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Use of hydroelectric dams to control evaporation and salinity in the Colorado River system

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CHAPTER 26

USE OF HYDROELECTRIC DAMS TO CONTROL EVAPORATION AND SALINITY IN THE COLORADO RIVER SYSTEM

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INTRODUCTION

The main stem reservoirs on the Colorado River comprise one of the largest and most heavily used freshwater bodies in the nation. These reservoirs (Lake Powell, Lake Mead, Lake Mohave and Lake Havasu) can store up to 53,590,400 acre-feet (66 x $10^9 m^3$) of water at their maximum capacities. Nonetheless, local water shortages still exist in some areas of the Colorado River Basin. There is also concern that salt concentrations are approaching levels that could severely affect municipal and agricultural uses [1]. Water shortages will become even more acute as demands for water increase with continued urban and agricultural development in the basin.

Water conservation and salinity control programs have already been adopted, or are under investigation, in most states using Colorado River water. Reductions in consumptive water uses through more efficient irrigation practices, power plant cooling and wastewater reuse will, to some extent, help alleviate future water shortages. However, this will not offset the rising demands, and basin-wide shortages could occur by the year 2000 [2]. Similarly, recent estimates indicate that salt concentrations in the river at Imperial Dam will rise to 1150 mg/1 as a result of flow depletions projected to occur during this century [1,3]. Construction of salinity control projects approved by Congress under PL 93-320 will significantly reduce salinity, but implementation of these projects will be costly and time consuming [3].

Water shortages and salinity control in the Colorado River system have thus far been addressed from the standpoint of reducing water uses and controlling point source salt inputs. Little attention has been given to investigating methods of reducing evaporation from the reservoirs, but studies conducted in 1952 and 1953 [4] showed that it was a major water loss from the Colorado River system. Moreover, high evaporation directly influences salinity because it increases the concentration of salts in the reservoirs. Although various schemes have been offered for reducing evaporation from Lake Mead, it has usually been viewed as an uncontrollable water loss. However, during the mid-1960s, U.S. Geological Survey and Bureau of Reclamation scientists estimated that cold-water discharges from Glen Canyon Dam would reduce evaporation in Lake Mead. The estimates were never published in report form but did appear in internal government memoranda and newspaper articles (Arizona Republic, May 19, 1966; Phoenix Gazette, July 28, 1966). Our analysis of historical evaporation data, and recent investigations in Lake Mead [5] indicate that evaporation did indeed decrease after Lake Powell was formed in 1963.

Advective energy (heat) inputs (Colorado River inflow) and outputs (Hoover Dam discharge) have a significant influence on the heat budget of Lake Mead [4,6]. Historically, the Colorado River inflow contributed large quantities of heat to the reservoir during the spring and early summer. However, the construction of Glen Canyon Dam and formation of Lake Powell in 1963 altered the natural temperature and flow cycles of the river [7]. Discharges of cold water from the hypolimnion (230 ft, 70 m) of Lake Powell have significantly reduced energy inputs to Lake Mead. Similarly, it appears that heat losses from the reservoir could be increased if Hoover Dam were operated from a surface, rather than deep-water, discharge. The combined effects of a cold-water discharge from Glen Canyon Dam and a surface discharge from Hoover Dam could reduce evaporation from Lake Mead by over 200,000 acre-feet ($2.47 \times 10^8 m^3$)/yr and result in considerable decreases in salinity. The purpose of this paper is to present data in support of these conclusions and to describe how the hydroelectric dams can be operated to minimize evaporative water losses from Lake Mead and reduce salinity in the Colorado River.

STUDY AREA

Lake Mead was formed in 1935 by construction of Hoover Dam. It extends 114 miles (183 km) from the mouth of Grand Canyon to Black Canyon, the site of Hoover Dam (Figure 1). Lake Mead is one of the largest reservoirs in the country with a surface area of 163,088 acres (660 km^2) and a volume of 29,185,245 acre-feet ($36 \times 10^9 m^3$), at the maximum operating level of 1227 ft (374 m) [8]. It is separated into two large basins by Boulder Canyon, located midway through the reservoir (Figure 1). The area above Boulder Canyon is referred to as the Upper Basin and that below as the Lower Basin. Hoover Dam is equipped with intake gates at 1045 ft (319 m) and 895 ft (273 m) elevations. The dam has been operated from the lower gates since 1954.

