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# The Impact of Reservoirs on Seasonal and Historical Salinity of the Colorado River

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## INTRODUCTION

The Colorado River Water Quality Improvement Program [1] will be the specific subject of several papers to be presented in this symposium. The objective of this paper is to describe a historical perspective of water resources development and to evaluate some of the impacts of reservoirs on salinity and the salinity control program.

## DEVELOPMENT IN THE COLORADO RIVER BASIN

Irrigation development in the Upper Basin began gradually after the beginning of settlement in about 1860. About 324,000 ha were being irrigated by 1905. Between 1905 and 1920 the development of irrigated land continued at a rapid pace, and by 1920 nearly 567,000 ha were being irrigated. The development then leveled off, and increase since that time has been slow because of physical and economic limitations.

Irrigation development began in the Lower Basin at about the same time as in the Upper Basin but was originally slowed by difficult diversions from the Colorado River with its widely fluctuating flows. Development of the Gila area began in 1875 and the Palo Verde area in 1879. Construction of the Boulder Canyon Project in the 1930's and other downstream projects since that time have provided the means for a continued expansion of the irrigated area.

Development and utilization of the basin's water resources result in depletions of streamflows, particularly the consumptive use of water by irrigated crops and exports to other basins. Reservoir evaporation and consumptive use of water for M&I purposes also produce significant depletions. Table I shows on the depletions from 1900 to 1979.

Table I. Average annual depletions (km$^3$)

| Period | Upper Basin | Lower Basin |
|---|---|---|
| 1970-1979 | 4.40 | 7.57 |
| 1960-1969 | 3.13 | 7.55 |
| 1950-1959 | 2.52 | 5.87 |
| 1940-1949 | 2.33 | 4.66 |
| 1930-1939 | 2.11 | 4.53 |
| 1920-1929 | 2.46 | 4.52 |
| 1910-1919 | 2.04 | 4.49 |
| 1900-1909 | 1.23 | 4.16 |

Transbasin exports and reservoir evaporation account for 80 percent of the increase in depletions since 1960. These depletions reduce the flow available to dilute more saline water; however, they add no salt to the system and, in the case of exports, they may slightly reduce the salt load by exporting salt with the diversion.

Exports from the headwaters of the basin could also conceivably reduce the basin salt load by removing water which would have otherwise picked up salts while moving downstream through the basin.

Total storage in the major reservoirs of the basin increased from virtually zero in 1935 to 29 km$^3$ in 1962 and 68 km$^3$ in 1982. The 1963-1980 period represents the initial filling of the major Upper Basin reservoirs with a combined capacity of approximately 42 km$^3$.

Table II. Colorado River Reservoir Statistics

| | Closure | Capacity(km$^3$) | Filled |
|---|---|---|---|
| Lake Mead | 1935 | 34.5 | 1941 |
| Lake Powell | 1963 | 33.3 | 1980 |
| Flaming Gorge | 1963 | 4.7 | 1973 |
| Navajo | 1963 | 2.1 | 1973 |
| Curecanti Unit | 1960-70 | 1.3 | 1968-78 |
| | (Lake Mead capacity in 1963) | | |

The reservoirs in the Upper Basin stored an average of 2.5 km3 of water a year. When the system reached full capacity in 1980, the system began discharging water which would have otherwise been stored. Glen Canyon Dam and Imperial Dam discharges were 28 percent and 60 percent above the 1970-1979 average in 1980 respectively [1].



