The Hydrologic History of the San Carlos Reservoir, Arizona, 1929-71, with Particular Reference to Evapotranspiration and Sedimentation

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The Hydrologic History of the San Carlos Reservoir, Arizona, 1929-71, with Particular Reference to Evapotranspiration and Sedimentation

By FRANK P. KIPPLE

GILA RIVER PHREATOPHYTE PROJECT

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CONVERSION FACTORS

English	*Multiply by*	*Metric (SI)*
acre-feet (acre-ft)	1.233×10^{-3}	cubic hectometers (hm^3)
miles (mi)	1.609	kilometers (km)
feet (ft)	.3048	meters (m)
cubic feet per second (ft^3/s)	2.832×10^{-2}	cubic meters per second (m^3/s)
acres	4.047×10^{-3}	square kilometers (km^2)
pounds per cubic feet (lb/ft^3)	16	kilograms per cubic meter (kg/m^3)
acre-feet per square mile (acre-ft/mi^2)	0.476×10^{-3}	cubic hectometers per square kilometer (hm^3/km^2)
gallons per day per square foot [(gal/day)/ft^2]	4.074×10^{-2}	cubic meters per day per square meter [(m^3/day)/m^2]
inches (in.)	25.4	millimeters (mm)
parts per million (ppm)	1.00[1]	milligrams per liter (mg/l)

LIST OF SYMBOLS

I_G	Gila River inflow at Calva
I_S	San Carlos River inflow at Peridot
I_T	Tributary inflow into the San Carlos Reservoir
O_G	Gila River outflow below Coolidge Dam
I_{GW}	Ground-water inflow
I_P	Precipitation input over the lake surface
O_E	Evaporation from the lake surface
O_{ET}	Evapotranspiration from the exposed surface of the reservoir
ΔS_R	Change in surface-water storage
ΔS_B	Change in bank storage
q	Ground-water flow
K	Hydraulic conductivity
m	Thickness of aquifer
u	Ground-water slope
w	Aquifer width
P	Rainfall
Q	Stream discharge
ΔS_T	Change in total reservoir storage
S	Weight of sediment discharge
C	Mean sediment concentration
S_i	Weight of sediment trapped by reservoir
E	Sediment trap efficiency of a reservoir
C_w	Mean winter sediment concentration
C_s	Mean summer sediment concentration
Q_w	Winter streamflow summations
Q_s	Summer streamflow summations
r	Ratio of summer to winter concentrations
S_y	Computed value proportional to weight of sediment deposited in a reservoir
i	Incremental storage reservoir
j	Water year
a	The ratio of the weight of larger sediment particles to the weight of total sediment
D_A	Distance estimated by simulation procedure from location of river discharge into the reservoir pool to the point where deposition is complete
D_B	Distance from any point along D_A to point where distribution of sediment is complete
x	Exponent of suspended sediment distribution
S_{s_B}	Computed amount proportional to weight of sediment deposited between point of inflow and any other downstream point

---

[1] See "Water Resources Data for Arizona, Part 2, Water Quality Records, 1973" for conversion factors when sediment concentration exceeds 8,000 ppm (factor varies depending on specific gravity of sediment and density of water).

D_{A_i}	Estimated distance from location of river discharge into incremental reservoir *i* to the point where deposition is complete
k	Incremental reservoir of deposition
D_{B_k}	Distance from upstream point of incremental reservoir *k*, in which simulated deposition is occurring, to the point where deposition is complete
S_{y_i}	A computed quantity which is proportional to total sediment weight entering an incremental reservoir from the stream
S_{s_i}	A computed quantity which is proportional to weight of suspended sediment inflow
S_{s_k}	A computed quantity which is proportional to weight of suspended sediment deposited in reservoir *k*
$S_{d_{k,j}}$	A computed quantity which is proportional to the suspended sediment weight deposited in reservoir *k* during water year *j*
S_{R_k}	A computed quantity which is proportional to the sediment weight deposited in an incremental reservoir during a period
S_R	The sum of all S_{R_k}
S_M	The volume of sediment measured
RATIO	A proportionality constant between sediment measured and sediment estimated
S_{e_k}	Estimate of the absolute sediment volume for incremental reservoir *k*
$Z_{k,j}$	The estimated decrease in storage for an incremental reservoir *k* from the start of a period to water year *j*

GILA RIVER PHREATOPHYTE PROJECT

THE HYDROLOGIC HISTORY OF THE SAN CARLOS RESERVOIR, ARIZONA, 1929-71, WITH PARTICULAR REFERENCE TO EVAPOTRANSPIRATION AND SEDIMENTATION

By FRANK P. KIPPLE

ABSTRACT

Reservoir data records were used in an investigation of evapotranspiration from the land area of San Carlos Reservoir and evaporation from the water-surface area. A water-budget analysis indicates that the evapotranspiration loss was 11.3 percent and the evaporation loss was 10.5 percent of the total outflow from the reservoir during 1931-71.

The water-budget computations were used to develop ratings relating lake stage to usable bank storage. The rating developed for the 1948-71 period indicates that usable bank storage is approximately 159,000 acre-ft (196 hm^3), or about 14 percent of total usable storage capacity, if the reservoir is filled to the spillway level of 2,511 ft (765 m).

A procedure was developed to simulate sediment deposition in the reservoir. The procedure was used to estimate the change in storage capacity between five reservoir capacity surveys made during the period 1914-66.

INTRODUCTION

PURPOSE AND SCOPE

Once a reservoir is put into operation, a number of progressive changes are produced which affect the hydrology of the reservoir. Prior to inundation, water vaporization from the reservoir area is from plant transpiration and from soils and off-channel ponding. During inundation vaporization is evaporation from the ponded water surface. The soils and topography are changed by the deposition of sediment and sometimes by bank erosion. The water table adjacent to the reservoir rises, and the bank storage of water is increased. Vegetation on exposed parts of the reservoir may be altered because of changes in soils and water availability. These changes are particularly significant for reservoirs where the streams convey large quantities of sediment and where fluctuations of the reservoir water level and the water surface areas are large. The records of inflow, outflow, surface-water storage, and sediment deposition provide the data for evaluating some of the changes for the San Carlos Reservoir.

An investigation of these changes, and of the reservoir hydrology in general, was made to evaluate reservoir evapotranspiration (*ET*) and the change in *ET* from 1929 to 1971. The investigation was made as part of the Gila River Phreatophyte Project, a study of the hydrologic effect of phreatophyte control by the U.S. Geological Survey (Culler and others, 1970). The evaluation of *ET* is made by use of a water-budget equation in which *ET* is the residual in the equation.

Secondary objectives included investigations of reservoir sediment deposition, lake evaporation, and reservoir bank storage. These investigations were essential prior to compilation of the water budget.

Data sources for this report include five surveys of reservoir capacity which provide a history of capacity change and sediment accumulation. Investigations of tributary runoff, precipitation, evapotranspiration, and lake evaporation were made as part of the Gila River Phreatophyte Project and furnish information for this report. Other sources of data are U.S. Geological Survey surface-water records (issued annually), Gila River Water Commissioner reports (issued annually), log books of precipitation and pan evaporation at Coolidge Dam, and climatic data published by the National Weather Service (issued annually).

ACKNOWLEDGMENTS

Much of the planning and data interpretation for this report was contributed by R. C. Culler, project chief of the Gila River Phreatophyte Project. Preparation of the report was under the direction of R. L. Hanson. Assistance and cooperation were received from personnel of the Arizona District office, U.S. Geological Survey, and of the San Carlos Project of the U.S. Bureau of Indian Affairs, supervised by H. D. Young, general engineer. Computations of lake

evaporation by energy-budget and mass-transfer methods were principally by J. Stuart Meyers, U.S. Geological Survey.

HISTORY OF THE SAN CARLOS PROJECT

The San Carlos Project was established to provide irrigation water to the Middle Gila District, Gila River Basin, Ariz. The district was defined by Davis (1897, p. 17) as "that portion from the mouth of Salt River to The Buttes above Florence and including the Pima Indian Reservation and the great Casa Grande Valley." Diversions of water from the upstream reaches of the Gila River by farmers during the period 1870-86 imperiled the water rights of the Indians on the Pima Reservation. An investigation was made by the Geological Survey to examine the possibility of providing a firm water supply to the Indians as reported by Davis (1897, p. 71). The construction of a dam on the Gila River at The Buttes 14 mi (23 km) east of Florence was recommended. Numerous other feasibility studies were made during the next 15 years, culminating in a report by the U.S. Army Corps of Engineers (1914) recommending a dam on the Gila River.

On June 7, 1924, Congress approved legislation that authorized the Secretary of the Interior through the Indian Service to construct a dam at the San Carlos site as part of the San Carlos Project. The construction of Coolidge Dam was started in January 1927 and completed in October 1928. Water impoundment began on November 15, 1928. The area within the boundary of the reservoir is administered, and the facilities at Coolidge Dam are operated, by the San Carlos Project, an agency of the Bureau of Indian Affairs.

Coolidge Dam is located in sec. 17, T. 3 S., R. 18 E., Gila County, Ariz., in the San Carlos Indian Reservation (fig. 1). The dam is a multidomed structure having a length, including two spillways, of 850 ft (259 m). Each of the three domes has a span of 180 ft (55 m) and a base thickness of 28 ft (8.5 m). The thickness decreases to 4 ft (1.2 m) at the top. The dam rises 203 ft (62 m) to the spillway at elevation 2,511 ft (765 m) above mean sea level and approximately an additional 25 ft (7.6 m) to the highway on top of the dam. A spillway is located on each side of the dam. Each spillway has three gates 50 ft (15 m) wide and 12 ft (3.7 m) high. Maximum storage capacity of 1,267,000 acre-ft (1,560 km^3) at elevation 2,523 ft (769 m) is reached when the gates are raised. The gates are now inoperative in the lowered position. The maximum safe release from spillways and outlets is 122,000 ft^3/s (3,455 m^3/s). The sill of the lowest outlet gate is at elevation 2,382.63 ft (726 m), providing an operating range, outlet to spillway, of 128.37 ft (39.13 m).

The principal purpose of the reservoir is to store water for irrigation of 100,000 acres (405 km^2) of land within the San Carlos Project. Fifty thousand acres (202 km^2) are Indian lands within the Gila River Reservation, and 50,000 acres (202 km^2) are privately owned lands in the Florence-Casa Grande Valley. Water released from Coolidge Dam is diverted from the Gila River channel at the Ashurst-Hayden Diversion Dam 68 mi (109 km) downstream. A power plant at Coolidge Dam contains two generators having a combined output of 10,000 kilovolt-amperes. Power generation is subordinate to irrigation requirements and is stopped when irrigation demands are curtailed. The reservoir is also used for recreation, and the recreational facilities are operated under lease by the San Carlos Apache Indian Tribe. Flood protection provided by the reservoir is an incidental benefit.

Water in the Gilla River was adjudicated by a court decree entered in 1935 (U.S. vs. Gila Valley Irrig. Dist. et al., 1935). Briefly, the decree divides the water between the upstream users in the Safford and Duncan Valleys, the Gila Valley Irrigation District, and the downstream users of the San Carlos Irrigation Project, on the basis of priority of appropriation. In addition to priority rights, upstream users are also entitled to apportioned rights, which are dependent on the amount of water stored in San Carlos Reservoir. As defined in the decree, the rights are determined as follows: On January 1 of each year, or as soon thereafter as there is water stored in the San Carlos Reservoir, which is available for release for use on lands of the San Carlos Project, the Gila Water Commissioner, who is appointed by the court to enforce the decree, shall apportion for the ensuing irrigation year to irrigated lands above the San Carlos Reservoir from the natural flow of the Gila River an amount of water equal to that stored in the San Carlos Reservoir less losses. It is also provided that if and when at any time, or from time to time, during the year storage in the reservoir shall be increased and made available to downstream users, the Commissioner shall make further and additional apportionments to upstream users which shall be equivalent in amount to the newly available stored water supply.

DEFINITIONS

The following are definitions of terms as used throughout this report:

Water year	October 1 to September 30
Surface-water storage capacity	The above-ground volume of a reservoir available to store water
Dead storage capacity, surface water	The above-ground volume of a reservoir below the invert of the lowest reservoir outlet, which cannot be evacuated by gravity

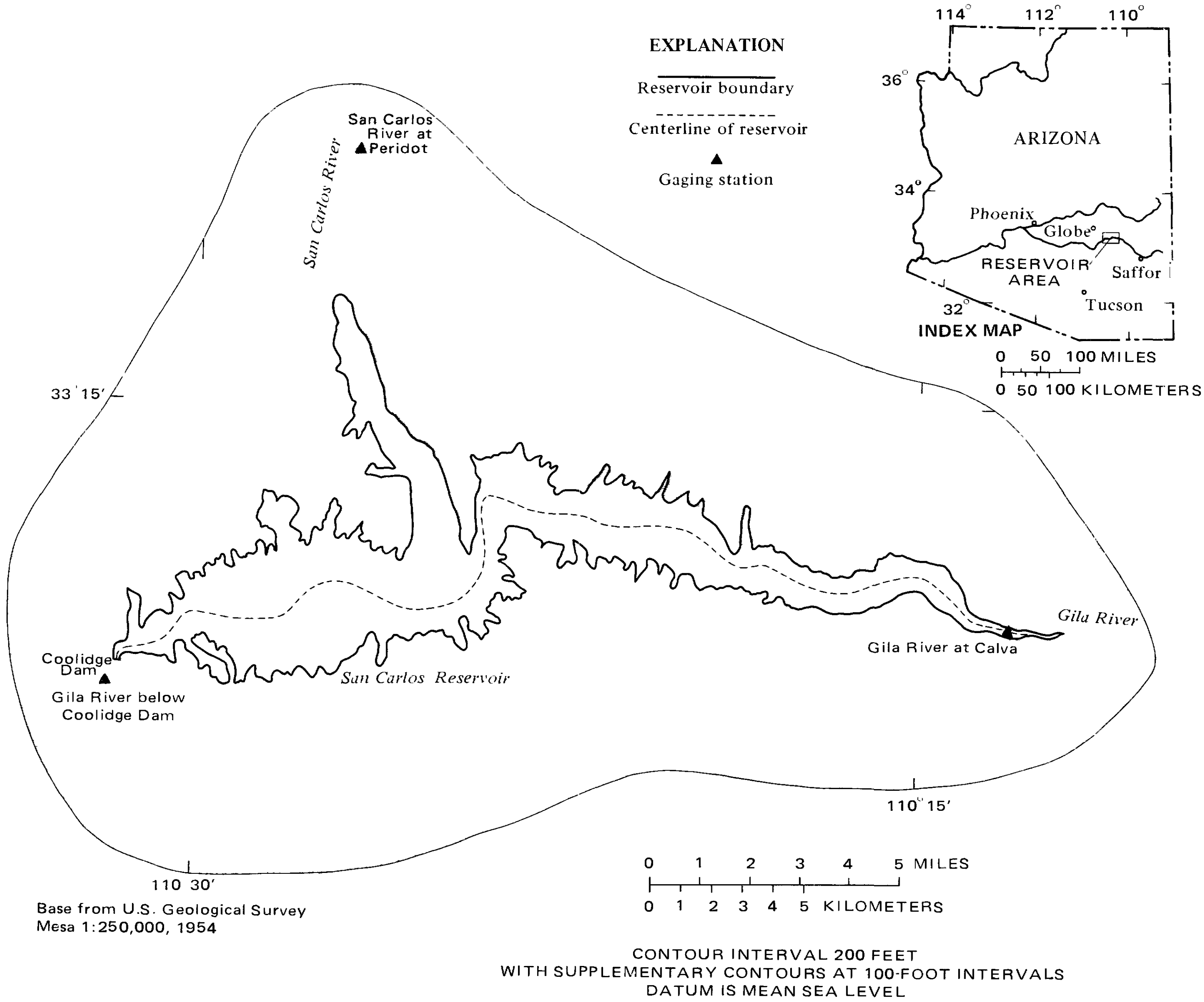

FIGURE 1.—Map showing reservoir boundary, location of gaging stations, and centerline of San Carlos Reservoir.

Usable surface-water storage capacity	The difference between surface-water storage capacity and dead storage capacity, defined as the volume available for release below the stage of maximum controllable level
Usable bank-storage capacity	The below-ground volume in the banks of a reservoir available for storage which can be evacuated by gravity

RESERVOIR SEDIMENT

SEDIMENT DEPOSITION AND CAPACITY SURVEYS

Sediment deposition in a reservoir, and the resulting reduction in water-storage capacity, affects water supply and water management, installations within the reservoir, and recreational activities. Management can, in turn, influence the sediment distribution and sediment compaction within the reservoir and the volume of sediment which passes through the reservoir by (1) regulating the stage, rate of water release, and frequency of sediment wetting and drying, (2) vegetative clearing, and (3) channel dredging. An inventory of sediment deposition can be obtained by use of data from reservoir-capacity surveys. In addition, these surveys provide the data used to establish the elevation-capacity and elevation-area ratings, which are needed for water management.

The volume of sediment deposited in the San Carlos Reservoir was calculated from the results of five surveys. The first survey was made during 1914 and 1915 for the Indian Irrigation Service to determine potential storage capacity of the proposed reservoir. The second and third surveys were completed in 1935 and 1937 by the Soil Conservation Service, the third at the request of the Gila Water Commissioner. A fourth survey was made in 1947 by the Corps of Engineers to assess changes in the capacity of the reservoir, mainly resulting from above-normal inflow in 1941-42 (Thorp and Brown, 1951). A map of the reservoir, scale 1:7,200, was produced by photogrammetric methods from the 1947 survey. Changes during the period 1947-66 were assessed by a fifth survey made in 1966 by the U.S. Geological Survey.

The survey of 1966 was made primarily to provide better water-surface area and storage-capacity data for the water-budget analysis of evapotranspiration. An above-normal lake level during the summer of 1966 provided an opportunity to obtain an economical survey of the reservoir. Control points at the ends of 51 range lines were established near the water's edge, and a recording fathometer was used to obtain a continuous record of the ground profile along each range line. The shorelines shown on aerial photography taken during 1966-67 were used to check some of the topographic data. Topographic changes within the study area of the Gila River Phreatophyte Project above the maximum 1966 pool level were obtained from cross-valley profiles repetitively surveyed (Burkham, 1972). Elevation data were plotted on copies of 1947 reservoir topographic maps of the U.S. Army Corps of Engineers and were used to locate 5-ft (1.5 m) contours for 1966.

Area curves from the five capacity surveys are contained in figure 2. Reservoir capacities between consecutive 5-ft (1.5 m) contours were computed using the elevation-area data of each survey. The curves of

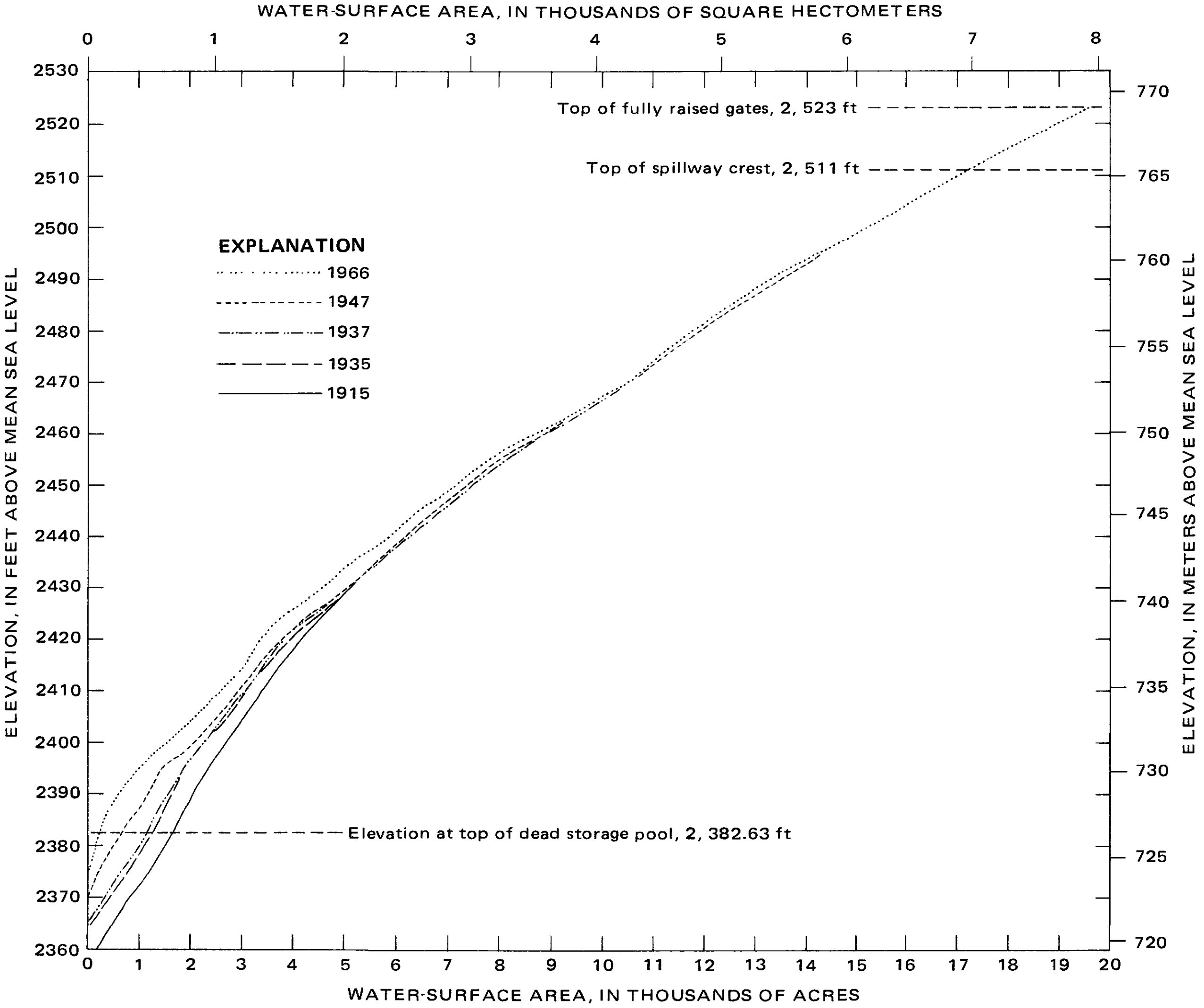

FIGURE 2.—Area curves for San Carlos Reservoir.

figure 3 show the elevation-capacity relations for all surveys. Water-surface areas and surface-water storage capacities for the surveys are listed by 5-ft (1.5 m)-elevation increments in table 1. Much of table 1 data is from Thorp and Brown (1951, table 1).

The earlier capacity surveys were not as detailed as later surveys because the needs were different. The 1914-15 reservoir survey was designed to describe agricultural lands and land use on the Gila and San Carlos River flood plains. The topography outside the flood plain area was included in this survey but was with less detail. More attention was given to defining flood-plain topography in the 1935 and 1937 surveys. Not until the 1947 survey, however, was the upland topography well defined. Capacity ratings for the first three surveys were adjusted to the more accurate 1947 survey by Thorp and Brown (1951, p. 9, 10) and are shown in table 1. The errors remaining after adjustments are significant in the analyses of this report. As an example of the errors remaining in the ratings, it is seen in table 1 that capacities computed for 5-ft-elevation increments in 1937 were greater than for corresponding 5-ft increments in 1935, in the range of 2,435 to 2,495 ft (742–760 m). Scour or compaction might have produced some of the increases, however, the increases extend about 25 ft (7.6 m) above the maximum water stage recorded prior to the 1937 surveys. The maximum reservoir elevation through 1937 was 2,471.56 ft (753 m), April 5, 1932. Another example of error in the first two surveys is indicated by no measured capacity change between surveys above certain stages, although considerable inflow occurred when the reservoir water level exceeded those stages. The 1935 capacity table was identical to the 1914–15 table above 2,435 ft (742 m) elevation, yet about 668,000 acre-ft (824 hm^3) of inflow occurred above this elevation during 1928–35.

SURFACE-WATER STORAGE LOSSES FROM SEDIMENT ACCUMULATION

The maximum surface-water storage capacity of the San Carlos Reservoir in November 1928 was 1,266,837 acre-ft (1,562 hm^3) at 2,523 ft (769 m). By 1966, sediment deposition had reduced the capacity by 96,719 acre-ft (119 hm^3) to 1,170,118 acre-ft (1,443 hm^3), a 7.6 percent loss. The loss in *usable* surface-water storage capacity was 72,476 acre-ft (89 hm^3) for the same period.