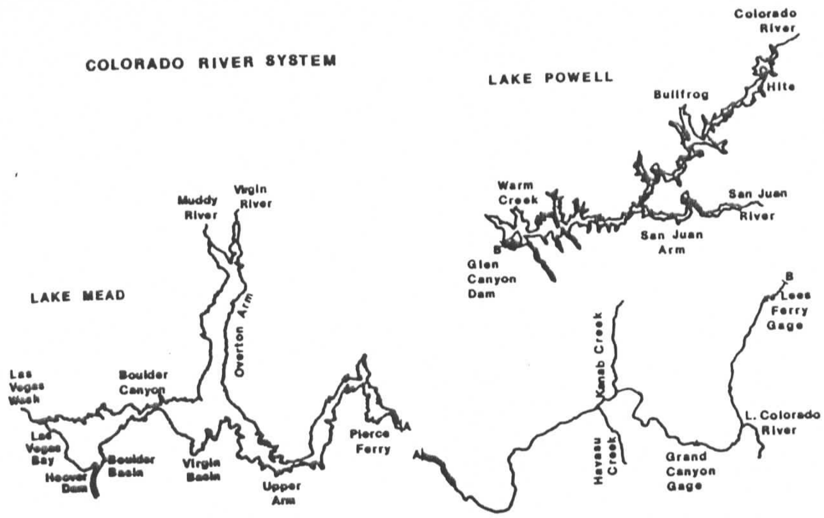

Figure 1. Map of the Colorado River System (Lake Mead and Lake Powell).

The Colorado River inflow to Lake Mead was unregulated prior to 1963 when Glen Canyon Dam was constructed 280 miles (451 km) upstream (Figure 1). Annual discharges are high [8,354,000 acre-feet ($10.3 \times 10^9 m^3$) in 1978], and seasonal discharge peaks usually occur during winter and summer. Discharges from Glen Canyon Dam are withdrawn from the hypolimnion (230 ft, 70 m) of Lake Powell and temperatures range from 7.5-13.5°C. The Colorado River inflow, via discharges from Lake Powell, comprises 98% of the inflow to Lake Mead. The remainder is derived from the Virgin and Muddy Rivers, which discharge into the Overton Arm, and Las Vegas Wash, which discharges secondary-treated sewage effluents into Las Vegas Bay (Figure 1).

DATA SOURCES AND METHODS

Historical evaporation data for Lake Mead and discharge data for Grand Canyon were obtained from "Surface Waters of the United States," U.S. Geological Survey Water-Supply Papers, Part 9, Colorado River Basin, until 1967. Grand Canyon temperature data and salinity data for Lake Mead were derived from the "Quality of Surface Waters in the United

States," U.S. Geological Survey Water-Supply Paper, Part 9, Colorado River Basin. After 1967, these data were obtained from "Water Resources Data for Nevada" or "Water Resources Data for Arizona" of the U.S. Geological Survey Water-Data annual reports.

Net advective energy was computed for Lake Mead from monthly data collected during October, 1977 - September, 1978, using Equation 1.

$$Q_v = \frac{q_i\,(T_i - T_r) - q_o(T_o - T_r)}{A}\, k_i\text{---}k_n \qquad (1)$$

where Q_v = net advected energy ($cal/cm^2 \cdot month$)
q_i = monthly discharge in Grand Canyon ($m^3/month$)
q_o = monthly discharge from Hoover Dam ($m^3/month$)
T_i = inflow temperature (°C) computed from Harbeck et al. [4] equation of (T_{gc} + 2.6°C) - (.04 T_{gc}) - 2.1 x 10^{-5} x q_i, where T_{gc} and q_i are the average monthly temperature and discharge (ft^3/sec) in Grand Canyon
T_o = outflow temperature (°C) measured at the lower intake gates 295 ft (90 m) near Hoover Dam from Paulson et al. [5]
T_r = reference temperature of 4.4°C
A = average monthly surface area in Lake Mead (cm^2) from Lara and Sanders [8]
k_i = unit conversion factors

Estimates of net advective energy for a surface discharge at Hoover Dam were computed by Equation 1 with T_o = monthly surface temperature (°C) near Hoover Dam from Paulson et al. [5].

Differences in evaporation rates from Lake Mead for a surface and hypolimnion discharge on Hoover Dam were computed from Equation 2 [6].

$$E = \frac{Q_{vh} - Q_{vs}}{L(1+R)}\, k_i\text{---}k_n \qquad (2)$$

where E = annual evaporation rate (cm/yr)
Q_{vh} = average net advective energy for the hypolimnion discharge ($cal/cm^2 \cdot day$)
Q_{vs} = average net advective energy for a surface discharge ($cal/cm^2 \cdot day$)
L = latent heat of vaporization (585 cal/cm^3)
R = average Bowen Ratio as estimated for Lake

Mead by Anderson and Pritchard [6] and Harbeck et al. [4] using monthly data from October 1977 - September 1978

k_i = unit conversion factors

Total evaporative water loss from Lake Mead was then determined by extrapolation from volume curves [8].

Using USGS data collected during the period from October 1977-September 1978 as initial model conditions (Table I), the effects of decreased evaporation on salinity in Lake Mead were determined by Equation 3.

$$Sc_t = \frac{Ss_{t-1} + (Si_t\alpha - So_t)}{V_t + Ev_t} k_i --- k_n \quad (3)$$

where Sc = salt concentration in Lake Mead (mg/l)

Ss = salt storage in Lake Mead (kg)

Si = salt inputs to Lake Mead (kg)

α = salt retention coefficient

So = salt output at Hoover Dam (kg)

V = Lake Mead volume (m^3)

Ev = evaporation reductions (m^3)

t = time interval (yr)

k_i = unit conversion factors

Table I. Parameters and Data Used in the Salinity Model for Lake Mead. Data Collected Oct. 1977 - Sept. 1978.

