (1965) published a table of the 20-year (1941–60) ionic burden, in tons, of the Colorado River at Lake Havasu based on analytical records of the Metropolitan Water District. For this report Hill's data were recomputed to give weighted averages representative of inflow to Lake Havasu (table 5), and the period of record was extended through 1965 by using analyses of the Geological Survey and the U.S. Public Health Service. The yearly weighted-average concentrations for Lake Havasu computed from Hill's table agree very well with those for the same years at Hoover Dam, except that Lake Havasu water generally has somewhat less calcium and bicarbonate than the Hoover Dam releases. This difference suggests continued precipitation of calcium carbonate in Lakes Mohave and Havasu.

TABLE 5.—*Annual weighted-average concentration for Colorado River at Lake Havasu, Ariz.-Calif.*

[Results in milligrams per liter unless otherwise indicated. All silica concentrations are estimated]

Water year	Total flow (acre-ft)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Dissolved solids		Hardness as $CaCO_3$	
										Sum			
										Milligrams per liter	Tons per acre-ft	Calcium, magnesium	Noncarbonate
1941	11,825,000	11	108	29	101		159	352	79	758	1.03	388	258
1942	17,468,000	12	102	28	98		159	329	78	726	.99	370	239
1943	11,691,000	13	94	28	95		158	305	75	688	.94	350	220
1944	13,898,000	11	90	27	94		158	294	75	669	.91	336	206
1945	12,447,000	11	86	28	95		158	288	76	662	.90	330	200
1946	10,962,000	11	86	28	97		159	288	78	666	.91	330	199
1947	10;416,000	12	86	28	96		158	287	78	664	.90	330	200
1948	12,581,000	12	85	27	93		155	279	76	648	.88	323	196
1949	12,917,000	12	82	25	88		152	264	72	618	.84	308	183
1950	12,224,000	12	77	25	85		151	252	66	591	.80	295	171
1951	8,656,000	13	81	26	93		153	270	75	633	.86	309	184
1952	13,872,000	13	79	26	92		150	270	73	627	.85	304	181
1953	12,786,000	13	75	24	83		145	247	64	577	.78	286	167
1954	9,815,000	14	82	29	93		153	278	76	648	.88	324	198
1955	9,333,000	14	88	31	108		152	316	92	724	.98	347	222
1956	7,375,000	14	96	34	121		152	352	106	798	1.09	379	254
1957	7,412,000	12	96	33	117		152	343	103	779	1.06	375	250
1958	11,738,000	13	88	28	93		150	286	82	664	.90	334	212
1959	9,458,000	13	80	26	83		140	265	69	605	.82	306	192
1960	8,808,000	13	80	26	89		140	269	75	621	.84	306	192
1961	8,320,000	12	96	27	96	4.6	157	299	85	702	.95	350	222
1962	7,939,000	12	104	27	102	4.3	159	325	91	748	1.02	373	244
1963	8,450,000	11	99	25	100	4.3	157	302	90	712	.97	349	220
1964	7,903,000	12	89	27	98	4.3	150	290	90	685	.93	334	210
1965	7,625,000	11	104	30	120	5.9	155	348	113	811	1.10	383	256

The table of weighted averages for Colorado River at Lake Havasu also represents very nearly the concentrations of water diverted for irrigation in the Colorado River Indian Reservation (Parker Valley, Ariz.) and in the Palo Verde Valley, Calif.

IMPERIAL DAM

At Imperial Dam the Colorado River water is divided into three parts: the major part is diverted to the All-American Canal, a lesser amount to the Gila Gravity Main Canal, and the remainder is released down the river channel. Samples are collected at regular intervals from the Yuma Main Canal, which receives water from the All-American Canal. The analyses of these samples, published in annual water-supply papers of the U. S. Geological Survey "Quality of Surface Waters of the United States" as Yuma Main Canal, thus represent the quality of the water at Imperial Dam. This water is used for irrigation and municipal supply in most areas below the dam and in much of the Salton Sea basin. The record in table 6 for Colorado River at Imperial Dam also includes some years during which the sampling was directly from the Colorado River at Yuma and some estimated averages.

Comparison of the data in table 5 with those in table 6 shows that concentrations of dissolved solids and most of the major ionic constituents at Imperial Dam are greater than those at Lake Havasu and that the differences have been increasing. The increases are caused mainly by irrigation drainage returned to the river in the Colorado River Indian Reservation (Parker Valley) and the Palo Verde Valley, where there have been rather large increases of irrigated acreage in the past 25 years. Diversion through the Colorado River aqueduct to southern California, however, has increased during the same period from nearly insignificant amounts to about one-seventh of the water released at Hoover Dam. This increase has resulted in less water being available to dilute the saline irrigation return flows from Parker and Palo Verde Valleys and thereby has raised the salinity of water at Imperial Dam.

MINERAL BURDEN OF THE LOWER COLORADO RIVER, 1926–65

The mineral burden, or dissolved load, of the Colorado River at any point is the total quantity (weight) of dissolved minerals in the water flowing

TABLE 6.—*Annual weighted-average concentration for Colorado River at Imperial Dam, Ariz.-Calif.*

[Results in milligrams per liter unless otherwise indicated. ^{e} (estimated) signifies concentrations determined indirectly instead of by weighting individual analyses]

Water year	Total flow (acre-ft)	Mean discharge (cfs)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids			Hardness as $CaCO_3$		Specific conductance (micromhos at 25°C)
														Sum				
													Residue at 180°C	Milligrams per liter	Tons per acre-ft	Calcium, magnesium	Noncarbonate	
1941	11,060,000	15,270	^{e}12	^{e}110	^{e}28	^{e}107	^{e}5.5	^{e}153	^{e}363	^{e}87	^{e}0.3	^{e}2.5	788	791	1.08	^{e}390	^{e}264	^{e}1,200
1942	16,980,000	23,460	^{e}12	^{e}103	^{e}27	^{e}105		^{e}156	^{e}336	^{e}79	^{e}.3	^{e}1.9	743	742	1.01	^{e}368	^{e}240	^{e}1,120
1943	10,820,000	14,950	14	96	26	97		158	312	72	.3	1.8	696	698	.95	346	217	1,050
1944	13,240,000	18,230	11	92	28	98	4.1	165	306	76	.3	2.5	699	700	.95	344	210	1,070
1945	11,800,000	16,300	11	91	29	99	5.3	163	300	82	.3	1.5	699	701	.95	346	212	1,070
1946	10,160,000	14,040	13	87	30	98	5.9	160	295	83	.2	1.0	692	692	.94	340	210	1,050
1947	9,714,000	13,420	12	92	31	104	4.1	165	310	89	.2	1.3	726	725	.99	357	222	1,100
1948	11,730,000	16,160	13	89	28	100	3.3	165	292	82	.2	1.5	690	690	.94	337	202	1,060
1949	12,270,000	16,940	13	88	28	89	6.4	165	281	74	.3	1.8	663	663	.90	334	200	1,010
1950	11,500,000	15,890	13	84	27	88	2.9	163	265	75	.3	1.4	637	637	.87	320	187	985
1951	7,766,000	10,730	14	86	28	101	5.2	172	281	87	.3	1.1	706	688	.94	330	188	1,050
1952	13,040,000	17,970	14	85	29	100	4.4	169	283	84	.3	1.4	700	684	.93	331	192	1,050
1953	11,970,000	16,540	14	83	29	95	4.2	170	273	79	.4	1.4	680	663	.90	326	186	1,020
1954	8,950,000	12,360	16	86	28	105	4.5	171	287	87	.3	1.3	726	699	.95	330	190	1,070
1955	8,398,000	11,600	16	95	33	121	5.2	170	333	106	.3	1.5	818	795	1.08	372	233	1,200
1956	6,323,000	8,710	15	106	34	137	5.6	173	375	126	.4	1.7	917	886	1,20	404	262	1,340
1957	6,279,000	8,673	13	110	34	130	5.4	175	364	126	^{e}.4	1.1	884	870	1.18	414	270	1,340
1958	10,707,000	14,790	20	93	27	117	4.9	171	304	97	.6	1.9	763	750	1.02	343	203	1,140
1959	8,246,000	11,390	^{e}17	91	25	107	^{e}4.5	164	^{e}288	^{e}96	^{e}.4	^{e}1.7	746	710	.97	330	196	1,080
1960	7,338,000	10,110	^{e}18	93	26	112	^{e}4.7	163	^{e}299	^{e}104	^{e}.4	^{e}1.6	764	739	1.01	339	205	1,130
1961	6,527,000	9,016	^{e}16	98	27	126	^{e}4.9	167	^{e}323	^{e}117	^{e}.4	^{e}2.0	821	797	1.08	356	218	1,220
1962	6,220,000	8,591	16	99	29	133	^{e}5.5	164	328	126	^{e}.6	1.8	814	820	1.12	366	232	1,260
1963	6,612,000	9,133	15	100	27	129	^{e}5.2	167	326	118	^{e}.6	1.2	799	804	1,09	360	224	1,240
1964	6,076,000	8,370	16	95	28	131	^{e}5.1	165	324	122	^{e}.5	1.4	835	806	1.10	352	216	1,240
1965	5,766,000	7,964	16	104	31	150	^{e}5.7	168	364	142	.4	1.1	912	894	1.22	387	249	1,380

in the river past that point in a definite time interval. Loads of specific periods are computed from the weighted-average concentrations found by chemical analyses and the volumes of streamflow in the same periods and are usually stated in tons per day or tons per year. In the unregulated part of the river, high concentrations and smaller loads generally occur during periods of low streamflow and low concentrations and larger loads occur during periods of high streamflow. Thus, prior to construction of Glen Canyon Dam, the seasonal loads above Lees Ferry changed less than the flows or concentrations. Below Hoover Dam, where streamflow is almost completely regulated, concentrations now change rather slowly and almost independently of river volume, whereas loads change very nearly in proportion to streamflow.

Although load computations have no immediate importance to water users, they are important in salinity appraisals because they show downstream movement of dissolved minerals and indicate chemical changes in the river and in the storage reservoirs.

Load analysis is a technique of investigating the chemical regimen of a river by comparing mineral loads carried at different points or during different times. In the remainder of this report, load analysis of the Colorado River is the principal investigative technique. Load analysis is used to investigate the chemical regimen first by considering the loads of all the dissolved solids and then by considering the dissolved-solids load as made up of individual ionic loads undergoing chemically related changes.

ANALYSIS OF DISSOLVED-SOLIDS LOADS

Plotting annual dissolved-solids loads near Grand Canyon against annual river discharges for the period 1926–62 (fig. 5) results in a scatter diagram unlike that produced by plotting the annual concentrations against annual discharges (fig. 5). The relation between the annual loads and the annual discharges can be represented approximately by a straight line for the range defined by data. As the load for a year of no flow would be zero, however, the relation logically includes a curving segment for very low annual flows. In contrast to the load-flow curve, which rises with increasing annual flow, the concentration-flow curve declines with increasing annual flows. The latter curve changes in slope at a decreasing rate as flow increases, and this change indicates that at very high discharges the mineral concentrations are mostly related to the solubility of products of rock weathering and are less controlled by the fairly constant quantities of soluble salts entering the river in ground-water flow.

The scatter of the points in figure 5 shows that the relation between the annual dissolved-solids loads at Grand Canyon and the annual discharges is somewhat variable. A question arises as to whether there have been any real changes in the chemical regimen during the period of record. Although the question cannot be positively answered, several different methods of plotting dissolved-solids loads against time or stream discharges give indications of a small change in regimen with the dissolved-solids load in proportion to discharge somewhat greater after the middle 1950's.

A mass diagram of cumulative dissolved-solids loads for Colorado River at Grand Canyon for 1926–62 shows six time-trends indicated by letter arrows in figure 6; the trends are predominantly related to wet or dry periods lasting for several years but may also be influenced by upstream developments. The trends shown for the 1960's resulted from the filling of Lake Powell and other upstream reservoirs. Although the diagram indicates trends lasting a few years have characterized the chemical

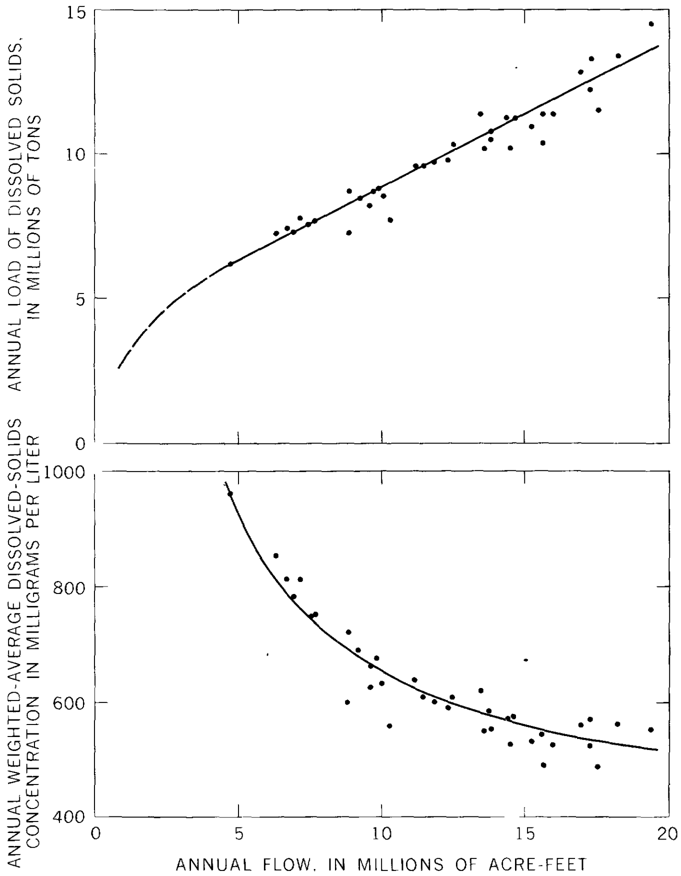

FIGURE 5.—Approximate relations of dissolved-solids load and concentration to flow of Colorado River near Grand Canyon, Ariz., 1926–62.

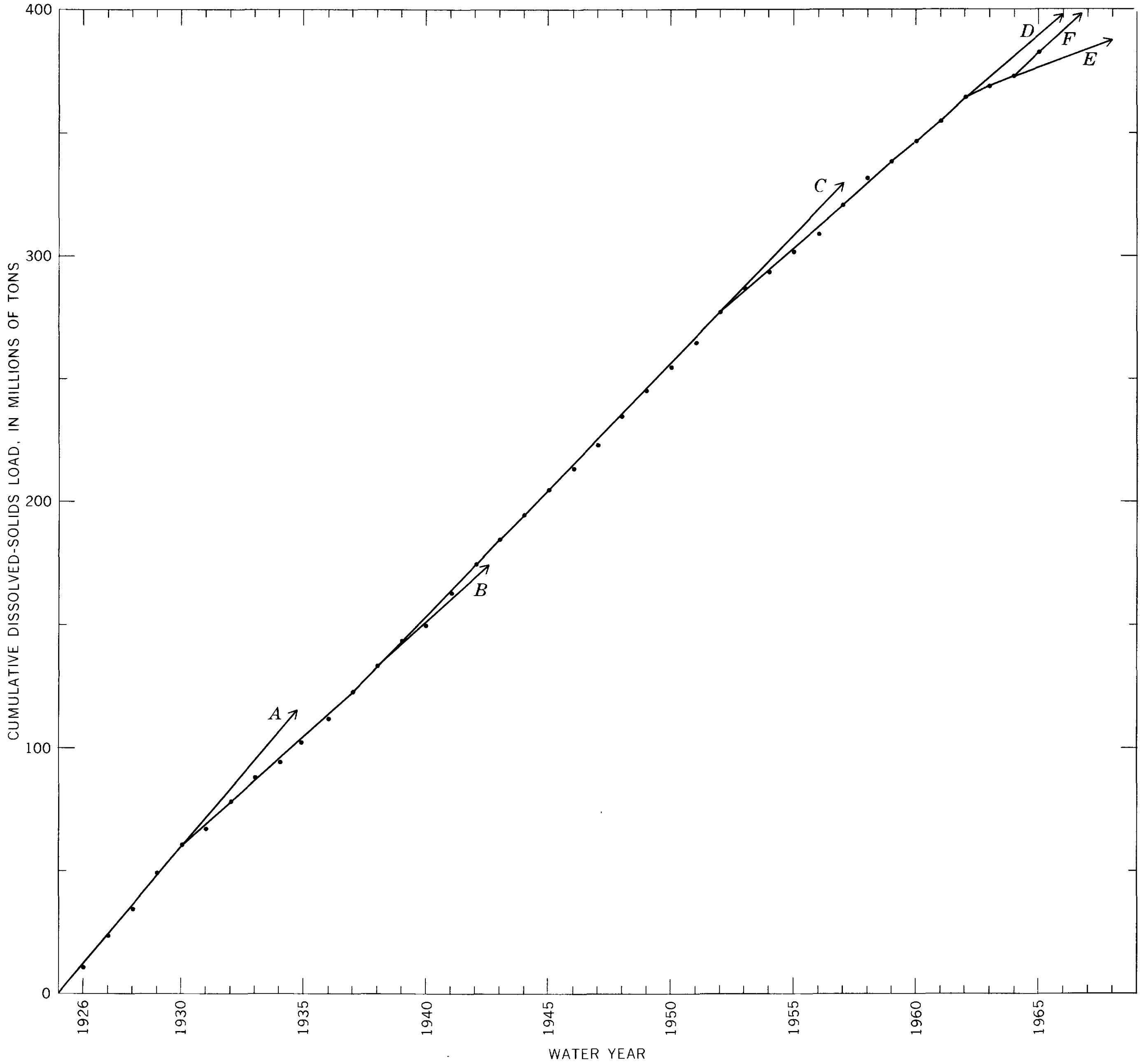

FIGURE 6.—Mass diagram of cumulative dissolved-solids load, Colorado River at Grand Canyon, 1926–65.

regimen of the Colorado River, the amount of changes indicated are quite small and do not suggest any major change during the period of record.