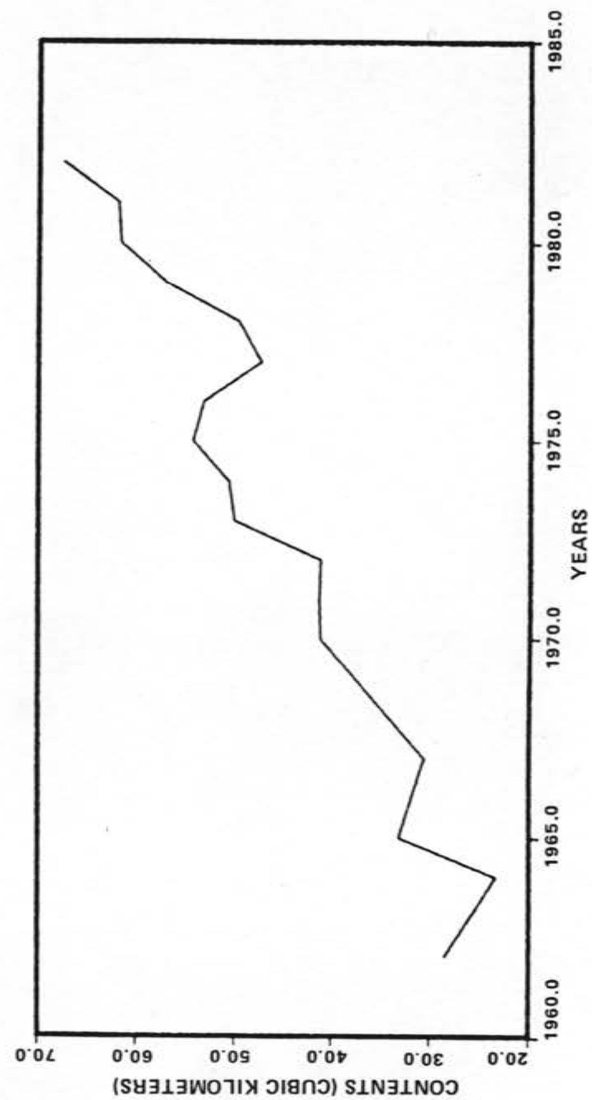


Figure 1. Combined reservoir contents for Flaming Gorge, Glen Canyon, and Hoover Dams.

## RESERVOIR IMPACTS ON SEASONAL VARIATION OF SALINITY

Prior to storage in Lake Mead, with the closure of Hoover Dam in 1935, the flow of the Colorado River was largely unregulated. The high runoff peaks and low base flow periods caused considerable seasonal fluctuation in Total Dissolved Solids (TDS). Figure 2 shows the pre- and post-impoundment salinity for the year before closure and 1980 for Hoover, Glen Canyon, and Flaming Gorge Dams.

Before Hoover Dam, TDS typically varied from 300 to 700 mg/L in May through August, but the September through April base flow TDS ranged from 700 to 1,300 mg/L. Since winter water use potential for irrigation in the Lower Basin was very high, salinity was recognized as a significant problem early in the development of the Colorado River.

Salinity in the Upper Basin can also be highly variable seasonally and of high enough levels to impact potential, as well as existing users. Table III shows the 1971-80 average monthly TDS at stations in the Upper Basin which exceeded 750 mg/L TDS more than 25 percent of the time. The TDS in these tributaries are not as significantly impacted by regulation as the lower mainstem.

Reservoir storage, in the basin, has increased the retention time of the system to 4-6 years and reduced salinity fluctuations. Figure 2 shows the impact of storage on the fluctuations below mainstem reservoirs. Salinity fluctuations near Hoover Dam typically ranged from 300 to 1,300 mg/L annually before regulation of the Colorado River. Annual variations today average less than 50 mg/L below Hoover Dam. Similar results can be seen in Figure 2 for Flaming Gorge and Glen Canyon Dams.

## RESERVOIR IMPACTS ON ANNUAL VARIATION OF SALINITY

Salinity since 1972 at Imperial Dam (see Figure 3) has shown a dramatic change from its historic pattern of variation. Salinity is fluctuating less from year to year, with the exception of 1980. It would also appear that salinity has generally declined and leveled off in the range of 810-830 mg/L.

Statistical analysis, using standard regression and t-test techniques, shows TDS to be increasing at an average rate of 3.9 mg/L per year for the 1941-1981 period and the 1972-1982 salinity varying within the 95 percent confidence interval shown in Figure 3.

The 1972 through 1980 decline in TDS is the likely result of a number of factors combining together. The most significant factor is filling of the Colorado River storage system. This increased the hydraulic retention time and,