Parameter	Symbol	Average	Units
Lake Mead Volume	V	25.48	$m^3 \times 10^9$
Colorado River Inflow	I	10.43	$m^3 \times 10^9$
Hoover Dam Discharge	O	9.48	$m^3 \times 10^9$
Salt Input	Si	73.714	$kg \times 10^8$
Salt Retention	α	0.8693	-
Salt Storage	Ss	172.76	$kg \times 10^8$
Salt Output	So	Variable	$kg \times 10^8$
Evaporation	Ev		
Reduction Minimum		1.48	$m^3 \times 10^8$
Maximum		2.63	$m^3 \times 10^8$

Evaporation reductions of 120,000 acre-feet ($1.48 \times 10^8 m^3$) and 213,000 acre-feet ($2.63 \times 10^8 m^3$) were used in the salinity model. These evaporation reductions were added to the 1978 water year average volume in Lake Mead ($25.48 \times 10^9 m^3$) during the first year of modeling. In subsequent years, these evaporation reductions were added to the annual discharges from Hoover Dam, using the 1978 water year (9.48

x $10^9 m^3$) as the initial discharge rate. Salinity decreases projected to occur from the Las Vegas Wash, Nevada and Grand Valley, Colorado Salinity Control Projects [3] were also incorporated in the salinity model.

RESULTS AND DISCUSSION

Temperature and Discharge Cycles

The construction of Glen Canyon Dam in 1963 drastically altered the seasonal temperature and discharge cycles in the Colorado River (Figure 2). River temperatures have increased by nearly 5°C during the late fall and winter but decreased by 10°C during the rest of the year. These temperature changes were caused by cold-water releases from Glen Canyon Dam. Water is withdrawn from the hypolimnion of Lake Powell, and discharge temperatures average about 8°C throughout the year. In the summer, river temperatures increase to 10-11°C at Grand Canyon and 15-16°C at Pierce Ferry, where the river enters Lake Mead. However, river temperatures are still nearly 10°C colder than for comparable spring and summer periods prior to 1963.

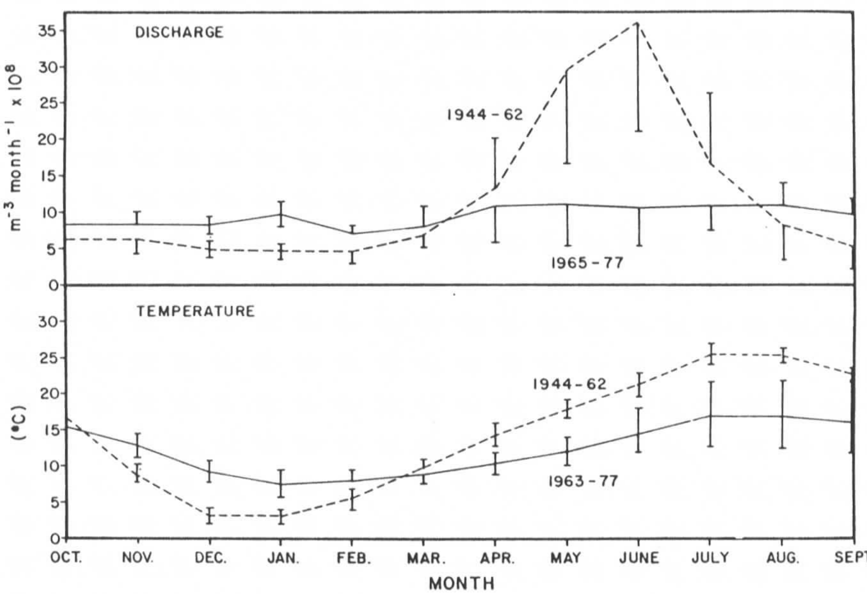

Figure 2. Historical Temperature and Discharge Data (±SD) in Grand Canyon for Pre-and Post-Lake Powell Periods [USGS Data]. From [7].

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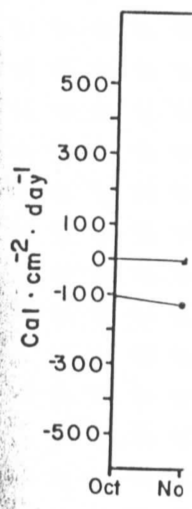

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Discharges from Glen Canyon Dam are regulated for power generation and flood control purposes. This has eliminated the spring discharge pulse that occurred historically due to runoff from the upper Colorado River drainage system (Figure 2). Monthly discharges are now subject to much less variation and peak discharges usually occur in summer when power demands are greatest.