These storage losses indicating that the total

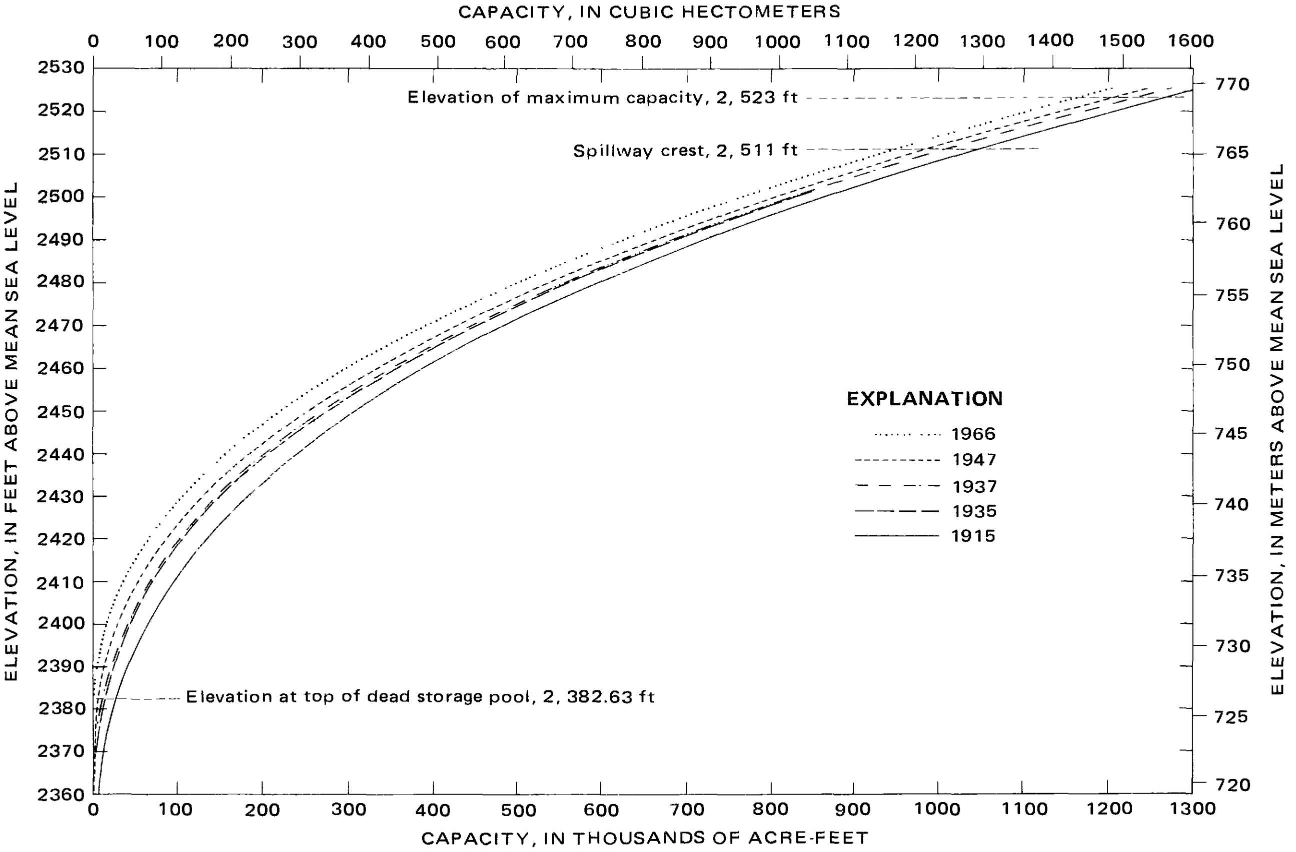

FIGURE 3.—Capacity curves for San Carlos Reservoir.

TABLE 1.—*Results of surface-water storage-capacity surveys*

	1914-15 survey (adjusted)[1]			1935 survey (adjusted)			1937 survey (adjusted)			1947 survey			1966 survey		
Elevation above mean sea level (ft)	Area (acres)	Capacity to next lower contour (acre-ft)	Cumulative capacity (acre-ft)	Area (acres)	Capacity to next lower contour (acre-ft)	Cumulative capacity (acre-ft)	Area (acres)	Capacity to next lower contour (acre-ft)	Cumulative capacity (acre-ft)	Area (acres)	Capacity to next lower contour (acre-ft)	Cumulative capacity (acre-ft)	Area (acres)	Capacity to next lower contour (acre-ft)	Cumulative capacity (acre-ft)
2308	Orignal bottom at dam		0	0	0	0	0	0			Original bottom at dam				
2365	489	6,060	6,060	66	5	5	55	4	4	0	0	0	0	0	0
2370	830	3,307	9,367	428	1,103	1,108	363	932	936	6	1	1	0	0	0
2375	1,116	4,946	14,323	768	2,949	4,057	622	2,434	3,370	227	450	450	13	22	22
2380	1,511	6,523	20,846	1,127	4,709	8,766	1,021	4,069	7,439	524	1,827	2,277	174	394	414
2385	1,825	8,162	29,008	1,362	6,213	14,979	1,264	5,704	13,143	803	3,293	5,570	291	1,150	1,564
2390	2,048	9,396	38,404	1,624	7,456	22,435	1,570	7,071	20,215	1,182	4,932	10,502	599	2,180	3,744
2395	2,309	10,626	49,030	1,824	8,615	31,050	1,835	8,504	28,719	1,454	6,578	17,080	968	3,880	7,624
2400	2,681	12,347	61,377	2,253	10,174	41,224	2,214	10,108	38,827	2,083	8,796	25,876	1,508	6,140	13,764
2405	3,079	14,522	75,899	2,651	12,247	53,471	2,717	12,306	51,133	2,493	11,425	37,301	2,065	8,897	22,661
2410	3,397	16,434	92,333	3,020	14,168	67,639	3,067	14,451	65,584	2,902	13,475	50,776	2,562	11,545	34,206
2415	3,706	18,315	110,648	3,481	16,239	83,878	3,430	16,234	81,819	3,315	15,531	66,307	3,061	14,039	48,245
2420	4,152	20,559	131,207	3,922	18,497	102,375	3,797	18,060	99,879	3,741	17,630	83,937	3,319	15,945	64,190
2425	4,612	23,984	155,191	4,537	21,129	123,504	4,455	20,609	120,487	4,391	20,309	104,246	3,859	17,929	82,119
2430	(2)	25,547	180,738	5,197	24,317	147,821	5,084	23,831	144,318	5,099	23,703	127,949	4,538	20,970	103,089
2435	(2)	28,303	209,041	5,649	27,108	174,929	5,648	26,818	171,136	5,564	26,650	154,599	5,095	24,069	127,158
2440	6,250	29,735	238,776	6,250	29,735	204,664	6,296	29,846	200,982	6,143	29,256	183,853	5,839	27,314	154,472
2445	6,845	32,727	271,503	6,845	32,727	237,391	6,896	32,969	233,951	6,731	32,174	216,029	6,372	30,519	184,991
2450	7,467	35,769	307,272	7,467	35,769	273,160	7,531	36,057	270,008	7,381	35,268	251,297	7,123	33,721	218,712
2455	8,060	38,809	346,081	8,060	38,809	311,969	8,145	39,180	309,188	7,971	38,371	289,669	7,751	37,174	255,886
2460	8,841	42,238	388,319	8,841	42,238	354,207	8,884	42,560	351,748	8,900	42,157	331,826	8,654	40,992	296,878
2465	9,778	46,529	434,848	9,778	46,529	400,736	9,808	46,712	398,460	9,617	46,282	378,108	9,668	45,783	342,661
2470	10,501	50,688	485,536	10,501	50,688	451,424	10,516	50,801	449,261	10,522	50,332	428,439	10,460	50,308	392,969
2475	11,187	54,212	539,748	11,187	54,212	505,636	11,183	54,238	503,498	11,133	54,131	482,570	11,078	53,839	446,808
2480	11,887	57,677	597,425	11,887	57,677	563,313	11,905	57,709	561,207	11,832	57,405	539,975	11,690	56,914	503,722
2485	12,682	61,413	658,838	12,682	61,413	624,726	12,685	61,466	622,673	12,689	61,291	601,266	12,524	60,525	564,247
2490	13,516	65,485	724,323	13,516	65,485	690,212	13,519	65,500	688,174	13,528	65,533	666,799	13,224	64,363	628,610
2495	14,320	69,582	793,905	14,320	69,582	759,793	14,320	69,589	757,763	14,320	69,612	736,411	14,212	68,576	697,186
2500	15,250	73,914	867,819	15,250	73,914	833,708	15,250	73,914	831,677	15,250	73,914	810,325	15,250	73,914	771,100
2505	16,116	78,407	946,226	16,116	78,407	912,114	16,116	78,407	910,084	16,116	78,408	888,732	16,116	78,407	849,507
2510	17,027	82,849	1,029,075	17,027	82,849	994,963	17,027	82,849	992,933	17,027	82,849	971,581	17,027	82,849	932,356
2515	17,991	87,536	1,116,611	17,991	87,536	1,082,499	17,991	87,536	1,080,468	17,991	87,536	1,059,116	17,991	87,536	1,019,892
2520	18,974	92,403	1,209,014	18,974	92,403	1,174,902	18,974	92,403	1,172,872	18,974	92,403	1,151,520	18,974	92,403	1,112,295
2525	19,985	97,389	1,306,403	19,985	97,389	1,272,291	19,985	97,389	1,270,260	19,985	97,389	1,248,908	19,985	97,389	1,209,684
2511[3]			1,046,203			1,012,091			1,010,061			988,709			949,484
2523[4]			1,266,857			1,232,725			1,230,695			1,209,343			1,170,118

[1] Use of these tables began in 1928 with closure of dam.

[2] Area on area-elevation curves interpolated from 2425 and 2440 contours.

[3] Spillway crest.

[4] Spillway crest with gates fully raised.

volume of sediment deposited was 96,719 acre-ft (119 hm³) also indicate that the mean annual volume for the period November 1928 to August 1966 was 2,553 acre-ft (3.1 hm³), which is equivalent to 0.20 percent of the original surface-water storage capacity. Table 2 includes storage capacity data, sediment deposition amounts and mean rates of deposition, and a comparison of sediment volume deposited to streamflow volume for all periods between surveys.

SEDIMENT DISTRIBUTION

The data of table 1 were used to calculate the volumes of sediment deposition for 5-ft (1.5 m)-elevation increments for the periods 1928–47, 1947–66, and 1928–66. (The capacity tables used in 1928 were obtained from the 1914–15 survey.) The computed volumes are given in table 3 and are illustrated in the vertical distribution graph of figure 4. Changes in elevation along the centerline of the reservoir resulting from sediment deposition are evident from the profiles shown in figure 5 for all surveys. The longitudinal centerline, as established on maps of the 1947 survey, was changed to more nearly center it with respect to the flood plain at a distance of 42,000 to 58,000 ft (12,800 to 17,700 m) upstream from the dam. The centerline, as revised, is shown in figure 1. Centerline distances from the dam to intercepts of centerline and contour lines were scaled from maps of all surveys except the 1937 survey, for which no maps were available. Centerline distances for the 1937 survey were based on the 1937 capacity-survey data and the 1935 centerline distances.

Longitudinal slope of the reservoir bottom below the 2,380-ft (725 m) contour has decreased from 0.00246 to 0.00057 during 1929–66. Above the 2,380-ft (725 m) contour the slope has decreased from 0.00167 to 0.00138. Over the entire 22-mi (35.4 km) reservoir length, the mean slope was 0.00188 in 1928, 0.00140 in 1935 and 1937, 0.00135 in 1947, and 0.00131 in 1966. The longitudinal slope of the San Carlos arm of the reservoir is about 0.00275. Changes in slope due to channel plugging are discussed in the next section.

A large sediment accumulation occurred in the lower parts of the reservoir, as indicated in table 3 and figures 4 and 5, which corresponds to the most

TABLE 2.—*Storage capacities, sediment deposition, and streamflow data*

A. Storage capacities

Year of survey	1928[1]	1935	1937	1947	1966
Surface-water storage capacity in acre-ft, at 2,523 ft (gates fully raised)	1,266,837	1,232,725	1,230,695	1,209,343	1,170,118
Surface-water storage capacity in acre-ft, at 2,511 ft (spillway crest)	1,046,203	1,012,091	1,010,061	988,709	949,484
Usable surface-water storage capacity in acre-ft, at 2,511 ft	1,021,060	1,000,916	999,231	984,875	948,584
Dead storage capacity in acre-ft, at 2,382.63 ft	25,143	11,175	10,830	3,834	900
Elevation of zero surface storage at time of capacity survey, in feet	2,309	[2] 2,354	[2] 2,354	2,370	2,374

B. Sediment deposition

Period	1928–35[1]	1935–37	1937–47	1947–66	1928–66[1]
Number of years in period	6.28	1.91	10.00	19.70	37.89
Volume of sediment deposited per period, in acre-ft	34,112	2,030	21,352	39,225	96,719
Mean annual deposition per period, in acre-ft	5,431	1,063	2,135	1,991	2,553
Sediment deposition per period in percent of original surface-water storage capacity at 2,523 ft	2.69	.16	1.69	3.09	7.63
Mean annual sediment deposited per period as percent of original surface-water storage capacity	.43	.08	.17	.16	.20
Sediment volume deposited in dead storage, in acre-ft	13,968	345	6,996	2,934	24,243
Dead storage loss by sediment deposition per period, in percent of original dead storage capacity	55.55	1.37	27.83	11.67	96.42
Stream inflow per period in acre-ft[3]	1,722,985	345,275	2,541,463	3,579,217	8,188,940
Ratio of sediment volume deposited to volume of stream inflow per period	.0198	.0059	.0084	.0110	.0118

[1] Beginning November 15, 1928.

[2] Approximate.

[3] Inflow of Gila River and San Carlos River.

TABLE 3.—*Volumes of sediment deposited by 5-ft-elevation intervals in San Carlos Reservoir during different periods*

Reservoir elevation (mean sea level)	Volume to next lower contour, in acre-ft		
	1928–47	1947–66	1928–66
2308	0	0	0
2365	6,060	0	6,060
2370	3,306	1	3,307
2375	4,506	428	4,934
2380	4,696	1,435	6,131
2385	4,869	2,143	7,012
2390	4,464	2,752	7,216
2395	4,048	2,698	6,746
2400	3,551	2,656	6,207
2405	3,097	2,528	5,625
2410	2,959	1,930	4,889
2415	2,784	1,492	4,276
2420	2,929	1,685	4,614
2425	3,675	2,380	6,055
2430	1,844	2,733	4,577
2435	1,653	2,581	4,234
2440	479	1,942	2,421
2445	553	1,655	2,208
2450	501	1,547	2,048
2455	438	1,197	1,635
2460	81	1,165	1,246
2465	247	499	746
2470	356	24	380
2475	81	292	373
2480	272	491	763
2485	122	766	888
2490	-48	1,170	1,122
2495	-30	1,036	1,006
2500	0	0	0
2505	0	0	0
2510	0	0	0
2515	0	0	0
2520	0	0	0
2525	0	0	0
Total	57,493	39,226	96,719

common range of stage of the reservoir pool. As a consequence, the surface-water dead storage capacity of the reservoir was reduced 96 percent from 25,143 acre-ft (31 hm³) to 900 acre-ft (1.1 hm³) from November 1928 to August 1966 (see table 2). The distribution of sediment is partly regulated by the physical features of the reservoir, such as longitudinal slope, cross-sectional dimensions, shape, vegetation on exposed ground surface, and inflow channel geometry. The location of deposition is also regulated by concentration and particle size of sediment inflow, by rate of streamflow, and by the stage and volume of water in storage.

THE EFFECT OF PHREATOPHYTES ON INFLOW CHANNELS

Phreatophytes can significantly reduce the conveyance of reservoir inflow channels, particularly if the stage of the water in the reservoir fluctuates widely. The flat fertile plain at the upstream end of the reservoir pool has a shallow water table and is periodically inundated, creating an ideal environment for phreatophytes such as saltcedar. Inundation may kill the plants, but the prolific seed production and rapid growth of saltcedar quickly recreates a dense thicket. When these sediment flats are exposed for extended periods of time, the saltcedar narrows the inflow channel by encroachment and can eliminate a continuous channel. During the period 1962-65, the inflow channel of the Gila River into the San Carlos Reservoir was blocked by a combination of conditions including encroachment by phreatophytes on the sediment, a reduction in channel gradient, and plugging by the deposition of floating debris.

Figures 6 and 7 show the sediment flats formed by deposition in the area above and below the confluence of the Gila and San Carlos Rivers. The upstream end of the reservoir pool was located in the area shown in these photographs during much of the period 1945-65.

During the period 1935-62 the location and alinement of the Gila River channel did not change signif-

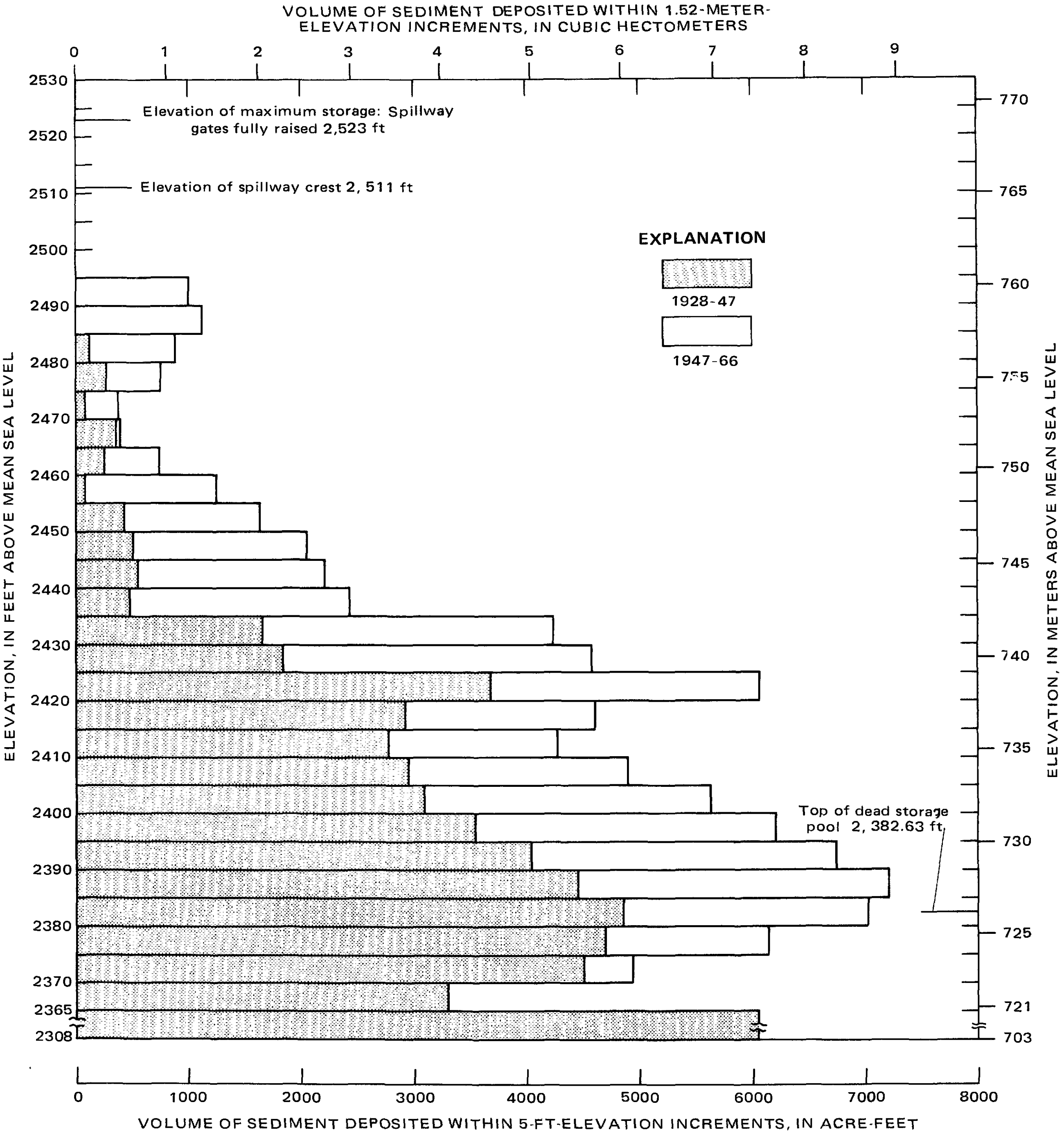

FIGURE 4.—Vertical distribution of the volume of sediment deposited within 5-ft (1.5 m)-elevation intervals at San Carlos Reservoir for the periods 1928–47 and 1947–66.

icantly as indicated by comparing figure 8 with figure 9. The width of the channel was appreciably reduced and natural levees had formed during this period, however. Figure 10 shows the levees along the banks of the inflow channel of the Gila River which had developed by August 1965. The riverbanks with abundant water supply and extensive exposure to sunlight are an excellent environment for saltcedar. This vigorous growth encroaches on the channel and thus reduces the conveyance capability of the channel during flood flows. When flows exceed the conveyance capacity of the channel, the excess water overflows the banks and inundates the adjacent flood plain. Sediment is then deposited on

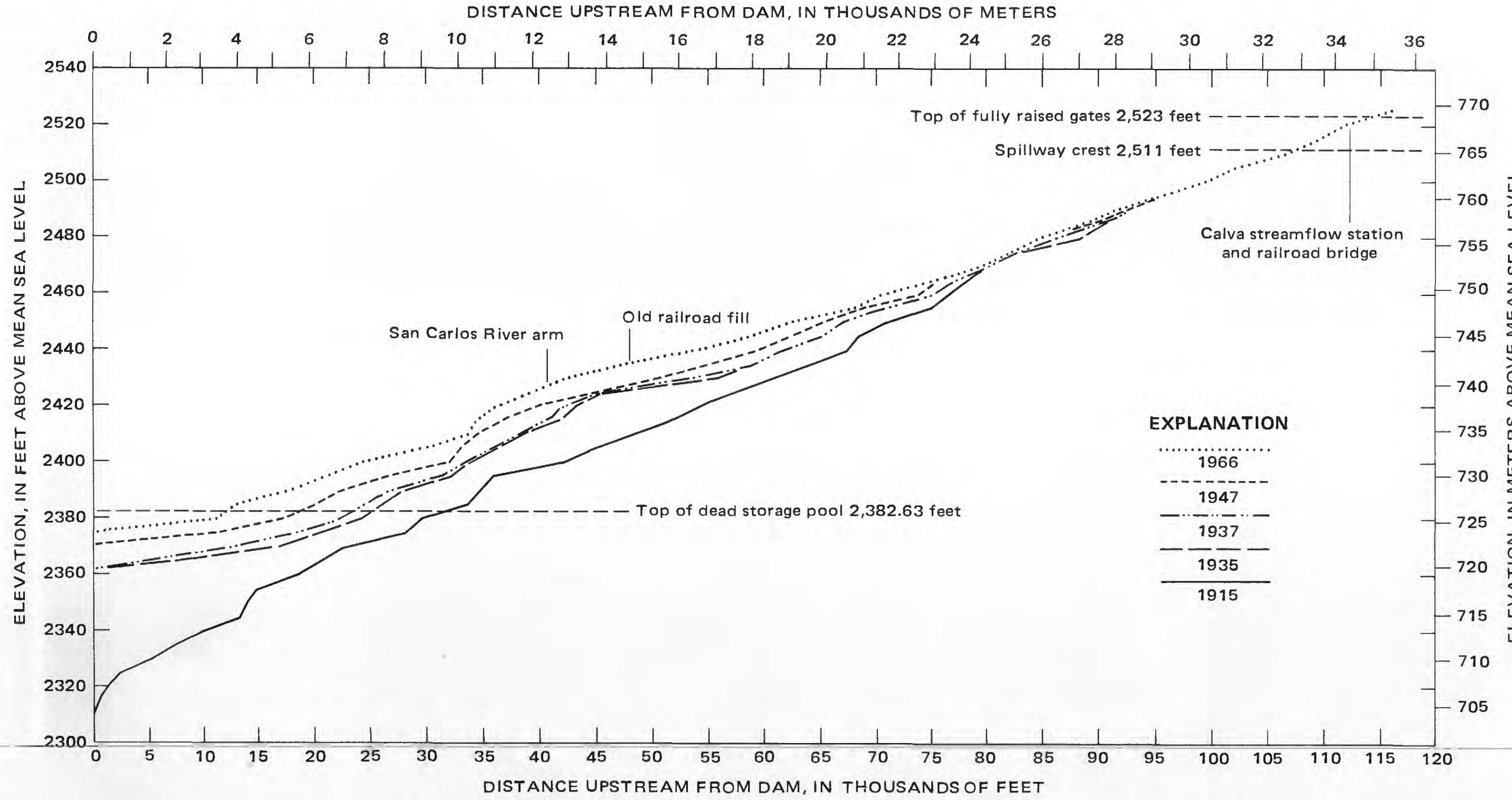

FIGURE 5.—Bottom profiles of San Carlos Reservoir along the principal longitudinal axis as determined by the five capacity surveys.