A double-mass diagram, produced by plotting cumulative dissolved-solids loads against cumulative annual river discharges at Grand Canyon (fig. 7), shows a nearly linear slope of about 0.8 prior to 1952, indicating a very stable load-flow regimen. After 1952, the plotted points increasingly diverge from the line with 0.8 slope. Such a change in slope suggests a change in the relation between the two variables cumulatively plotted. The departures after 1952 from the previous line of relation, however, are small and in the same direction and are attributed to the expansion of storage of the headwater areas of the river in Colorado and transmountain diversion of water from them. These regimen changes began about 1950 and increased irregularly thereafter.

To ascertain whether the changing relation indi-

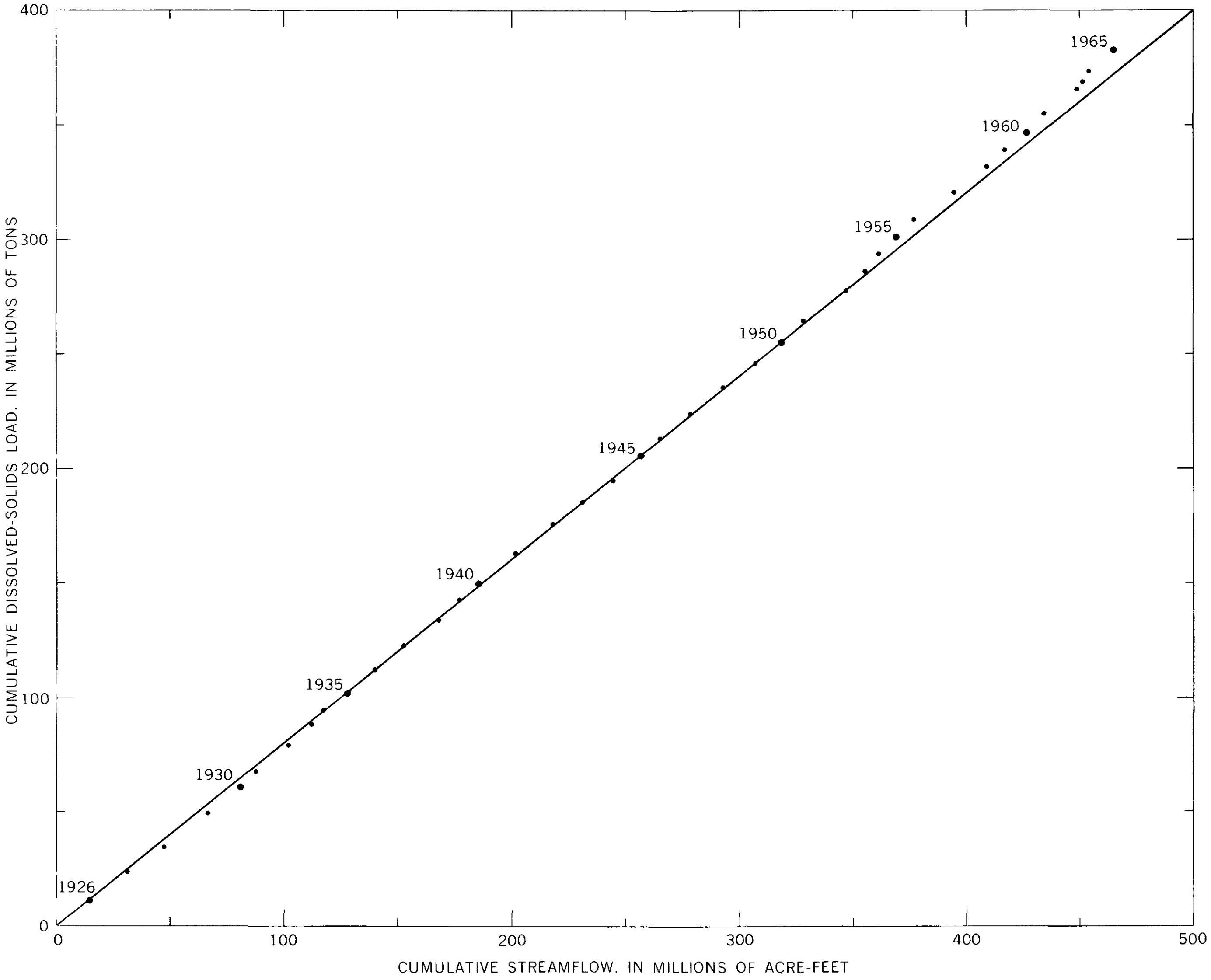

FIGURE 7.—Double-mass diagram of cumulative dissolved solids load to streamflow, Colorado River at Grand Canyon, 1926–65.

cated by figure 7 is mainly related to factors causing variation in annual streamflow, parallel differential mass diagrams for the Colorado River at Grand Canyon relating the cumulative departures of annual discharge and annual dissolved-solids loads to their means for the period were plotted together (fig. 8). The joint plotting suggests that any climatic variation affecting streamflow also affects dissolved-solids loads but to somewhat lesser degree.

ANALYSIS OF IONIC LOADS

One of the most informative methods of appraising the chemical regimen of the Colorado River is analysis of ionic-load variations. The annual loads of the several ions constituting the bulk of the mineral burden of the river vary individually, so the portion of the dissolved-solids burden represented by each ion changes from year to year. Approximate relations of annual constituent loads to discharge near Grand Canyon are indicated by lines on scatter diagrams in figure 9. The scatter of the points on the three cation and the chloride diagrams are rather well defined. The much greater scatter for sulfate and bicarbonate results from the variability of sources of inflow because some Upper Basin tributaries contribute large sulfate loads compared

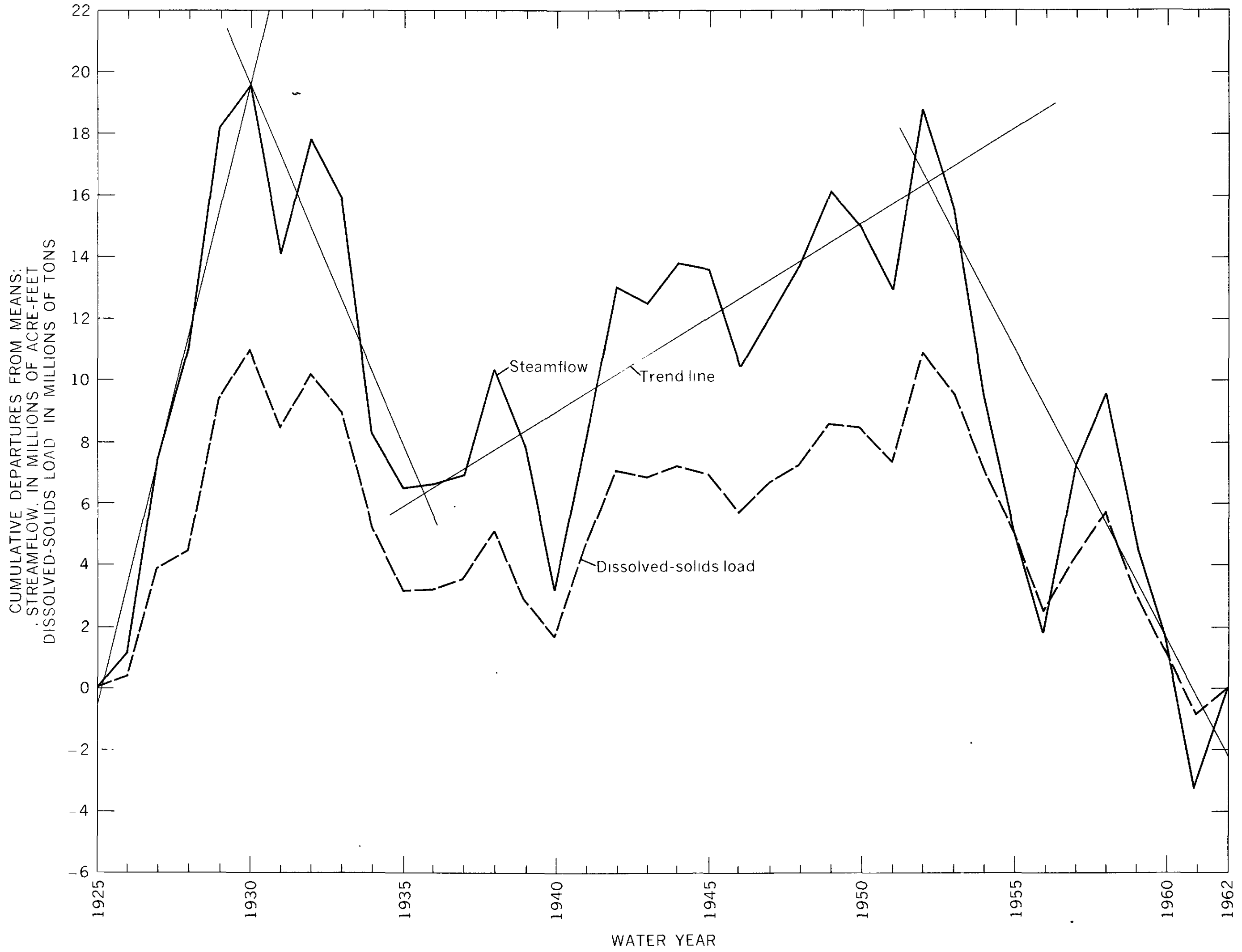

FIGURE 8.—Comparative differential mass diagrams for streamflow and dissolved-solids load, Colorado River at Grand Canyon, 1926–62.

with their bicarbonate loads and others yield much less sulfate in relation to bicarbonate.

Five-year progressive averages of ionic loads near Grand Canyon, compared with those below Hoover Dam in figure 10, emphasize the time-associated changes in the chemical character of water in the river resulting from storage in Lake Mead. The decreasing differences between the 5-year averages at the two points indicate that solution of gypsum (calcium sulfate) and common salt (sodium chloride) was much greater during the early years of reservoir storage than it has been recently. The new holdover storage of water in Lake Powell (which began in 1963) substantially reduced both the flow and the ionic loads downstream, so the last three 5-year progressive averages are lower than those for 5-year loads before storage in Lake Powell began.

Accumulated ionic loads have also been used by several authors to show chemical changes in water moving down the river. Howard (1960) compared tonnages of major ionic constituents at Grand Canyon with those below Hoover Dam to estimate chemical precipitation in Lake Mead and solution from its bed. More recently Hill (1965) and Bliss (1965) compared ionic loads expressed in tons-equivalent at Lees Ferry and at Lake Havasu for intervals of 20 years or more and used the comparisons to estimate the future average salinity of Colorado River water at Lake Havasu. Loads in tons-equivalent are computed by dividing the individual ionic loads in tons by their respective chemical-equivalent weights. This method of stating loads has the advantage that equivalency simplifies computations and makes chemical change readily detectable.

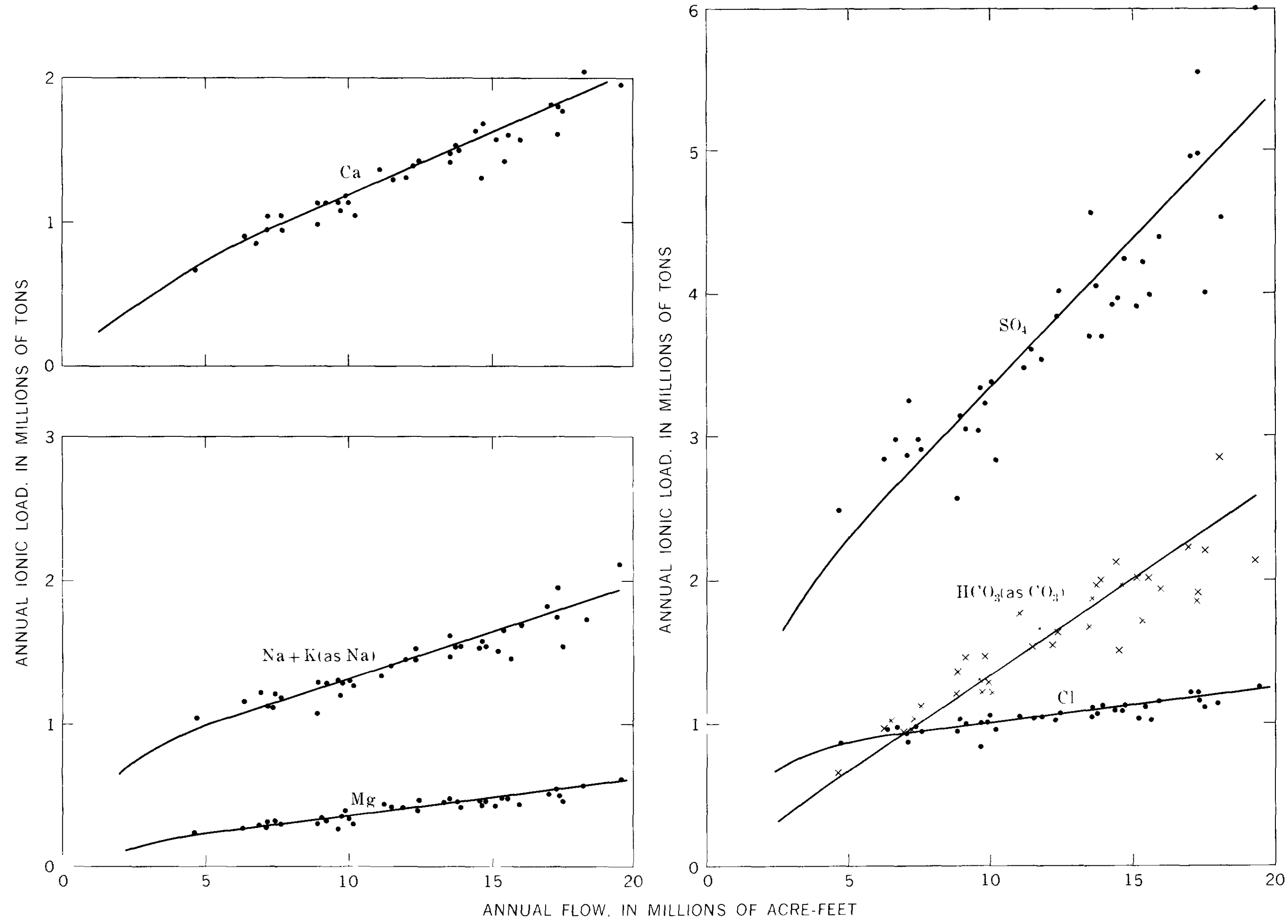

FIGURE 9.—Approximate relations of annual ionic load of principal constituents to annual flow of Colorado River near Grand Canyon, Ariz., 1926–62.

Comparison of individual ionic loads at widely separated sampling points for single years is not very informative because the time required for water to flow down the river and the modifying effect of the large holdover reservoirs obscure some chemical effects. Better understanding of the pattern of salt accretion and movement in the lower Colorado River is obtained by comparisons of flow and load totals for successive periods of a few years each. To facilitate such comparisons, cumulative totals of streamflow and ionic loads for successive 5-year periods are given on table 7 for the five lower Colorado River sites with long-time chemical-quality records. Also shown are computed gains or losses of ionic loads during the specified periods caused by increments to streamflow, changes in reservoir storage, or diversions out of the Colorado River basin.