Energy Advection

The alterations in temperature and discharge cycles in the Colorado River have had a significant influence on energy advection into Lake Mead. Investigations conducted in 1948 by Anderson and Pritchard [6] and in 1952-53 by Harbeck et al. [4] showed that large quantities of energy were advected into Lake Mead during spring and early summer (Figure 3). Advection contributed 300-400 cal/cm^2·day of heat to the reservoir during these periods. This was nearly half that derived from solar radiation. In contrast to pre-Lake Powell periods, advection now contributes minimal heat to Lake Mead (Figure 3). Cold-water discharges from Glen Canyon Dam resulted in a net heat gain of only 9.04 cal/cm^2·day during 1977-1978. This has had a marked influence on evaporation rates from the reservoir.

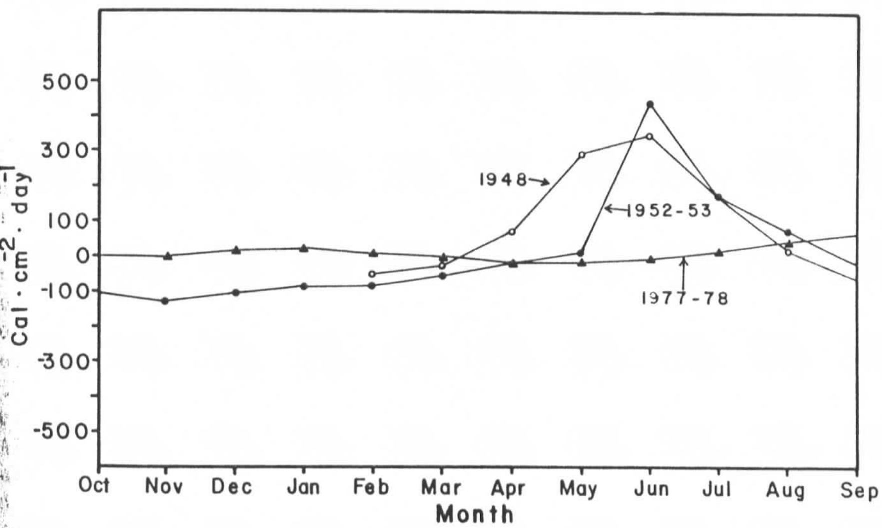

Figure 3. Net Advective Energy in Lake Mead During 1948 [6], 1952-53 [4] and in 1977-78 [This Study].

Evaporation from Lake Mead

Annual evaporation rates from Lake Mead, as reported by the U.S. Geological Survey, averaged 85.2 inches (216 cm)/yr prior to the construction of Glen Canyon Dam (Figure 4). Evaporation rates decreased significantly after 1964 when Lake Powell was filled to operating levels and discharges were increased to normal. In the period from 1965-1970, evaporation rates decreased to about 74 inches (188 cm)/yr which reflects the changes in energy advection caused by cold-water discharges from Glen Canyon Dam. Advection was especially pronounced during this period because of low lake elevations in Lake Mead and relatively high discharges from Glen Canyon Dam (Figure 5). Annual discharges were 65% of the Lake Mead volume in 1965 and averaged nearly 50% throughout the period.

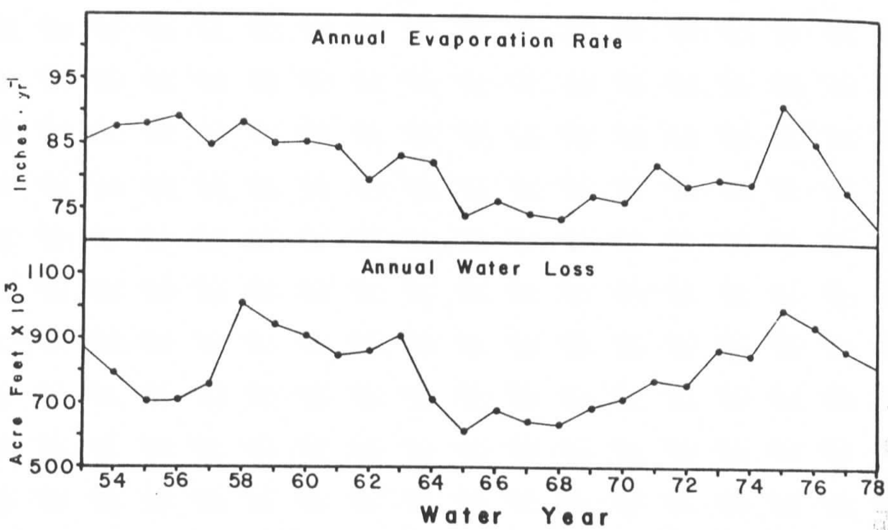

Figure 4. Historical Rates of Annual Evaporation and Total Evaporative Water Losses from Lake Mead [USGS Data].

The volume of Lake Mead rose steadily from 1964 through 1974, but river discharges remained fairly constant after 1965 (Figure 5). This lessened the influence of advection on the reservoir heat budget, and evaporation rates increased somewhat during 1970-1974. The abrupt increases in evaporation rates in 1975-76 and subsequent decreases in 1977-78

(Figure 4) were not related to changes in river discharges or reservoir volumes (Figure 5). Rather, it appears these variations were caused by changes in methods of estimating evaporation.