FIGURE 6.—Aerial view looking downstream (west) on April 20, 1965, showing the sediment flats at the confluence of the Gila and San Carlos Rivers within the San Carlos Reservoir. The reservoir pool, with water-surface elevation at 2,419.00 ft (737 m) above sea level and usable contents of about 60,000 acre-ft (74 hm³), is shown in the upper right center of the photograph. The Gila River channel is at the lower right and the San Carlos River channel is at the right center. The dark areas are well-established saltcedar.

FIGURE 7.—Aerial view looking upstream (north) on April 20, 1965, showing the San Carlos River on the left and the Gila River on the right. The lower center part of this photograph overlaps the right center part of figure 6. The area shown in figures 6 and 7 includes the area periodically inundated by reservoir water during the period 1945–65.

the flood plain because of decreased velocity of the overbank flow. Intermittent channels and pools are formed on the flood plain and provide a surface irrigation for the saltcedar.

FIGURE 8.—Aerial view of channel conditions of the Gila River upstream from the San Carlos River in 1935—7 years after the completion of Coolidge Dam. The upstream end of the reservoir pool is shown in the lower left. The Gila River flood plain shown in the photograph had been inundated by the reservoir pool during the period 1929–35. Soil Conservation Service photograph.

FIGURE 9.—Aerial view of conditions of a part of the Gila River channel above the San Carlos River in June 1962. Flow in the river is from upper right to lower left. The channel is continuous, but a comparison of this photograph with figure 8 indicates that the width has been reduced and the riverbed has been considerably elevated. Extensive ephemeral off-channel ponds are shown in the vicinity of the abandoned railroad crossing.

Figure 11 shows a saltcedar thicket after the reservoir water has receded following an inundation

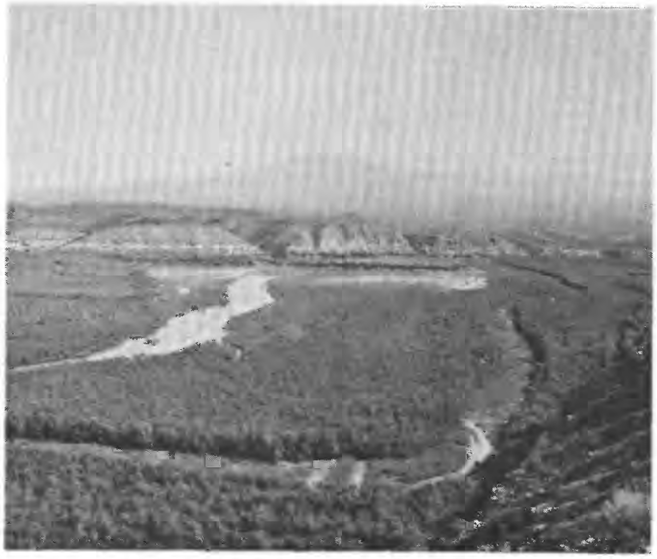

FIGURE 10.—View looking downstream (south) on August 18, 1965, at the Gila River flood plain from a point 2 mi (3.2 km) upstream from the mouth of the San Carlos River. The former Gila River inflow channel extends from the lower left corner along the right side of the photograph. The natural levees and vigorous bankside saltcedar are apparent. Deposition elevated the channel above the surrounding flood plain. In the lower foreground numerous channels cross the former main channel at right angles. The water surfaces shown near the center of the photograph are ephemeral off-channel ponds. The roadbed fill approach to the abandoned railroad bridge shows as a dark line in the center of the photograph.

FIGURE 11.—Flood-plain conditions after the area was inundated by the reservoir pool. The water had been higher than the treetops, thus killing the saltcedar. The white bands on the dead tree stems are mud deposited during the reservoir recession.

of sufficient depth to kill the plants. The soggy ground conditions, obvious in the photograph, are ideal for subsequent germination and establishment of saltcedar growth.

The plugging of the inflow channel of the Gila River during 1962-65 occurred within the 4.1-mi (6.6 km) reach shown in figure 12.

The deposition of sediment and reduction in slope of the flood plain since construction of Coolidge Dam in 1928 are shown in figure 13. The constriction caused by the railroad fill at the abandoned railroad bridge site was partly responsible for the exceptional depth of sediment deposits and the resulting decrease in slope in this reach of flood plain. Deposition of sediments at the mouth of the San Carlos River may also have been responsible. The combination of a reduction in channel width due to encroachment by vegetation and a reduction in channel velocities due to reduced slopes ultimately caused the deposition of debris shown in figure 14. Logs and sediment formed a dam practically eliminating the conveyance capabilities of the channel. Saltcedar then became established in the debris and sediment to create an erosion-proof channel plug as shown in figure 15.

The formation of a channel plug causes channel filling which quickly progresses upstream as indicated in figure 12. The upstream end of the debris plug deposited by a flood discharge during the period July 15-22, 1964, is shown in figure 16. Large concentrations of debris are a characteristic of summer floodflows on the Gila River. As described by Burkham (1970), these flows originate from intense individual thunderstorms which produce high rates of runoff from small tributary watersheds but only rarely do they produce large rates of flow on the main channel. The high rates on the tributaries strip debris from the watersheds, convey the debris to the Gila River, and thence downstream on what is generally a moderate flow in the Gila channel. The progress of the plugging phenomenon as shown in figure 12 was 1.5 mi (2.4 km) in 1963, 1.8 mi (2.9 km) in 1964, and 0.8 mi (1.3 km) in 1965 and is primarily the result of summer flows.

In the summer of 1965, a channel was excavated by dragline parallel to the plugged natural channel. The high discharge in the Gila River during December 1965 to May 1966 raised the water level in San Carlos Reservoir to an elevation which inundated most of the Gila River flood plain shown in figure 12. An excavated inflow channel has been maintained for the Gila River since 1966.

SEDIMENT TRAP EFFICIENCY

Sediment trap efficiency is the ability of a reservoir to retain sediment and is expressed in percent of total incoming sediment (Gottschalk, in Chow, 1964). A

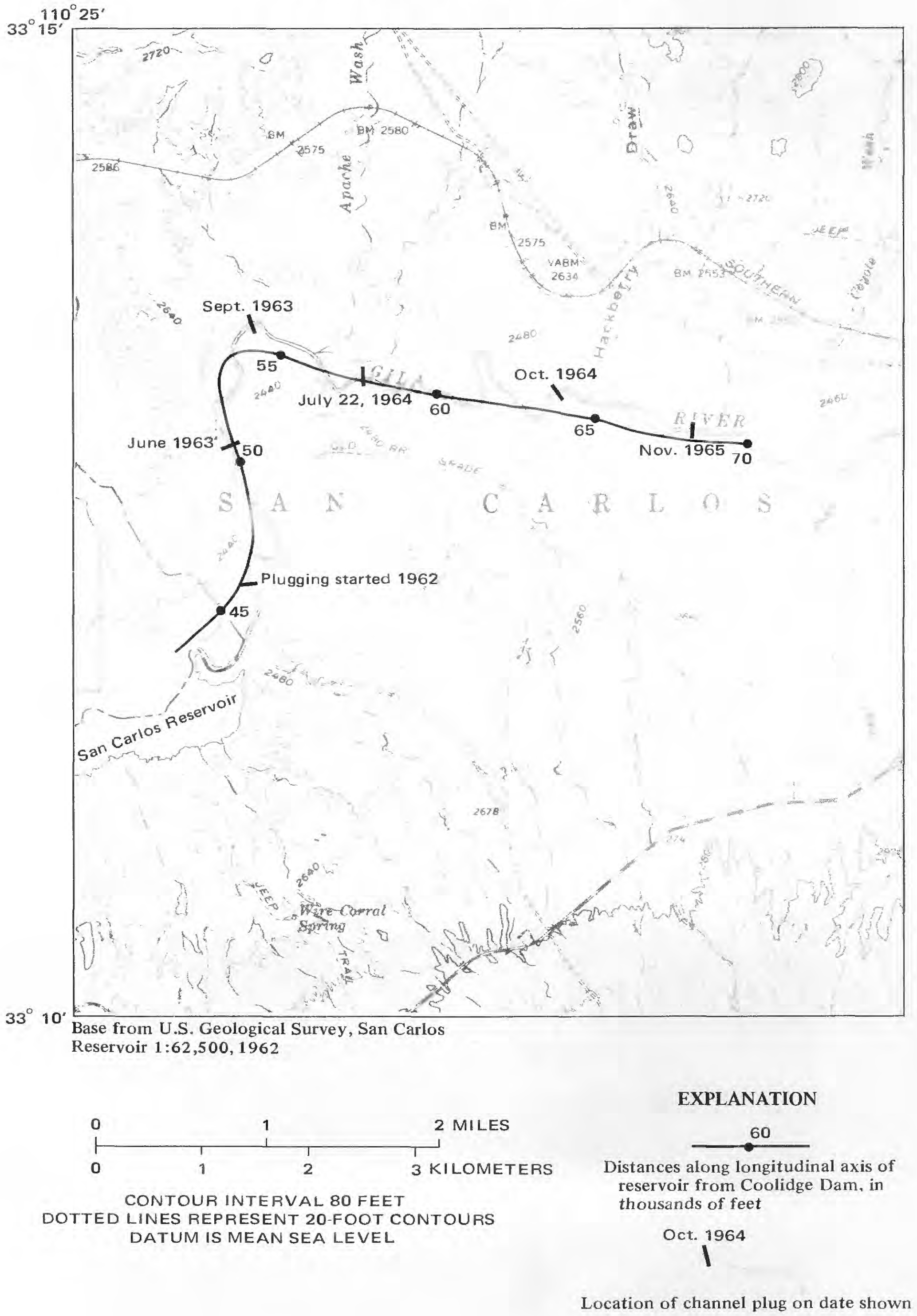

FIGURE 12.—Extent of channel plugging in Gila River on indicated dates.

sediment trap efficiency of 83 percent was predicted for San Carlos Reservoir by the U.S. Army Corps of Engineers (1914, p. 30). The remainder of the sediment was expected to pass through in suspension or by sluicing.

There are no records of sediment inflow or outflow

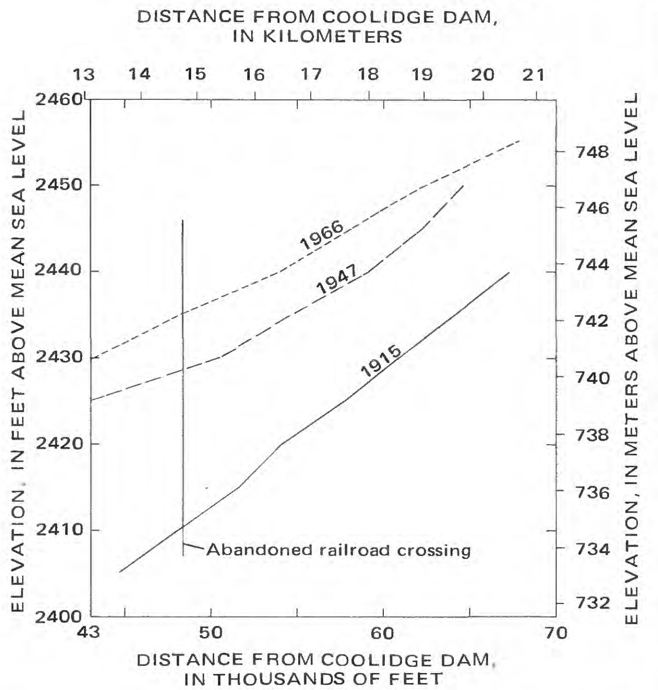

FIGURE 13.—Profiles along the longitudinal axis of San Carlos Reservoir showing changes in bed elevations and slope within the reach of channel plugging.

FIGURE 14.—View of the Gila River looking north from a point 2.6 mi (4.2 km) upstream from the mouth of the San Carlos River photographed in September 1964. The debris in the channel is part of a recently deposited channel plug. Flow is from right to left.

FIGURE 15.—Downstream view on July 15, 1965, of a reach of the Gila River channel which had been plugged in 1964. Saltcedar is becoming established in the former channel bottom.

FIGURE 16.—Aerial view of channel plugging in the Gila River on July 22, 1964. Flow is from right to left.

for San Carlos Reservoir, so trap efficiency is not known; it probably exceeds the predicted 83 percent. Trap efficiency should be 96 percent or more at San Carlos Reservoir, according to Gottschalk (in Chow, 1964, fig. 17-I-6).

ANALYSIS OF SEDIMENT DATA

The U.S. Army Corps of Engineers reported (1914, p. 29-30) predictions of the volume of sediment deposition based in part on streamflow records and on 15 sediment samples collected from deposits along the Gila River. Streamflow records of 1890 and

1895–1912 indicate that the mean annual streamflow was 346,000 acre-ft (427 hm³). In the 1914 report, the predicted specific weight of deposited sediments was 70 lb/ft³ (1,120 kg/m³), predicted volume of deposition at 100 percent trap efficiency was 1.3 percent of total streamflow, and the predicted trap efficiency was 83 percent. Based on these predictions and measured streamflow, the estimated mean annual volume of reservoir sediment deposits was 3,740 acre-ft (4.6 hm³).

Records of streamflow from November 1928 through August 1966 show the mean annual streamflow was 216,120 acre-ft (266 hm³), or 63 percent of the predicted flow. The mean annual volume of sediment deposition was 2,553 acre-ft (3.15 hm³), or 68 percent of the predicted volume.

A mean sediment concentration for stream discharge can be estimated from measured volumetric changes in reservoir deposits because a reservoir is a collector for fluvial sediment moved by all transport methods. The mean sediment concentration computed from the information in the 1914 report is 14,478 ppm (14,615 mg/l). The mean concentration from November 1928 through August 1966 is 13,684 ppm (13,808 mg/l) when computations are made using measured streamflow and sediment deposition and when estimates of trap efficiency, specific weight of deposits, and specific gravity are 96 percent, 70 lb/ft³ (1,120 kg/m³), and 2.65, respectively.

On a volumetric basis, sediment accumulated at an average rate of 0.0118 (volume of sediment deposited/volume of streamflow) from November 1928 to August 1966. The rates for the periods between surveys, chronologically, are 0.0198, 0.0059, 0.0084, and 0.0110, as listed in table 2.

INTERPOLATION OF ELEVATION-CAPACITY RATINGS BETWEEN CAPACITY SURVEYS

Elevation-capacity relations were defined for each reservoir survey. Significant changes in these relations between surveys required the development of a systematic method of interpolating changes during the periods.

The simplest method of interpolation is to pro-rate storage capacity change by time between consecutive surveys. This method of interpolation can be applied either to change in total storage capacity or to change by increments of the total reservoir storage.

Interpolation can also be made by pro-rating the change in storage capacity according to streamflow. Because the loss in storage capacity is the volume of sediment deposition, this method is basically the use of a mean sediment concentration computed for a period. The storage loss for any time interval is estimated as the product of this mean concentration and the interval streamflow. (See table 2 for period rates for San Carlos Reservoir.) This storage loss can be obtained graphically for San Carlos Reservoir by using accumulated streamflow and figure 17. The inset in figure 17 shows measured change in storage compared to measured streamflow for each of the periods between surveys.

The method of interpolating storage change adopted for use in this report employs the equivalency of the loss in surface-water storage capacity and the change in sediment deposits. A procedure for simulating deposition was developed and used to estimate the sediment volume deposited each water year. The development of this procedure and its application in providing yearly capacity ratings is described in the section "Development of Surface-Water Storage-Capacity Ratings."

HYDROLOGY

WATER-BUDGET EQUATION

A water budget is used in this report for presentation of an historical accounting of the hydrology of San Carlos Reservoir for water years 1931–71. The water-budget equation for San Carlos Reservoir is

$$I_G + I_S + I_P + I_{GW} + I_T - O_G - O_E - O_{ET} \pm \Delta S_R \pm \Delta S_B = 0. \qquad (1)$$

The components of the water budget are identified as follows:

I_G =Gila River inflow at Calva,
I_S =San Carlos River inflow at Peridot,
I_P =precipitation input over the lake surface,
I_{GW} =ground-water inflow,
I_T =tributary inflow downstream from the Gila and San Carlos River gaging stations,
O_G =Gila River outflow below Coolidge Dam,
O_E =evaporation from the lake surface,
O_{ET} =evapotranspiration from the exposed land surface of the reservoir,
ΔS_R =change in surface-water storage, and
ΔS_B =change in bank storage.

Neither the evapotranspiration nor the change in bank storage was measured. Before evapotranspiration could be computed by the water-budget equation, estimates of bank storage were necessary. A discussion of the evaluation of each water-budget component is presented in the following sections.

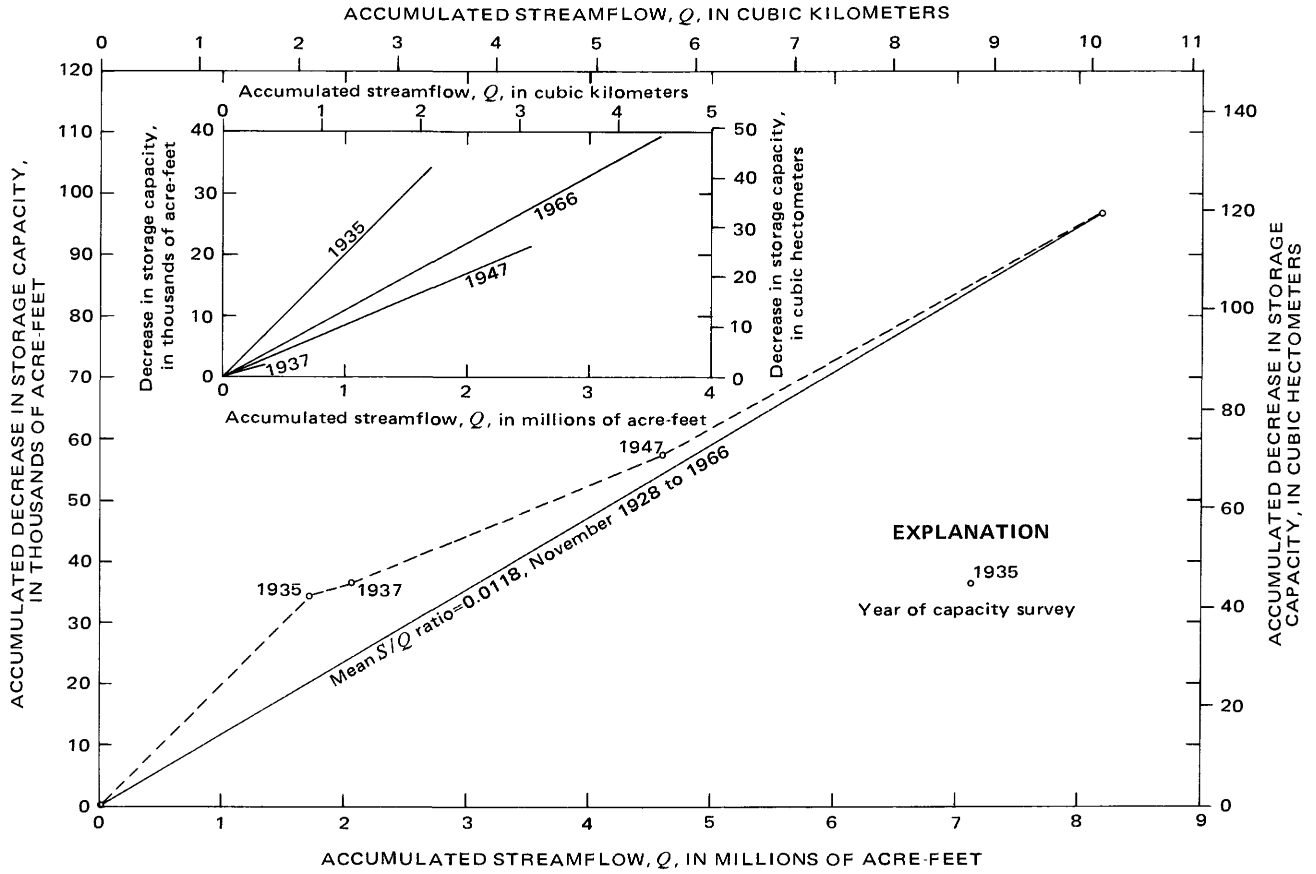

FIGURE 17.—Relation between accumulated decrease in storage capacity and accumulated streamflow by capacity survey periods. Inset shows relation of storage capacity change and streamflow for each period.

SURFACE FLOW

GILA RIVER AND SAN CARLOS RIVER INFLOW

Records of streamflow into the reservoir for the 1929-71 water years were taken from U.S. Geological Survey Water-Supply Papers 1313 and 1733 and from U.S. Geological Survey annual state reports of Arizona streamflow. Inflow records used in this study are primarily those for the Gila River at Calva and the San Carlos River at Peridot. Some of the 1929 inflow data were estimated from reservoir outflow data and changes in reservoir storage. Additional sources of Gila River streamflow information include reports by Burkham (1970) and the U.S. Army Corps of Engineers (1914).

Figure 18 shows the total annual streamflow into the reservoir for water years 1929-71. The streamflow data are included in table 17. The mean annual inflow for this period was 214,940 acre-ft (265 hm^3), and the annual median was 159,000 acre-ft (196 hm^3). The large difference between the mean and median values is caused by infrequent years of extremely high flow. Of the annual totals 67 percent is less than the mean because of the influence of these infrequent extreme annual totals.

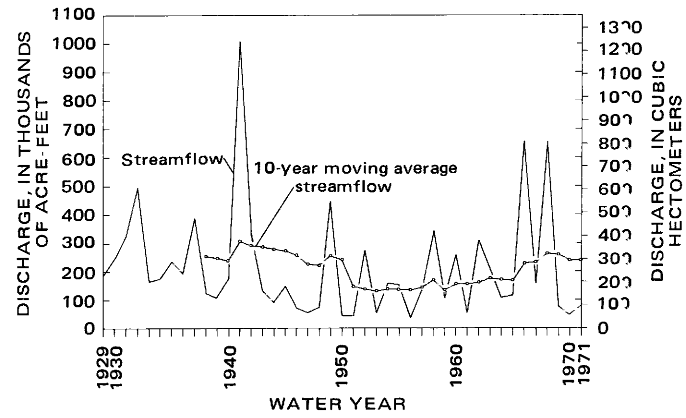

FIGURE 18.—Annual combined Gila River and San Carlos River inflows to San Carlos Reservoir for water years 1929-71.

Mean annual streamflow, 1929-71, into the reservoir was 33,450 acre-ft (41 hm^3) for the San Carlos River and 181,490 acre-ft (224 hm^3) for the Gila River.

The San Carlos River, with 8.6 percent of the contributing area, produced 15.6 percent of the total streamflow into the reservoir. Annual streamflow of the San Carlos River ranged from 6.2 percent of the total streamflow into the reservoir in 1959 to 40 percent of the total streamflow in 1956.

A generally declining trend in annual streamflow coincided with a similar declining trend in annual precipitation from about 1920 to 1962 (Burkham, 1970, fig. 7). The trend is not as evident during the period of reservoir operation included in this report (1929-71). The many years of low runoff during the 1940's and 1950's are distinct in the 10-year moving average flow graphed in figure 18, but the average annual runoff was higher near the beginning and end of the study period. Annual streamflow exceeded the mean only twice (1949 and 1952) during the 15-year period 1943-57. By contrast, annual streamflow exceeded the mean 14 times during the 43 year period 1929-71 and 5 times during the 11 year period 1958-68. A histogram of annual inflow volumes is shown in figure 19 for water years 1929-71.