Several changes in river-basin development need to be considered in making comparisons between the 5-year periods. For example, during the 25-year period of 1941–65, diversion to the Colorado River aqueduct increased from nearly zero to approximately full capacity of the aqueduct. Lake Mohave filled in the middle of the period. Storage in Lake Powell began early in 1963 and increased nearly every month thereafter. Also, combined irrigated acreage in the Parker, Palo Verde, and Cibola Valleys approximately tripled, so consumptive use of water by irrigation may have tripled. Differences between gains or losses for identical items in table 7 are related to all those developments.

When the 5-year tables are compared, certain loads are found to be more or less proportional to flows, whereas other loads show little relation to flows. Chloride loads above Lake Mead, in particular, appear to be mostly unrelated to flow. For example, the maximum chloride load at Lees Ferry for any of the four periods prior to closure of Glen Canyon Dam was only about 10 percent more than the minimum chloride load even though the maxi-

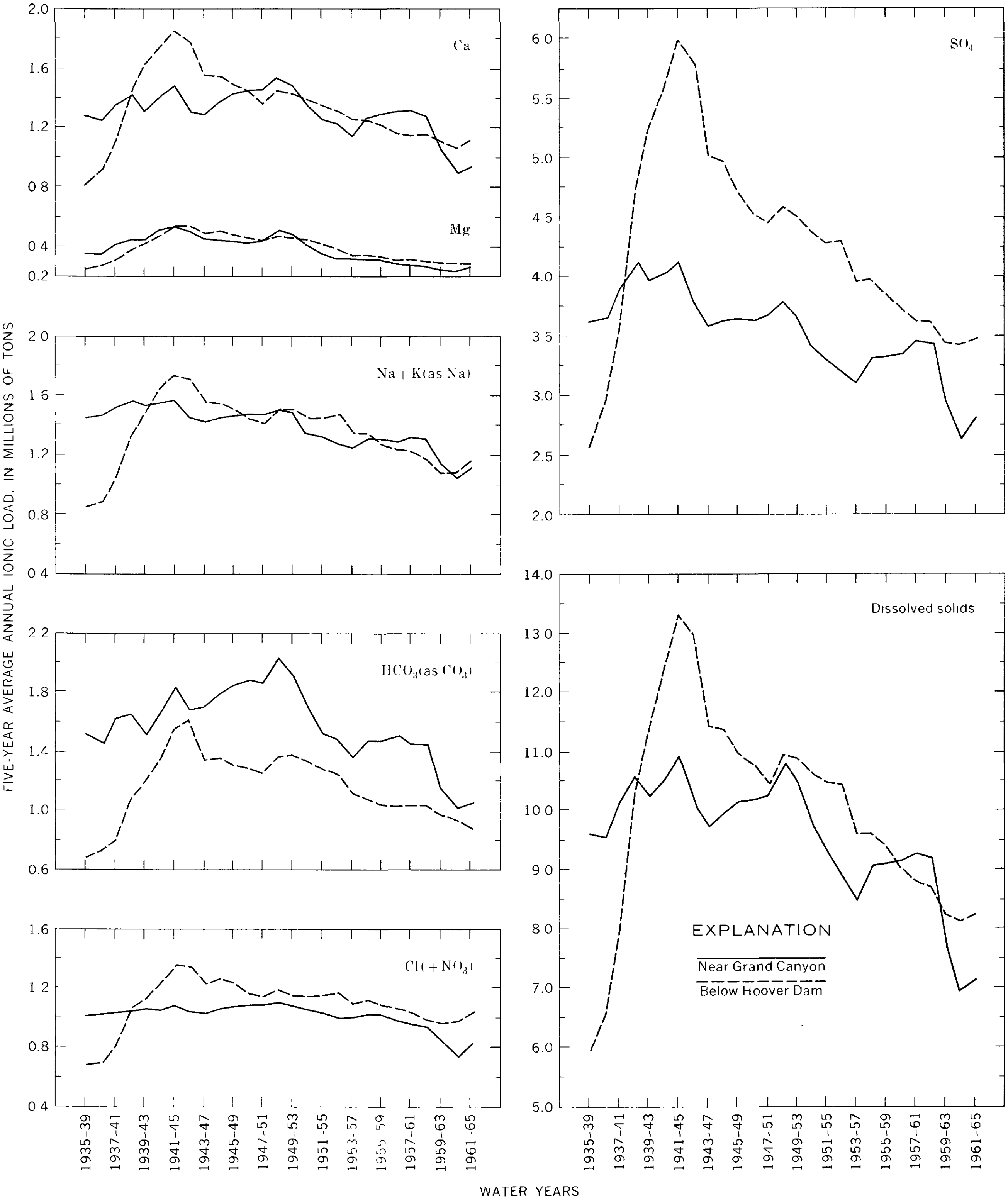

FIGURE 10.—Progressive 5-year average ionic and dissolved-solids load, Colorado River near Grand Canyon and below Hoover Dam, 1935–65.

TABLE 7.—*Five-year summary of streamflow and ionic burden of lower Colorado River from Lees Ferry to Imperial Dam*

[Ionic gains (+) and losses (−) in thousands of tons-equivalent; streamflow and storage change in thousands of acre-feet]

Measuring point or increment	Total streamflow or storage change	Cations			Total cations or anions	Anions		
		Ca	Mg	Na + K		HCO_3	SO_4	$Cl + NO_3$
1941–45								
1. Lees Ferry	69,000	303.5	177.1	278.8	759.4	232.9	410.3	116.2
2. Lees Ferry to Grand Canyon	+2,030	+65.1	+14.2	+54.8	+134.1	+69.3	+21.2	+43.6
3. Grand Canyon	71,030	368.6	191.3	333.6	893.5	302.2	431.5	159.8
4. Grand Canyon to Hoover Dam	−1,054	+67.7	+28.8	+35.8	+132.3	−49.3	+149.3	+32.1
5. Storage change in Lake Mead	−476	+28.4	−4.5	+21.5	+45.4	−3.6	+43.5	+5.5
6. Hoover Dam release	69,500	464.7	215.6	390.9	1,071.2	249.3	624.5	197.4
7. Storage change in Lake Havasu	−165	−.5	−.6	−.4	−1.5	−.7	−.5	−.3
8. Hoover Dam to Colorado River aqueduct intake	−2,006	−25.6	−3.6	−5.2	−34.4	−10.9	−24.4	+.9
9. Flow at Colorado River aqueduct intake	67,329	438.6	211.4	385.3	1,035.3	237.7	599.6	198.0
10. Diversion to Colorado River aqueduct	−221	−1.4	−.7	−1.2	−3.3	−.8	−1.9	−.6
11. Parker Dam release	67,108	437.2	210.7	384.1	1,032.0	236.9	597.7	197.4
12. Parker Dam to Imperial Dam	−3,208	−10.5	−14.1	+3.9	−20.7	−9.8	−10.5	−.4
13. Inflow to Imperial Dam	63,900	426.7	196.6	388.0	1,011.3	227.1	587.2	197.0
1946–50								
1. Lees Ferry	61,262	299.7	168.1	243.6	711.4	233.5	369.9	108.0
2. Lees Ferry to Grand Canyon	+887	+60.3	+8.1	+59.9	+128.6	+73.2	+9.1	+46.3
3. Grand Canyon	62,149	360.0	176.5	303.5	840.0	306.7	379.0	154.3
4. Grand Canyon to Hoover Dam	−2,474	−18.6	+3.0	+.3	−15.3	−91.2	+67.5	+8.4
5. Storage change in Lake Mead	+1,165	+18.2	+6.3	+11.3	+35.8	+2.8	+27.5	+5.5
6. Hoover Dam release	60,840	359.6	185.8	315.1	860.5	218.3	474.0	168.2
7. Storage change in Lake Havasu	−375	−1.8	−1.1	−1.7	−4.6	−1.4	−2.2	−1.0
8. Hoover Dam to Colorado River aqueduct intake	−1,365	−23.9	−9.7	+6.9	+26.7	−12.8	−14.2	+.3
9. Flow at Colorado River aqueduct intake	59,100	333.9	175.0	320.3	829.2	204.1	457.6	167.5
10. Diversion to Colorado River aqueduct	−690	−4.2	−2.1	−3.8	−10.1	−2.4	−5.7	−2.0
11. Parker Dam release	58,410	329.7	172.9	316.5	819.1	201.7	451.9	165.5
12. Parker Dam to Imperial Dam	−3,036	−.2	+4.3	+3.6	+7.7	+.9	−.9	+7.0
13. Inflow to Imperial Dam	55,374	329.5	177.2	320.1	826.8	202.6	451.7	172.5
1951–55								
1. Lees Ferry	49,955	279.2	147.3	232.1	658.6	217.8	339.0	101.8
2. Lees Ferry to Grand Canyon	+732	+34.7	+10.9	+52.7	+98.3	+43.7	+7.8	+46.8
3. Grand Canyon	50,687	313.9	158.2	284.8	756.9	261.5	346.8	148.6
4. Grand Canyon to Hoover Dam	−1,238	+5.4	−15.6	+22.6	+12.4	−75.0	+75.4	+12.0
5. Storage change in Lake Mead	+7,648	+19.0	+22.9	+8.1	+50.0	+24.8	+22.3	+2.9
6. Hoover Dam release	57,097	338.3	165.5	315.5	819.3	211.3	444.5	163.5
7. Storage changes in Lakes Mohave and Havasu	−832	−8.0	−2.7	−7.8	−18.5	−3.4	−10.6	−4.5
8. Hoover Dam to Colorado River aqueduct intake	−1,803	−33.2	+2.7	−8.4	−38.9	−25.1	−11.1	−2.7
9. Flow at Colorado River aqueduct intake	54,462	297.1	165.5	299.3	761.9	182.8	422.8	156.3
10. Diversion to Colorado River aqueduct	−1,320	−7.3	−4.2	−7.5	−19.0	−4.5	−10.5	−4.0
11. Parker Dam release	53,142	289.8	161.3	291.8	742.9	178.3	412.3	152.3
12. Parker Dam to Imperial Dam	−3,018	+3.9	+2.5	+22.3	+28.7	+12.3	−1.2	+17.6
13. Inflow to Imperial Dam	50,124	293.7	163.8	314.1	771.6	190.6	411.1	169.9
1956–60								
1. Lees Ferry	56,204	314.6	136.0	223.7	674.3	243.0	327.2	104.1
2. Lees Ferry to Grand Canyon	+1,225	+8.1	+6.5	+53.9	+68.5	+6.3	+17.7	+44.5
3. Grand Canyon	57,429	322.7	142.5	277.6	742.3	249.3	344.9	148.6
4. Grand Canyon to Hoover Dam	−2,397	−.1	+13.0	+18.4	+31.3	−52.1	+73.2	+10.2
5. Storage change in Lake Mead	+7,848	−30.6	−14.0	−24.7	−69.3	−24.4	−32.6	−12.3
6. Hoover Dam release	47,184	292.0	141.5	271.3	704.8	172.8	385.5	146.5
7. Storage changes in Lakes Mohave and Havasu	−178	+1.3	+.5	+1.4	+3.2	−.2	+2.4	+1.0
8. Hoover Dam to Colorado River aqueduct intake	−2,215	−27.7	+2.9	−11.2	−36.0	−26.2	−8.7	−1.1
9. Flow at Colorado River aqueduct intake	44,791	265.6	144.9	261.5	672.0	146.4	379.2	146.4
10. Diversion to Colorado River aqueduct	−3,107	−18.3	−10.0	−18.1	−46.4	−10.1	−26.2	−10.1
11. Parker Dam release	41,684	247.3	134.9	243.9	625.6	136.3	353.0	136.3
12. Parker Dam to Imperial Dam	−2,791	+9.6	−10.4	+37.0	+36.2	+10.1	+.4	+25.7
13. Inflow to Imperial Dam	38,893	256.9	124.5	280.4	661.8	146.4	353.4	162.0

TABLE 7.—*Five-year summary of streamflow and ionic burden of lower Colorado River from Lees Ferry to Imperial Dam*—Continued

Measuring point or increment	Total stream-flow or storage change	Cations			Total cations or anions	Anions		
		Ca	Mg	Na + K		HCO_3	SO_4	Cl + NO
	1961–65							
1. Lees Ferry	37,147	222.0	99.0	181.7	502.7	149.8	271.3	81.6
2. Lees Ferry to Grand Canyon	+1,602	+13.0	+8.9	+50.3	+72.2	+17.7	+10.6	+43.9
3. Grand Canyon	38,749	235.0	107.9	232.0	574.9	167.5	281.9	125.5
4. Grand Canyon to Hoover Dam	−2,053	+18.8	+13.7	+17.5	+50.0	−35.8	+62.1	+23.7
5. Storage change in Lake Mead	+5,230	+22.4	+3.0	+3.9	+29.3	+16.3	+14.7	−1.7
6. Hoover Dam release	41,926	276.2	124.6	253.4	654.2	148.0	358.7	147.5
7. Storage changes in Lakes Mohave and Havasu	+93	−.6	−1.0	−2.3	−3.9	+.1	−2.3	−1.7
8. Hoover Dam to California aqueduct intake	−1,739	−6.8	−.8	+.9	−6.7	−8.3	−.2	+1.8
9. Flow at Colorado River aqueduct intake	40,280	268.8	122.8	252.0	643.6	139.8	356.2	147.6
10. Diversion to Colorado River aqueduct	−5,480	−36.6	−16.8	−34.4	−87.8	−19.0	−48.6	−20.2
11. Parker Dam release	34,800	232.2	106.0	217.6	555.8	120.8	307.6	127.4
12. Parker Dam to Imperial Dam	−3,599	−22.3	−7.2	+33.3	+3.8	−5.1	−13.9	+22.8
13. Inflow to Imperial Dam	31,201	209.9	98.8	250.9	559.6	115.7	293.7	150.2

mum flow was 40 percent greater than the minimum. The computed chloride increases between Lees Ferry and Grand Canyon never differed as much as 5 percent from the average for the entire period.

The load summaries not only indicate where fairly constant saline increments enter the river but also help distinguish temporary from continuing chemical effects. For example, all the summaries show decreases in bicarbonate and increases in sulfate in the reach between Grand Canyon and Hoover Dam, which includes Lake Mead. As some bicarbonate must be brought into the lake in Virgin River and other inflow, the consistent decreases in bicarbonate can be explained only as the result of continuing precipitation of calcium carbonate in the lake. The continuing gains in sulfate in the same reach indicate solution of calcium sulfate from the bed of Lake Mead; and because sulfate is also brought into the lake in Virgin River and other inflows, the solution of calcium sulfate is more definitely indicated by the 5-year progressive average loads (fig. 10) than by the increases downriver. Precipitation of calcium carbonate in Lakes Mohave and Havasu is strongly suggested by the continuing decreases in both calcium and bicarbonate between Hoover Dam and Parker Dam.

Comparison of the ionic loads, both by 5-year periods and downriver from Lake Mead, illustrates the changes in the chemical regimen of the lower Colorado River resulting from increasing diversion and use of water. Thus, the steadily increasing diversion of water to the Colorado River aqueduct has contributed to the increase in ionic concentrations at Imperial Dam because the quantity of water available for diluting the more concentrated inflows is reduced by the amount of the diversion. In addition, increases in concentrations at Imperial Dam have resulted from the leaching and irrigation of previously uncultivated lands in the Parker and Palo Verde Valleys. Return flows from irrigation in the two valleys contain relatively high concentrations of sodium and chloride leached from the fields, as reflected in the considerable increases in both the loads and concentration of these constituents at Imperial Dam.

AVERAGE ANNUAL IONIC BURDEN OF THE COLORADO RIVER

Almost inevitably, questions arise as to what is the average mineral burden of the Colorado River and how this burden varies during periods of high or low flow. Generally, it is agreed that the longer the period of record, the better the future values of hydrologic variables can be estimated. Thus a 40-year (1926–65) summary of the ionic burden of the Colorado River at Grand Canyon (table 8) by 5-year periods is a better indicator than the previously discussed 25-year summary of the Colorado River mineral burden. In this 40-year summary the values for the 5-year period 1961–65 are partly estimated, being corrected for the change in storage in Lake Powell and the other upper Colorado River storage reservoirs. Adjustments were made for both the water and the salts retained in the reservoirs.