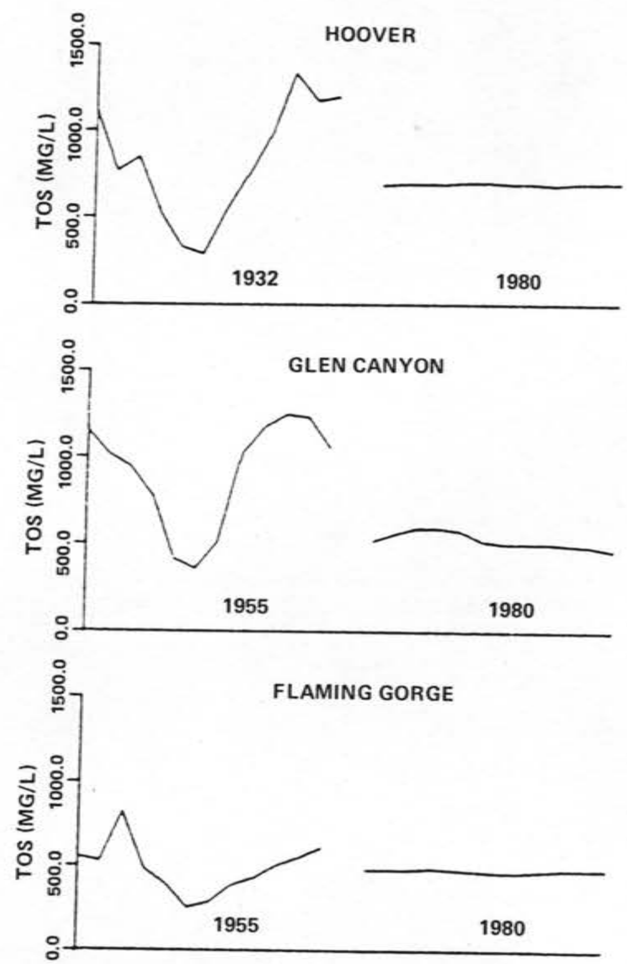


**Figure 2. Pre and post impoundment salinities for Flaming Gorge, Glen Canyon, and Hoover Dams.**

Table III. Seasonal Variation of TDS at Selected Stations in the Colorado River Basin for 1971-1980

| | Average TDS (mg/L) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| Duchesne Rv nr Randlett, Ut | 853 | 853 | 1,066 | 1,199 | 846 | 654 | 1,110 | 1,404 | 1,368 | 1,375 | 1,257 | 934 |
| San Rafael Rv nr Green Rv, Ut | 3,132 | 2,824 | 2,985 | 3,110 | 3,066 | 2,125 | 2,449 | 2,838 | 2,846 | 2,772 | 3,287 | 3,603 |
| Gunnison Rv nr Grand Jct, Co | 515 | 559 | 581 | 522 | 515 | 581 | 985 | 1,022 | 1,029 | 963 | 772 | 588 |
| Dolores Rv nr Cisco, Ut | 2,493 | 2,346 | 1,963 | 640 | 603 | 463 | 956 | 1,963 | 2,735 | 2,735 | 2,684 | 3,051 |
| Colorado Rv nr Cisco, Ut | 750 | 765 | 779 | 640 | 419 | 375 | 647 | 1,038 | 1,051 | 1,000 | 890 | 801 |



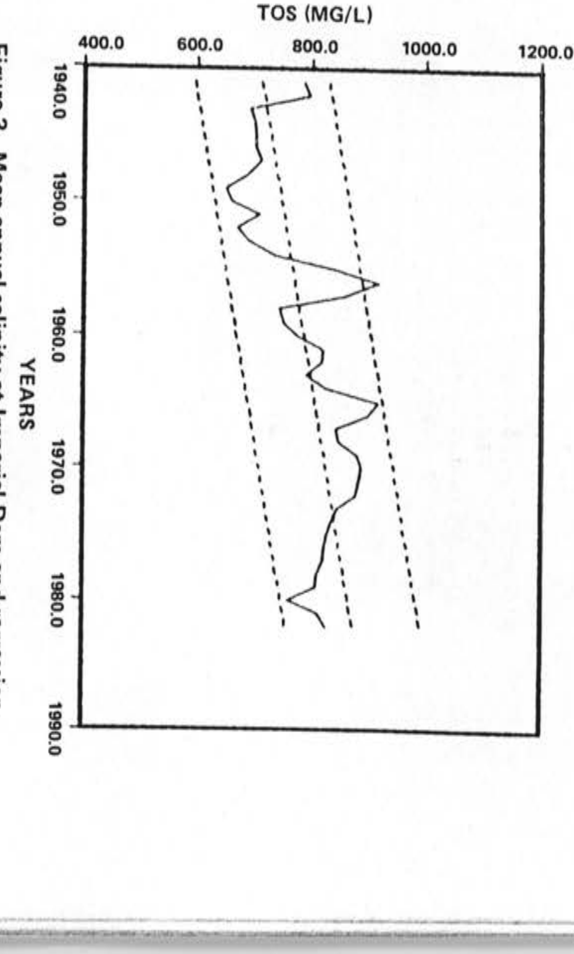

Figure 3. Mean annual salinity at Imperial Dam and regression showing the 95 percent confidence interval.