Of special interest to users of San Carlos Reservoir water is the probable water supply over time durations of a year or more. Table 4 shows the 1930-71 historical extremes in both maximum and minimum supply for several time durations.

Table 5 gives the computed mean monthly inflows for the Gila and San Carlos Rivers and their combined total inflows, based on 1930-71 data. Figure 20 compares the mean monthly streamflows of the two rivers in percent of their mean annual totals. In general, the mean monthly discharges for both rivers follow similar seasonal patterns. The greatest monthly volumes typically occur during several months of the winter season as the result of frontal storms passing over most or all of the basin. The period of increased runoff generally begins in December and extends through March. The mean winter and spring (November to June) inflow is 155,480 acre-ft (192 hm^3), but flow is highly variable from year to year. The variability is demonstrated in that the average deviation from the November to June mean is 137,000 acre-ft (169 hm^3), an 88 percent deviation.

Increased streamflow from summer storms normally begins in July, peaking in August, and may continue high into October. Individual summer storms are smaller in areal extent than winter storms and are more highly variable in precipitation intensity, but the total summer streamflow is slightly more consistent than the total winter and spring streamflow. The mean streamflow from July through October is 59,480 acre-ft (73 hm^3), and the mean deviation of 37,450 acre-ft (46 hm^3) is 63 percent of mean summer streamflow.

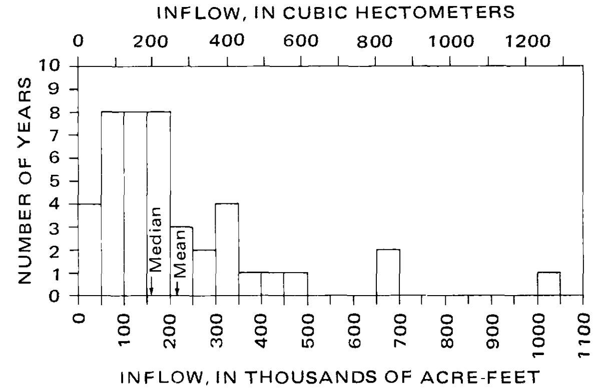

FIGURE 19.—Frequency of occurrence of inflow volumes, water years 1929-71.

TABLE 4.—*Maximum and minimum volumes of water supplied by streamflow into San Carlos Reservoir for different time durations, in acre-ft*

Duration of period	1 year	3 years	5 years	7 years	10 years
Maximum inflow for specific period and dates of period	1,005,180 (1941)	1,518,810 (1940-42)	1,775,650 (1937-41)	2,309,870 (1936-42)	3,041,280 (1932-41)
Minimum inflow for specific period and dates of period	34,740 (1956)	198,880 (1969-71)	444,140 (1944-48)	755,440 (1950-56)	1,301,020 (1944-53)

TABLE 5.—*Mean monthly inflows for the Gila River, the San Carlos River, and for both rivers 1930-71*

Month	Mean monthly Gila River inflow (acre-ft)	Mean monthly San Carlos River inflow (acre-ft)	Combined total mean monthly inflow (acre-ft)
Oct	8,587	821	9,408
Nov	5,845	809	6,654
Dec	14,948	5,782	20,730
Jan	26,594	5,611	32,205
Feb	28,826	6,843	35,669
Mar	31,669	6,307	37,976
Apr	14,966	1,035	16,001
May	6,702	265	6,967
June	972	95	1,067
July	6,041	1,126	7,167
Aug	23,272	3,461	26,733
Sept	12,933	1,255	14,188

TRIBUTARY INFLOW

Tributary discharge from 390 mi^2 (1,010 km^2) flows directly into the reservoir between the stream gaging stations (Gila River at Calva and San Carlos River at Peridot) and the dam. It is convenient for water-budget computations that flow seldom occurs in the tributaries and that mean annual tributary flow is probably less than 2 percent of the mean annual input from all sources. Significant tributary runoff

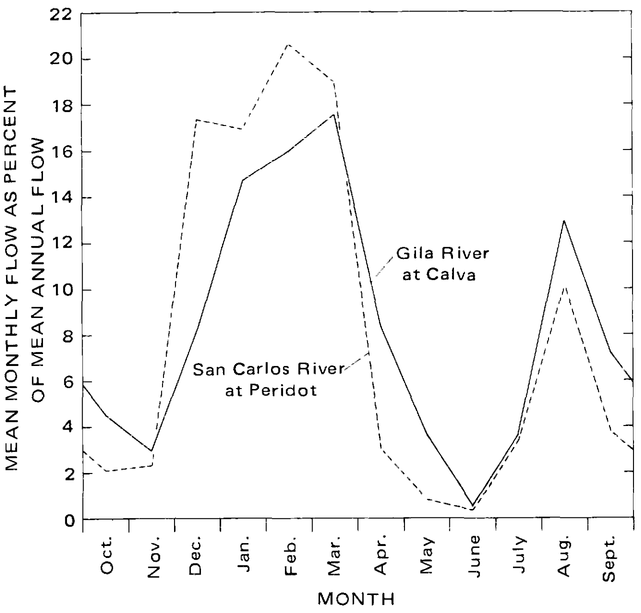

FIGURE 20.—Mean monthly flow as a percent of mean annual flow for the Gila and San Carlos Rivers.

usually occurs only during the summer storm season, July through October.

Tributary inflows from 72.6 mi^2 (188 km^2) of the gaged tributary area entering the reservoir below the Calva gaging station were determined for the summer storm seasons of 1964-71 (Burkham, 1976). Totals of seasonal runoff from this area, and runoff per unit area, are listed in table 6.

Several methods were used to estimate seasonal runoff from all areas tributary to the reservoir. In the first method, runoff was assumed to be spatially constant. The seasonal runoff values per square mile for 1964-71, from table 6, were multiplied by the 390-mi^2 (1,010 km^2) tributary area and the results listed in column 2 of table 7.

The tributary runoff estimates of column 3 in table 7 are results of a rainfall-runoff correlation. Rainfall was measured for the Gila River Phreatophyte Project in gages located near the downstream ends of the tributary streams. The tributary runoff data is from table 6. The regression equation relating rainfall and runoff data was

$$Q = -0.382 + 0.093P, \text{ where } P \geqslant 4, \qquad (2)$$

with rainfall, P, and runoff, Q, given in inches. The regression line and the data used to develop equation 2 are plotted in figure 21. The equation was used to estimate runoff from the 390-mi^2 (1,010 km^2) tributary area using seasonal precipitation at San Carlos Reservoir. The correlation between seasonal rainfall measured on the Gila River Phreatophyte Project area and seasonal rainfall at the San Carlos Reservoir weather station is poor. Runoff estimates in column 3 of table 7 are probably poor partly because of this high spatial variability in rainfall intensities.

Burkham (1974) indicated that the mean seasonal runoff from all the study watersheds for the period 1963-71 was about 9 acre-ft/mi^2 (0.004 hm^3/km^2). Seasonal tributary runoff into the reservoir using

TABLE 6.—*Tributary inflow into the San Carlos Reservoir along a reach of the Gila River*

Water year	Seasonal tributary runoff (acre-ft)	Mean seasonal runoff (acre-ft/mi^2)
1964	616	8.5
1965	[1] 732	9.9
1966	301	4.1
1967	1,560	21.5
1968	228	3.1
1969	229	3.2
1970	86	1.2
1971	2,220	30.6

[1] Includes an additional gaged area of 1.0 mi^2 (2.59 km^2).

TABLE 7.—*Estimated tributary inflow into San Carlos Reservoir*

Water year (1)	Estimated seasonal runoff, in acre-ft Based on runoff measured for part of the area (2)	From rainfall-runoff relation, equation 2 (3)	Based on 9 acre-ft/mi^2 (4)	Average of columns 3 and 4 (5)
1931		3,660	3,510	3,580
1932		0	3,510	1,760
1933		1,420	3,510	2,460
1934		1,800	3,510	2,660
1935		4,520	3,510	4,020
1936		0	3,510	1,760
1937		0	3,510	1,760
1938		0	3,510	1,760
1939		0	3,510	1,760
1940		0	3,510	1,760
1941		10,470	3,510	6,990
1942		1,320	3,510	2,410
1943		890	3,510	2,200
1944		8,640	3,510	6,070
1945		2,520	3,510	3,010
1946		6,190	3,510	4,850
1947		3,600	3,510	3,550
1948		1,650	3,510	2,530
1949		1,860	3,510	2,680
1950		1,550	3,510	2,530
1951		2,340	3,510	2,930
1952		1,720	3,510	2,620
1953		0	3,510	1,760
1954		11,460	3,510	7,430
1955		10,420	3,510	6,960
1956		0	3,510	1,760
1957		0	3,510	1,760
1958		9,330	3,510	6,420
1959		8,330	3,510	5,920
1960		4,370	3,510	3,940
1961		6,670	3,510	5,080
1962		2,460	3,510	2,980
1963		3,660	3,510	3,580
1964	3,320	11,730	3,510	7,620
1965	3,860	370	3,510	1,940
1966	1,600	13,660	3,510	8,580
1967	8,380	8,100	3,510	5,800
1968	1,210	0	3,510	1,760
1969	1,250	1,460	3,510	2,480
1970	470	3,620	3,510	3,560
1971	11,930	4,310	3,510	3,910
Mean	[1] 3,998	[2] 3,758	[2] 3,510	[2] 3,631

[1] Eight (8) year mean.
[2] Forty-one (41) year mean.

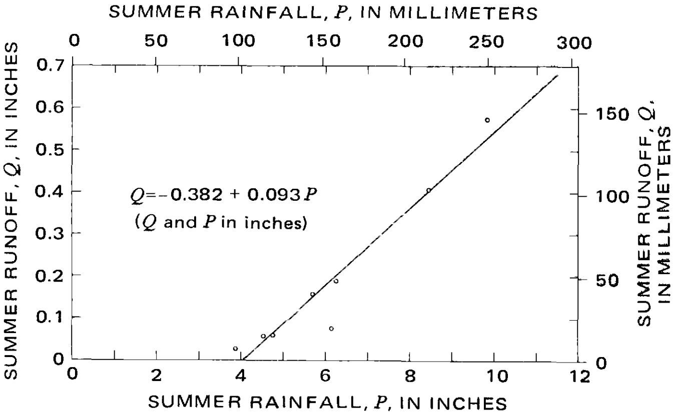

FIGURE 21.—Relations between measured rainfall and tributary runoff for summer seasons 1964–71 from 72.6 mi² (188 km²) of area tributary to San Carlos Reservoir.

this rate is 3,510 acre-ft (4.33 hm³), as shown in column 4 of table 7.

These methods do not accurately estimate seasonal tributary runoff to San Carlos Reservoir for each year. However, the individual means at the bottom of column 2 through column 4 of table 7 deviate less than 10 percent from the average of the means. The close agreement of mean values suggests that the 41-year water budget is improved by the addition of tributary runoff estimates.

The average of the estimates from columns 3 and 4 of table 7 was selected somewhat arbitrarily to define the seasonal totals to include in the water budget and column 5 of table 7. The estimates in column 3 assume that a seasonal variability of precipitation is uniform in space. The estimates in column 4 assume runoff is uniform in space and time.

GILA RIVER OUTFLOW

About 78 percent of all inflow into San Carlos Reservoir is released downstream into the Gila River. Releases are based on reservoir supply and the needs of the San Carlos Project near Coolidge, Ariz. Records of releases are based on river-stage data obtained at a flume 0.4 mi (0.6 km) downstream from Coolidge Dam, at the U.S. Geological Survey gaging station, Gila River below Coolidge Dam, Ariz. Streamflow records have been available at this station from 1939 to 1971 and near this location for much of the period 1899–38.[1]

Discharge data for water years 1931–71 are included in the water budget. Mean monthly discharges of the Gila River below Coolidge Dam are shown in table 8 and are an indication of seasonal demands of water for irrigation.

The peak instantaneous discharge since the dam was constructed was 1,350 ft³/s (38 m³/s) on July 28, 1952. No flow occurred several times prior to 1938, when the gaging station was about 0.2 mi (0.3 km) upstream from its present location. The minimum flow after 1938 was about 0.4 ft³/s (0.011 m³/s) which includes the discharge of Warm Springs, a tributary to the Gila River.

GROUND-WATER INFLOW

From 1963 to 1972, ground-water data were collected and analyzed as part of the Gila River Phreatophyte Project. The part of the Gila River Phreatophyte Project area within the boundaries of the reservoir (fig. 1) included an 8 mi (13 km) reach of the Gila River flood plain below the Calva gaging station. Computations of ground-water inflow into the reservoir were based on results of the project's ground-water analyses (Hanson and others, 1972; Hanson, 1972).

The geologic water-bearing units along the Gila River have been identified as alluvium and basin fill. The alluvium was deposited in a trench incised in the basin fill. Two components compose the alluvium: flood-plain alluvium and terrace alluvium. Terrace alluvium covers the basin fill in the trough and extends above the flood plain on the adjoining slopes. Flood-plain alluvium overlies the terrace alluvium in the flood-plain region and averages about 50 ft (15 m) in depth and 5,000 ft (1,500 m) in width. The basin fill extends a considerable distance up the slopes beyond the terrace alluvium.

Water enters the basin fill on the mountain slopes and moves generally toward the flood plain. Where the basin fill is in contact with the alluvium, sufficient head exists to create a slow upward movement of water from basin fill to the overlying alluvium. Another ground-water source into the reservoir is

TABLE 8.—*Mean monthly discharge of the Gila River below Coolidge Dam, 1931–71*

Month	Discharge, in acre-ft
Oct	8,580
Nov	5,980
Dec	6,640
Jan	3,160
Feb	6,920
Mar	16,330
Apr	21,140
May	20,800
June	24,050
July	25,880
Aug	21,840
Sept	18,110

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[1] Quoting from the 1971 annual report of U.S. Geological Survey surface-water records, Gila River below Coolidge Dam, Arizona, "*Records available.*—July to October 1899, April 1900 to March 1902, July to September 1902, December 1902 to December 1904, January to May 1905 (gage heights only), June to November 1905, August 1910 to February 1911 (gage heights only), April 1914 to current year. Published as 'at San Carlos' 1899–1911, as 'near San Carlos' 1914–1926, and as 'at Coolidge Dam' 1927–38."

downvalley flow through the saturated flood-plain alluvium. A small amount of ground water enters the reservoir from the alluvium deposited by tributary streams but is considered insignificant.

Downvalley ground-water movement in the Gila River flood plain alluvium has been computed at 5.1 acre-ft (0.0063 hm^3) per day (Hanson, 1972, p. 25). Hanson, Kipple, and Culler (1972, p. 317) estimated basin-fill inflow along the Gila River at 0.82 acre-ft (0.0010 hm^3) per day per 1,000 acres (4.05 km^2). This is equivalent to about 0.50 acre-ft (0.00062 hm^3) per day per downvalley mile, or 10.5 acre-ft (0.0129 hm^3) per day over the 21-mi (33.8 km) reach from the Calva streamflow station to the dam. The sum of the alluvial inflow and basin-fill inflow is 15.6 acre-ft (0.0192 hm^3) per day in the Gila River part of the reservoir.

Flood-plain alluvial flow (q) for the San Carlos River at Peridot was computed from the equation

$$q = K \cdot m \cdot w \cdot u \ , \qquad (3)$$

where K is the hydraulic conductivity estimated for Gila River flood-plain alluvium at 5,200 gal/day/ft^2 (212 $m^3/day/m^2$) and is assumed the same for the flood-plain alluvium along the San Carlos River, m is the depth of alluvium and is estimated to be 30 ft (9 m), w is the alluvial width of about 2,800 ft (850 m), u is the slope of the downvalley ground-water surface and is estimated to be equal to the downvalley flood-plain slope of 0.00275. Equation 3 gives q equal to 3.7 acre-ft (0.0046 hm^3) per day. The reach of the San Carlos River from the Peridot gaging station to the river mouth is 9.2 mi (14.8 km). Assuming that the San Carlos River flood plain has the same basin-fill inflow per unit area as the Gila River flood plain, the inflow per downvalley mile per day is 0.50 acre-ft (0.00062 hm^3) times the ratio of alluvium widths (2,800 ft/5,000 ft) for the two flood plains, or 0.28 acre-ft (0.00034 hm^3) per mile per day. Basin-fill inflow along the 9.2 mi (14.8 km) San Carlos River reach is therefore about 2.6 acre-ft (0.0032 hm^3) per day. The sum of the basin-fill and alluvial ground-water contribution from the San Carlos River basin is 6.3 acre-ft (0.0078 hm^3) per day.

PRECIPITATION

Records of precipitation at San Carlos Reservoir were obtained from National Weather Service publications and log books at Coolidge Dam. Table 9 includes annual precipitation totals for water years 1931-71. The mean annual precipitation was 13.87 in. (352 mm) and ranged from 6.46 in. (164 mm) in 1934 to 30.53 in. (775 mm) in 1941.

TABLE 9.—*Annual (water year) precipitation, in inches, at San Carlos Reservoir, 1931-71*

Water year	Precipitation	Water year	Precipitation	Water year	Precipitation
1931	15.57	1945	13.53	1959	11.74
1932	14.19	1946	11.56	1960	15.36
1933	13.49	1947	9.45	1961	11.02
1934	6.46	1948	9.27	1962	13.34
1935	19.64	1949	13.63	1963	14.87
1936	11.61	1950	11.14	1964	12.94
1937	12.98	1951	11.87	1965	14.00
1938	11.75	1952	18.61	1966	27.17
1939	10.65	1953	10.81	1967	13.34
1940	12.50	1954	19.16	1968	16.53
1941	30.53	1955	14.08	1969	13.41
1942	12.94	1956	9.05	1970	13.28
1943	11.82	1957	11.17	1971	8.85
1944	14.96	1958	19.87		

Mean monthly precipitation at San Carlos Reservoir for the period ranged from 0.21 in. (5.3 mm) in May to 2.19 in. (56 mm) in August. Seasonal trends are evident in the mean monthly precipitation data of table 10. The monthly extremes, also listed in table 10, indicate the large variation in precipitation. The mean precipitation for the summer season (July through October) is 5.89 in. (150 mm), or 42 percent of the mean annual total. Precipitation for the remainder of the year averaged 7.98 in. (203 mm) during the 41 years.

The volume of daily precipitation into the reservoir was computed as the product of daily precipitation measured at the San Carlos Reservoir weather station and the surface area of the water in storage for the day. Water year volumes of precipitation falling onto the water in storage are listed in table 17. From 1931 through 1971, the total accumulated volume of precipitation falling directly onto the water surface of the reservoir was computed as 203,900 acre-ft (251 hm^3), about 2.2 percent of reservoir input from all sources.

EVAPORATION

Evaporation from San Carlos Reservoir is significant because of the warm, dry environment in which the reservoir is located. Evaporation, as used in the San Carlos Reservoir water budget, is computed as direct loss from the surface area of the reservoir pool.

Daily pan evaporation data for water years 1931-71 were available for the weather station at San Carlos Reservoir. Saturday and holiday pan evaporation readings were omitted from 1930 through April 1948. The history of changes to the evaporation pan at the dam is available in the National Weather Service publication, "Substation History for Arizona."

Reservoir pool evaporation is computed as the product of measured pan evaporation and the evaporation pan coefficient. A daily volume of computed pool evaporation is the product of daily pan evaporation, the pan coefficient, and daily surface area of the

TABLE 10.—*Mean monthly precipitation and monthly extremes (1931–71) at San Carlos Reservoir*

Month	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
Mean monthly precipitation, in inches	0.88	1.07	1.80	1.44	1.33	1.28	0.52	0.21	0.33	1.62	2.19	1.20
Minimum monthly precipitation, in inches	.0	.0	.0	.0	.0	.0	.0	.0	.0	.08	.25	.0
Maximum monthly precipitation, in inches	4.28	3.73	8.53	4.00	3.26	6.02	2.29	.98	1.40	4.68	5.99	3.61

pool. Records of daily pool evaporation volumes have been published in annual reports of the Gila River Water Commissioner beginning in 1936. A pan coefficient of 0.7 was used by the Gila River Water Commissioner in computations of pool evaporation.

In December 1963, the U.S. Geological Survey established a station about 350 ft (107 m) from the San Carlos Reservoir weather station to collect radiation and air temperature data for use in computing pool evaporation by energy-budget and mass-transfer methods. Wind movements and water-surface temperature data were recorded on raft-mounted instruments at either one or two locations on the lake; the number and location of rafts was determined by the surface area of the pool. Streamflow temperature profiles (thermal surveys) of the pool were made every 2 or 3 weeks to measure changes in stored energy.

The energy-budget equation is based on the principle of conservation of energy. Measurements are made of most of the incoming and outgoing energy components and of changes in stored energy in the water body. The unmeasured energy remaining as a residual of the energy-budget equation includes energy for the evaporation process, energy of sensible-heat exchange, and energy advected by evaporated water. The energy-budget method has been described by Anderson (1954).

In the mass-transfer method, evaporation is treated as the turbulent transport of water vapor in the boundary layer overlying the water surface. The method requires data of wind speed, vapor pressure of the air, and vapor pressure of saturated air at water-surface temperature. A detailed description of the mass-transfer method is available in Marciano and Harbeck (1954).

Computations of lake evaporation were made by energy-budget and mass-transfer methods for 93 periods during 1964–71. Occasional incomplete data reduced the number of periods of reliable data to 72. A pan coefficient was computed for each period. The average pan coefficient was 0.80 for the 8 years of record.

Annual pan evaporation at San Carlos Reservoir is shown in the upper portion of figure 22 for water years 1931–71. Mean annual (water year) pan evaporation was 97.3 in. (2,470 mm), and water-year extremes ranged from the 1941 low of 83.6 in. (2,120 mm) to the high in 1939 of 111.4 in. (2,830 mm).

At San Carlos Reservoir, annual pan evaporation appears to have followed a downward trend, as indicated by the plot of 5-year moving averages shown in figure 22. During this same 41-year period, annual precipitation also indicates a decreasing trend (Burkham, 1970). This seems contradictory because the decrease in precipitation implied that evaporation potential might have increased. Thus, it was necessary to investigate further pan evaporation data at San Carlos Reservoir.

Pan evaporation is affected by the conditions of both the pan and the immediate environment, conditions which can change independently of changes in climate. In an attempt to evaluate the reliability of the pan evaporation data at San Carlos Reservoir, the data were compared with pan evaporation data at other Arizona stations. Figure 23 compares the 5-year moving average of pan evaporation at San Carlos Reservoir with the 5-year moving average of

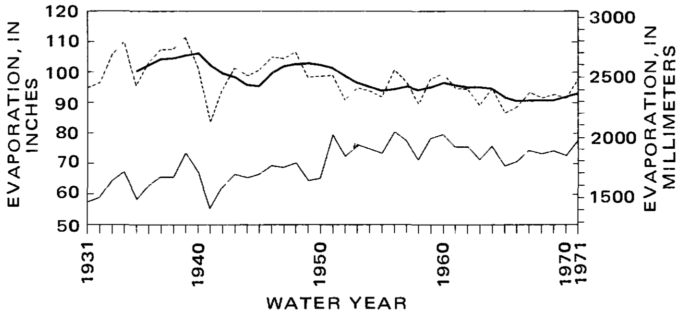

FIGURE 22.—Evaporation at San Carlos Reservoir for water years 1931–71.

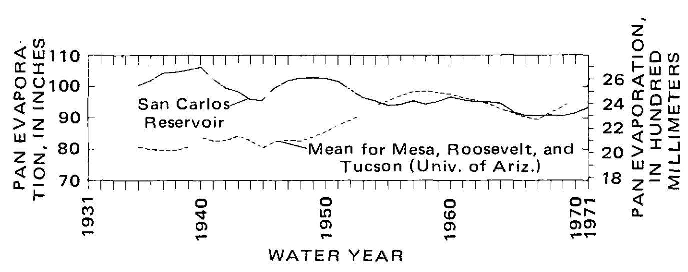

FIGURE 23.—Five-year moving averages of pan evaporation at San Carlos Reservoir and the mean of pan evaporation at Mesa, Roosevelt Lake, and at Tucson (Univ. of Ariz.) for water years 1931-71.

the mean of annual pan evaporation for Mesa, Roosevelt Lake, and Tucson (Univ. of Ariz.). The trend at San Carlos Reservoir is downward for much of the 1931-71 period as opposed to an upward trend at the other stations. Changes in the relation between the San Carlos Reservoir data and the mean of the other three stations were found to have occurred in about 1938 and 1950 by use of a double-mass curve (fig. 24). Accordingly, three separate time periods were used in computing evaporation from the reservoir: (1) 1931-38, (2) 1939-50, and (3) 1951-71.