The 5-year summaries of ionic loads in table 8 were used to compute 5-year, 10-year, 20-year, and

TABLE 8.—*Forty-year summary of ionic burden for Colorado River at Grand Canyon by 5-year periods, 1926-65*

[Ionic loads in thousands of tons-equivalent; streamflow in acre-feet]

Period	Total streamflow	Cations			Total cations or anions	Anions			Acre ft.
		Ca	Mg	Na + K		HCO_3	SO_4	Cl + NO_3	Tons-equivalent
1926–30	80,160,000	395.0	203.2	368.1	966.3	296.9	502.2	167.2	83.0
1931–35	47,577,000	261.6	137.5	277.0	676.1	195.1	334.3	146.7	70.4
1936–40	57,413,000	320.2	159.8	301.8	781.8	247.4	384.4	150.0	73.4
1941–45	71,030,000	368.6	191.3	333.6	893.5	302.2	431.5	159.8	79.5
1946–50	62,149,000	360.0	176.5	303.5	840.0	306.7	379.0	154.3	74.0
1951–55	50,687,000	313.9	158.2	284.8	756.9	261.5	346.8	148.6	67.0
1956–60	57,429,000	322.7	142.5	277.6	742.8	249.3	344.9	148.6	77.3
1961–65[1]	53,404,000	315.5	145.5	303.8	764.8	220.1	387.2	157.5	69.8
40-year total	479,849,000	2,657.5	1,314.5	2,450.2	6,422.2	2,079.2	3,110.3	1,232.7	74.7
Average of 5-year periods	59,981,000	332.2	164.3	306.3	802.8	259.9	388.8	154.1	74.7

[1] Estimated; adjusted for storage in Lake Powell and other upper Colorado River project reservoirs.

40-year average annual ionic loads at Grand Canyon (table 9). The values in table 9 indicate the variability which has occurred for equivalent time intervals in the past, and, therefore, with appropriate considerations of the changes resulting from the works of man, the values can be taken as indicators of what might occur in future. The loads show considerable variation by 5-year periods, but they trend towards uniformity when averaged for longer periods. They also indicate that with increased storage now available the ionic loads will continue to vary but within a narrow range.

The 5-year average streamflow during 1931–35 was the lowest since the beginning of records in 1896. Therefore, the loads at Grand Canyon during 1931–35 must have been close to the minimum which can be expected during any future 5-year period, if adjustments are made for the effects of Upper Basin reservoirs.

Ionic burden at Lees Ferry as determined by other investigators

Although both the length and completeness of sampling make the Grand Canyon record the best

TABLE 9.—*Averages of streamflow and ionic burden of Colorado River at Grand Canyon for different periods*

[Averages assume no storage in upper Colorado River Storage project reservoirs. Ionic loads in thousands of tons-equivalent; streamflow in acre-feet]

Length of period	Period averaged	Average streamflow	Cations			Total cations or anions	Anions			Acre ft.
			Ca	Mg	Na + K		HCO_3	SO_4	Cl + NO_3	Tons-equivalent
5-year	1926–30	16,032,000	79.0	40.6	73.6	193.2	59.4	100.4	33.4	83.0
	1931–35	9,515,000	52.3	27.5	55.4	135.2	39.0	66.9	29.3	70.4
	1936–40	11,483,000	64.0	32.0	60.4	156.4	49.5	76.9	30.0	73.4
	1941–45	14,206,000	73.7	38.3	66.7	178.7	60.4	86.3	32.0	79.5
	1946–50	12,430,000	72.0	35.3	60.7	168.0	61.3	75.8	30.9	74.0
	1951–55	10,137,000	62.8	31.6	57.0	151.4	52.3	69.4	29.7	67.0
	1956–60	11,486,000	64.6	28.5	55.5	148.6	49.9	69.0	29.7	77.3
	1961–65	10,681,000	63.1	29.1	60.8	153.0	44.0	77.5	31.5	69.8
10-year	1926–35	12,774,000	65.6	34.1	64.5	164.2	49.2	83.6	31.4	77.8
	1931–40	10,499,000	58.2	29.7	57.9	145.8	44.2	71.9	29.7	72.0
	1936–45	12,844,000	68.9	35.1	63.5	167.5	55.0	81.5	31.0	76.7
	1941–50	13,318,000	72.9	36.8	63.7	173.4	60.9	81.1	31.4	76.8
	1946–55	11,284,000	67.4	33.5	58.8	159.7	56.8	72.6	30.3	70.7
	1951–60	10,812,000	63.7	30.1	56.2	150.0	51.1	69.2	29.7	72.1
	1956–65	11,083,000	63.8	28.8	58.1	150.7	46.9	73.2	30.6	73.5
20-year	1926–45	12,809.000	67.3	34.6	64.0	165.9	52.1	82.6	31.2	77.2
	1931–50	11,908,000	65.5	33.3	60.8	159.6	52.6	76.5	30.5	74.6
	1936–55	12,064,000	68.1	34.3	61.2	163.6	55.9	77.1	30.6	73.7
	1941–60	12,065,000	68.3	33.4	60.0	161.7	56.0	75.1	30.6	74.6
	1946–65	11,183,000	65.6	31.1	58.5	155.2	51.9	72.9	30.4	72.1
40-year	1926–65	11,996,000	66.4	32.9	61.3	160.6	52.0	77.8	30.8	74.7

NOTE.—Range in total cations and anions: 5-year averages, 135.2; 10-year averages, 145.8–173.4; 20-year averages, 155.2–165.9.

basis for describing the ionic burden of the lower Colorado River, previously published computations of this burden have been based on the Lees Ferry record. Hill (1965) computed the ionic burden at Lees Ferry for 1941–60 from the weighted-average concentrations as published in water-supply papers of the U.S. Geological Survey ("Quality of Surface Waters in the United States") without correcting yearly averages for years with incomplete records but instead by estimating for missing years. Bliss (1965) estimated data for years of no record by correlation and computed an average ionic burden for 1930–60. Iorns, Hembree and Oakland (1965) computed a weighted average for the period 1914–57 from a table of average concentrations for selected flow ranges and a flow-duration curve. Table 10 gives the average loads at Lees Ferry published by the above individuals and the weighted averages computed for the present study. The weighted averages include periods during which sampling was done only at Grand Canyon. The Grand Canyon record for these periods was adjusted to a probable record at Lees Ferry on the basis of the average gain of minerals between the two stations during periods when both records were complete. Unfortunately, this procedure cannot be used to compute concentration for the period Iorns uses because no sampling occurred before 1926; however, the estimate for 1926–65 was found to be comparable with Iorns' estimate for 1914–57.

IONIC BUDGET OF THE COLORADO RIVER FROM LEES FERRY TO IMPERIAL DAM, 1961–65

A detailed ionic budget is one of the most useful aids to understanding the chemical regimen of the lower Colorado River. Such a budget is a summary of determined or estimated ionic loads carried past key river points in downstream order. The budget includes estimates of gains from principal tributaries and of losses to major diversions, as well as computations of gains and losses in the storage reservoirs. An ionic budget serves both as an identification of principal sources of increments to the ionic loads carried by the river and as a base for predicting what might happen to water quality if present diversions are either expanded or reduced or if new diversions are made from the river.

Comparison of the weighted averages in table 10 indicates that considerably more variation of period loads at Lees Ferry results from the choice of base period than from the manner in which missing records are estimated. It also appears from the table that Hill, Bliss, and Iorns, Hembree and Oakland may have understated the sulfate burden at Lees Ferry by a small percentage.

An ionic budget computed for a single year has questionable value because the flow pattern of any individual year may not be representative of the usual amounts of water in the various river reaches considered, because passage of water through storage reservoirs produces slow chemical changes not easily determinable on an annual basis, and because flows of individual tributaries may be highly abnormal in any selected year. Also, the ionic contributions of the various tributaries cannot generally be defined in terms of specific years because sampling studies on different tributaries are generally not concurrent and are of unequal length and intensity. On the other hand, an ionic budget prepared for a long period has questionable value because of the many changes in river regimen resulting from Upper Basin developments, construction of Upper and Lower Basin storage reservoirs, and continuing changes in amounts of diversion and return flow in the Lower Basin. As a result of such changes, long-time averages of ionic loads are likely to be quite different from future average annual loads. Thus, ionic budgets prepared for a long period of a few recent years appear to be most meaningful. Accordingly, a detailed ionic budget for the Colorado River reach extending from Lees Ferry to Imperial Dam is presented only for the 5-year period 1961–65.

TABLE 10.—*Comparative computations of average annual streamflow and ionic burden for Colorado River at Lees Ferry*

[Ionic loads in thousands of tons-equivalent. Streamflow in acre-feet]

Period summarized	Authority	Average streamflow	Cations			Total cations or anions	Anions		
			Ca	Mg	Na + K		HCO_3	SO_4	Cl + NO_3
1941–60	Hill (1965)	11,821,000	60.8	32.1	47.1	140.0	48.5	70.0	21.5
1941–60	Irelan (this report)	11,821,000	59.9	31.4	48.9	140.2	46.4	72.3	21.5
1930–60	Bliss (1965)	11,314,000	56.3	30.1	47.5	133.9	43.9	68.6	21.4
1930–60	Irelan (this report)	11,314,000	56.8	30.4	48.5	135.7	42.6	71.9	21.2
1926–65	Irelan (this report)	11,689,000	58.0	30.9	50.2	139.1	42.4	75.0	21.7
1914–57	Iorns (1965)	12,706,000	60.0	32.7	48.3	141.0	49.4	71.5	20.1

The items in the ionic budget were computed from a variety of source analyses. Ionic loads at the five principal sampling sites on the river were computed from the previously described weighted averages. Ionic loads at other sites were obtained by allowing for gains from tributaries, losses by diversions, and gains or losses caused by changes in reservoir levels. Ionic loads contributed by tributaries were computed mostly from chemical analyses published in various issues of the annual water-supply series of the U.S. Geological Survey "Quality of Surface Waters of the United States." Some of these were computed from weighted averages, and others from unweighted analyses selected as the most representative for the period 1961–65. Some ionic loads, however, were computed from incomplete analyses corrected in a variety of ways. Ionic loads in drain waters were computed from unpublished analyses obtained during this investigation. The analyses used to represent the tributaries and drains in the ionic budget are given in table 11. The following paragraphs give explanations of the sources of analyses, the computations made from them, the significance of the sampled flows, and the changes computed between sampling sites or tributaries.

LEES FERRY

The use of Lees Ferry as a reference point in other Colorado River studies makes this a desirable point at which to begin an ionic budget. The average flow and ionic loads at Lees Ferry during 1961–65, however, are not comparable with those of earlier 5-year periods because storage of water in Lake Powell and other upper Colorado River reservoirs began during the period. On September 30, 1965, a total of 11,724,000 acre-feet of water was held in the new upper Colorado River storage project reservoirs, and most of it accumulated after March 13, 1963, when storage began in Lake Powell. In addition, approximately one-fourth of the inflow to Lake Powell is estimated to have been retained in bank storage. Thus, in about 2½ years about 15 million acre-feet of water and its dissolved ionic loads, which previously would have flowed past Lees Ferry, were retained upstream. Yet, the water being released from Lake Powell on September 30, 1965, had a substantially lower concentration than the average at Lees Ferry during the 1961–65 period. This may have been the result of uneven mixing of the water in the lake, or it may have resulted from precipitation of calcium carbonate in the stored water.

To allow for the storage effects, the 5-year flows and ionic loads determined from records at Lees Ferry for 1961–65 were adjusted for the new upriver storage, by assuming that all the stored water had the concentration of Lake Powell releases in September 1965. The ionic budget (table 12) begins with these adjusted quantities. The estimated average flow and loads retained in storage, including bank storage, are given next. Following that, the table gives the flow and loads at Lees Ferry as they actually were measured.

PARIA RIVER

In the Colorado River Compact the Paria River basin is considered part of the Upper Basin. The flow and ionic loads of the Colorado River at the compact point, however, include contributions from the Paria River. Therefore, it is necessary to add these contributions to those of the Colorado River at Lees Ferry to obtain the quantities passing from the Upper Basin to the Lower Basin. Chemical analyses of water samples collected periodically from the Paria River near its mouth are reported in some of

TABLE 11.—*Representative analyses of tributary inflow to lower Colorado River between Lees Ferry and Imperial Dam*

[Results in milligrams per liter unless otherwise indicated]

No.	Source	Date (*weighted average)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Dissolved solids (residue at 180°C)	Specific conductance (micromhos at 25°C)
1.	Paria River at Lees Ferry	1914–57*	--------	121	57	134		203	608	23	1,090	1,480
2.	Little Colorado River at Cameron, Ariz.	1952*	16	29	5	98		162	57	80	368	624
3.	Blue Springs	June 21, 1965	17	91	64	793		396	163	1,220	2,500	4,520
4.	Bright Angel Creek at mouth	Aug. 4, 1952	8	42	21	4.9		223	14	3	203	347
5.	Tapeats Creek at mouth	June 25, 1965	--------	36	11	4.1		168	3.8	1.3	147	267
6.	Havasu Springs	Oct. 20, 1950	18	133	48	27		588	36	48	602	1,030
7.	Virgin River at Littlefield, Ariz.	1961*	20	364	88	263		314	1,060	330	2,160	3,040
8.	Bill Williams River at Planet, Ariz.	Aug. 8, 1931	36	45	11	65		228	41	46	362	--------
9.	Colorado Indian Reservation, Upper Main Drain	May 26, 1965	19	138	43	183		256	450	170	1,130	1,780
10.	Colorado Indian Reservation, Palo Verde Drain	Oct. 24, 1962	20	92	30	105		176	292	95	722	1,180
11.	Colorado Indian Reservation, Lower Main Drain	Oct. 15, 1964	22	178	65	391		288	675	442	1,920	2,970
12.	Palo Verde District, Olive Lake Drain	Dec. 13, 1963	14	130	40	145		256	375	144	930	1,550
13.	Palo Verde District, outfall drain	Jan. 10, 1964	14	132	45	371		292	525	380	1,570	2,610

TABLE 12.—*Average annual streamflow and ionic burden of the Colorado River, Lees Ferry to Imperial Dam, 1961–65*

[Streamflow in acre-feet; ionic gains (+) and losses (—) in thousands of tons-equivalent]

No.	Source	Streamflow	Cations			Total cations or anions	Anions		
			Ca	Mg	Na + K		HCO_3	SO_4	$Cl + NO_3$
1.	Colorado River at Lees Ferry, adjusted for storage	10,360,000	60.50	27.32	50.70	138.52	40.48	75.32	22.72
2.	Retained in storage	−2,931,000	−16.10	−7.52	−14.36	−37.98	−10.52	−21.06	−6.40
3.	Colorado River at Lees Ferry, actual flow	7,429,000	44.40	19.80	36.34	100.54	29.96	54.26	16.32
4.	Paria River at compact point	19,000	.16	.13	.14	.43	.08	.33	.02
5.	Colorado River at Lees Ferry	7,448,000	44.56	19.93	36.48	100.97	30.04	54.59	16.34
6.	Little Colorado River near Cameron	136,000	.27	.08	.80	1.15	.50	.22	.43
7.	Blue Springs (near mouth of the Little Colorado River)	161,000	.99	1.15	7.55	9.69	1.42	.74	7.53
8.	Residual Lees Ferry to Grand Canyon	5,000	1.18	.42	1.57	3.17	1.54	.83	.80
9.	Colorado River at Grand Canyon	7,750,000	47.00	21.58	46.40	114.98	33.50	56.38	25.10
10.	Bright Angel Creek	26,000	.07	.06	.01	.14	.13	.01	.00
11.	Tapeats Creek	50,000	.13	.06	.00	.19	.18	.01	.00
12.	Havasu Springs (in Havasu Creek)	48,000	.43	.26	.08	.77	.63	.05	.09
13.	Virgin River at Littlefield	109,000	2.75	1.09	1.67	5.51	.78	3.33	1.40
14.	Residual, Grand Canyon to Lake Mead	137,000	3.38	1.47	1.76	6.61	1.72	3.40	1.49
15.	Net inflow to Lake Mead	8,120,000	53.76	24.52	49.92	128.20	36.94	63.18	28.08
16.	Evaporation from and chemical precipitation in Lake Mead	−781,000	−10.38	−.20	−.02	−10.60	−10.60	0	0
17.	Solution from bed to Lake Mead		7.38	0	0	7.38	0	5.62	1.76
18.	Inflow to Lake Mead, corrected for evaporation and chemical changes in the lake	7,339,000	50.76	24.32	49.90	124.98	26.34	68.80	29.84
19.	Adjustments for change in storage	+1,046,000	+4.48	+.60	+.78	+5.86	+3.26	+2.94	−.34
20.	Colorado River below Hoover Dam	8,385,000	55.24	24.92	50.68	130.84	29.60	71.74	29.50
21.	Evaporation from and chemical precipitation in Lakes Mohave and Havasu	−390,000	−1.50	−.22	−.27	−1.99	−1.90	−.09	.00
22.	Solution from beds of Lakes Mohave and Havasu		0	0	.27	.27	0	0	.27
23.	Bill Williams River	42,000	.14	.06	.18	.38	.24	.05	.09
24.	Adjustment for change in storage in Lakes Mohave and Havasu	+19,000	−.12	−.20	−.46	−.78	+.02	−.46	−.34
25.	Colorado River at Colorado River aqueduct intake in Lake Havasu	8,056,000	53.76	24.56	50.40	128.72	27.96	71.24	29.52
26.	Diversion to Colorado River aqueduct	−1,096,000	−7.32	−3.36	−6.88	−17.56	−3.80	−9.72	−4.04
27.	Colorado River below Parker Dam	6,960,000	46.44	21.20	43.52	111.16	24.16	61.52	25.48
28.	Diversion to Colorado River Indian Reservation	−454,000	−3.03	−1.38	−2.84	−7.25	−1.58	−4.01	−1.66
29.	Colorado River flow below diversion	6,506,000	43.41	19.82	40.68	103.91	22.58	57.51	23.82
30.	Return flow from Colorado River Indian Reservation in Upper Main Drain	151,000	1.41	.72	1.63	3.76	.86	1.92	.98
31.	Colorado River above Palo Verde Diversion Dam	6,657,000	44.82	20.54	42.31	107.67	23.44	59.43	24.80
32.	Net diversion to Palo Verde Canal	−749,000	−5.04	−2.31	−4.76	−12.11	−2.63	−6.69	−2.79
33.	Return flow from Colorado River Indian Reservation in Palo Verde Drain	27,000	.17	.09	.17	.43	.11	.22	.10
34.	Return flow from Colorado River Indian Reservation in Lower Main Drain	96,000	1.16	.70	2.23	4.09	.62	1.84	1.63
35.	Return flow from Palo Verde Valley in Olive Lake Drain	16,000	.14	.07	.14	.35	.09	.17	.09
36.	Return flow from Palo Verde Valley in outfall drain	349,000	3.13	1.76	7.66	12.55	2.27	5.19	5.09
37.	Diversions to Cibola Valley	−24,000	−.17	−.08	−.18	−.43	−.09	−.23	−.11
38.	Residual, Parker Dam to Imperial Dam	−132,000	−2.23	−1.01	+2.61	−.63	−.67	−1.19	+1.23
39.	Colorado River at Imperial Dam	6,240,000	41.98	19.76	50.18	111.92	23.14	58.74	30.04