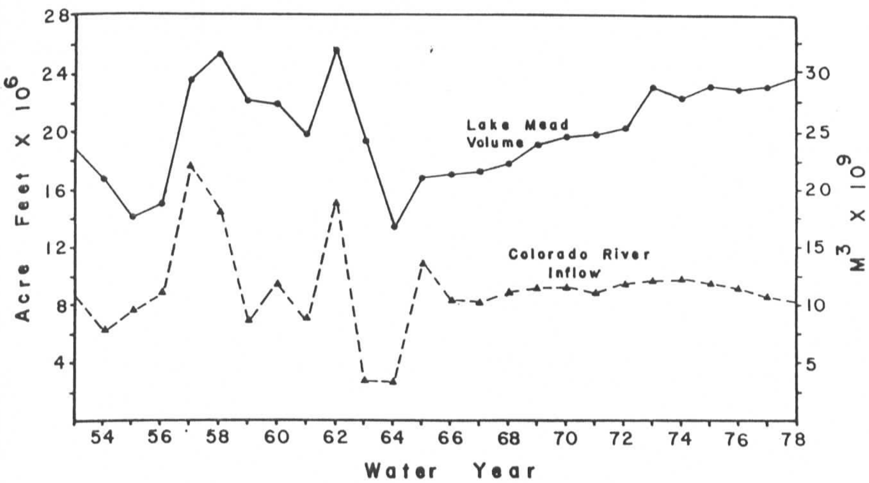

Figure 5. Average Annual Volumes for Lake Mead and Inflows from Grand Canyon [USGS Data].

Evaporation rates in Lake Mead have historically been estimated with the mass transfer method using equations developed by Harbeck et al. [4]. Evaporation rates were routinely adjusted for changes in energy advection and storage. This was discontinued in October, 1974, and evaporation rates rose sharply in 1975 and 1976. The mass transfer method was still used to estimate evaporation, but, in February of 1976, the coefficient in the equation was changed, and evaporation rates immediately decreased. This indicates that the abnormally high evaporation rates for 1975 and 1976 were caused by failures to adequately compensate for advection. Although evaporation rates for 1977 and 1978 appear reasonable in comparison to other post-Lake Powell years, recent data collected in limnological studies of Lake Mead [5] indicate that evaporation rates are still being overestimated.

Temperatures in the Upper Basin of Lake Mead are generally colder than in the Lower Basin [5]. In 1980, surface temperatures in Virgin Basin were often 1-2°C colder than in

Boulder Basin (Figure 6). This was especially evident during the spring and early summer, and only on a few occasions did surface temperatures in Virgin Basin exceed those in Boulder Basin. Although these temperature differences could reflect regional variations in climatology over the reservoir, they are most likely due to advection from the Colorado River inflow. The circulation patterns in Lake Mead are such that the Colorado River inflow is confined primarily to the Upper Basin [5]. The river forms a density current that extends to Virgin Basin and into the Overton Arm. The Virgin Basin appears to act like a large "mixing bowl" [6] and only when river discharges are high does the density current extend into the Lower Basin [5]. This usually occurs during late-summer after periods of prolonged, high discharges from Glen Canyon Dam.

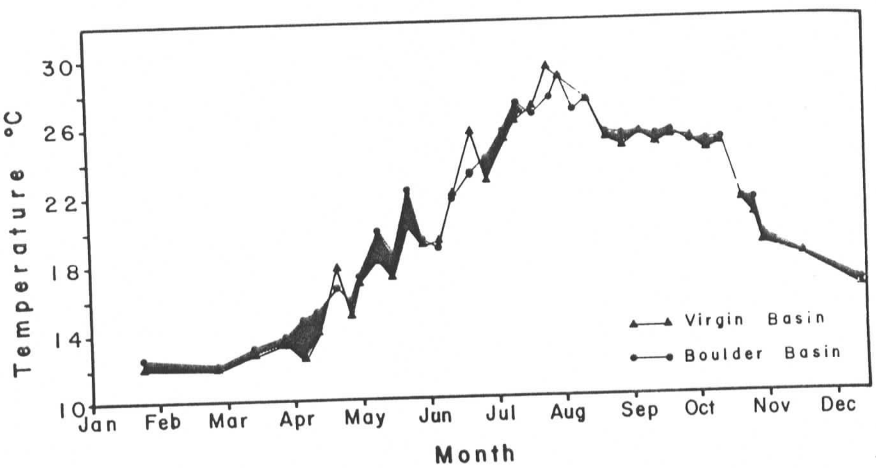

Figure 6. Surface Temperatures in Boulder Basin and Virgin Basin During 1980 [Lake Mead Limnological Research Center Data].