For period 3, a pan coefficient of 0.78 was derived

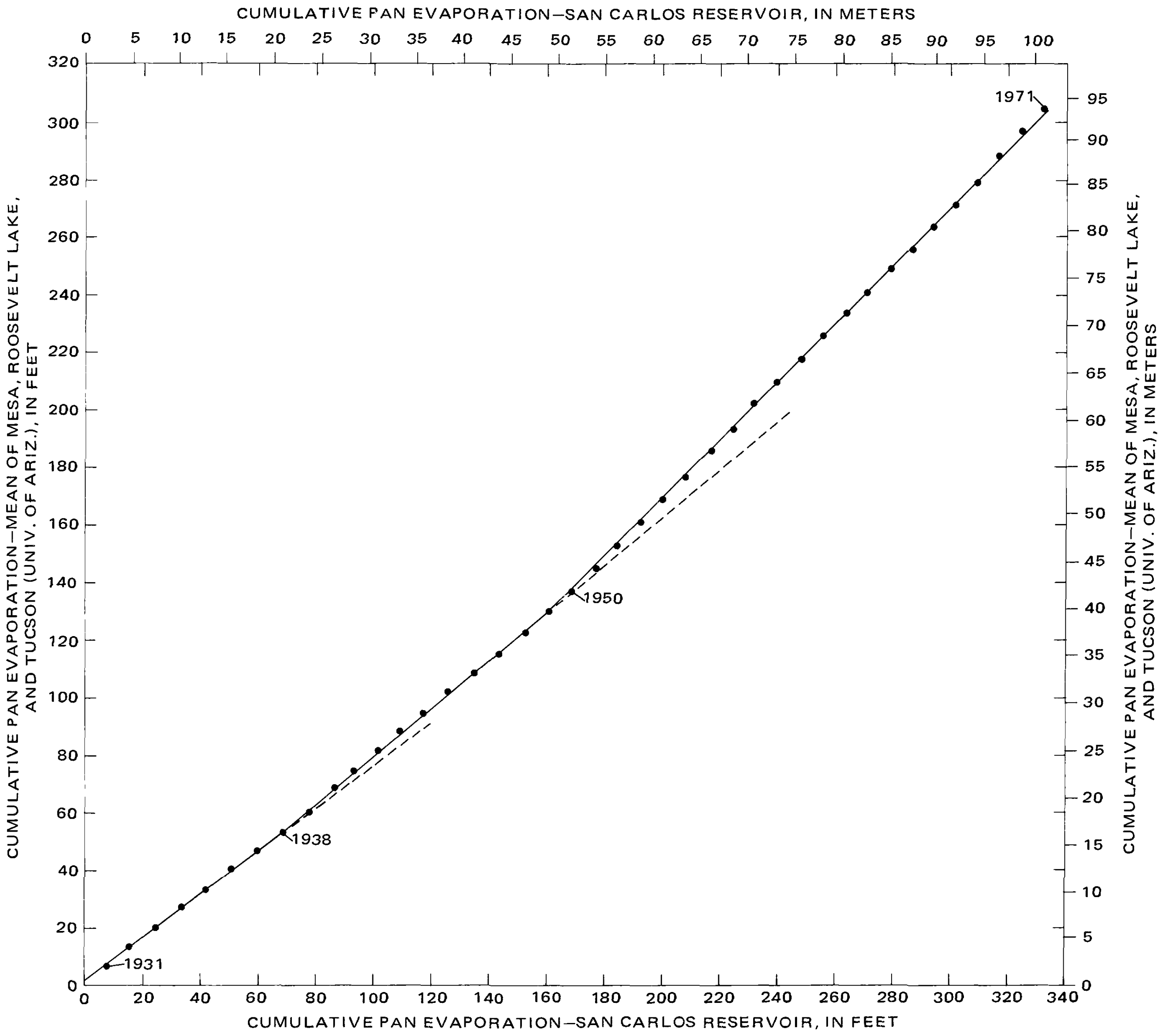

FIGURE 24.—Double-mass diagram of cumulative pan evaporation for San Carlos Reservoir and mean of Mesa, Roosevelt Lake, and at Tucson (Univ. of Ariz.) for water years 1931-71.

from computed lake evaporation at San Carlos Reservoir and the average of pan evaporation for Mesa, Roosevelt Lake, and Tucson (Univ. of Ariz.). This coefficient was assumed applicable in periods 1 and 2 also, when computing San Carlos Reservoir evaporation on the basis of pan evaporation at the other three stations. San Carlos Reservoir pan coefficients for periods 1 and 2 were 0.61 and 0.66, respectively, obtained from the relation: San Carlos Reservoir pan coefficient for a period equals computed lake evaporation divided by measured pan evaporation. Periods 1 and 2 pan coefficients were applied to annual pan evaporation measured at San Carlos Reservoir to compute annual lake evaporation. The annual pan evaporation, pan coefficients, and corresponding computed lake evaporation amounts for the 41-year study period are included in table 11. Computed lake evaporation is compared with the San Carlos Reservoir pan evaporation in figure 22. The annual lake evaporation expressed as volumetric loss is given in table 17. Mean annual depth of evaporation was 69.95 in. (1,780 mm) and represents 10.5 percent of the outflow from the reservoir. Mean monthly depths of evaporation from the lake are shown in table 12.

Monthly differences between the computed pan coefficients shown in table 12 are caused primarily by changes in available energy. There was not sufficient confidence in the computed monthly pan coefficients for use in computations of lake evaporation, although it is evident that the relation between pan evaporation and lake evaporation is subject to seasonal change.

WATER STAGE AND SURFACE-WATER STORAGE AT SAN CARLOS RESERVOIR

Prior to January 15, 1937, water stage was determined by use of reference points of known elevation on a series of stakes. A continuous record of lake stage was made from January 1937 through 1971 using a water-stage recorder. Daily stage records were applied to the elevation-capacity relations (fig. 3) to obtain daily reservoir storage contents. Daily records of stage and usable surface-water contents are published in the annual reports of the Gila River Water Commissioner. Usable surface-water storage data are also contained in annual U.S. Geological Survey reports. Figure 25 shows beginning-of-month reservoir stages for water years 1929-71. Total surface-water storage and change in surface-water storage were obtained from the yearly elevation-capacity ratings and are shown in table 18 by water year. The derivations of these ratings are described in the section "Development of Surface-Water Storage-Capacity Ratings."

TABLE 11.—*Evaporation at San Carlos Reservoir by water year 1931-71*

Water year	Pan evaporation (in.)	Pan coefficient	Computed lake evaporation (in.)
1931	94.47	0.61	57.63
1932	96.46	.61	58.84
1933	105.45	.61	64.32
1934	109.86	.61	67.01
1935	95.64	.61	58.34
1936	103.00	.61	62.83
1937	107.54	.61	65.60
1938	107.56	.61	65.61
1939	111.35	.66	73.49
1940	101.83	.66	67.21
1941	83.64	.66	55.20
1942	94.34	.66	62.26
1943	101.13	.66	66.75
1944	98.73	.66	65.16
1945	100.81	.66	66.53
1946	104.80	.66	69.17
1947	104.20	.66	68.77
1948	106.18	.66	70.08
1949	98.30	.66	64.88
1950	98.68	.66	65.13
1951	98.82	.80	79.06
1952	90.55	.80	72.44
1953	94.84	.80	75.87
1954	93.73	.80	74.98
1955	91.49	.80	73.19
1956	100.35	.80	80.28
1957	96.54	.80	77.23
1958	89.03	.80	71.22
1959	97.63	.80	78.10
1960	99.30	.80	79.44
1961	94.60	.80	75.68
1962	94.63	.80	75.70
1963	89.13	.80	71.30
1964	94.81	.80	75.85
1965	86.74	.80	69.39
1966	88.58	.80	70.86
1967	93.12	.80	74.50
1968	91.39	.80	73.11
1969	92.56	.80	74.05
1970	91.19	.80	72.95
1971	97.47	.80	77.98

TABLE 12.—*Mean monthly evaporation and mean monthly pan coefficients for San Carlos Reservoir*

Month	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
Mean monthly lake evaporation in inches, 1931-71	5.01	2.66	1.57	1.73	2.52	4.42	6.57	9.03	10.58	10.28	8.46	7.12
Mean monthly pan coefficients from energy-budget computations, 1964-71	.88	1.00	1.05	.74	.66	.68	.65	.69	.75	.79	.79	.86
Mean monthly pan coefficients from mass-transfer computations, 1964-71	.90	1.10	.93	.71	.68	.66	.66	.70	.71	.83	.82	.79

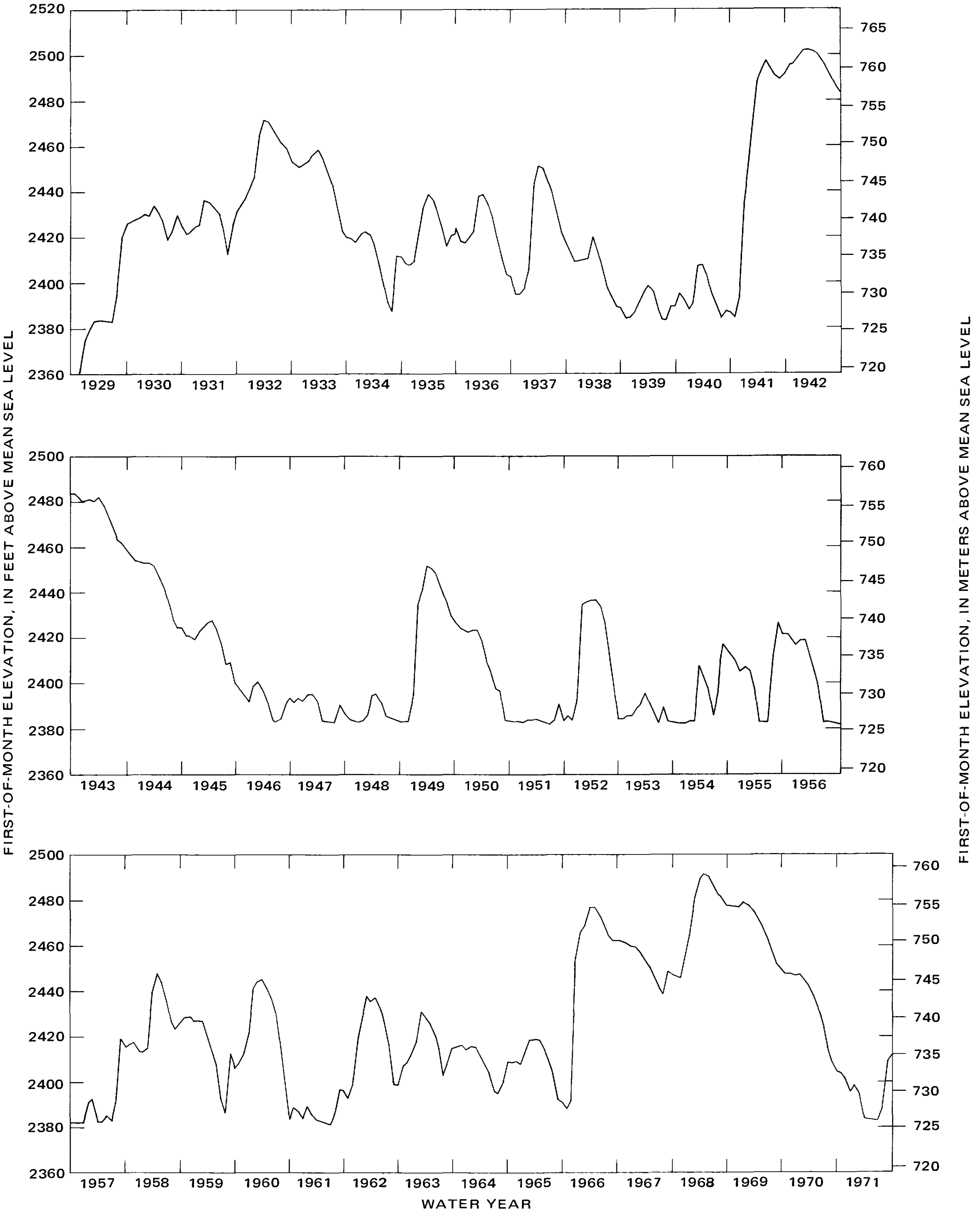

FIGURE 25.—Beginning-of-month lake stage of San Carlos Reservoir for water years 1929–71.

The highest reservoir stage of record (1929–71 water years) was 2,501.62 ft (762.49 m) above mean sea level on March 18, 1942[2]. Usable surface-water storage at that elevation was 819,200 acre-ft (1,010 hm^3) using 1947 capacity tables. This storage is about 83 percent of the usable surface-water storage capacity at 2,511 ft (765 m). Other peak stages recorded were 2,491.17 ft (759.31 m) in 1968 and 2,477.30 ft (755.08 m) in 1966. Usable surface-water storages at these elevations were 643,324 acre-ft (793 hm^3) and 417,673 acre-ft (515 hm^3) using 1966 elevation-capacity tables.

The minimum stage has fallen to, or below, the lowest outlet elevation of 2,382.63 ft (726.22 m) at some time during 14 of the 43 years of record. At other times, inflow was barely sufficient to keep the pool level above the stage of zero usable surface-water storage. The pool level was below 2,385 ft (727 m) elevation about 15 percent of the time and can occur at any time of the year.

A summation of the number of days in which mean daily stage was within a prescribed elevation interval was needed prior to frequency analyses of storage. Figure 26 is a graph and listing of the number of daily occurrences within each 5-ft (1.5-m) stage interval.

The cumulative number of days for which the lake stage was above a specified elevation is expressed as a percentage of the total days of record in figure 27. Figure 27 shows that stage exceeded elevation 2,439 ft (743 m) only 25 percent of the time. Elevation 2,416 ft (736 m) was exceeded 50 percent of the time, and elevation 2,392 ft (729 m) was exceeded 75 percent of the time.

Figure 28 is a time-storage curve which shows the percentage of time that usable surface-water storage was equal to or greater than a given volume, based upon first-of-month storages. Usable surface-water storage exceeded 176,000 acre-ft (217 hm^3) only 25 percent of the time, 64,000 acre-ft (78.9 hm^3) 50 percent of the time, and 11,000 acre-ft (13.6 hm^3) 75 percent of the time.

Table 13 shows the usable surface-water storage available at the beginning of each month at 25, 50, 75, and 100 percent of the time, as an indicator of seasonal availability.

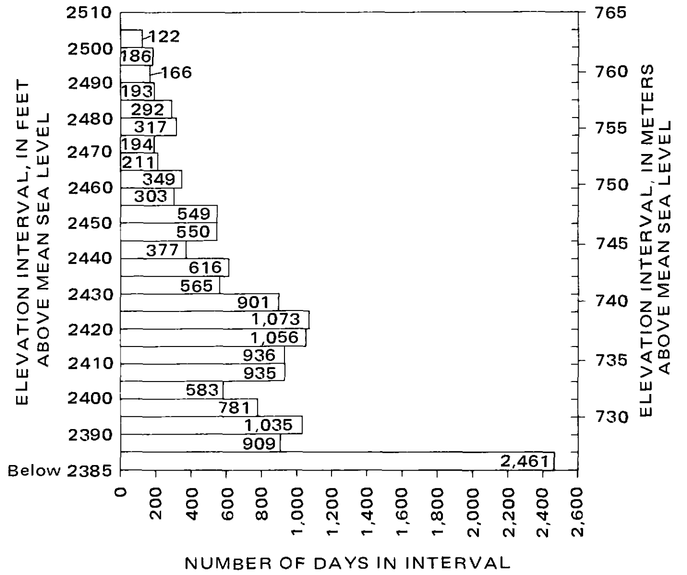

FIGURE 26.—Number of days in which lake stage was within a particular elevation interval for water years 1929–71.

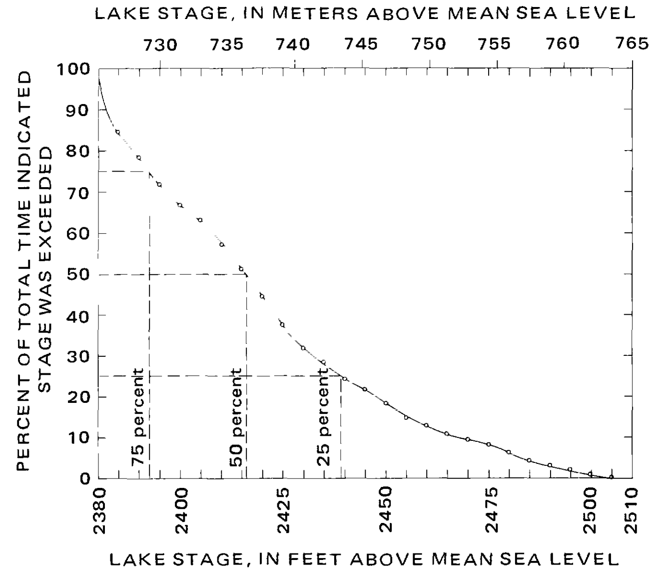

FIGURE 27.—Percentage of time lake stage of San Carlos Reservoir equaled or exceeded a given elevation for water years 1929–71.

BANK STORAGE

A part of the total storage in a reservoir in addition to surface-water storage is bank storage. In some reservoir water budgets, the change in bank storage has been treated as being equal to the residual of a water-budget equation, even when the residual included significant evapotranspiration losses, ground-water inflow, and so forth. For this investigation the change in bank storage is considered a separate water-budget component. The symbols for the reservoir storage terms are as follows:

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[2] Prior to January 1, 1948, gage datum was 0.72 ft (0.22 m) below mean sea level. (See U.S. Geological Survey, 1954, p. 636). No adjustments were made in this report for the datum change except that the peak stage listed has been adjusted to datum used after January 1948. The error in the water budget introduced by datum change is small because the computed annual change in surface-water storage is not significantly affected.

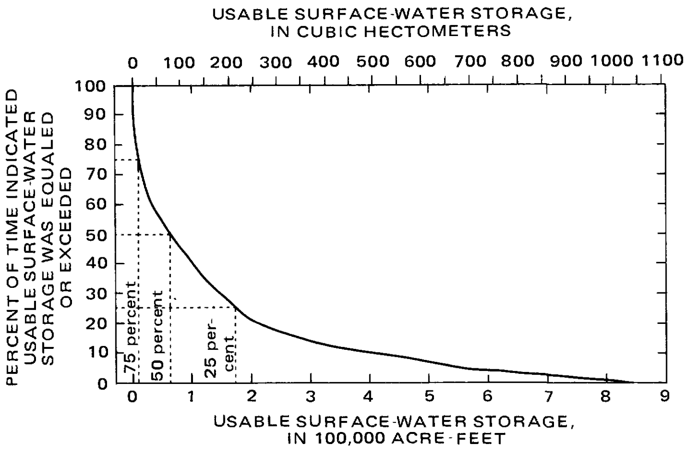

FIGURE 28.—Percentage of time usable surface-water storage at San Carlos Reservoir equaled or exceeded a given volume for water years 1929–71.

S_T is the total water in storage,
S_R is water contained in surface-water storage,
S_B is the water contained in bank storage, and
Δ indicates the change in an associated storage term.

Inflow and outflow from bank storage can be computed by use of combined water-budget and modeling methods for some reservoirs, as demonstrated by Simons and Rorabaugh (1971). At San Carlos Reservoir insufficient ground-water data were collected to model aquifer response. However, by applying the water budget of the reservoir to selected short periods during the winter, estimates of bank storage were made.

The change in bank storage, ΔS_B, at San Carlos Reservoir was estimated for short budget periods by solving a modified form of equation 1. The periods selected included winter months when ΔS_B was a significant budget component and when evapotranspiration, O_{ET}, was insignificant. Tributary flow was not included because no flow was assumed in winter (Burkham, 1974). Equation 1 as applied was

$$\Delta S_B = I_G + I_S + I_P + I_{GW} - O_G - O_E \pm \Delta S_R. \quad (4)$$

The rate of change in bank storage is dependent upon the change in surface-water storage, ΔS_R, so it is important that ΔS_R be small for a month or more before and after the evaluation period. Table 14 illustrates the application of equation 4 in computing ΔS_B for the winter period January through April of 1965.

ΔS_B was determined for each of 23 winter periods of significant ΔS_B increases. ΔS_B was not determined for periods of decreasing S_B because all periods of a significant decrease in S_B corresponded to periods of high evapotranspiration rates.

Several procedures were used to investigate the

TABLE 13.—*Percentage of time that available monthly surface-water storage was less than amount shown*

Percentage of time	Usable surface-water storage, in acre-ft											
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
25	6,820	3,150	11,200	8,700	20,100	29,100	35,700	21,000	12,700	950	5,000	8,200
50	50,300	48,000	46,000	55,000	93,400	104,000	113,000	115,000	97,000	70,100	44,000	47,000
75	113,000	103,000	107,000	138,000	198,000	194,000	260,000	235,000	203,000	165,000	140,000	116,000
100	689,000	744,000	752,000	802,000	835,000	843,000	841,000	816,000	779,000	727,000	676,000	659,000

TABLE 14.—*Example of water budget used to determine change in bank storage*

Month (water year 1965)	Water surface stage (ft)[1]	Change in stage (ft)	Surface-water storage, S_R (acre-ft)	Change in surface-water storage, ΔS_R (acre-ft)	Inflow[2] (acre-ft)	Outflow[3] (acre-ft)	Change in total storage, ΔS_T[4] (acre-ft)	Change in bank storage, ΔS_B[5] (acre-ft)
Jan	2,407.47	5.88	29,790	15,464	18,986	619	18,367	2,903
Feb	2,413.35	5.28	45,254	16,446	24,840	4,810	20,030	3,584
Mar	2,418.63	.33	61,700	1,069	17,327	14,715	2,612	1,543
Apr	2,418.96	-.45	62,769	-1,458	10,642	11,748	-1,106	352
	2,418.51		61,311					
Jan–Apr totals		11.04		31,521			39,903	8,382

ΔS_B/ft = 759 acre-ft/ft
$\Delta S_B/\Delta S_T$ = .210
$\Delta S_B/\Delta S_R$ = .266

Average stage = 2,412.99 ft
Average S_R = 45,550 acre-ft
Elevation corresponding to average S_R = 2,413.45 ft

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[1] Values for beginning and end of month.

[2] Inflow is the sum of Gila River inflow, San Carlos River inflow, precipitation on water surface, and ground-water inflow.

[3] Outflow is the sum of Gila River outflow and evaporation.

[4] ΔS_T equals inflow minus outflow.

[5] $\Delta S_B = \Delta S_T - \Delta S_R$.

relation between bank-storage capacity, S_B, and water-surface stage. In the first procedure, the ratio $\Delta S_B/\Delta S_R$ was compared to stage, where ΔS_B and ΔS_R values were from the water budgets. In the second procedure, the ratio $\Delta S_B/\Delta S_T$ was compared to stage. ΔS_T is the change in total storage, computed in the water budget as the difference between inflow and outflow components. Relations of ΔS_B to ΔS_R and ΔS_B to ΔS_T are shown in figure 29 for two winter budget periods. The need for extending the time period of the water budget past the period of rapidly increasing surface-water storage is obvious in the upper ends of the curves in figure 29*A*. These curves show S_R and S_T decreased during April but S_B increased because of the time lag between inflow into surface-water storage and subsequent movement into bank storage. Figure 29*B* is included to show the small increase in S_B, when compared to changes in S_R and S_T, in December 1967 and January 1968. This condition occurred because gravity drainage from bank storage was incomplete at the start of the period. As a result, only the February through May period of 1968 was used in the analyses of bank storage. Figure 29*A* also shows that the cumulative plots of ΔS_B versus ΔS_R and ΔS_T define the ratios $\Delta S_B/\Delta S_T$ and $\Delta S_B/\Delta S_R$ from the slopes of lines drawn from the start to end of the period.