the annual water-supply papers. Iorns, Hembree, and Oakland (1965) prepared a mineral-concentration duration table which related the salinity of the river water to discharge. The analysis of Paria River water given in table 11 was obtained from the duration table and corresponds to the 1961–65 average flow. Paria River water is primarily a calcium sulfate solution, low in chloride but containing considerable sodium bicarbonate. The computed loads (table 12, item 4) indicate that the Paria River has a negligible effect on the salinity of Colorado River water downstream.

LITTLE COLORADO RIVER

An important segment of the flow of the Little Colorado River, the largest tributary entering the Colorado between Lees Ferry and Imperial Dam, is the discharge from Blue Springs, which are in the river channel a few miles above its mouth. In the ionic budget, Little Colorado River refers to the river flow above the springs.

Little Colorado River was sampled for several years at Cameron Ariz., about 45 miles above its mouth, where it is dry for extended periods nearly every year. Because of the uncertainty of the adequacy of sampling during early portions of some flow periods, the water-supply papers give weighted-average concentrations only for the year 1952, when the river flow was more than twice the average annual flow. Study of the sampling records, however, indicates that the 1952 analyses were not greatly different from those obtained in the other years represented by sampling. Consequently, the 1961–65 average load for the Little Colorado River was computed by multiplying the 1952 measured load by the ratio of the 1961–65 average flow to the 1952 flow. This procedure probably results in the Little Colorado River's being represented by an analysis somewhat lower in concentration than the true 1961–65 weighted average and by a somewhat greater load than the true load for the period.

The water of Little Colorado River above Blue Springs is less concentrated than that of the Colorado River at Lees Ferry. Therefore, in years of substantial discharge the Little Colorado River water may moderately reduce the usual gain in dissolved-solids concentration between Lees Ferry and Grand Canyon. The average flow during 1961–65 was too small for this reduction to be significant.

BLUE SPRINGS

Blue Springs here refers to the entire group of springs near the mouth of the Little Colorado River and not to the single large spring sometimes referred to as Blue Springs. Although samples of water obtained from different springs in the group have varied in composition, analyses of samples of mixed outflow obtained near the mouth of the river have indicated nearly uniform composition of the mixed flow. An analysis of one such sample taken when the Little Colorado River above the springs was dry represents the combined spring flow as shown in tables 11 and 12. Measurements of discharge made at the mouth of the Little Colorado River when the river was dry at Cameron indicate a nearly constant spring discharge of about 161,000 acre-feet per year. Discharge from Blue Springs apparently accounts for most of the increases in ionic concentrations in Colorado River water between Lees Ferry and Grand Canyon. Most of the increment of the mineral load of the Colorado River derived from the springs is sodium chloride; the computations indicate that the springs add more sodium chloride to the river's mineral burden than all the other tributaries between Lees Ferry and Imperial Dam combined.

UNMEASURED INFLOW FROM LEES FERRY TO GRAND CANYON

Several small tributaries with unknown annual discharges enter the Colorado River between Lees Ferry and Grand Canyon. A residual estimate of their combined flow, less river evaporation, is obtained by subtracting the sum of the Colorado River flow at Lees Ferry, the Paria River flow, the Little Colorado River flow at Cameron, and the Blue Spring discharge from the recorded flow at Grand Canyon. The ionic load residuals are obtained by a similar computation, but because the evaporation is unknown, the average concentration of the inflow cannot be approximated. The mineral increment contributed by inflow and possibly by solution from the streambed has about the general composition of limestone water, with calcium and magnesium bicarbonates constituting about half the increment and sodium sulfate and sodium chloride constituting nearly equal parts of the remainder.

GRAND CANYON

The significance of the Grand Canyon station as a record point has been discussed previously. During the 5-year period 1961–65 when flow below Lake Powell was partly controlled, the percentage of increase in flow between Lees Ferry and Grand Canyon was about one-third of the percentage of increase in mineral burden.

BRIGHT ANGEL CREEK

Most of the flow of Bright Angel Creek originates in springs which emerge near the base of the Muav Limestone, several thousand feet above the Colorado River but also several thousand feet below the north rim of the Grand Canyon. Water is pumped from Roaring Springs, one of the largest of the Bright Angel Creek sources, to supply facilities on the north rim of the Grand Canyon. Intermittent sampling near its mouth has shown that the ordinary flow of the creek is always low in mineral content and that most of the dissolved minerals are calcium bicarbonate. The creek adds an insignificant amount of minerals to the load of the Colorado River and whenever in flood has a considerable temporary diluting effect on the river water.

TAPEATS CREEK

Entering the Colorado River about 45 miles below the mouth of Bright Angel Creek, Tapeats Creek is fed by springs in the Muav Limestone. Johnson and Sanderson (1968) gave analyses of the creek water, and on the basis of a few discharge measurements they estimated the discharge as a little less than twice the discharge of Bright Angel Creek. The Tapeats Creek water is similar in composition to but even less mineralized than the Bright Angel Creek water.

HAVASU CREEK

Most of the flow of Havasu Creek, the largest tributary on the south side of Grand Canyon, originates from Havasu Springs and has been measured only occasionally. By assuming that a 1950 analysis of the spring water (table 11) is representative of the creek's mineral contribution, it has been determined that Havasu Creek adds mostly calcium bicarbonate to the load of the Colorado River. As Havasu Creek is known to be depositing travertine below the springs, it is possible that the computed additions to the mineral burden of the Colorado River (table 12, item 12) are high.

VIRGIN RIVER

There is considerable uncertainty in estimating increments of ionic constituents added to the Colorado River by the Virgin River. Several years of chemical-quality records were obtained at Littlefield, Ariz., about 40 miles above the mouth of the Virgin River, but because of diversions for irrigation downstream, the mineral burden at Littlefield that actually reaches the Colorado River is somewhat uncertain. It is assumed herein, however, that the water and salts passing Littlefield represent the flow into the river. The weighted average for 1952 was used to represent the Virgin River concentrations because the 1952 discharge was almost the same as the 5-year average for 1961–65. Virgin River water is high in calcium sulfate, but the river also carries substantial amounts of sodium chloride which enter it from springs in Utah.

UNMEASURED INFLOW BETWEEN GRAND CANYON AND HOOVER DAM

Simultaneous solution of lakebed minerals and chemical precipitation of calcium carbonate in Lake Mead make ionic budgeting of the reach between Grand Canyon and Hoover Dam speculative. Mineral increments entering the reach from the four major tributaries, Bright Angel Creek, Tapeats Creek, Havasu Springs, and Virgin River, have been estimated from chemical and discharge information, but increments possibly as large derived from many small springs and minor tributaries cannot be estimated directly. Also, the ionic increments in the unmeasured inflow cannot be estimated by differences as was done for the reach between Lees Ferry and Grand Canyon because the gains and losses in Lake Mead constitute part of the unmeasured differences; so the arbitrary assumption was made in preparing table 12 that the combined increments from all unmeasured inflow (item 14) are equal to the sums of the measured increments from the four tributaries. The volume of the unmeasured streamflow was computed by subtracting the sum of the Colorado River flow at Grand Canyon and the flows of the four named tributaries from the net inflow to Lake Mead (determined as explained in the next section).

The sizes of the ionic increments derived under this assumption seem reasonable, considering the quantities of ionic loads entering other reaches of the river. The unmeasured ionic load increments might, however, reasonably have been estimated to be as little as one-half or as much as double the tabulated quantities.

Thus, the quantities of flows and ionic loads entering Lake Mead (table 12, item 15) are sums of those for the river at Grand Canyon, for the four tributaries, and for the just-described residuals.

CHEMICAL CHANGES IN LAKE MEAD

It has been known for many years that chemical precipitation of calcium carbonate is nearly continuous in the body of Lake Mead and that at the same time other minerals are continuously being dissolved from some of the sedimentary formations that constitute part of its bed. The mineral budgeting makes possible quantitative appraisals of these two chemical processes.

The 5-year streamflow and ionic-load averages below Hoover Dam (table 12, item 20) were determined from the annual streamflow and chemical-quality records. Adjustments (item 19) were made to allow for a net decline in lake contents during the 5 years and for a corresponding decline of mineral contents by assuming that chemical analyses of water samples taken at the beginning and end of the 5-year period represented the mineral contents of the entire lake when sampled. The differences between these last two sets of computations (item 18) were assumed to represent the 5-year average effective flows and loads at Hoover Dam—that is, the average flows and loads which would have occurred if there had been a constant lake level during the period instead of a net decline. The average net inflow to Lake Mead (item 15), used previously to compute the unmeasured inflow between Grand Canyon and Hoover Dam, was then computed as the sum of the effective annual flow at Hoover Dam and the average of the evaporation losses reported for the lake.

The differences between the ionic loads computed for the net inflow to Lake Mead (item 15) and the effective flow at Hoover Dam (item 18) must represent either chemical precipitation or mineral solution. In the mineral budget, as prepared, anion dominance was assumed to determine whether precipitation or solution had occurred. Thus, the decrease in bicarbonate loads computed for the two flows indicates precipitation of calcium carbonate in the lake. In contrast, the computed gains of both sulfate and chloride must have been the result of solution of lakebed minerals. In the ionic budget the cation gains and losses were arbitrarily assigned in such a way that the bicarbonate losses caused by precipitation (item 16) and the sulfate and chloride gains resulting from solution (item 17) were balanced ionically; thus no unaccountable gains and losses resulted between points with measured loads. The fact that calcium changes were sufficient to account for nearly all the cation gains and losses, within small errors, suggests that the assumptions were reasonable.

During the 5 years 1961–65, the indicated chemical precipitation in Lake Mead (item 16) somewhat exceeded the estimated solution of minerals from its bed (item 17). Hence, the lake storage influenced the chemical composition of the released water more than it affected the total mineral load. During some earlier periods, however, the load was markedly affected by the lake. (See fig. 10.)

BILL WILLIAMS RIVER

From Hoover Dam to Imperial Dam the Colorado River flows through a succession of narrow canyons and wide valleys and has only one sizeable tributary—the Bill Williams River. Although this tributary river contributes a few thousand acre-feet to the Colorado River every year and a few hundred thousand acre-feet during rare years of extraordinary flow, flow is perennial only in a few short reaches; at the mouth of the river the flow is intermittent. The Bill Williams was sampled intermittently at Planet, Ariz., for many years, but averages and loads were never computed. Study of the analyses indicates that the water in this river is always much lower in mineral content than the Colorado River water. It nearly always contains less than 450 mg/l dissolved solids, with bicarbonate the major constituent. The Bill Williams River was not sampled during 1961–65. Accordingly, it is represented by an analysis (table 11) selected from the old record (Howard, 1955). Load computations (table 12, item 23) indicate that the Bill Williams has negligible effect on the mineral burden of the Colorado River water below its mouth.

CHEMICAL CHANGES IN LAKES MOHAVE AND HAVASU

The quality-of-water records at Hoover and Parker Dams show the chemical character of river water passing them. By reasoning similar to that used to establish the effects of Lake Mead, the combined effects of Lakes Mohave and Havasu on Colorado River loads during 1961–65 were established. The computations resulted in small adjustments (table 12, item 24) in the water and mineral contents of the two lakes. Evaporation and calcium carbonate precipitation (item 21) together account for most of the chemical changes occurring between the two dams. The amount of increase in mineral load (item 22) seems to be so small that it is insignificant and well within the overall errors of the mineral budget. Evidently, there are no major sources of minerals which are unaccounted for. Consequently, no residual was included for this reach in table 12.

DIVERSION TO COLORADO RIVER AQUEDUCT

The Colorado River aqueduct intake, in Lake Havasu, is the uppermost point in the lower Colorado River where relatively large volumes of water are now diverted. Although pumping of water through the aqueduct to cities of southern California began in 1939, the amounts diverted were at first quite small compared with the flow of the river and did not reach 5 percent of the annual river flow until 1955, when pumping was 413,000 acre-feet. Thereafter, the annual diversion increased more rapidly; during the 5-year period 1961–65 it averaged more than 1 million acre-feet and increased every year except 1962. The recent large diversion to the California aqueduct has an important effect on the salinity of Colorado River water at Imperial Dam because it reduces the amount of water available to dilute the somewhat saline return flows from the irrigated areas in the Parker and Palo Verde Valleys. Only part of the increase in concentration at Imperial Dam, however, is a result of the increased diversion through the aqueduct. Part of the increase is a result of a rapid expansion of irrigation in the two valleys and the consequent increases in the volumes of saline returns.

PARKER DAM TO IMPERIAL DAM

Between Parker and Imperial Dams the Colorado River flows through the Parker, Palo Verde, and Cibola Valleys, which together form a continuous valley referred to in some early reports as the Great Colorado Valley. Diversions to irrigate the Parker Valley are made at Headgate Rock Dam, a few miles north of Parker, Ariz. Diversions to irrigate the Palo Verde Valley are made at the Palo Verde Dam, several miles north of Blythe, Calif. Irrigation return flows from Parker Valley reenter the Colorado River both above and below Palo Verde Dam. Return flows from irrigation in Palo Verde Valley reenter the river opposite Cibola Valley. Water is pumped to irrigate areas in Cibola Valley from the river and from wells in the flood plain. As the alluvial aquifer is largely recharged from the river, the pumpage from the wells is a draft on the river. There are no surface drains in the Cibola Valley. As much as 20,000 acres may have been added to the irrigated area in the 15 years prior to 1965. Leaching of soluble salts from new lands not previously irrigated has probably resulted in substantial additions to the Colorado River's mineral burden at Imperial Dam.

The part of the ionic budget describing gains and losses in the reach between Parker and Imperial Dams (table 12, items 27–38) is based on analyses of water samples collected at approximately monthly intervals during 1962–65 from major drains in the Parker and Palo Verde Valleys and less frequently from canals and wasteways. Only the principal ionic constituents were determined for most of the samples; however, several complete analyses were made of samples from each drain. These unpublished analyses indicated rather small variations in the composition and concentration of water in the individual drains and rather marked variations from drain to drain. For the ionic budget, the 5-year average concentrations were obtained by averaging all the determined concentrations for each ion and using the complete analysis that most closely corresponded to the composition suggested by the group of ion averages. Analyses used to represent average concentrations are given in table 11.

The residual of unmeasured gains and losses (table 12, item 38) appears very reasonable considering the many diversions and returns between Parker and Imperial Dams.