Historically, adjustments to evaporation rates for changes in energy storage in Lake Mead have been based on temperature measurements made at Hoover Dam intake towers [4]. This decision was reached on the basis of data collected in 1952-1953, which showed that temperature differences between the Upper and Lower Basins were minimal. This is no longer the case with cold-water discharges from Glen Canyon

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Dam. The Hoover Dam intake towers, being located at the distant end of the reservoir, would be one of the last areas in Lake Mead to be influenced by cold-water discharges. Temperatures at the dam could be considerably higher than elsewhere in the reservoir, particularly in comparison to the Upper Basin. Estimates of reservoir-wide evaporation based on data from the Hoover Dam intake towers could, therefore, also be higher than actual evaporation. Hydrologists at the Bureau of Reclamation have consistently observed an overall gain of water in Lake Mead. Based on a ten-year average during 1960-1970, the measured Lake Mead contents exceeded water budget estimates by approximately 230,000 acre-feet ($2.84 \times 10^8 m^3$)/yr (USBR data). This could, in part, be due to an overestimate of evaporation from the reservoir since 1963 when advection was altered by construction of Glen Canyon Dam.

Although measured evaporation rates may be somewhat too high in the period after 1963, it is still evident that cold-water discharges from Glen Canyon Dam have significantly reduced evaporation from Lake Mead. If we exclude the 1975 and 1976 values, which are clearly too high, pre- and post-Lake Powell evaporation rates average 85.2 inches (216 cm)/yr and 76.8 inches (195 cm)/yr. This is equivalent to a reduction in annual water loss of at least 93,376 acre-feet ($1.2 \times 10^8 m^3$), which is very similar to predictions made during the mid-1960s. Government scientists reported that cold-water discharges would reduce evaporation by about 100,000 acre-feet ($1.23 \times 10^8 m^3$)/yr. Operation of Glen Canyon Dam from a deep discharge is thus an extremely effective method of reducing evaporation from Lake Mead.

Manipulation of Evaporation Rates

It has long been known that reservoirs operated from a deep discharge store heat, whereas, those operated from a surface discharge dissipate heat [9]. The principle here is quite simple and depends only on the formation of thermal gradients in the reservoir. In Lake Mead, surface temperatures exceed hypolimnion temperatures during all periods of the year, except winter when the reservoir is completely mixed and isothermal. The temperature gradient is particularly sharp during summer when surface temperatures reach 27-30°C, compared to 11-12°C in the hypolimnion. In the period from October, 1977 - September, 1978, operation of Hoover Dam from the deep discharge resulted in an average, net advective heat gain of 9.04 $cal/cm^2 \cdot day$ (Table II). However, this would have decreased to -29.55 $cal/cm^2 \cdot day$ if the dam had been operated from a surface discharge over this period. The net difference in advection between surface and deep discharge would be -38.59 $cal/cm^2 \cdot day$ (Table II). Using

Equation 2, with L = 585 cal/cm^3 and a Bowen Ratio (R) of -0.108, this would be equivalent to a decrease in reservoir evaporation rates of -0.07395 cm/day or -26.99 cm/yr (-10.6 inches/yr). At the average lake elevations for 1977-78 (1186 ft), this would result in an annual reduction in water loss of 119,779 acre-feet ($1.48 \times 10^8 m^3$). The approach used to derive this estimate is very simplified in that other variables in the heat budget were not included in the calculations. It was assumed that solar radiation, net radiation and change in energy storage would be similar regardless of discharge depth. As was pointed out by U.S. Bureau of Reclamation scientists in their review of a previous report [10], these assumptions may not be entirely valid. Extensive studies will be required to determine how other variables in the heat budget will change with discharge depth. Nonetheless, the estimate appears to be a reasonable approximation of water loss savings based on conclusions from earlier studies on Lake Mead. Harbeck et al. [4] made similar estimates with data collected in 1952-53 and concluded that a surface discharge would reduce evaporation in Lake Mead by 72,000 acre-feet ($8.9 \times 10^7 m^3$)/yr at lake elevations of 1174 ft (358 m). This is similar to the present estimate if differences in lake elevations are taken into consideration.

Table II. Net Advective Energy Estimates in Lake Mead For a Surface and Hypolimnion Discharge at Hoover Dam [5].