The third and principal procedure of analyzing bank storage at San Carlos Reservoir was based on the relation between a change in bank storage and a change in stage. The computed ΔS_B for a budget period was divided by the range in stage, giving the rate ΔS_B/ft. Because each rate, ΔS_B/ft, is related to a specific range of stage, the rate must be associated with the stage which seems most representative of the budget period. A representative water-surface stage is easily obtained from either of two calculations. The first calculation simply determines the mean of the beginning and ending stages for the period. In the second calculation, considered better, the mean value of the beginning and ending surface-water storages for the period is applied to elevation versus surface-water capacity tables to obtain the corresponding stage. The stage for each period is plotted against the corresponding ΔS_B/ft of the period to define the ratings of ΔS_B and stage as shown in figure 30 for San Carlos Reservoir data. The winter stage and storage data obtained from the water budget of the reservoir and used in the above three procedures are tabulated in table 15.

The 1931-47 stage and storage data define one curve of figure 30, and the other was defined by data of 1948-71. The shift in the rating with time reflects an increase in bank storage due to sediment accumulation in the reservoir. The data were inadequate to define more than the two ratings shown in figure 30. Much of the scatter exhibited by points from the 1931-47 data is due to inaccuracies in the early

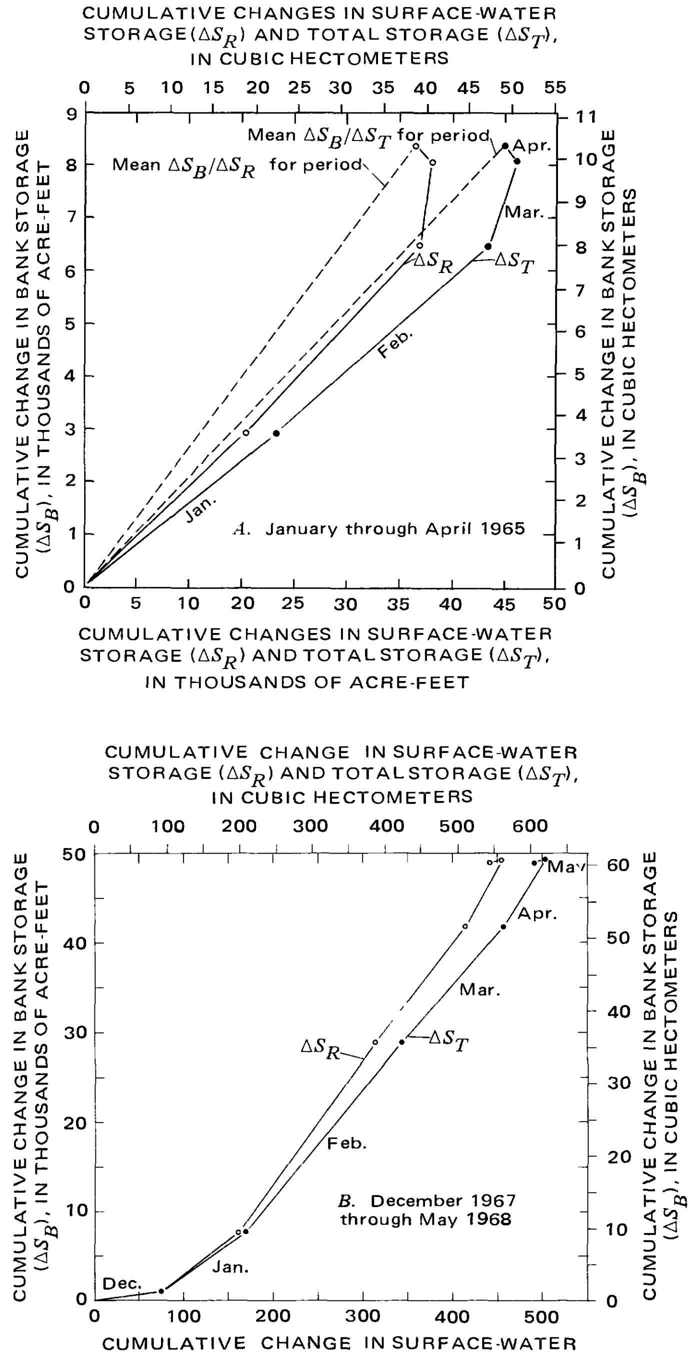


FIGURE 29.—Relations of cumulative ΔS_B to cumulative ΔS_R and cumulative ΔS_B to cumulative ΔS_T for the periods (*A*) January through April 1965 and (*B*) December 1967 through May 1968.

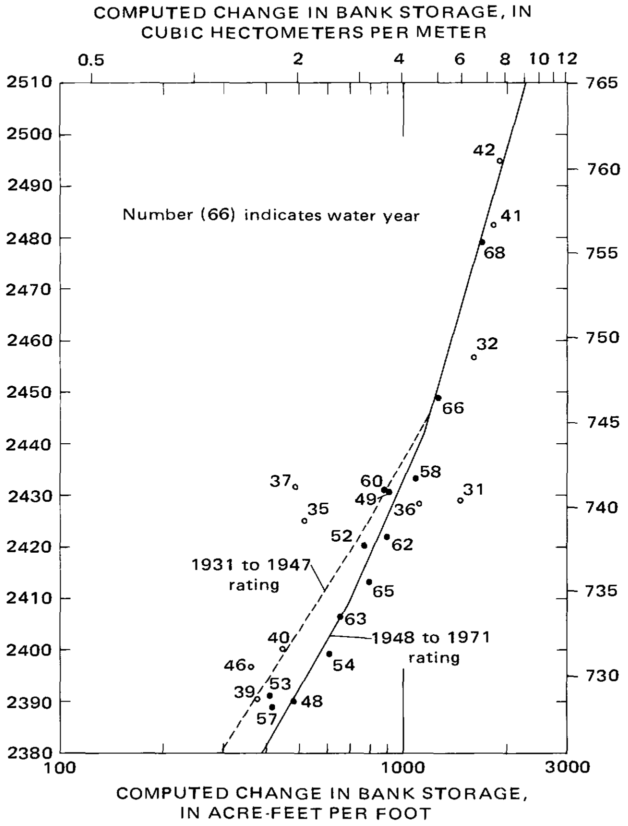


FIGURE 30.—Relation between the computed change in bank-storage capacity and elevation at San Carlos Reservoir for water years 1931-47 and 1948-71.

capacity surveys. The data points for 1931 and 1932 include an increment of water which went into nonretrievable bank storage when the reservoir initially filled.

Table 16 includes usable bank storage capacity ratings for the 1931-47 and 1948-71 periods based on figure 30. It was not practical or necessary to make an elevation-capacity rating of total bank storage because an estimate of bank dead storage would have been required.

The usable bank-storage capacity at the spillway elevation of 2,511 ft (765 m) was about 152,800 acre-ft (188 hm^3) for 1931-47 and about 159,200 acre-ft (196 hm^3) for 1948-71 (table 16). At this elevation, usable bank-storage capacity is about 14 percent of total usable storage capacity. At lower reservoir elevations, table 16 shows that usable bank storage sometimes exceeds usable surface-water storage.

S_B is never static because of the time of response required to adjust to changes in S_R. However, the quantity of water required to place S_B and S_R in equilibrium at the end of a water year is usually small in comparison to water-year budget totals and for expediency was assumed zero.

The fact is stressed that reservoir water availability is more than just the amount in usable surface-water storage. Figure 31 shows this difference by comparison of 1966 ratings of usable surface-water storage capacity and total usable storage capacity.

WATER-BUDGET ANALYSES

The water budget utilizes the conservation of mass equation

$$I - O = \Delta S, \qquad (5)$$

where I is inflow, O is outflow, and ΔS is change in storage. Identification of all the I, O, and ΔS components included in the water budget of San Carlos Reservoir is given in equation 1.

The water budget was computed by months and by water years for the 41 years of record using equation 1. Data for all the yearly inflow and outflow budget components except O_{ET} are recorded in table 17. Analyses of computed O_{ET} data are included in the following section on evapotranspiration. Table 18 lists the storage values, ΔS_R and ΔS_B, the summation of the inflow and outflow components given in table 17, and the evapotranspiration, O_{ET}, for each water year during the 41-year period of record.

The data in tables 17 and 18 were used to compare the magnitude of each inflow component with the total inflow for the period 1931-71. The outflow components were compared similarly. Gila River streamflow contributed 78.2 percent of the total inflow; the San Carlos River, 14.5 percent; ground water, 3.5 percent; precipitation, 2.2 percent; and tributary flow, 1.6 percent. The outflow components and percent of total outflow are: Gila River, 78.2 percent; evapotranspiration, 11.3 percent; and lake surface evaporation, 10.5 percent. Figure 32 compares the relative magnitude of each component.

EVAPOTRANSPIRATION

Water loss by evapotranspiration (*ET*) from the exposed surface of San Carlos Reservoir occurs by plant transpiration and by evaporation from soil, litter, and ephemeral ponds. Water in the reservoir area becomes available for *ET* by movement from streams, ground water, reservoir surface-water storage, and by direct precipitation on the exposed surface. Annual *ET* computed by equation 1 is listed in table 18 and plotted in figure 33.

Large errors in the computed *ET* losses occur when one or more of the hydrologic components of the reservoir are in a state of rapid transition at the end of a budget period. The annual *ET* shown in figure 33

TABLE 15.—*Results of procedures to determine bank storage capacity at San Carlos Reservoir*

Water year	Period included	ΔS_I (acre-ft)	ΔS_R (acre-ft)	ΔS_B (acre-ft)	Starting and ending elevations (ft)	Mean elevation (ft)	Mean S_R (acre-ft)	Elevation of mean S_R (ft)	$\frac{\Delta S_B}{\Delta S_T}$	$\frac{\Delta S_B}{\Delta S_R}$	$\frac{\Delta S_B}{\text{ft}}$
1931	Nov.-Mar.	92,277	71,812	20,465	2421.76 2435.66	2428.71	163,059	2429.20	0.222	0.285	1,472
1932	Dec.-Apr.	323,063	270,007	53,056	2437.73 2470.90	2454.31	338,814	2456.68	.164	.196	1,600
1935	Dec.-Apr.	136,282	121,428	14,854	2407.76 2436.31	2422.03	122,006	2424.65	.109	.122	520
1936	Jan.-Apr.	88,530	71,804	16,726	2420.04 2435.00	2427.52	137,102	2428.15	.189	.233	1,118
1937	Jan.-Apr.	264,946	239,274	25,672	2397.78 2450.46	2424.12	153,975	2431.80	.097	.107	487
1939	Nov.-Apr.	22,826	18,513	4,313	2384.10 2396.26	2390.18	19,935	2390.86	.189	.233	355
1940	Jan.-Mar.	49,777	40,906	8,871	2387.96 2407.94	2397.95	35,185	2400.03	.178	.217	444
1941	Mar.-June	359,660	312,877	46,783	2468.09 2493.92	2481.00	578,220	2482.04	.130	.150	1,811
1942	Sept.-Mar.	215,359	190,272	25,087	2488.80 2501.98	2495.39	753,257	2495.24	.116	.132	1,903
1946	Jan.-Feb.	17,718	14,577	3,141	2391.87 2400.59	2396.23	21,236	2396.69	.177	.215	360
1948	Jan.-Apr.	18,858	12,962	5,896	2383.03 2395.33	2389.18	10,521	2390.08	.313	.455	479
1949	Dec.-Apr.	312,140	251,306	60,834	2383.18 2450.70	2416.94	129,452	2430.58	.195	.242	901
1952	Dec.-Mar.	196,070	155,216	40,854	2383.33 2436.55	2409.94	80,936	2420.16	.208	.263	768
1953	Jan.-Mar.	14,686	10,544	4,142	2385.53 2395.65	2390.59	9,690	2391.44	.282	.393	409
1954	Mar.	51,082	36,336	14,746	2383.19 2407.50	2395.34	21,043	2394.74	.289	.406	607
1957	Jan.-Feb.	11,715	7,422	4,293	2382.50 2392.86	2387.68	5,795	2389.00	.366	.578	414
1958	Feb.-Apr.	204,404	167,062	37,342	2413.04 2447.30	2430.17	133,899	2433.59	.183	.224	1,090
1960	Nov.-Mar.	196,941	163,768	33,173	2408.03 2445.25	2426.64	117,198	2430.93	.168	.203	891
1962	Nov.-Apr.	181,480	141,049	40,431	2392.17 2437.22	2414.70	77,624	2421.96	.223	.287	897
1963	Oct.-Dec.	39,560	30,557	9,003	2398.57 2412.27	2405.42	29,343	2406.40	.228	.295	657
1965	Jan.-Apr.	39,904	31,521	8,383	2407.47 2418.51	2412.99	45,550	2413.46	.210	.266	799
1966	Nov.-May	520,735	414,683	106,052	2388.17 2472.32	2430.24	210,140	2448.77	.204	.256	1,260
1968	Feb.-May	320,492	279,289	41,203	2466.03 2490.27	2478.15	488,088	2479.03	.129	.148	1,700

for 1941 is an example of this condition. This error is compensated, however, by an error of equal magnitude but of opposite sign during the following year(s) and is of no significance in the 41-year mean annual *ET* rate.

Determination of the size of the "exposed surface area of the reservoir" is a prerequisite to computing the *ET* by depth. The reservoir area at 2,525 ft (770 m) is 19,925 acres (8,064 hm^2). This area excludes approximately 60 acres (24 hm^2) which lie within the reservoir boundary but are upstream from the Gila River Calva station. Added to the reservoir area, however, are 925 acres (374 hm^2) in the San Carlos River flood plain between the Peridot gaging station and the reservoir boundary, giving a total of 20,850 acres (8,438 hm^2) as the maximum area possible for *ET* loss. At any specific time, the exposed surface area available for *ET* loss is 20,850 acres (8,438 hm^2), less the lake surface area.

Surface conditions on the exposed area ranged from open bodies of shallow water to dense phreatophytes and from wet to very dry soil. Optimum surface conditions for high *ET* exist over a large reservoir area following a major lake stage recession such as occurred in 1942–45.

The computed volume of monthly *ET* was divided by the mean monthly exposed area providing a value of monthly *ET* depth. Water year totals of these monthly *ET* depths are listed in table 19 and are plotted in figure 34. The computed mean annual depth of *ET* was 1.47 ft (0.448 m).

For each month, 41 values of *ET* depths were available from the water budget. All monthly values were used to indicate the most common range in *ET* for

TABLE 16.—*San Carlos Reservoir elevation-capacity tables of usable bank storage, usable surface-water storage, and total usable storage*

Elevation (ft)	Period 1931-47			Period 1948-71		
	Cumulative usable storage, in acre-ft			Cumulative usable storage, in acre-ft		
	Bank S_B	Surface water S_R	Total S_T	Bank S_B	Surface water S_R	Total S_T
2382.63[1]	0	[2] 0	0	0	[3] 0	0
2385	770	1,735	2,505	1,006	660	1,666
2390	2,520	6,668	9,188	3,269	2,845	6,114
2395	4,483	13,249	17,732	5,769	6,728	12,497
2400	6,670	22,041	28,711	8,531	12,865	21,396
2405	9,095	33,468	42,563	11,581	21,749	33,330
2410	11,795	46,941	58,736	14,931	33,308	48,239
2415	14,820	62,474	77,294	18,581	47,343	65,924
2420	18,185	80,102	98,287	22,531	63,284	85,815
2425	21,945	100,411	122,356	26,806	81,217	108,023
2430	26,095	124,115	150,210	31,431	102,202	133,633
2435	30,670	150,760	181,430	36,431	126,269	162,700
2440	35,720	180,020	215,740	41,831	153,572	195,403
2445	41,270	212,197	253,467	47,606	184,059	231,665
2450	47,295	247,463	294,758	53,706	217,811	271,517
2455	53,720	285,832	339,552	60,131	254,977	315,108
2460	60,495	327,993	388,488	66,906	295,976	362,882
2465	67,620	374,278	441,898	74,031	341,707	415,738
2470	75,120	424,606	499,726	81,531	392,073	473,604
2475	83,020	478,736	561,756	89,431	445,822	535,253
2480	91,320	536,141	627,461	97,731	502,827	600,558
2485	100,020	597,432	697,452	106,431	503,363	669,794
2490	109,145	662,965	772,110	115,556	627,710	743,266
2495	118,720	732,575	851,295	125,131	696,272	821,403
2500	128,770	806,491	935,261	135,181	770,200	905,381
2505	139,345	884,898	1,024,243	145,756	848,607	994,363
2510	150,470	967,746	1,118,216	156,881	931,456	1,088,337
2511	152,750	984,874	1,137,624	159,161	948,584	1,107,745
2515	162,170	1,055,286	1,217,456	168,581	1,018,996	1,187,577

[1] Elevation of zero usable storage.
[2] From 1947 tables of usable surface storage.
[3] From 1966 tables of usable surface storage.

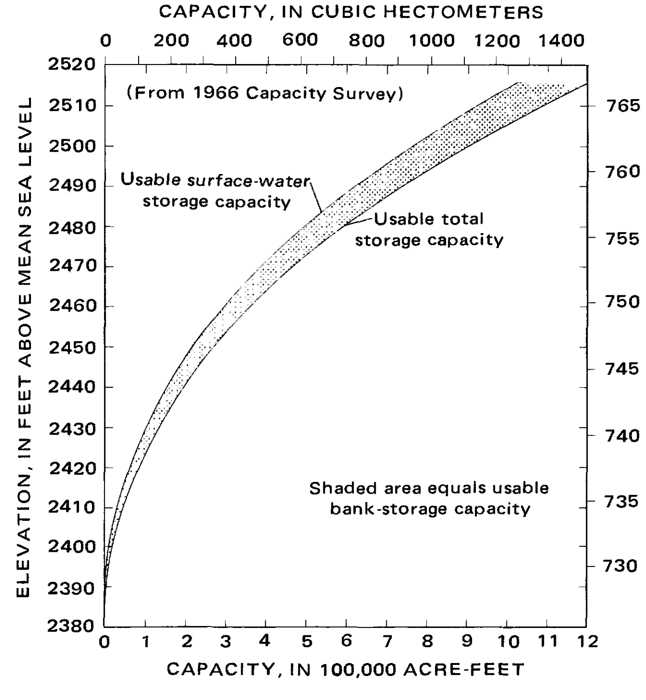


FIGURE 31.—Elevation-capacity relations for usable surface-water storage, usable bank storage, and total usable storage in 1966, for San Carlos Reservoir.

each month, to show the monthly extremes, and to illustrate the seasonal *ET* trend. In figure 35, the range of the central two-thirds of the values for each month is bracketed. This approximately corresponds to the number of values included in one standard deviation. The seven values above and seven below the bracketed range were plotted for each month. The monthly medians have also been identified in figure 35. The occurrences of extreme values of computed *ET* usually coincide with periods of vigorous change in one or more water-budget components. An unrealistic extreme resulted when bank storage had not adjusted to the change in stage, although changes in lake stage and changes in bank storage were assumed simultaneous in water-budget computations. The mean annual *ET* of the monthly medians in figure 35 is 1.45 ft (0.442 m). This value corresponds to the mean of the annual *ET* values in figure 34, computed as 1.47 ft (0.448 m).

The seasonal trend of *ET* is obvious in figure 35 in spite of the large scatter exhibited. After excluding extreme values (outliers) the data were examined for possible changes in rates over the life of the reservoir and for obtaining more realistic values of mean monthly *ET* depths. The monthly data were separated into 4 periods of 10 years each, beginning with 1931. Within a 10-year period, the maximum and minimum extremes were omitted from the 10 values for each month, and a mean monthly *ET* was obtained from the 8 remaining values. Figure 36

TABLE 17.—*Summations of San Carlos Reservoir inflow-outflow components by water year, 1931–71*

	Inflows for year in acre-ft						Outflows for year in acre-ft		
Water year	Gila River	San Carlos River	Precipitation	Ground water	Tributary	Total inflow	Gila River	Evaporation	Total outflow[1]
1931	289,917	36,677	5,850	7,994	3,580	344,018	223,920	23,008	246,928
1932	442,175	51,950	9,565	8,015	1,760	513,465	256,150	44,455	300,605
1933	149,072	16,802	7,399	7,994	2,460	183,727	334,910	36,244	371,154
1934	160,085	13,733	1,895	7,994	2,660	186,368	184,660	15,416	200,076
1935	149,423	87,670	6,684	7,994	4,020	255,791	184,553	21,554	206,107
1936	150,165	44,559	3,659	8,015	1,760	208,157	228,090	22,162	250,252
1937	317,944	46,630	3,717	7,994	1,760	378,046	279,621	29,436	309,057
1938	106,170	15,713	2,505	7,994	1,760	134,142	189,720	14,321	204,041
1939	91,500	18,378	1,362	7,994	1,760	120,994	102,426	9,365	111,791
1940	158,275	15,858	1,891	8,015	1,760	185,799	160,720	10,323	171,043
1941	803,991	201,192	22,378	7,994	6,990	1,042,546	215,724	54,381	270,105
1942	314,222	25,273	16,250	7,994	2,410	366,150	352,030	74,465	426,495
1943	102,531	30,191	10,954	7,994	2,200	153,870	365,140	60,302	425,442
1944	80,725	13,161	7,512	8,015	6,070	115,483	297,430	34,186	331,616
1945	131,705	17,038	3,863	7,994	3,010	163,610	216,290	20,734	237,024
1946	55,627	15,233	1,245	7,994	4,850	84,949	74,550	7,049	81,599
1947	45,607	11,141	796	7,994	3,550	69,088	59,983	5,467	65,450
1948	63,511	10,390	620	8,015	2,530	85,066	68,270	5,913	74.183
1949	422,114	23,192	3,863	7,994	2,680	459,843	254,061	29,914	283.975
1950	37,441	5,908	2,709	7,994	2,530	56,583	148,860	13,692	162.552
1951	35,304	9,134	808	7,994	2,930	56,170	36,347	4,866	41.213
1952	191,624	80,840	4,658	8,015	2,620	287,758	229,435	22,710	252 145
1953	42,937	8,384	861	7,994	1,760	61,936	49,319	5,983	55.302
1954	116,372	42,254	2,345	7,994	7,430	176,396	68,964	10,579	79,543
1955	123,593	26,899	3,194	7,994	6,960	168,639	97,710	12,342	110,052
1956	20,858	13,886	2,053	8,015	1,760	46,572	109,062	12,572	121.634
1957	128,264	9,136	586	7,994	1,760	147,740	52,123	5,288	57,411
1958	296,372	47,883	5,676	7,994	6,420	364,345	243,220	28,118	271.338
1959	97,574	6,419	2,290	7,994	5,920	120,197	147,870	15,965	163 835
1960	193,693	64,990	3,809	8,015	3,940	274,447	256,896	26,884	283 780
1961	45,499	6,189	461	7,994	5,080	65,223	25,312	2,449	27,761
1962	275,405	33,567	2,650	7,994	2,980	322,596	246,730	21,971	268 701
1963	175,069	34,123	3,340	7,994	3,580	224,106	141,430	18,074	159 504
1964	94,351	10,301	1,697	8,015	7,620	121,984	107,170	12,697	119 867
1965	90,948	24,550	2,803	7,994	1,940	128,234	121,999	13,688	135 687
1966	533,205	119,391	13,948	7,994	8,580	683,118	226,476	53,587	280 063
1967	148,375	11,295	7,697	7,994	5,800	181,162	255,250	44,067	299.317
1968	579,171	72,822	12,339	8,015	1,760	674,107	281,340	70,871	352.211
1969	60,545	15,599	11,171	7,994	2,480	97,789	315,376	59,744	375 120
1970	31,214	12,502	5,889	7,994	3,560	61,159	218,860	28,413	247,273
1971	59,775	19,247	861	7,994	3,920	91,786	57,463	5,777	63 240
1931–71 totals	7,412,348	1,370,100	203,853	327,964	148,890	9,463,160	7,485,460	1,009,032	8,494.492

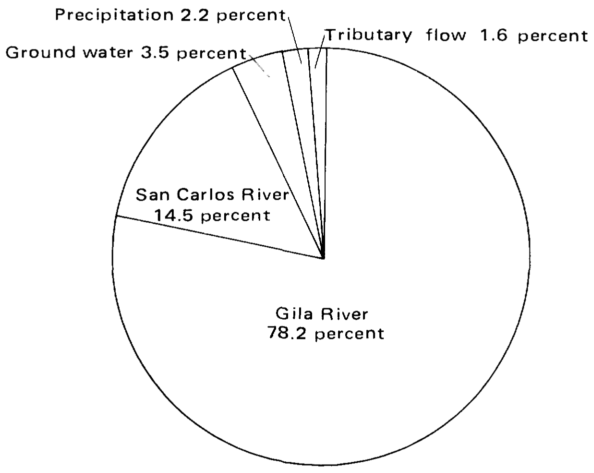
[1] Does not include evapotranspiration losses.

shows the resulting monthly means for each 10-year period. The seasonal trend is apparent for all four periods, but no obvious changes in *ET* rates can be detected during the life of the reservoir.