IONIC ACCOUNTING OF PRINCIPAL IRRIGATION AREAS ABOVE IMPERIAL DAM

The salt balance of an irrigated area was defined by Scofield (1940) as the relationship between the quantity of dissolved mineral salts delivered to an area in irrigation water and the quantity removed from the area by the drainage. Scofield called an excess of removal over import a favorable salt balance and a deficiency of removal an unfavorable salt balance. The terminology of Scofield, although much used, has been opposed because an excess of deposition or withdrawal is not a balance. Nevertheless, those managing irrigation projects have become very conscious of possible salt accumulation in irrigated areas. For that reason, statements which Scofield might have termed "salt balances" are included in an accounting format (table 13).

By assembling the data from table 12 on inflow to and outflow from Parker and Palo Verde Valleys, it is possible to show the water and mineral budget of the two valleys. Item 1, table 13, gives the 1961–65 average annual water and ionic budget for Parker Valley that was computed by subtracting the sum of the water and ionic loads diverted from the Colorado River in water used to irrigate the valley from the water and loads returned to the river in the three principal drains. The accounting indicates leaching of common salt (sodium chloride) from the valley soils and suggests some replacement of sodium

TABLE 13.—*Average annual water use and ionic burden in irrigated areas, Parker Dam to Imperial Dam, 1961–65*

[Water use in acre-feet. Ionic gain (+) and losses (—) in thousands of tons-equivalent]

No.	Areal designation (method of determination)	Water use	Cations			Total cations or anions	Anions		
			Ca	Mg	Na + K		HCO_3	SO_4	Cl + NO_3
1.	Parker Valley (Reservation Main Canal less three drains)	−180,000	−0.29	+0.13	+1.19	+1.03	+0.01	−0.03	+1.05
2.	Palo Verde Valley (Palo Verde Canal less two drains)	−384,000	−1.77	−.48	+3.04	+.79	−.27	−1.33	+2.39
3.	Combined area, Parker Dam to Imperial Dam	−720,000	−4.46	−1.44	+6.66	+.76	−1.02	−2.78	+4.56

in the soils by calcium. Item 2 in the table shows the water and ionic budget for Palo Verde Valley that was obtained by subtracting the returns in two drains from diversions to the valley. The accounting suggests that some precipitation of gypsum and calcite is occurring in the valley soils and that there is loss of additional calcium from the water to the soil. The principal change in this valley, as in the Parker Valley, is a net removal of sodium chloride.

The valley budgets computed from available records are inherently inexact because of unmeasured seepage returns to the river. A combined budget for the Colorado River reach between Parker and Imperial Dams (table 13, item 3) reduces these errors. This combined budget, which is based on good streamflow and quality-of-water records during 1961–65, indicates deposition of calcite and gypsum, some base-exchange replacement of calcium by sodium, and removal of sodium chloride (probably mostly derived from leaching), but does not show where the chemical gains and losses occurred.

GENERAL CHARACTERISTICS OF THE COLORADO RIVER WATER BELOW IMPERIAL DAM

The lower Colorado became a managed river when Hoover Dam was closed, but for many years the flow of the river exceeded downstream needs. The salinity of local water supplies became a serious concern in the part of the Colorado River service area downstream from Imperial Dam only when developed needs for water became about equivalent to the flow of the river. So long as there was substantially more flow in the river than required by irrigators (the usual condition prior to the 1960's), diversion procedures and irrigation practices were developed on the basis of convenience, with little attention being paid to saline drain waters other than to remove them from farmed areas in surface drains.

Nearly all the water now (1969) reaching Imperial Dam (about 6 million acre-ft annually) is used for irrigation or public supply in the United States and Mexico. The present chemical regimen of the lower river, however, is complicated because the flow of the river is greatly depleted at the dam and because numerous drains and wasteways with differing chemical characteristics empty into it and the tributary Gila River. Continuous efforts are made to closely control both the amount and quality of the water reaching Morelos Dam, the principal Mexican diversion point.

The part of the Colorado River service area (the area receiving irrigation water from the Colorado River; figs. 11, 12) in the United States downstream from Imperial Dam is mostly simply divided into the Yuma area (flood plain and mesas along the Colorado and Gila Rivers, west of the Gila Mountains), the Wellton-Mohawk area (Gila River flood plain and terrace, east of the Gila Mountains), and the Salton Sea area (irrigated valleys in the Salton Sea basin). For some descriptions the Yuma area is further divided into the Bard-Winterhaven Valley, in California, and the Yuma Valley, the North and South Gila Valleys, and the Yuma Mesa, in Arizona. Delivery of the irrigation water and drainage arrangements are by projects of the U.S. Bureau of Reclamation or by legally organized irrigations districts. The areas receiving Colorado River water and their canal and drainage systems are described in more detail in the companion report by Hely (1969).

Most of the Colorado River water used in the United States is diverted at Imperial Dam, but a small part, at times including most of the water used in the city of Yuma, Ariz., is diverted directly from the river downstream from the dam. This water has generally been more saline than the water at the dam.

Above the Wellton-Mohawk area the Gila River channel is nearly always dry, but at its mouth this river has a small perennial flow resulting from return flow from irrigation with Colorado River water and pumpage from drainage wells. The salinity of the water in the lower Gila River is nearly always substantially greater than that of the water in the Colorado River, and the salinity of the water in the Colorado River at Morelos Dam is more variable and nearly always considerably greater than that at Imperial Dam.

Mexico's annual entitlement to Colorado River water (1,500,000 acre-ft, min) is defined by treaty to include water reaching Mexico in irrigation drain and wasteway channels. Most of this water is diverted from the Colorado River at Morelos Dam, west of Yuma, but somewhat less than 10 percent enters Mexico in a large drain and a small canal which cross the international boundary near San Luis, Ariz., south of Yuma. There is usually little flow in the Colorado River channel downstream from Morelos Dam except for seepage, small returns from three wasteways, and water deliberately bypassed around Morelos Dam through a recently constructed wastewater conveyance channel. At times there have been small diversions by pumping directly from the river below Morelos Dam, both in the United States and in Mexico. The quality of the

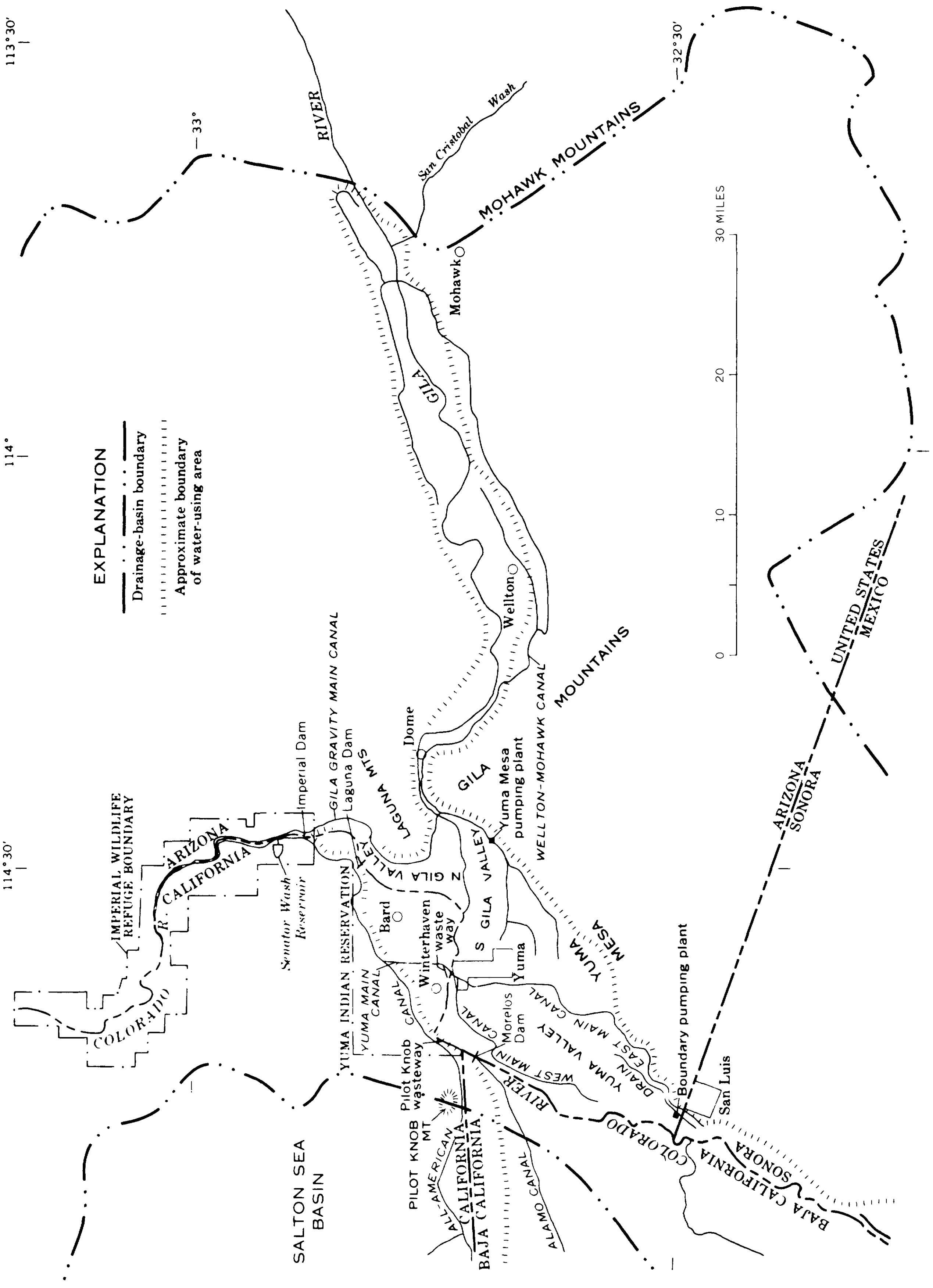

FIGURE 11.—Principal features of the Wellton-Mohawk and Yuma areas.

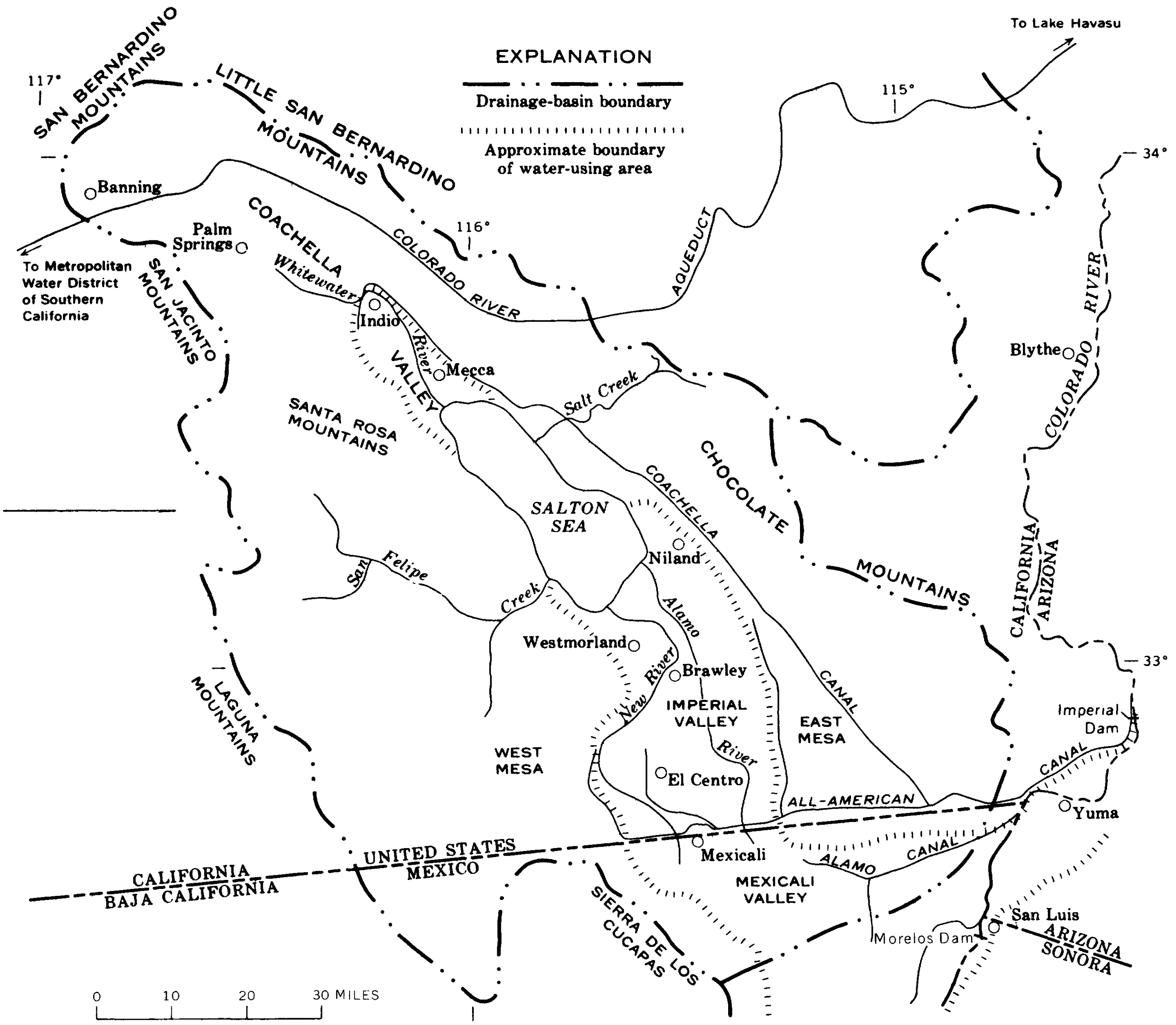

FIGURE 12.—Principal features of the Salton Sea area and vicinity.

water diverted for use in Mexico is quite variable, but almost all of it has higher dissolved-solids content than the water at Imperial Dam.

Pumping of ground water from large-capacity wells drilled to control water levels in a water-logged strip on the east side of Yuma Valley began in 1955 and steadily increased thereafter. Pumping from drainage wells was extended later to the South Gila Valley and the Wellton-Mohawk area. Salinity, however, did not become very troublesome until the summer of 1961, when pumping was greatly increased in the Wellton-Mohawk area; there, more than 60 wells were pumped into a newly constructed wastewater conveyance channel that extended nearly to the mouth of the Gila River. The increased pumping of saline water resulted in a large and abrupt increase in the salinity of the Colorado River water used for public supply in Yuma, Ariz., and for irrigation and public supply in Mexico. The water company supplying the city of Yuma temporarily abandoned its intake in the Colorado River and obtained water diverted at Imperial Dam. Most Mexican water users had no alternative source of public supply, and their principal source of irrigation water was affected. Consequently, control of the salinity of Colorado River water flowing to Mexico became, and has remained (to 1969), a subject of international negotiations.

Among steps taken to control salinity of water at Morelos Dam were controlled releases of water at Imperial Dam to provide better dilution, temporary cessation of pumping from some of the more saline wells in the Wellton-Mohawk area, drilling of additional wells in areas where salinity was lower so that salinity of pumped water could be controlled somewhat, and construction of additional drainage works. By the early part of 1966, substantial control of the saline drainage had been achieved by these methods and by construction of a concrete-lined extension of the conveyance channel to a point below Morelos Dam, with provision for release of water either above or below the dam. The total number of drain wells in the Wellton-Mohawk area was then about 100.

Because of the constantly increasing pumping of saline ground water for drainage and the construction and operation of new drain channels, the chemical regimen of the Colorado River changed so much during 1961–65 that averages for the period are not particularly relevent to present or future conditions. Hence, the chemical regimen of the lower river is described for the single year 1966 rather than the 5-year period 1961–65 used to describe the river's regimen upstream from Imperial Dam.

Chemical analyses representatives of surface-water quality at representative sites on rivers, drains, and wasteways in the Yuma and Wellton-Mohawk areas during 1966 are given in table 14. (Many of the smaller drains and wasteways are not shown in figure 11, but the areas in which they are situated are indicated. Exact locations are given in the water-supply papers of the U.S. Geological Survey and state reports in which the discharge records are published.) The table includes weighted-average concentrations, arithmetic averages, and selected analyses, depending upon the basic data available. To show progressive changes, the analyses for the Colorado River, the Gila River, and the Wellton-Mohawk Conveyance Channel are given in downstream order. The analyses of samples from other channels are grouped geographically.