Month	Colorado River			Hoover Dam					Lake Mead		
	Inflow[1] Temp.	Discharge	Energy[4]	Hypolimn.[2] Discharge Temp.	Epilimn.[2] Discharge Temp.	Discharge	Hypolimn.[4] Discharge Energy	Surface[4] Discharge Energy	Surface Area	Hypolimn. Discharge Net Advect. Energy	Epilimn. Discharge Net Advect. Energy
	(°C)	($m^3 \times 10^8$)	($cal \times 10^{16}$)	(°C)	(°C)	($m^3 \times 10^8$)	($cal \times 10^{16}$)	($cal \times 10^{16}$)	($cm^2 \times 10^{12}$)	($cal \cdot cm^{-2} \cdot day^{-1}$)	($cal \cdot cm^{-2} \cdot day^{-1}$)
Oct 77	13.0	5.2	0.447	12.0	22.3	5.3	0.403	0.949	5.34	+2.66	-30.30
Nov 77	12.4[3]	4.8	0.384	12.0	20.5	5.6	0.426	0.902	5.31	-2.64	-32.52
Dec 77	11.5	9.5	0.675	12.0[3]	16.6[3]	5.9	0.448	0.720	5.35	+13.69	-2.71
Jan 78	10.9	10.9	0.709	12.0	12.7	2.9	0.220	0.241	5.46	+28.89	+2.65
Feb 78	11.0	7.1	0.469	12.0	12.5	5.3	0.403	0.429	5.50	+4.29	+2.60
Mar 78	12.0[3]	9.3	0.707	12.1	16.4	9.1	0.701	1.092	5.55	+0.35	-22.38
Apr 78	13.0	5.9	0.507	11.7	15.1	11.1	0.810	1.188	5.46	-18.50	-41.5[illegible]
May 78	12.0[3]	6.9	0.524	12.0	19.3	10.6	0.806	1.579	5.46	-16.66	-62.33
Jun 78	11.0	9.3	0.614	12.3	22.0	8.1	0.640	1.426	5.46	-1.59	-49.57
Jul 73	15.8	9.4	1.072	12.0	27.0	10.3	0.783	2.328	5.36	+17.39	-75.59
Aug 78	14.7	13.2	1.360	12.0	24.8	11.0	0.836	2.244	5.37	+31.48	-53.10
Sep 78	14.7	12.5	1.288	12.3	22.5	6.2	0.490	1.122	5.41	+49.17	+10.2[illegible]
										+9.04*	-29.55*

*Average

[1] Inflow temperature = (T + 2.6°C) - 0.04 (T) - ($2.1 \times 10^{-5} \times q$)

Where T and q are Grand Canyon temperature in °C and mean discharge in CFS (Harbeck et al. 1958). Grand Canyon temperature from USGS data.

[2] Discharge temperatures are the Lake Mead temperatures at each depth of discharge near the Hoover Dam intake towers. Lake Mead surface and hypolimnion (90 m) temperatures from UNLV data.

[3] Average of preceding and following months.

[4] Advected energy computed reference 4.4°C.

It thus appears that the ideal strategy for reducing evaporation from Lake Mead would be to continue operating Glen Canyon Dam from a deep discharge and shift Hoover Dam to a surface discharge. This could result in a combined reduction in water loss of 213,155 acre-feet ($2.63 \times 10^8 m^3$)/yr, at the 1977-78 lake levels. Such reductions in water loss would constitute one of the best water conservation programs available for the Colorado River.

Influences on Reservoir Salinity

Reductions in evaporative water losses from Lake Mead would result in significant decreases in salinity of the reservoir. Inflows of cold water from Glen Canyon Dam are probably already causing reductions in salt concentrations in the Upper Basin of Lake Mead, although data are not available to estimate the magnitude. Water loss reductions derived from operating Hoover Dam with a surface discharge would act to further decrease salinity, especially in the Lower Basin.

Dissolved solids concentrations at the Hoover Dam intake towers in Lake Mead averaged 676 mg/l during water year 1978. Evaporation reductions of 120,000 acre-feet ($1.48 \times 10^8 m^3$), achieved with a surface discharge at Hoover Dam; or 213,000 acre-feet ($2.63 \times 10^8 m^3$), achieved with a cold-water discharge on Glen Canyon Dam and a surface discharge on Hoover Dam, would reduce salinity in Lake Mead by 9 mg/l and 16 mg/l, respectively (Figure 7). These salinity reductions would occur within a five-year period and are comparable to those which will be achieved by the Las Vegas Wash, Nevada (8 mg/l) and Grand Valley, Colorado (19 mg/l) Salinity Control Projects (Figure 7) [3]. This would serve to effectively augment salinity control projects on the Colorado River.

Feasibility of Operating Hoover Dam from a Surface Discharge

There are several potential problems associated with operation of Hoover Dam from a surface discharge [4]. First, this would require modifying the intake structures. Hoover Dam is currently equipped with intake gates at 895 ft (273 m) (lower gates) and 1045 ft (319 m) (upper gates) elevations. At the 1978 lake elevations of 1186 ft (361 m), operation from the upper gates would still result in withdrawal of cold, hypolimnion waters [12]. Intake gates would have to be installed at higher elevations to permit withdrawal of warm water. Engineering studies would have to be done to evaluate the feasibility and cost-effectiveness of such modifications. Hydraulic studies should also be conducted to insure that the intake structures would indeed withdraw surface waters and not pull cold water from deeper strata in the reservoir.