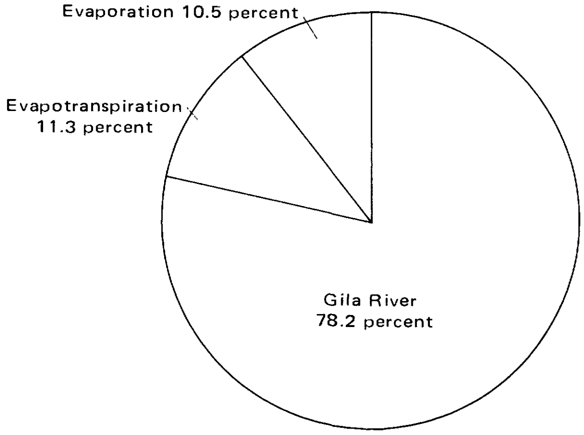
The average of the annual mean *ET* values computed from these four periods is 1.51 ft (0.460 m), which is slightly higher than that obtained when the maximum and minimum extremes are included in the computation. The monthly mean and median *ET* values and the water-year means from the data shown in figures 35 and 36 are listed in table 20.

Two characteristics can be noted about the seasonal trends in the computed *ET* values shown in figures 35 and 36. First, the computed *ET* is essentially zero during the winter months from December through February in part because zero *ET* was used in the development of the bank-storage ratings. Second, the reservoir surface-water storage normally increases during August, and the bank storage response to this increase does not approach equilibrium until sometime in September. As a result, August *ET* was often underestimated and September *ET* overestimated.

Vegetation increased on the exposed areas of the reservoir flood plain, especially following the 1941–42 floods (Turner, 1974, fig. 4). If an increasing trend in *ET* could have been conclusively shown, changes in *ET* would have been correlated with the increase in vegetation. Data used in figure 34 were examined for an indication of increased *ET*, since no increasing trend was evident in figure 36. Mean annual *ET* was computed for the selected periods shown in figure 34. Only those periods of least stage change were used, thereby eliminating periods when soil-moisture content was high over large areas. Thus, a greater percentage of the total *ET* should have been through transpiration and not by evaporation from exposed areas of bare ground. Mean annual *ET* depths were computed as 0.93 ft (0.28 m) from 1934 to 1940, 1.07 ft (0.33 m) from 1945 to 1957, and 1.48 ft (0.45 m) from 1959 to 1965. This shows an apparent increase in *ET*, but as figure 34 indicates, the range in annual



INFLOW



OUTFLOW

FIGURE 32.—Relative magnitude of inflow and outflow water-budget components.

amounts during each period is too great to state definitely that the increase is related to vegetation changes.

The total exposed surface area of the reservoir extends outside the flood plain because much of this surface area was occasionally inundated. Generally, however, the highest rates of *ET* are from the flood-plain portion of the area. Use of the total exposed surface area prevented making a more accurate evaluation of vegetative *ET* losses.

Flood-plain vegetation in the reservoir area was removed beginning in the 1967 water year. A comparison of monthly before-clearing and after-clearing data was made for periods 1961-66 and 1967-71 to evaluate vegetative consumptive use (transpiration). The results of these comparisons were inconclusive, however, because the *ET* rates were too greatly affected by the large fluctuations in lake stage from 1966 to 1971.

Although precipitation falling on the exposed area of the reservoir is a reservoir inflow, a distinction is made between the relation of this inflow to *ET* and the relation of inflow from other sources to *ET*. The *ET* loss computed by the water budget (table 18) represents a loss in usable reservoir water. Normally, only a minimal amount of the input from direct precipitation on the exposed areas is ever a part of "usable" contents. The fact that precipitation is distributed on the surface enhances the possibility for immediate and total *ET*. Vaporization of the precipitation depletes the energy available for vaporizing water from other sources, but this effect is temporary in arid regions because of the infrequent and limited quantity of precipitation.

All precipitation on the exposed ground area of the reservoir is an additional *ET* loss. This added *ET* is assumed equal to precipitation measured at the San Carlos Reservoir weather station. *ET* from this precipitation source was added to the *ET* computed from the water budget of the reservoir (table 18) to give the total *ET* from the reservoir water-surface area and adjacent exposed ground area. The average annual total *ET* for the 1931-71 period is 2.62 ft (0.80 m). A comparison of this value with the computed water-budget *ET* values in table 20 indicates that precipitation on the exposed area of the reservoir contributed an average of about 1.2 ft (0.37 m) per year to the total *ET*.

DEVELOPMENT OF SURFACE-WATER STORAGE-CAPACITY RATINGS

SIMULATION OF THE SEDIMENT DEPOSITIONAL PROCESS

Interpolations of capacity changes between capacity surveys were made by using a procedure which included simulating the sediment depositional process in the San Carlos Reservoir. The simulation procedure was structured about three basic phases of the depositional process:

1. Sediment inflow
2. Sediment distribution
3. Sediment compaction

Equations were developed to represent each phase. The "best fit" values of variables in the equations were selected by minimizing the difference between the volumes of sediment measured and estimated.

Measurements of sediment accumulation were available from only four separate periods between 1929 and 1966. However, volumes of sediment deposited within 5-foot-elevation increments were defined from each survey, and these volumes provided the

TABLE 18.—*Water-budget summations*

Water year	Water-surface elevation (ft)	Surface-water storage (acre-ft)	Surface-water storage change (acre-ft)	Bank storage (acre-ft)	Change in bank storage (acre-ft)	Inflow (acre-ft)	Outflow[1] (acre-ft)	Evapo-transpiration[2] (acre-ft)
	2424.40	139,361		21,495				
1931	2430.66	163,401	-24,040	26,699	-5,204	344,018	246,928	67,846
1932	2453.53	309,714	-146,313	51,831	-25,132	513,467	300,605	41,417
1933	2420.26	110,631	199,083	18,390	33,441	183,727	371,154	45,097
1934	2411.85	73,647	36,984	12,914	5,476	186,368	200,076	28,751
1935	2421.78	108,450	-34,803	19,530	-6,616	255,791	206,107	8,266
1936	2402.50	44,980	63,470	7,882	11,647	208,158	250,252	33,024
1937	2418.04	91,210	-46,230	16,872	-8,989	378,046	309,057	13,769
1938	2388.26	16,138	75,072	1,911	14,961	134,142	204,041	20,134
1939	2389.28	16,465	-327	2,268	-357	120,994	111,791	8,519
1940	2386.48	11,276	5,189	1,288	980	185,800	171,043	20,926
1941	2491.64	696,666	-685,390	112,286	-110,998	1,042,546	270,105	-23,947
1942	2483.99	594,180	102,486	98,263	14,023	366,150	426,495	56,164
1943	2459.22	329,562	264,618	59,438	38,825	153,870	425,442	31,871
1944	2424.70	105,620	223,942	21,720	37,718	115,484	331,616	45,528
1945	2399.67	26,578	79,042	6,526	15,194	163,610	237,024	20,822
1946	2393.68	15,211	11,367	3,965	2,561	84,949	81,599	17,278
1947	2386.02	6,260	8,951	1,468	2,497	69,088	65,450	15,087
1948	2382.75	3,542	2,718	83	1,384	85,067	74,183	14,986
1949	2426.77	109,452	-105,910	28,443	-28,360	459,843	283,975	41,598
1950	2383.36	3,694	105,758	334	28,109	56,583	162,552	27,898
1951	2382.81	3,060	634	108	226	56,170	41,213	15,817
1952	2384.00	3,499	-439	596	-488	287,759	252,145	34,687
1953	2382.57	2,581	918	10	586	61,936	55,302	8,138
1954	2414.91	59,024	-56,443	18,515	-18,506	176,396	79,543	21,904
1955	2421.74	81,836	-22,812	24,019	-5,503	168,639	110,052	30,272
1956	2382.30	2,004	79,832	-101	24,120	46,573	121,634	28,891
1957	2415.56	58,111	-56,107	19,023	-19,124	147,740	57,411	15,098
1958	2426.49	97,988	-39.877	28,184	-9,161	364,345	271,338	43,970
1959	2406.50	31,538	66,450	12,586	15,598	120,197	163,835	38,410
1960	2382.89	1,830	29,708	141	12,445	274,448	283,780	32,821
1961	2396.51	11,920	-10,090	6,603	-6,462	65,223	27,761	20,910
1962	2398.57	14,064	-2,144	7,741	-1,138	322,596	268,701	50,613
1963	2415.18	51,660	-37,596	18,723	-10,962	224,106	159,504	16,044
1964	2408.87	33,078	18,582	14,174	4,549	121,985	119,867	25,250
1965	2391.17	4,469	28,609	3,854	10,320	128,234	135,687	31,476
1966	2462.23	316,729	-312,260	70,084	-66,230	683,118	280,063	24,565
1967	2447.11	195,739	120,990	50,180	19,904	181,162	299,317	22,738
1968	2477.86	471,372	-275,633	94,179	-43,998	674,108	352,211	2,265
1969	2448.82	205,212	266,160	52,266	41,912	97,789	375,120	30,741
1970	2404.54	20,781	184,431	11,300	40,966	61,159	247,273	39,283
1971	2412.27	37,542	-16,761	16,588	-5,288	91,786	63,240	6,498

[1] Does not include evapotranspiration losses.

[2] Excludes precipitation from exposed area of reservoir.

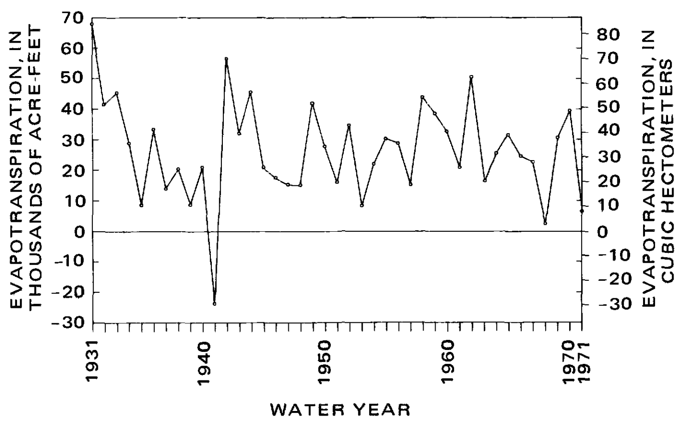


FIGURE 33.—Annual evapotranspiration from exposed area of reservoir computed by reservoir water budget.

basis for developing and testing the simulation of the sediment depositional process. In the simulation, each storage unit identified by a 5-foot-elevation increment is considered a separate surface-water storage reservoir.

The sediment inflow phase of the simulation procedure provided estimates of weight of incoming sediment by assuming that sediment inflow is a function of streamflow. The limitation of this assumption is the large range of sediment concentrations which occur for any given water discharge. However, for long time periods it is assumed that use of mean sediment concentrations is acceptable, if adjustments are made for seasonal differences in concentration.

According to the U.S. Army Corps of Engineers (1914, par. 92, p. 30), the total sediment discharge in summer averaged about 2.5 percent, by weight, of the discharge of the water-sediment mixture. In winter, the ratio of discharges was approximately 0.5 percent, so the summer-to-winter concentration ratio was about 5:1. Burkham (1972, p. 8) derived a similar ratio based on 1965-70 U.S. Geological Survey data

TABLE 19.—*Total evapotranspiration* (ET) *for San Carlos Reservoir, by water year*

Water year	*ET* as residual of water budget (ft)	*ET* from precipitation of exposed reservoir surface (ft)	Total *ET* (ft)
1931	3.55	1.30	4.85
1932	3.18	1.18	4.36
1933	2.88	1.12	4.00
1934	1.08	.54	1.62
1935	.20	1.64	1.84
1936	1.81	.97	2.78
1937	.86	1.08	1.94
1938	.97	.98	1.95
1939	.29	.89	1.18
1940	.93	1.04	1.97
1941	-3.08	2.54	-.54
1942	7.86	1.08	8.94
1943	2.95	.98	3.93
1944	2.71	1.25	3.96
1945	.97	1.13	2.10
1946	.58	.96	1.54
1947	.57	.79	1.36
1948	.61	.77	1.38
1949	2.41	1.14	3.55
1950	1.42	.93	2.35
1951	.63	.99	1.62
1952	1.86	1.55	3.41
1953	.31	.90	1.21
1954	.66	1.60	2.26
1955	1.20	1.17	2.37
1956	1.48	.75	2.23
1957	.61	.93	1.54
1958	2.25	1.66	3.91
1959	1.78	.98	2.76
1960	1.66	1.28	2.94
1961	.75	.92	1.67
1962	2.69	1.11	3.80
1963	.62	1.24	1.86
1964	.91	1.08	1.99
1965	1.54	1.17	2.71
1966	2.31	2.26	4.57
1967	1.13	1.11	2.24
1968	.37	1.38	1.75
1969	2.48	1.12	3.60
1970	2.21	1.11	3.32
1971	.05	.74	.79

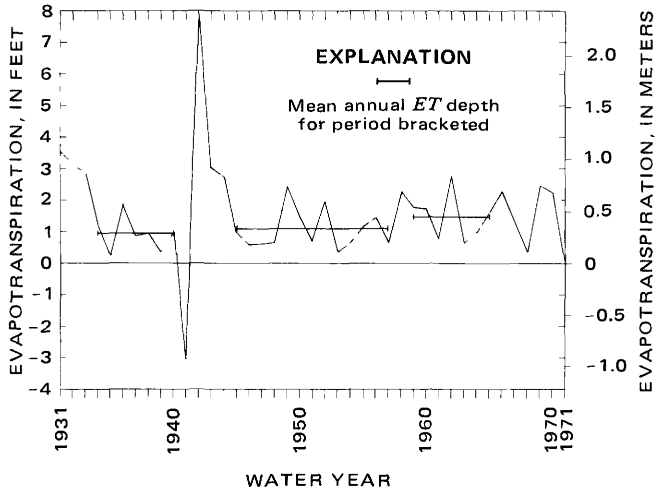


FIGURE 34.—Annual depth of evapotranspiration from the exposed surface of San Carlos Reservoir for water years 1931-71.

of suspended sediment for the Gila River station at the head of Safford Valley, which is located about 50 mi (80 km) upstream from San Carlos Reservoir. The change in this ratio from the Safford Valley site to the reservoir is not known, nor is it known how the ratio would be affected by using total sediment

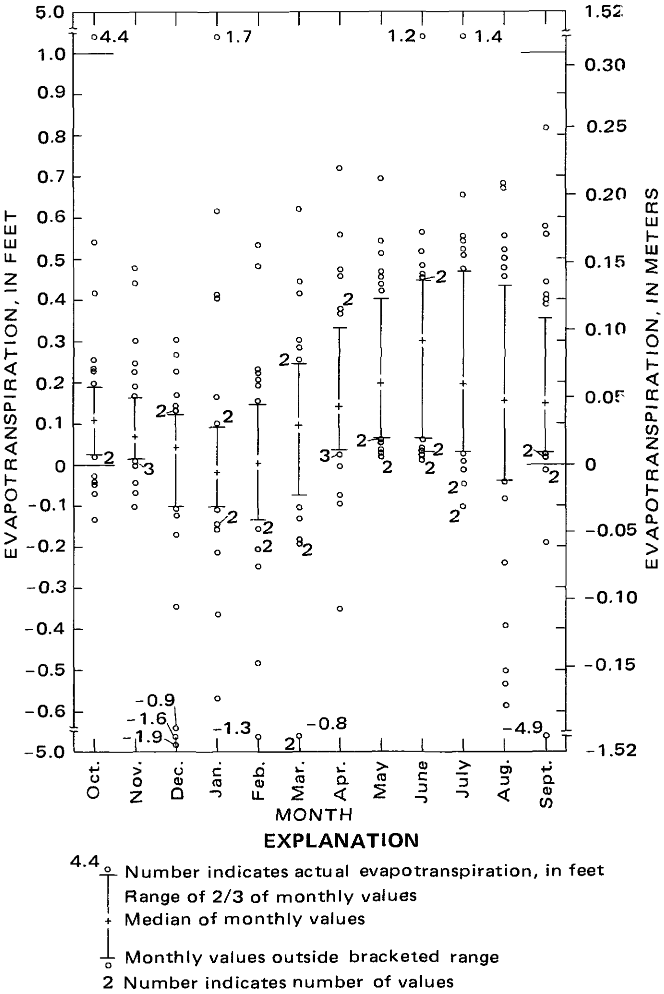


FIGURE 35.—Computed monthly evapotranspiration at San Carlos Reservoir for water years 1931-71.

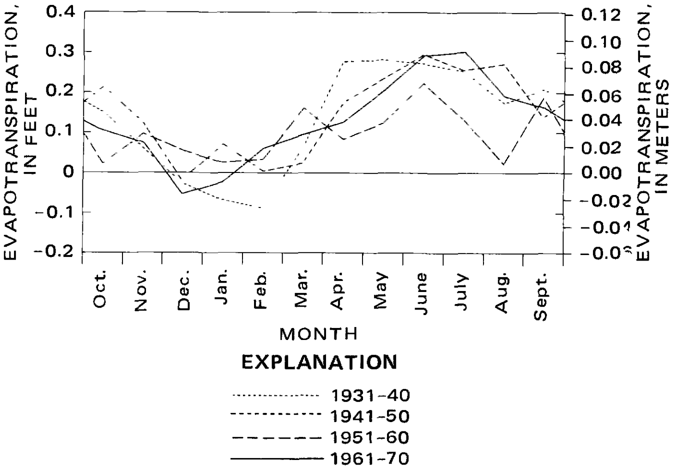


FIGURE 36.—Mean monthly evapotranspiration depths computed for 10-year periods.

TABLE 20.—*Mean monthly evapotranspiration* (ET) *computed from 4 periods of 10 years each, and median monthly evapotranspiration for 41 years*

	Computed monthly ET (ft)												
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Annual
Mean monthly from 4 periods of 10 years each	0.123	0.092	–0.009	0.003	0.004	0.062	0.168	0.212	0.274	0.239	0.166	0.176	1.510
Median of 41 monthly values	.109	.071	.044	- .018	.005	.099	.142	.193	.300	.198	.155	.150	1.448

discharge instead of solely the suspended sediment discharge. Estimates of the magnitude of deposition in San Carlos Reservoir were made with ratios of summer-to-winter concentrations in the range of 1:1 to 10:1 for the four periods prior to implementing the total simulation procedure. Comparison between estimates and measurements of deposition showed that results using the suggested 5:1 concentration ratio were only slightly better than those using a 1:1 ratio.

A general equation relating the weight of sediment discharged by a stream to the stream inflow volume during a fixed time interval is

$$S=CQ\,, \tag{6}$$

where S is the weight of sediment discharged, C is the mean sediment concentration expressed as the weight of sediment per unit volume of inflow, and Q is the volume of stream inflow. The weight of sediment retained by the reservoir, S_i, is equal to S times the trap efficiency, E. The weight of trapped sediment is therefore

$$S_i=SE=ECQ. \tag{7}$$

When equation 7 is expanded to include seasonal terms for C and Q, it becomes

$$S_i = E(C_wQ_w + C_sQ_s)\,, \tag{8}$$

where C_w and C_s are the mean winter and summer sediment concentrations, respectively, and Q_w and Q_s are the winter and summer streamflow summations, respectively.

The ratio r, where $r = C_s/C_w$, was one of the variables for which an optimum value was sought in defining the sediment deposition equations. Substituting r into equation 8 gives

$$S_i = EC_w(Q_w + rQ_s), \tag{9}$$

which eliminates C_s from the equation. A value of r was assumed for the initial trial through the simulation procedure. The value of r was adjusted in subsequent trials to improve the results from the simulation procedure.

E and C_w were assigned values of unity because both are constant during each trial of the simulation which compares the estimated with the measured sediment deposition. Equation 9 was modified for these assigned values, and the resulting equation provided estimates, designated S_y, which were proportional to S_i. The modified equation is

$$S_y = rQ_s + Q_w\,. \tag{10}$$

Each daily streamflow amount was assigned to the 5-foot-elevation increment (incremental storage reservoir) into which streamflow occurred; the proper incremental reservoir was determined by the lake stage at the end of the day. Daily streamflow data was summed according to water year, season of the year, and incremental reservoir. The proportional sediment weight, S_y, for each year and each incremental storage reservoir was computed by inserting the appropriate Q_s and Q_w sums into equation 10. Table 21 shows a generalized chart of $S_{y_{i,j}}$ into a reservoir, where $i = 1$ to n designates the incremental storage reservoirs and $j = 1$ to m designates the water years.

In table 21, the proportional sediment weight for any given year is determined by summing the $S_{y_{i,j}}$ values in the column corresponding to that year. Similarly, a summation of $S_{y_{i,j}}$ values for a particular row of the table is the proportional sediment weight for an elevation-increment of storage. The total S_y for a period is therefore

TABLE 21.—*Chart of notation used to identify time and inflow location of computed proportional sediment weights,* $S_{y_{i,j}}$

		Water year, j					
		1	2	•	•	m -1	m
Incremental storage reservoir, i	1	$S_{y_{1,1}}$	$S_{y_{1,2}}$	•	•	$S_{y_{1,\,m-1}}$	$S_{y_{1,m}}$
	2	$S_{y_{2,1}}$	$S_{y_{2,2}}$	•	•	$S_{y_{2,m-1}}$	$S_{y_{2,m}}$
	•	•	•	•	•	•	•
	•	•	•	•	•	•	•
	n - 1	$S_{y_{n-1,1}}$	$S_{y_{n-1,2}}$	•	•	$S_{y_{n-1,\,m-1}}$	$S_{y_{n-1,\,m}}$
	n	$S_{y_{n,1}}$	$S_{y_{n,2}}$	•	•	$S_{y_{n,m-1}}$	$S_{y_{n,m}}$

$$S_y=\sum_{i=1}^{n}\sum_{j=1}^{m} S_{y_{i,j}}. \tag{11}$$

The second phase in the sediment depositional process is the distribution of sediment inflow within a reservoir. As a stream merges with pooled reservoir water, water velocities decrease, resulting in deposition of sediment.

In this preliminary simulation the reservoir is assumed uniform in width and bottom configuration. Another assumption is that the larger sediment particles are deposited immediately upon entry into the surface-water storage pool of the reservoir.

The weight of larger sediment particles to the total sediment weight was defined as a. Selection of an optimum a was done in the simulation procedure by comparing estimated with measured sediment deposition. The $S_{y_{i,j}}$ values were divided into two parts by use of the equation

$$S_y=a\,S_y+(1.0-a)S_y. \tag{12}$$

The quantity $(1.0-a)S_y$ is the part of S_y made up of the smaller (suspended) sediment particles. Some of this quantity of smaller particles is assumed to be deposited within the incremental storage reservoir where the stream enters the storage pool, and the remainder is assumed to move to lower incremental reservoirs and is then deposited.

The computed weight of smaller particles, $(1.0-a)S_y$, was designated S_s to reduce equation symbolism. S_s was exponentially distributed over the distance from the point of inflow to a point where deposition is considered complete. Referring to figure 37, the deposition of suspended sediment was distributed from point A, the point of inflow, to point C, over the distance D_A. B is a point along D_A, and D_B is the distance from point B to point C. The ratio of the weight of suspended sediment passing point B to that which passed point A is $\left(\frac{D_B}{D_A}\right)^x$, where x is the exponent of distribution.

In the simulation procedure, the proportional weight of suspended sediment passing B is equal to $S_s\left(\frac{D_B}{D_A}\right)^x$. The difference between quantities passing A and B is the proportional weight of suspended sediment deposited between A and B, designated S_{s_B}. Accordingly,

$$S_{s_B}=S_s\left[1.0-\left(\frac{D_B}{D_A}\right)^x\right] \tag{13}$$

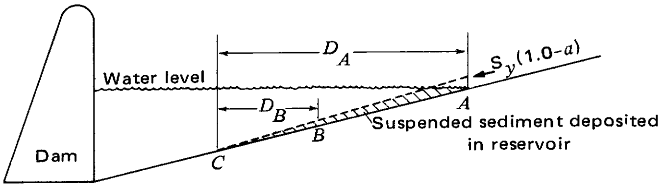


FIGURE 37.—Sketch identifying terms used in simulation of suspended sediment distribution.