The large number of surface drainage and waste channels emptying into the Colorado River below Imperial Dam and the Gila River complicates appraisal of surface-water quality. Discharge records are published for 28 distinct channels discharging to the rivers, as well as for river discharges at several points. Some of the drain channels have been sampled sufficiently for good generalizations about water-quality variation; others have not. River discharges have not been regularly determined at the junction of the Colorado and Gila Rivers, although daily sampling has been conducted on both rivers just above the junction. Therefore, because of the absence or paucity of data, the ensuing salinity appraisal is in part conjectural. Some of the smaller waste and drain channels are assumed to have patterns of water-quality variation similar to patterns in other nearby drains, and averages of the daily analyses for the Colorado and Gila Rivers at their

TABLE 14.—*Representative analyses, in milligrams per liter, of surface water in Colorado River Basin at and below Imperial Dam, 1966 water year*

No.	Source	Date (*weighted average; **arithmetic average)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Dissolved solids (sum)	Specific conductance (micromhos at 25°C)
1.	Colorado River at Imperial Dam	1966*	9	100	34	143		170	340	146	857	1,410
2.	Colorado River above Gila River	1966**	12	106	40	197		208	388	202	1,050	1,700
3.	Colorado River at north international boundary	1966*	10	125	47	254		203	396	339	1,270	2,140
4.	Colorado River at south international boundary	1966*	20	223	91	737		243	725	1,120	3,040	4,810
5.	Gila River above Wellton-Mohawk area	1966*	16	68	21	171		160	115	267	738	1,380
6.	Gila River at Dome	1966*	11	86	29	244		176	183	375	1,020	1,770
7.	Gila River at mouth	1966**	21	174	77	518		292	500	792	2,230	3,710
8.	Wellton-Mohawk Conveyance Channel (total)	1966*	25	325	148	1,140		339	925	1,890	4,620	7,570
9.	Wastegate discharge, Mode 1	1966*	25	298	135	995		347	875	1,610	4,110	6,610
10.	Wastegate discharge, Mode 2	1966*	25	325	148	1,120		352	925	1,850	4,570	7,420
11.	Wastegate discharge, Mode 3	1966*	24	345	143	1,250		320	975	2,050	4,950	7,950
12.	North Gila, Drain 1	May 13, 1966	21	130	52	306		292	525	298	1,480	2,430
13.	North Gila Bruce Church Drain	June 17, 1966	30	183	64	261		408	575	252	1,570	2,330
14.	South Gila pump outlet channel 3	Mar. 29, 1966	22	234	116	720		348	500	1,290	3,060	5,040
15.	South Gila pump outlet channel 2	Feb. 22, 1966	19	190	84	540		240	475	925	2,350	4,100
16.	South Gila pump outlet channel 1	May 13, 1966	23	162	60	478		296	475	675	2,020	3,530
17.	South Gila pump outlet channel 4	Nov. 26, 1965	23	338	150	905		328	575	1,860	3,960	6,790
18.	Reservation Main Drain 4	June 16, 1966	21	127	54	204		280	412	230	1,190	1,890
19.	East Main Canal, at international boundary	June 13, 1966	20	111	42	272		204	300	398	1,240	2,160
20.	Yuma Main Drain at boundary pumping plant	June 13, 1966	22	158	60	348		300	525	428	1,690	2,750

confluence are assumed to represent discharges computed by summation of measured inflows in several upstream channels.

Some of the analyses in table 14 are probably not very representative of concentrations occurring after 1966, whereas others may reflect later conditions rather well. Thus, Colorado River water at Imperial Dam (item 1) is quite like the later weighted-average analyses in table 6 (which summarized water quality at Imperial Dam for 25 years) and is probably not greatly different from weighted averages which may be computed for this station in the next few years. In contrast, the Colorado River at the south international boundary (item 4) represents a particular pattern of flows below Morelos Dam which is unlikely to be repeated. The analysis for the Colorado River above the Gila River (item 2) reflects the effects of evapotranspiration from phreatophytic vegetation and some irrigation return flow on the relatively small release from Imperial Dam. This analysis also is similar to many analyses of Colorado River water collected at Yuma prior to the beginning of substantial pumping of drainage wells. The analysis for the Colorado River at the north international boundary (item 3) reflects the effort to control salinity by selective pumping of drainage wells.

The analyses listed for the Gila River also are probably unrepresentative for future concentrations. During the winter of 1965–66, floods in the Salt River basin above Phoenix resulted in storage of about 200,000 acre-feet of low-salinity water in the Painted Rock reservoir on the Gila River, about 100 miles east of Yuma. This was the first water stored in the reservoir since the dam was completed in 1959. The flood water was released slowly over several months, and much of it was dissipated in the dry river channel below the dam. At least 30,000 acre-feet of the low-salinity water, however, passed the Gila River gaging station at Dome, Ariz., near the dividing point between the Wellton-Mohawk and Yuma areas. Analyses of samples taken at Dome and upstream from the Wellton-Mohawk area were used to compute the yearly concentrations given as items 5 and 6 in table 14. The salinity of the water passing Dome was somewhat higher than that above the Wellton-Mohawk area because of small irrigation return flows draining into the river in the area.

The flow of the Gila River at its mouth (item 7, table 14) includes the flood water passing Dome, the normal drainage from irrigation entering the river between Dome and its mouth, and an unusual increment of Wellton-Mohawk drainage pumped into and released from the Wellton-Mohawk Conveyance Channel through the gate known as Mode 1. This release was required by construction activities, and it is unlikely that as much water will be released into the Gila River through this gate during future years as during 1966. Flow in the Gila River at its mouth included water discharged from three concrete-lined drainage channels in the South Gila Valley which carry only ground water pumped from drainage wells. One of the channels became operative in 1966 and therefore probably delivered somewhat less water to the river than will be usual in future.

The conveyance channel is now (1969) the main drainage discharge for the Wellton-Mohawk area, although some seepage flows resulting from irrigation still move down parts of the Gila River channel. The weighted-average concentration of all flow in the conveyance channel during 1966 is given by item 8 in table 14. The corresponding dissolved-solids concentration of water released into the Gila River through the upper gate is given as wastegate discharge, Mode 1 (item 9). Water released into the Colorado River above Morelos Dam is given as wastegate discharge, Mode 2 (item 10). Water bypassing Morelos Dam and released below it is given as wastegate discharge, Mode 3 (item 11). Although the dissolved-solids concentration of the Wellton-Mohawk drainage was always much greater than that of the Colorado River, comparison of the various weighted averages indicates that there were significant differences in the average concentrations at the various sampling points. The concentration of water pumped from the drainage wells in the Wellton-Mohawk area differs from well to well. The planned operation is for future pumping to be conducted so that the more concentrated waters will be pumped when there is the most dilution water available at Morelos Dam. Thus, the variations in weighted-average concentrations in the conveyance channel noted for 1966 may not be very representative of the concentrations for future years.

Chemical analyses selected to represent the quality of water in smaller drain channels in the Yuma area are given by items 12–20, table 14. They illustrate the considerable variability of water flowing into the Colorado and Gila Rivers or passing across the Mexican boundary. Items 12 and 13 are drain waters from the North Gila Valley, an area not affected by pumping from drain wells. They indicate only moderately altered Colorado River water. Items 14–17 are representative of ground waters pumped from drainage wells screened in the coarse gravel zone in the South Gila Valley. The sampling records show that water quality in these channels differs from time to time, depending upon which wells are being pumped. Each channel, however, has developed a consistent pattern of chemical characteristics. All these channels, like the Wellton-Mohawk Conveyance Channel, carry water in which the chloride concentration consistently exceeds the sulfate concentration.

The chemical characteristics of water in the Reservation Main Drain (item 18) are similar to those of the drains in the North Gila Valley. The water in the East Main Canal at the boundary (item 19) reflects the pumping of two or three drain wells into the residual canal flow. Some drain well water also is discharged into the Yuma Main Drain. The normal flow in this drain, however, is so large compared with the pumpage from wells that its chemical characteristics (item 20) are more similar to those of the drain water from the North Gila.

IONIC BUDGETS FOR THE COLORADO RIVER BELOW IMPERIAL DAM AND GILA RIVER

An ionic budget for the Colorado River from Imperial Dam to the south international boundary, computed for the single year 1966 from the chemical analyses summarized in table 14, is given in table 15. This budget is based on the assumption that the chemical analyses of water from the Yuma Main Canal are representative of water in all the main canal wasteways discharging unused water to the rivers. The monthly Yuma Main Canal analyses, however, were weighted according to the corresponding monthly flows discharged at budgeted points on the canals.

The budget in table 15 is comparable with the ionic budget for the Colorado River from Lees Ferry to Imperial Dam (table 12) except that it represents average annual loads for the year 1966 only. It shows great depletions of river flows and mineral loads resulting from diversions at Imperial Dam, numerous gains from there to Morelos Dam, diversions at Morelos Dam, and the quantities in the river at the south international boundary where the Colorado River leaves the United States.

A separate ionic budget for the Gila River from above the Wellton-Mohawk area to the river's mouth for 1966 is given in table 16. As indicated by this budget the Gila River was a losing stream above Dome gaging station during 1966 and a gaining

TABLE 15.—*Streamflow ionic budget of the Colorado River, Imperial Dam to south international boundary, 1966*

[Streamflow in acre-feet; ionic gains (+) and losses (−) in thousands of tons-equivalent]

No.	Source	Streamflow	Cations			Total cations or anions	Anions		
			Ca	Mg	Na + K		HCO_3	SO_4	Cl + NO_3
1.	Colorado River above Imperial Dam	5,777,700	39.20	21.92	48.87	109.99	21.92	55.70	32.37
2.	Diversion to All-American Canal	−4,601,000	−31.23	−17.55	−38.76	−87.54	−17.46	−44.34	−25.74
3.	Diversion to Gila Gravity Main Canal	−855,700	−5.81	−3.15	−7.29	−16.25	−3.22	−8.27	−4.76
4.	Colorado River below Imperial Dam	321,000	2.16	1.22	2.82	6.20	1.24	3.09	1.87
5.	Canal wastes from North Gila Valley	6,200	.04	.02	.05	.11	.02	.06	.03
6.	North Gila Drain 1	7,100	.06	.04	.13	.23	.05	.10	.08
7.	Miscellaneous inflow above Gila River	+4,700	+.18	+.24	+.96	+1.38	+.26	+.47	+.65
8.	Colorado River above Gila River	339,000	2.44	1.52	3.96	7.92	1.57	3.72	2.63
9.	Gila River at mouth	141,000	1.66	1.21	4.33	7.20	.92	1.99	4.29
10.	South Gila pump outlet channel 4	5,600	.13	.09	.30	.52	.04	.08	.40
11.	Reservation Main drain 4	38,700	.33	.23	.47	1.03	.24	.45	.34
12.	Yuma Main Canal wasteway	106,400	.72	.41	.95	2.08	.42	1.04	.62
13.	Miscellaneous inflow, Gila River to wasteway	+5,900	+.04	+.03	+.05	+.12	+.03	+.05	+.04
14.	Colorado River below Yuma Main Canal wasteway	636,600	5.32	3.49	10.06	18.87	3.22	7.33	8.32
15.	Pilot Knob wasteway	752,700	5.11	2.86	6.28	14.25	2.86	7.16	4.23
16.	Wellton-Mohawk Conveyance Channel wastegate, Mode 2	95,000	2.10	1.57	6.30	9.97	.74	2.49	6.74
17.	Miscellaneous inflow below Yuma Main Canel wasteway	+26,700	+.27	+.01	+.05	+.33	+.02	−.05	+.36
18.	Colorado River at north international boundary	1,511,000	12.80	7.93	22.69	43.42	6.84	16.93	19.65
19.	Diversion at Morelos Dam to Alamo Canal	−1,411,000	−11.88	−7.41	−20.93	−40.22	−6.34	−15.81	−18.07
20.	Colorado River below Morelos Dam	100,000	.92	.52	1.76	3.20	.50	1.12	1.58
21.	Wellton-Mohawk Conveyance Channel wastegate, Mode 3	74,400	1.74	1.19	5.50	8.43	.53	2.05	5.85
22.	Wasteway discharges from Yuma Valley below Morelos Dam	7,200	.05	.03	.06	.14	.03	.07	.04
23.	Loss by seepage below Morelos Dam	−31,800	−.44	−.22	−.80	−1.46	−.25	−.17	−1.04
24.	Colorado River at south international boundary	149,800	2.27	1.52	6.52	10.31	.81	3.70	6.43

TABLE 16.—*Streamflow and ionic burden of the lower Gila River, Wellton-Mohawk area to mouth, 1966*

[Streamflow in acre-feet; loads in thousands of tons-equivalent]

No.	Source	Streamflow	Cations			Total cations or anions	Anions		
			Ca	Mg	Na + K		HCO_3	SO_4	$Cl + NO_3$
1.	Gila River above Wellton-Mohawk area	99,500	0.46	0.23	1.00	1.69	0.35	0.32	1.02
2.	Seepage loss in Wellton Mohawk area	−60,300	−.23	−.10	−.44	−.77	−.20	−.12	−.45
3.	Gila River at Dome	39,200	.23	.13	.56	.92	.15	.20	.57
4.	Canal wastes from North Gila Valley	8,600	.06	.03	.07	.16	.03	.09	.04
5.	Drains from North Gila Valley	1,300	.01	.01	.02	.04	.01	.02	.01
6.	South Gila pump outlet channel 3	13,100	.21	.17	.55	.93	.10	.18	.65
7.	South Gila pump outlet channel 2	19,200	.25	.18	.61	1.04	.10	.26	.68
8.	Wellton-Mohawk Conveyance Channel wastegate, Mode 1	30,300	.61	.46	1.78	2.85	.23	.75	1.87
9.	South Gila pump outlet channel 1	29,100	.32	.20	.81	1.33	.19	.39	.75
10.	Gila River at mouth (by summation, items 3–9)	140,800	1.69	1.18	4.40	7.27	.81	1.89	4.57
11.	Gila River at mouth (by weighting periodic analyses)	141,000	1.66	1.21	4.33	7.20	.92	1.99	4.29

stream from Dome to its mouth. Because of unusually high flow in the Gila River above the budget area, the 1966 mineral load passing Dome is not likely to happen again except during periods of exceptional rainfall. In the Gila River budget, the sums of the increments of streamflow and ionic loads (item 10) computed for all entering flows (items 3–9) are compared with quantities computed from the chemical-quality record obtained from sampling at its mouth (item 11). The close agreement between the two differently computed loads strengthens confidence in the assumptions used in budgeting.

The largest ionic increments added to the Gila River loads during 1966 entered the river in water released from the Wellton-Mohawk Conveyance Channel through the Mode 1 gate. As this gate is not planned for use in the future, except during short periods, the future additions to Gila River ionic loads from this source are likely to be negligible. If this is true, there may be some decrease in salinity of water at the Colorado River intake for the Yuma water supply. Reduction of release through gate 1 is not likely to have any effect on the salinity of Colorado River water at Morelos Dam because water previously released through gate 1 generally will be released through gate 2 above the dam.

The complex pattern of surface diversions and return flows in this part of the lower Colorado River service area obscures the effects of the distribution and use of the river water. By selecting and rearranging items in the two budgets, however, some clarification of the ways that water developments have affected stream water quality is achieved. Thus, an inflow-outflow analysis (table 17) combining changes in areas in the Colorado River basin downstream from Imperial Dam receiving Colorado River water simplifies budget understanding. In this analysis the quantities of water and mineral ions arriving at Imperial Dam are reduced by the quantities going out of the Colorado River basin in the All-American Canal. To these adjusted quantities are added the quantities of water and mineral ions in the Gila River as it enters the Wellton-Mohawk area. The sum is a statement of the combined water and mineral supply for the United States and Mexican parts of the service area. The five outflows to Mexico are then added to give the total surface flows and ionic loads entering Mexico. The differences between the outflows to Mexico and the combination water supply constitute a statement of the draft on surface water and concurrent mineral regimen in the combined Wellton-Mohawk and Yuma areas. Negative quantities represent water use, increase of ground-water storage, and mineral deposition or storage; positive quantities represent mineral removal from the combined areas.

Obviously the net water depletion and ionic gains and losses determined according to the summary at the end of table 17 were not uniformly distributed in the irrigated areas receiving Colorado River water. By (1) computing seepage losses in the large water-supply canals and in the unlined section of the Wellton-Mohawk Conveyance Channel; (2) computing the gains or losses of water and dissolved minerals diverted to and removed from the individual irrigated sections; and (3) considering unmeasured increases in flow of the Colorado River and their mineral increments, it is possible to distribute the gains and losses as shown in table 18.