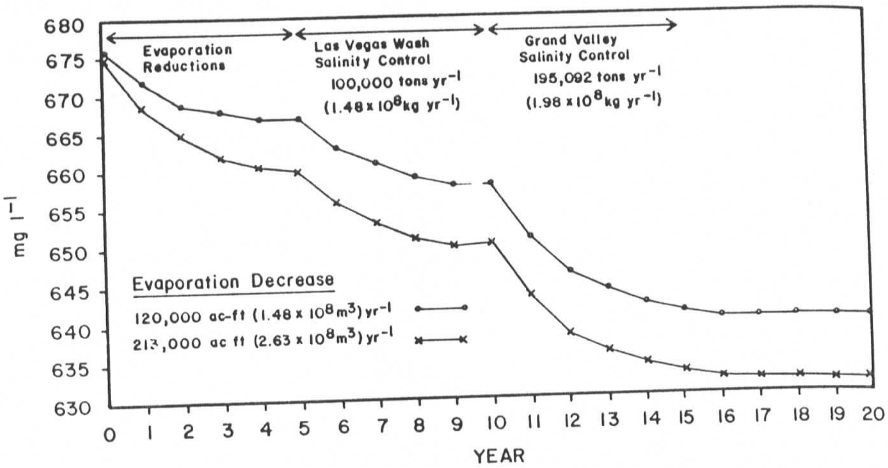

Figure 7. Salinity Model for Lake Mead Projecting Average Reservoir Salt Concentrations for Evaporation Reductions and Various Salinity Control Projects.

A second problem that needs to be considered relates to the impacts of warm-water discharges on downstream uses. The Black Canyon area below Hoover Dam supports a popular cold-water trout fishery that could be adversely influenced by warm-water discharges from Hoover Dam. Recent studies, however, have shown that warm-water discharges could benefit reproduction of aquatic insect populations that comprise an important food resource for trout [13]. Aquatic insects require seasonal temperature cycles, like those that existed historically, to complete their life cycle [14]. Discharge temperatures from Hoover Dam are now virtually constant at 12-13°C throughout the year and appear to be the cause for declines in aquatic insect populations in Black Canyon. Operation of Hoover Dam from a surface discharge would restore seasonal temperature cycles in the river and perhaps enhance production of aquatic insects. This, combined with stocking of warm-water tolerant rainbow trout, could insure that a viable trout fishery was still preserved in Black Canyon.

Warm-water discharges from Hoover Dam could also result in increased evaporation from Lake Mohave and Lake Havasu, the downstream reservoirs. The temperature structure in upper Lake Mohave is currently influenced by cold-water discharges from Hoover Dam [5]. However, the river forms an underflow in Lake Mohave and mixing is not sufficient to advectively cool the entire reservoir. Surface temperatures in Lake Mohave frequently exceed those in Lake Mead, and discharges of warm water from Hoover Dam will probably not contribute more heat to the reservoir than it currently assimilates from solar radiation. Temperature data are too limited to allow for speculations on how evaporation could be altered in Lake Havasu. However, the surface area of Lake Mohave and Lake Havasu are each roughly one-third that of Lake Mead. Net water losses and salinity in the river would probably still be reduced, even if warm-water releases did increase evaporation rates in these reservoirs.

Finally, operation of Hoover Dam from a surface discharge would alter the nutrient budget for Lake Mead. Total nitrogen retention in Lake Mead would increase by 66% and total phosphorus by 60% with a surface discharge on Hoover Dam [11]. This, in turn, would elevate productivity in the reservoir, particularly in the Lower Basin where wastewater inflows from Las Vegas Wash contribute large amounts of phosphorus to the reservoir [15]. However, this could be beneficial to the largemouth bass population which has undergone a serious decline in Lake Mead. This decline appears to be related to a decrease in reservoir fertility that occurred after Glen Canyon Dam was constructed in 1963 [16,17]. High nutrient losses from the deep-water discharge at Hoover Dam have further contributed to this decline in fertility. A surface discharge could help sustain greater fertility in Lake Mead, and perhaps provide a better food base for the bass populations [11].

The environmental and engineering problems associated with operation of Hoover Dam from a surface discharge do not appear to be insurmountable. Some of the environmental questions are being addressed in limnological studies currently being conducted for the Office of Water Research and Technology, or in fisheries investigations being conducted by the regional fisheries biologists and the U.S. Fish and Wildlife Service. The engineering problems, however, will clearly require additional investigations to determine whether the existing intake structures can be modified to cost-effectively withdraw surface waters from Lake Mead.

In addition, further limnological studies should be done in Lake Mead to determine if the present methods of estimating evaporation are accurate, evaluate estimates of water loss savings made in this paper, and better assess the relationship of salinity to evaporation in the reservoir.

This should be accompanied by similar investigations in Lake Mohave and Lake Havasu to evaluate how evaporation rates and salinity in those reservoirs would change with a surface discharge on Hoover Dam. The operation of the proposed pump-storage units (Spring Canyon and Rifle Range sites) should be included in these investigations since it is likely they can be used to further reduce evaporation in the reservoirs. If water were withdrawn from the hypolimnion of the reservoir with the pump-storage units and released via a diffuser into the epilimnion, it could result in significant cooling of the surface waters.

There are, therefore, a number of possible ways to operate hydroelectric facilities to reduce evaporative water losses and salinity in the Colorado River system. Cold-water discharges from Glen Canyon are already operating to reduce evaporation and salinity in Lake Mead. Operation of Hoover Dam from a surface discharge or use of pump-storage systems to further cool surface waters could result in greater reductions in evaporative water losses and salinity. These methods would certainly help preserve precious water supplies and water quality in the Colorado River.

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