The optimum values for the distance D_A and the distribution exponent x were found in the procedure which selected best estimates of sediment deposition.

To simulate distribution of suspended sediment into incremental reservoirs, D_A and D_B of equation 13 were redesignated D_{A_i} and D_{B_k}, respectively. The subscript i represents the incremental reservoir into which sediment entered the reservoir pool, and k represents the incremental reservoir for which deposition is being computed. Point A is the upstream limit of reservoir i, and point B is the upstream limit of reservoir k. S_{y_i} is the computed quantity proportional to sediment weight entering incremental reservoir i at point A, so the suspended sediment fraction of S_{y_i} is S_{s_i}. The suspended sediment which passes into reservoir k at point B is consequently computed as $S_{s_i}\left(\frac{D_{B_k}}{D_{A_i}}\right)^x$. The sediment passing into the next lower incremental reservoir, $k+1$, is $S_{s_i}\left(\frac{D_{B_{k+1}}}{D_{A_i}}\right)^x$. The difference between these two amounts, S_{s_k}, is proportional to the suspended sediment weight deposited in incremental reservoir k and is given as

$$S_{s_k}=S_{s_i}\left[\left(\frac{D_{B_k}}{D_{A_i}}\right)^x-\left(\frac{D_{B_{k+1}}}{D_{A_i}}\right)^x\right]. \tag{14}$$

The S_{s_i} total for each incremental reservoir was distributed by S_{s_k} amounts into the appropriate incremental reservoirs by equation 14. Distribution of S_{s_i} started with $k=1$ and continued through successively lower incremental reservoirs to either the lowest incremental reservoir or to the end of D_{A_i} (at point C), whichever came first. Incremental reservoirs were numbered from 1, for the upper reservoir, to n, for the lowest, and S_{s_i} was distributed into all incremental reservoirs from $i=1$ to $i=n$.

If the optimal value selected for D_{A_i} was greater than the distance from point A to the dam, a part of the S_{s_i} quantity could not be distributed by equation 14. This remaining quantity was distributed uniformly over the distance from point A to the dam as shown in figure 38.

For San Carlos Reservoir, distribution was made by water year. Thus, within each of the four periods, the deposition was categorized by the incremental storage reservoir of deposition and by water year. For incremental reservoir k and for any water year j, designation of the computed amount deposited was $S_{d_{k,j}}$.

The simulating process continues with the compaction phase after the sediment is distributed and deposited. Lane and Koelzer (1943) presented a compaction equation to estimate unit weight of sediments at a specified time following deposition. This equation requires knowing the "in place" composition of the sediment and its specific weight 1 year after deposition. This information was unavailable for San Carlos Reservoir. However, the Lane and Koelzer equation was applied to the reservoir using estimates of percentages of sand, silt, and clay deposited after 1 year and an estimate of the specific weight of the deposit. The amount of compaction estimated by this method was found to be small compared to the probable error in the simulation of sediment deposition. Also, the addition of a compaction equation to the simulation procedure resulted in unacceptable parameter values in the sediment inflow and distribution equations. For these reasons, the compaction of reservoir sediments was deleted from further computations.

With deletion of the compaction phase from the simulation, the results of only the sediment inflow and sediment distribution phases were used in making estimates of sediment deposited. The computed proportional weights for distributed sediments—the $S_{d_{k,j}}$ amounts—were summed for each incremental reservoir and for each of the periods including the 1929-66 period. The incremental reservoir sums are designated S_{R_k}, and the total S_{R_k} amount of a period is S_R. S_R can be expressed as

$$S_R = \sum_{k=1}^{n} \sum_{j=1}^{m} S_{d_{k,j}}, \tag{15}$$

where the range of incremental reservoirs is from $k=1$ to $k=n$ and the water years range from $j = 1$ to $j = m$.

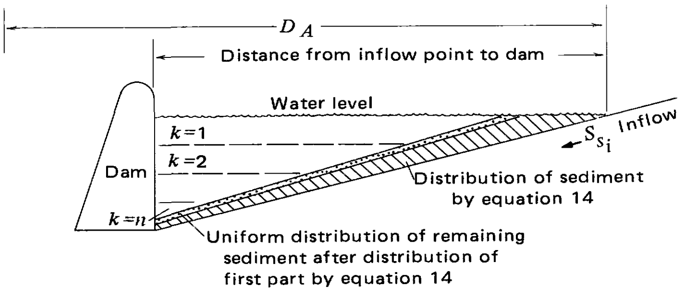


FIGURE 38.—Sketch showing distribution of suspended sediment, S_{s_i}, when distance D_A was computed as greater than the distance from inflow point (A) to the dam.

The relation between simulated deposition and measured deposition was established for each period by the following equation:

$$S_M = \text{RATIO}\ (S_R), \tag{16}$$

where S_M is the total volume of sediment deposited in the period. RATIO is a proportionality constant whose value is affected by E and C_w of equation 9, which had been set equal to unity for the computation procedure. RATIO also includes a unit conversion to relate the measured volume of S_M to S_R. Each repetition of the simulation produced a different value for RATIO.

The estimate of absolute volume of deposited sediment, S_{e_k}, was made for each 5-foot incremental reservoir by multiplying the periods RATIO times the S_{R_k} of the incremental reservoir:

$$S_{e_k} = \text{RATIO}\ (S_{R_k}). \tag{17}$$

The value of one or more of the variables, r, a, x, or D_A, was changed slightly for each trial of the simulation procedure. The optimum values of variables were naturally those which produced the best sediment estimates. A listing of the variables and optimum values are shown in table 22 for the four periods between capacity surveys and for the 1929-66 period.

TABLE 22.—*Optimum values of variables from simulation of the sediment depositional procedure.*

Period number and dates	Variables			
	r	a	x	D_A
No. 1, 1929-35	13.20	0.25	1.30	60 000 ft
No. 2, 1935-37	1.80	.40	.88	40 000 ft
No. 3, 1937-47	2.35	.38	.82	72 000 ft
No. 4, 1947-66	1.35	.55	.82	16 000 ft
No. 5, 1929-66	4.65	.35	1.60	56 000 ft

Symbols:

r is the seasonal ratio of summer to winter sediment concentration.

a is the percent, by weight, of total sediment load deposited when streamflow reaches the reservoir pool.

x is the exponent of the expression for the distribution of suspended sediment.

D_A is the distance along the reservoir centerline from the point of inflow to the point where no sediment remains to be deposited.

INTERPRETATION OF SIMULATION RESULTS

The range of the summer-to-winter concentrations (r = 1.35–13.2) in table 22 is not unexpected for the time periods and geographical area considered but may not be meaningful because varying discharge, velocities, and so forth, were not considered. A comparison of differences between the summer and winter suspended sediment concentrations at several southern Arizona locations shows that, for short periods, r can vary more than that shown in table 22. The period 5 data suggest that the ratio of summer-to-winter concentrations for the 38-year period 1929–66 actually approached the 5:1 value discussed on page 32.

The variable a ranges from 0.25 to 0.55 in table 22 and averages 0.39, indicating that about 40 percent of the total sediment was deposited near the entry of the San Carlos and Gila Rivers into the reservoir pool. This 40 percent probably is the approximate bed material discharge of the San Carlos and Gila Rivers.

It was assumed prior to determining an optimum x, that x would be equal to, or greater than, 1.0; that is, the rate of suspended sediment deposition would be at least as great at the point of inflow as in any other part of the reservoir. The selection of the optimum x did not confirm this assumption for all periods. The values of x determine the curvature of the relations in figure 39. These relations show the proportional distributions of sediment deposits along the reservoir using the optimum values of a, D_A, and x determined by the simulation procedure.

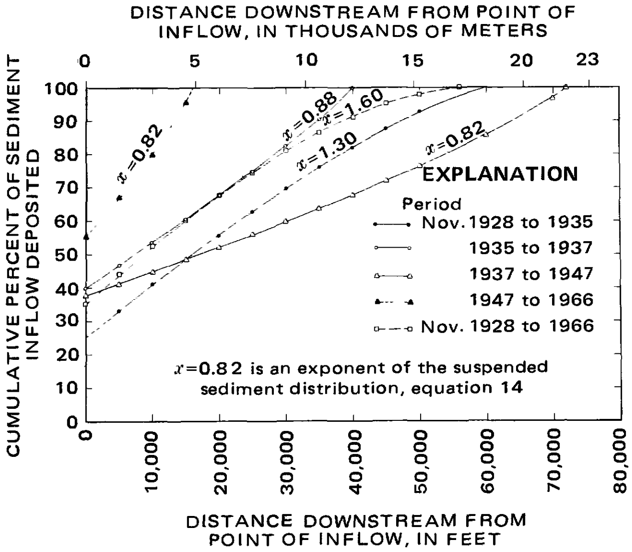


FIGURE 39.—Simulated sediment deposition, in percent, downstream from point of inflow.

In table 22 D_A is an approximation of the average distance over which sediment is deposited. For shorter time periods D_A can be considerably different because the distance through which sediment is transported is affected by the rate of inflow, the volume of water in surface storage, constrictions in reservoir, and so forth. It appears from optimizing D_A that sediment distribution sometimes occurred throughout the reservoir, even when surface-water storage was a great amount.

Sediment inflow at San Carlos Reservoir does not appear to move far into the pooled water under low streamflow conditions, as illustrated by period 4 results in figure 39. Inaccuracies in the storage capacity ratings adversely affected all measurements and estimates of sediment deposition. Also, sediment distribution based on mean cross-sectional velocities or daily streamflow volume rather than the mean distance, D_A, may improve the sediment model. These indications emphasize the need for more development of the sediment distribution model.

Figure 40*A* shows a comparison between the volumes of deposits measured and computed during period 5 for all incremental reservoirs. In figure 40*B* a comparison is made between cumulative volumes of measured and computed sediment deposits for period 5. The summations were determined by progressively adding the volume of deposit in an incremental reservoir to the sum of the deposits in all lower incremental reservoirs.

PROCEDURE TO DEVELOP RATINGS

Reservoir surface-water storage values for the water budget of water years 1929, 1935, 1937, 1947, and 1966 were obtained from surface-water capacity ratings of the five surveys. Ratings for water years 1967 through 1971 were interpolated on the basis of estimated volumes of sediment deposited from the simulation procedure by using the parameter values of period 5. For all other years, surface-water storage ratings were developed by interpolating storage changes between capacity surveys.

The development of a rating of surface-water storage for each water year was begun by inserting the optimum parameter values of table 22 into the simulation procedure. Estimates of absolute sediment volumes, Se_k, were obtained for all incremental reservoirs during the periods between surveys. The ratio of the measured to estimated volumes, SM_k/Se_k, was computed for each incremental reservoir of each period. Table 23 lists the SM_k, Se_k, and SM_k/Se_k values for period 3.

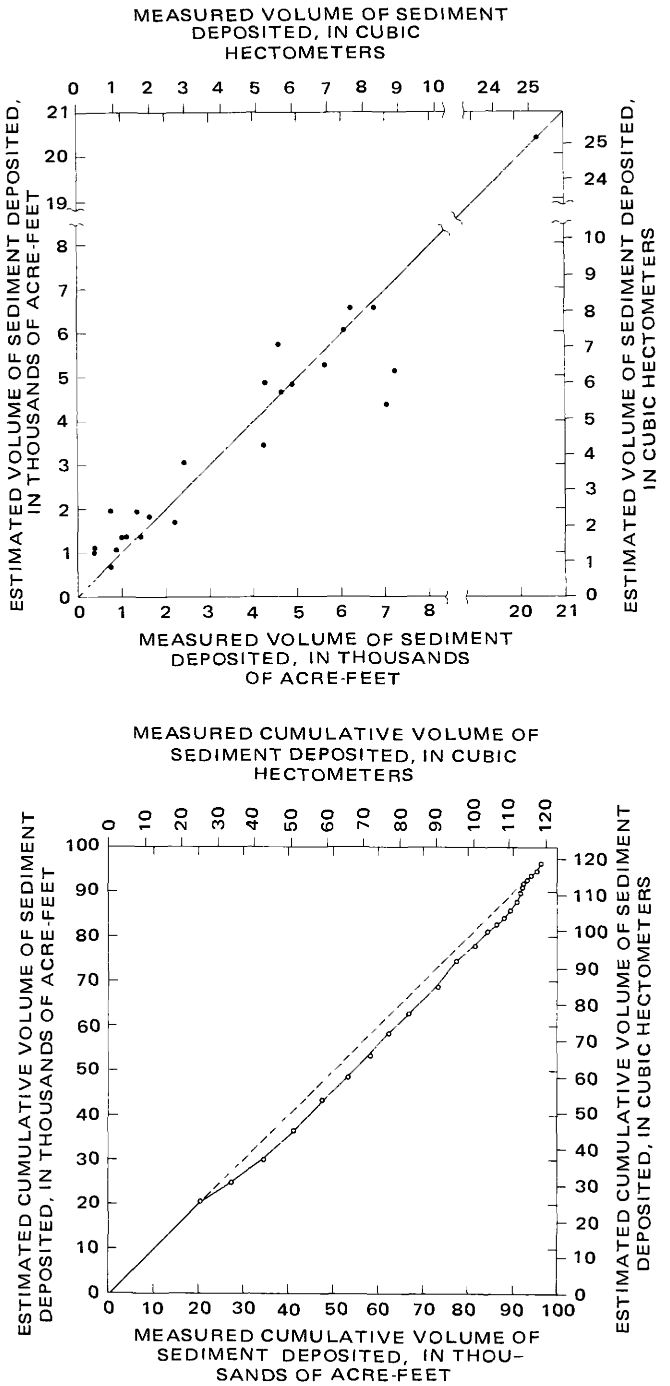


FIGURE 40.—*A*, Comparison between the volumes of deposits measured and estimated for each incremental reservoir, 1929–66. *B*, Comparison between volumes of estimated and measured deposits cumulative by 5-ft-elevation increments upward from lowest part of reservoir, 1929–66 water years.

The sediment volume accumulated in each incremental reservoir was also estimated in the simulation from the beginning of a period to each subsequent year in the period. These volumes are designated $S_{e_{k,j}}$. Completion of these estimates concluded the simulation procedure, but much of the interpolative computations remained to be done. The estimates were multiplied by the appropriate incremental reservoir ratio, S_{M_k}/S_{e_k}. This adjustment was required so that the interpolated storage change from sediment deposition over a period equaled the measured sediment deposition. The symbol Z distinguishes an interpolated volume from the estimated volume, S_e. Therefore, the volume for any incremental reservoir is

TABLE 23.—*Volumes of sediment deposits measured* (S_{M_k}) *and computed* (S_{e_k}) *for 1937–47, and the* S_{M_k}/S_{e_k} *ratios*

Elevation increment (ft)	S_{M_k} (acre-ft)	S_{e_k} (acre-ft)	S_{M_k}/S_{e_k}
below 2380	5,162	5,160	1.00
2380–2385	2,411	718	3.36
2385–2390	2,139	780	2.74
2390–2395	1,926	2,189	.88
2395–2400	1,312	861	1.52
2400–2405	881	740	1.19
2405–2410	976	695	1.40
2410–2415	703	854	.82
2415–2420	430	428	1.01
2420–2425	300	1,042	.29
2425–2430	128	1,586	.08
2430–2435	168	661	.25
2435–2440	590	594	.99
2440–2445	795	572	1.39
2445–2450	189	462	.41
2450–2455	809	515	1.57
2455–2460	403	714	.56
2460–2465	430	439	.98
2465–2470	469	418	1.12
2470–2475	107	321	.33
2475–2480	304	298	1.02
2480–2485	175	760	.23
Above 2485	0	0	—

$$Z_{k,j} = S_{e_{k,j}} \left(\frac{S_{M_k}}{S_{e_k}} \right). \qquad (18)$$

The annual $Z_{k,j}$ quantities listed in table 24 for a part of period 3 are the estimated losses in surface-water storage through interpolation from the beginning of the period in 1937 to the start of the year shown. Subtraction of $Z_{k,j}$ for an incremental reservoir from the surface-water capacity at the start of the period gives an adjusted capacity. Adjusted surface-water storage capacities for each year were then assembled into an elevation-capacity rating for the year. The elevation and corresponding adjusted capacity values are shown in table 25 for water years 1938–42.

A comparison was made between a computer-developed rating and a rating developed by curve fitting to determine whether computer-developed ratings were acceptable for the investigation. Surface-water storage capacities for 1966 from table 1 by 5-foot-elevation increments were used in both

TABLE 24.—*Estimated change in surface-water storage capacity, Z, from start of period 3 to 1942, by 5-ft-elevation increments*

Elevation increment (ft)	Estimated loss in surface-water storage capacity, *Z*, in acre-ft				
	Water year				
	1938	1939	1940	1941	1942
Below 2380	680	1,142	1,663	2,570	3,705
2380–2385	210	360	636	1,008	1,688
2385–2390	93	173	504	1,291	1,699
2390–2395	133	363	575	864	1,291
2395–2400	93	141	327	542	850
2400–2405	88	124	146	243	547
2405–2410	118	239	239	369	613
2410–2415	113	233	233	233	440
2415–2420	98	184	184	184	312
2420–2425	47	53	53	53	114
2425–2430	20	20	20	20	70
2430–2435	28	28	28	28	112
2435–2440	171	171	171	171	445
2440–2445	208	208	208	208	588
2445–2450	66	66	66	66	153
2450–2455	222	222	222	222	555
2455–2460	0	0	0	0	216
2460–2465	0	0	0	0	228
2465–2470	0	0	0	0	329
2470–2475	0	0	0	0	67
2475–2480	0	0	0	0	237
2480–2485	0	0	0	0	73
Above 2485	0	0	0	0	0

TABLE 25.—*Computed capacity ratings of surface-water storage used for 1938 through 1942*

Elevation (ft)	Cumulative surface-water storage capacity in acre-ft by water year				
	1938	1939	1940	1941	1942
2380	6,759	6,297	5,776	4,869	3,734
2385	12,253	11,641	10,844	9,565	7,750
2390	19,231	18,539	17,411	15,345	13,122
2395	27,602	26,680	25,340	22,985	20,335
2400	37,617	36,647	35,121	32,551	29,593
2405	49,835	48,829	47,281	44,614	41,352
2410	64,168	63,041	61,493	58,696	55,190
2415	80,289	79,042	77,494	74,697	70,984
2420	98,251	96,918	95,370	92,573	88,732
2425	118,813	117,474	115,926	113,129	109,227
2430	142,624	141,285	139,737	136,940	132,988
2435	169,414	168,075	166,527	163,730	159,694
2440	199,089	197,750	196,202	193,405	189,095
2445	231,850	230,511	228,963	226,166	221,476
2450	267,841	266,502	264,954	262,157	257,380
2455	306,799	305,460	303,912	301,115	296,005
2460	349,359	348,020	346,472	343,675	338,349
2465	396,071	394,732	393,184	390,387	384,833
2470	446,872	445,533	443,985	441,188	435,305
2475	501,110	499,771	498,223	495,426	489,476
2480	558,819	557,480	555,932	553,135	546,948
2485	620,285	618,947	617,398	614,601	608,341
2490	685,785	684,446	682,898	680,101	673,841
2495	755,274	754,035	752,487	749,690	743,430
2500	829,288	827,949	826,401	823,604	817,344
2505	907,695	906,356	904,808	902,911	895,751
2510	990,544	989,205	987,657	984,860	978,600
2511	1,007,672	1,006,333	1,004,785	1,001,988	995,728
2515	1,078,079	1,076,740	1,075,192	1,072,395	1,066,135

TABLE 26.—*Comparison of segments of surface-water storage capacity ratings made by curve fitting and by computer*

Elevation (ft)	Surface-water storage capacity, in acre-ft		Difference between ratings, acre-ft
	Developed by curve fitting	Computer developed	
2410.0	33,308	33,308	0
.1	33,563	33,589	26
.2	33,819	33,869	50
.3	34,076	34,150	74
.4	34,334	34,431	97
.5	34,593	34,711	118
.6	34,854	34,992	138
.7	35,116	35,273	157
.8	35,379	35,554	175
.9	35,643	35,834	191
2411.0	35,908	36,115	207
.1	36,175	36,396	221
.2	36,443	36,676	233
.3	36,712	36,957	245
.4	36,982	37,238	256
.5	37,253	37,518	265
.6	37,526	37,799	273
.7	37,800	38,080	280
.8	38,075	38,361	286
.9	38,351	38,641	290
2412.0	38,628	38,922	294
.1	38,906	39,203	297
.2	39,185	39,483	298
.3	39,465	39,764	299
.4	39,746	40,045	299
.5	40,028	40,325	297
.6	40,310	40,606	296
.7	40,593	40,887	294
.8	40,877	41,168	291
.9	41,162	41,448	286
2413.0	41,448	41,729	281
.1	41,734	42,010	276
.2	42,021	42,290	269
.3	42,309	42,571	262
.4	42,598	42,852	254
.5	42,888	43,132	244
.6	43,179	43,413	234
.7	43,471	43,694	223
.8	43,764	43,975	211
.9	44,058	44,255	197
2414.0	44,353	44,536	183
.1	44,648	44,817	169
.2	44,944	45,097	153
.3	45,241	45,378	137
.4	45,539	45,659	120
.5	45,838	45,939	101
.6	46,137	46,220	83
.7	46,437	46,501	64
.8	46,738	46,782	44
.9	47,040	47,062	22
2415.0	47,343	47,343	0

ratings. Attention was given to the rate of change in capacity with respect to 0.1-ft (0.03 m)-elevation changes in the curve-fitted rating. The computer rating was developed to 0.1-ft (0.03 m)-elevation intervals by use of a constant elevation-capacity ratio over each 5-foot-elevation increment. A sample of these ratings is given in table 26. The largest volumetric difference between ratings was 763 acre-ft (0.94 hm^3) at 2,462.5 ft (751 m) elevation, which is 0.063 percent of the total surface-water storage capacity. The mean deviation of the 0.1 ft (0.03 m) differences between ratings was 0.23 percent. From these comparisons it was concluded that use of either rating was acceptable.

SUMMARY AND CONCLUSIONS

Existing records of the hydrology of many reservoirs can be used to make an inexpensive evaluation of reservoir performance. The records may provide sufficient data to estimate available water in bank storage and to determine water losses by evaporation and transpiration within the reservoir boundary. It is frequently possible to investigate changes in storage capacity and in the volume of sediment deposition by use of existing capacity-survey information.

At San Carlos Reservoir, the water loss by evapotranspiration (*ET*) was greatest during and soon after large water-level recessions when considerable surface areas of the reservoir were uncovered. During these periods the potential for *ET* was high because the exposed soils had a high water content. *ET* computed by the reservoir water budget averaged 26,230 acre-ft (32.3 hm^3) per year or 11.3 percent of the total reservoir outflow. Mean annual depth of *ET* from the exposed area was computed as 1.47 ft (0.448 m) in the water budget. When precipitation on the exposed surface of the reservoir was included, *ET* depth was 2.62 ft (0.800 m) annually. The changes in *ET* caused by the increasing amount of vegetation during the period of record were not readily apparent from the existing San Carlos Reservoir data.

Evaporation from the water surface of the lake averaged 24,611 acre-ft (30.3 hm^3) per year and accounted for 10.5 percent of the total outflow from the reservoir. During the period 1964-71 when evaporation was computed by energy-budget and mass-transfer methods, the computed pan coefficient was 0.80.

Sediment deposition in the reservoir from 1929 to 1966 totaled 96,719 acre-ft (119 hm^3) and averaged 2,553 acre-ft (3.1 hm^3) per year. The mean volume of sediment deposited was 1.2 percent of streamflow for this 38-year period.

Usable water in bank storage was computed by water budgets during winter periods when *ET* was considered minimal and changes in surface-water storage were large. Usable bank storage was found to be about 14 percent of total usable storage at the elevation of maximum storage capacity. At lower reservoir elevations, this percentage was even greater. Ratings were developed relating usable bank storage to stage.

The simulation of the sediment depositional process in a reservoir was developed primarily to aid in interpolating capacity changes between capacity surveys. The simulation was successful for the purposes of this study. For applications in which the primary objectives are to predict location and amounts of sediment deposited and to estimate compaction, the simulation model needs further testing and modification.

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