The distribution of ionic gains and losses in table 18 is related to both present and past irrigation and drainage patterns. Part of the gains in the Colorado

TABLE 17.—*Streamflow and ionic burden of inflow and outflow for combined Wellton-Mohawk and Yuma areas, 1966*
[Streamflow in acre-feet; ionic loads in thousands of tons-equivalent]

No.	Measuring point or description	Streamflow	Cations			Total cations or anions	Anions		
			Ca	Mg	Na + K		HCO_3	SO_4	$Cl + NO_3$
	Available supply of surface water and mineral ions								
1.	Colorado River at Imperial Dam	5,777,700	39.20	21.92	48.87	109.99	21.92	55.70	32.37
2.	All-American Canal below Pilot Knob (loss)	−3,299,000	−22.39	−12.52	−27.90	−62.81	−12.52	−31.81	−18.48
3.	Net supply from Colorado River	2,478,700	16.81	9.40	20.97	47.18	9.40	23.89	13.89
4.	Gila River flow into Wellton-Mohawk area	99,500	.46	.23	1.00	1.69	.35	.32	1.02
	Total surface water supply and contained minerals	2,578,200	17.27	9.63	21.97	48.87	9.75	24.21	14.91
	Outflows in surface channels								
5.	Colorado River at north international boundary	1,511,000	12.80	7.93	22.69	43.42	6.84	16.93	19.65
6.	Wellton-Mohawk drainage discharge below Morelos Dam through Mode 3	74.400	1.74	1.19	5.50	8.43	.53	2.05	5.85
7.	Three wasteways from Yuma Valley entering river below Morelos Dam	7,200	.05	.03	.06	.14	.03	.07	.04
8.	East Main Canal wasteway discharge across international boundary	5,000	.04	.02	.08	.14	.02	.04	.08
9.	Yuma Main Drain discharge at boundary pumping plant	123,400	1.32	.83	2.53	4.68	.83	1.83	2.02
	Total surface outflow and contained minerals	1,721,000	15.95	10.00	30.86	56.81	8.25	20.92	27.64
	Areal change								
10.	Outflow–inflow (plus (+) = gain; minus (−) = loss)	−857,200	−1.32	+.37	+8.89	+7.94	−1.50	−3.29	+12.73

River undoubtedly resulted from seepage from the parallel sections of the Gila Gravity and All-American Canals. Induced seepage of Colorado River water probably also occurs in the areas adjacent to the river which are irrigated by pumped ground water. Thus, ground-water pumpage in the Island, an area within a former river meander not served by surface-water canals, may account for the apparent mineral retention in the Bard-Winterhaven and North Gila Valleys. Mineral removal is indicated for the Wellton-Mohawk and South Gila Valleys, the two areas showing minimum surface drainage, a long history of former ground-water irrigation, and present drainage from wells. The seepage loss from the Wellton-Mohawk Conveyance Channel probably moved towards the drainage wells in the South Gila Valley. Irrigation of the undrained Yuma mesa also accounts for movement of water to the South Gila Valley, the only area from which more water was pumped than was applied for irrigation.

The relatively large removal of minerals from the South Gila Valley and Wellton-Mohawk area cannot be expected to continue at the present rate indefinitely, and it is probable that the outflow of minerals from these areas will slowly decline.

QUALITY OF SURFACE WATER IN THE SALTON SEA BASIN IN CALIFORNIA

The Imperial Valley and part of the Coachella Valley in California depend almost entirely on water diverted to them from the Colorado River through the All-American Canal and its branches. Water in the distributary canals in the two valleys has been found by sampling surveys to have practically the same salinity as the Colorado River water diverted at Imperial Dam. Hence, so long as the quality of diverted water is suitable for irrigation and enough is applied to prevent accumulation of salts in the soil, salinity problems in the two valleys will be limited to those resulting from application of river water to naturally saline soils or soils made saline by artificially high water tables that cause concentration of salts in the capillary fringe.

The natural saline-mineral content of soils and subsoils in parts of both the Imperial and Coachella Valleys was high before irrigation began. Soils in some areas were too saline for successful irrigation

TABLE 18.—*Distribution of surface-water and dissolved-mineral gains (+) and losses (−) for combined Wellton-Mohawk and Yuma areas, 1966*

[Streamflow in acre-feet; dissolved minerals in thousands of tons-equivalent]

No.	Channel reach or geographic area	Streamflow	Cations			Total cations or anions	Anions		
			Ca	Mg	Na + K		HCO_3	SO_4	Cl + NO_3
1.	Gila Gravity Canal leakage, Imperial Dam to Mesa pumping plant	−45,200	−0.32	−0.16	−0.40	−0.88	−0.17	−0.42	−0.29
2.	North Gila Valley	−41,800	−.27	−.14	−.28	−.69	−.13	−.36	−.20
3.	Wellton-Mohawk area	−305,900	+1.31	+1.69	+9.86	+12.86	−.33	+.95	+12.24
4.	Wellton-Mohawk Conveyance Channel, Gila siphon to Morelos Dam	−10,000	−.18	−.25	−.59	−1.02	−.09	−.19	−.74
5.	South Gila Valley	+44,600	+.72	+.59	+2.00	+3.31	+.46	+.80	+2.05
6.	Yuma Mesa	−267,600	−1.80	−.99	−2.27	−5.06	−1.01	−2.60	−1.45
7.	All-American Canal leakage, Imperial Dam to below Pilot Knob wasteway	−47,600	−.33	−.28	−.32	−.93	−.18	−.53	−.22
8.	Yuma Main Canal leakage, from turnout to siphon	−2,200	−.01	−.01	−.02	−.04	−.01	−.02	−.01
9.	Bard-Winterhaven Valley	−47,600	−.25	−.09	−.26	−.60	−.08	−.38	−.14
10.	Yuma Valley	−171,200	−.68	−.27	+.11	−.84	−.27	−1.01	+.44
11.	Unmeasured inflow to Colorado River from Imperial Dam to Morelos Dam. (Sum lines 7, 13, 17, table 15.)	+37,300	+.49	+.28	+1.06	+1.83	+.31	+.47	+1.05
12.	Total of gains and losses	−857,200	−1.32	+.37	+8.89	+7.94	−1.50	−3.29	+12.73

until they were leached. Early irrigation, particularly in the Imperial Valley, was mostly carried on without any provision for drainage except that which occurred through natural channels. As the farmland was all nearly level and had little natural drainage, some waterlogging soon occurred, and consequently the acreage of saline soils began to increase. Constructions of drainage systems to remedy the situation in the Imperial Valley began about 1925. Drainage systems have since been expanded to cover most of the irrigated portions of both valleys. Although considerable salt was dissolved from its bed, much of the salt content of the Salton Sea (Hely and others, 1966) is believed to have originated from minerals leached from the irrigated soils of the two valleys, and a lesser amount was derived from the water diverted from the Colorado River.

The Imperial Irrigation District has long been concerned about salt accumulation in Imperial Valley. The present quantity of drainage from the valley is about 1¼ million acre-feet per year. The district for many years has obtained approximately monthly analyses of water samples collected from the Alamo and New Rivers at the Mexican border and near their mouths, and also occasional analyses of samples from some of the 30 or more artificial drain channels which flow directly into the Salton Sea. Since 1943 the Imperial Irrigation District has computed annual mineral budgets by using its analyses and averages representing the monthly composition of All-American Canal water. According to the district's computations, mineral salts accumulated in the valley through 1948, but since then the quantities of dissolved mineral salts leaving the valley in drain water have exceeded the quantities entering the canal water.

The salinity of water flowing into the Salton Sea from the Alamo and New Rivers varies depending on the proportions of canal water and drainage water in each of the rivers. A very small part of the flow in the Alamo River and a much larger part of the flow in the New River is drain water from the irrigated part of the Salton Sea basin in Mexico, generally referred to as the Mexicali Valley. Some of each river's flow is canal water spilled into the river or a drain, some is wastewater diverted from the lower ends of flooded fields following irrigation, and some is seepage entering the drains from fields. As the relative quantities continually change, the salinity of the two rivers fluctuates rather erratically and without much relation to season. The New River water, however, is almost always considerably more saline than the Alamo River water.

Partial chemical analyses of monthly samples obtained from Alamo and New Rivers and analyses of less frequent samples obtained from selected drains in the valley during 1961–65 indicate that it would not be possible to define a mineral budget for the Imperial Valley without much more frequent sampling and more complete chemical analyses. Consequently, a mineral budget for the Imperial Valley is not included in this report.

Coachella Valley, unlike Imperial Valley, is underlain by productive aquifers containing water of relatively low salinity. In 1948, when importation of Colorado River water to Coachella Valley began, about 20,000 acres were being irrigated by pumping from wells, and extensive lowering of the ground-water levels had occurred. As Colorado River water became available and irrigated acreage expanded greatly, river water replaced much of the ground water previously used for irrigation, and thereafter ground-water levels in irrigated areas began to rise. Recently, about 60,000 acres in the valley have been irrigated with Colorado River water. Some of the water brought in by canal may still be going into ground-water storage, but in most of the irrigated area water levels have risen until surface drain channels now flow continuously.

The Whitewater River channel is the major natural drainage for the Coachella Valley. Prior to the importation of Colorado River water, the Whitewater River channel was dry most of the time, but during recent years the river has had perennial flow averaging a little more than 100 cubic feet per second. In addition to the river, there are 20 artificial channels, some of which flow continuously and some intermittently, that empty directly into the Salton Sea. About 60 percent of the drainage from Coachella Valley enters the sea through Whitewater River.

Approximately monthly samples of water from the Whitewater River water were analyzed at Yuma during 1962–65. Unfortunately the drains were not systematically sampled at that time, and only a few partial analyses of the drain water were made. Although the limited data suggest that the water in the drains is similar to that in the river, a reliable ionic budget for the Coachella Valley cannot be computed from the chemical data. Rough computations for 1962 and 1963, however, suggest that more chloride left the valley than entered in the canal water and that the quantities of sulfate entering and leaving were nearly equal.

There is no perennial flow from nonirrigated areas into the Salton Sea, except for seepage from Coachella Canal that enters via Salt Creek. Both Salt Creek, which enters the sea on the northeast side, and San Felipe Creek, which enters it on the southwest side, drain large areas and sometimes for a few hours discharge large volumes of water that is low in mineral content. This water, however, is not much of an asset because there is no practical way of using it before it enters the sea.

Analyses of water samples collected by the Geological Survey from the Alamo, New, and Whitewater Rivers selected to be representative of high and low concentrations regularly observed are given in table 19. Although the analyses do not represent maximums and minimums they are probably within about 20–25 percent of usual annual extremes. Each pair of analyses is a general measure of the salinity characteristics of the sampled river at the point of sampling.

Each river discharging to the Salton Sea has its own characteristic salinity pattern. Thus, the Alamo River water characteristically contains more sulfate than chloride at the Mexican boundary, and the relative proportion of chloride to sulfate increases towards its mouth. The water flowing from Mexico in the New River is always high in chloride relative to sulfate, and although the proportion of chloride to sulfate decreases downstream, the chloride remains dominant to the river's mouth. The Whitewater River water generally contains about twice as much sulfate as chloride. Sodium is the principal cation in the water in all three rivers. The analytical records suggest that some salvage of less-saline inflows to the Alamo and Whitewater Rivers might be practicable but that New River water has a much smaller salvage poten-

TABLE 19.—*Selected chemical analyses of surface water in the Salton Sea basin*

[Results in milligrams per liter unless otherwise indicated]

No.	Source	Date	Discharge (Cfs)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Dissolved solids (sum)	Specific conductance (micromhos at 25°C)
1.	Alamo River at international boundary	Feb. 5, 1962	2.0	13	199	108	611		311	1,000	690	2,490	4,150
2.	Alamo River at international boundary	May 2, 1962	4.2	14	172	76	380		288	675	455	1,910	3,200
3.	Alamo River near Niland	Dec. 30, 1964	639	13	250	160	726		254	975	1,160	3,410	5,530
4.	Alamo River near Niland	Mar. 26, 1965	786	10	230	108	550		224	825	833	2,670	4,180
5.	New River at international boundary	Jan. 12, 1965	124	25	284	93	1,580		260	675	2,560	5,350	9,000
6.	New River at international boundary	June 15, 1965	122	22	266	126	1,330		240	750	2,190	4,800	7,940
7.	New River near Westmoreland	Dec. 30, 1964	386	20	250	123	1,120		268	850	1,750	4,250	7,010
8.	New River near Westmoreland	Mar. 26, 1965	543	14	238	108	827		256	750	1,310	3,380	5,430
9.	Whitewater River near Mecca	Nov. 17, 1964	82	18	166	51	600		336	950	472	2,420	3,670
10.	Whitewater River near Mecca	June 7, 1965	139	18	170	44	530		336	825	435	2,190	3,410

tial. Salvage of water from Alamo or New Rivers would be chiefly a matter of recovering spilled canal water or reducing the amount of spill. Hence, quality of water already in the river may be unimportant for salvage operations. Moreover, any water-salvage operations would tend to reduce inflow to the Salton Sea and result in reduction, or perhaps early loss, of its recreational value because of increased salinity.

Such adverse effects might, however, be counteracted by proposed regulation of the volume and salinity of the sea.

SUMMARY OF CONCLUSIONS

The study of the chemical regimen of the lower Colorado River warrants the following general conclusions:

1. Under natural (virgin) conditions both the composition and concentration of water in the Colorado River below Lees Ferry, Ariz., varied both seasonally and annually, but probably did not substantially change downstream.
2. During the period 1926–62 (prior to closure of Glen Canyon Dam), the chemical regimen of the Colorado River at Grand Canyon and upstream, although probably somewhat different from the virgin regimen, was relatively stable. There may, however, have been small increases in average mineral concentrations, particularly towards the end of the period, caused by construction of reservoirs, increased irrigation, and increased out-of-basin diversions in headwater areas.
3. Most of the mineral burden of the Colorado River, like most of its flow, originates in the Upper Basin.
4. Blue Springs, near the mouth of the Little Colorado River, add the largest individual increment to the mineral burden of the Colorado River below compact point and above Imperial Dam. This increment, which is nearly constant because of the constancy of spring flow, consists mainly of sodium chloride (common salt).
5. Virgin River, although its annual flow is highly variable, generally contributes the second largest increment to the mineral burden between compact point and Imperial Dam. This variable increment consists mainly of gypsum (calcium sulfate), but includes a considerable amount of common salt.
6. The other tributaries between compact point and Imperial Dam add only minor increments to the Colorado River's mineral burden.
7. The natural fluctuations in the dissolved-mineral concentrations in the Colorado River water have been greatly reduced as a result of construction of storage reservoirs in which floodflows and low flows mix, but they have not been eliminated.
8. Average concentrations of dissolved minerals in Colorado River water downstream from Lake Mead have been increased as a result of evaporation from the lake surface and solution from its bed, but these increases have been partly offset by precipitation of calcium carbonate in the body of the lake.
9. The amount of solution from the bed of Lake Mead appears to be slowly decreasing.
10. There is no evidence of appreciable solution of minerals from beds of Lakes Mohave and Havasu.
11. The effects of the recently constructed storage reservoirs above compact point on salinity of water below that point are still uncertain, but it appears likely that the mineral concentrations in the lower river will become temporarily stabilized at somewhat lower levels than those which prevailed during 1965. Additional upstream storage and irrigation projects now proposed (1969), however, will tend to increase the mineral concentration when in operation.
12. Increasing yearly diversions of Colorado River water out of the basin through the Colorado River aqueduct have contributed to the recent increases in salinity of water at Imperial Dam by reducing the flow available to dilute the relatively saline irrigation return flows.
13. Leaching of newly cultivated lands in Parker and Palo Verde Valleys have also been principal causes of higher concentrations at Imperial Dam.
14. The salinity of water in the Colorado River at Imperial Dam has increased moderately in recent years, but it is still satisfactory for public supply and for continued irrigation if provision is made to prevent accumulation of salts in the soil.
15. The chemical characteristics of water in the Colorado River downstream from Imperial Dam and in the tributary Gila River below the Wellton-Mohawk area are erratically variable and depend upon the volumes and concentrations of irrigation return flows from many sources, including ground water pumped into drain channels to control water levels.

16. Mineral-budget computations indicate that harmful salt quantities are not now accumulating in the parts of the Colorado River basin in the United States served with Colorado River water.
17. Continued control of pumping of saline ground water will be necessary if the quality of Colorado River water diverted at Morelos Dam is to be maintained at or near its present level.
18. Under present irrigation and drainage arrangements probably no harmful salt quantities are accumulating in the parts of the Imperial and Coachella Valleys irrigated with Colorado River water.
19. Water-management practices to prevent unused canal water from entering streams draining to the Salton Sea might contribute to the available supply of water in the Imperial and Coachella Valleys. If the sea remains unregulated, however, any substantial reduction of flow to the sea would tend to reduce its volume, raise its salinity, and reduce its recreational value.

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