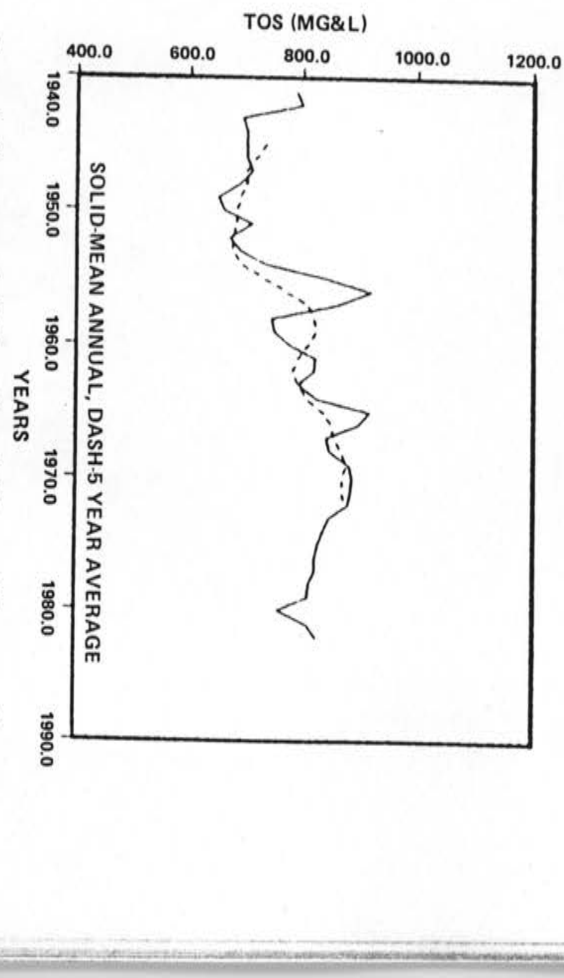

Figure 4. Mean annual salinity at Imperial Dam and 5-year moving average salinity.

as the system neared filling in 1980, it began discharging water which would have otherwise been stored.

The result of the increased retention time (4-6 years) would be to smooth the year to year variation, as well as the seasonal variation, in TDS. A 5-year moving average for 1941-1970 is shown in Figure 4. The moving average is used to simulate the dampening effect of the retention time on annual salinities. Although crude, this method puts the 1972-1979 salinities in a historical perspective by comparing the annual fluctuation before and after 1972.

The increase in retention time has altered the basic character of the Colorado River. The system is responding less to seasonal and annual variations in hydrologic conditions. The system has changed, for the most part, from a flow-through to a mixed reactor system and only overpowering hydrologic conditions can sharply impact the seasonal or annual TDS in the Lower Basin.

In 1980, discharge at Imperial Dam was 160 percent of the 1970-79 average. This discharge was due to the reservoir system being at near capacity and the need for anticipatory flood control releases. The increase in discharge percent salinity in the Lower Basin to be diluted by approximately 6 percent. This pattern of salinity fluctuation is likely to be repeated whenever the system is near full capacity and unable to store flows greatly in excess of demands. Since the Upper Basin has yet to fully develop its portion of the Colorado River, flows in excess of demands should occur at a fairly high frequency in the near future. On an average, the flow will be increased by 2.5 $km^3$ per year over the filling period (1963-1980) of the major Upper Basin reservoirs.

Variations in virgin water supply could have a significant impact on the excess flows. For example, the average annual water supply for 1970-80 was 1.6 $km^3$ higher than the 1955-65 supply. This increase in water supply is likely to have contributed to the decline in salinity.

Several investigators have shown there exists a potential for salts to be gained or lost in reservoirs within the basin. Howard [2] discussed the possibility of calcium carbonate precipitation and leaching of salts in Lake Mead. Paulsen and Baker [3] have proposed similar mechanisms on Lakes Mead and Powell. Studies on Lake Powell [4, 5] and Flaming Gorge [6, 7] have lent qualitative support to the potential of calcium carbonate precipitation.

Quantification of the loss of salts may well prove challenging. Salinity mass balances of reservoirs are usually plagued by shortages of data, monitoring programs which were designed to evaluate other problems, and the need to indirectly measure TDS using conductivity. Reservoir inflow TDS-conductivity relationships often have problems



with sampling frequency since the inflows to reservoirs are more variable than the outflows.

A recent study by Messer, et al [8] reviewed "Natural Salinity Removal in Mainstem Reservoirs: Mechanisms, Occurrence, and Water Resources Impacts." Messer concluded "Although the authors of reservoir studies in the semi-arid western states have frequently suggested that salinity removal may occur, the magnitudes are usually small and within the range of error of the calculations . . . . In the case of Lake Powell, model error, sampling error in determining salt storage in the water column, and failure to account for bank storage are sufficient to account for the apparent salinity removal." Messer's findings do not disprove the mechanisms; they simply point out the problems in quantifying the potential for precipitation of calcium carbonate.

Studies on Flaming Gorge and Lake Powell [9] have shown these reservoirs to have retained higher TDS waters and routed lower salinity flows through the system in the 60's and 70's. A chemocline in Flaming Gorge Reservoir produced a chemical density barrier which prevented the bottom TDS - hypolimnion waters from mixing with the low salinity runoff water overhead.

During the winter of 1981-82, this chemocline was displaced by reservoir turnover. The ability of Flaming Gorge Reservoir to retain high TDS waters may not persist in the future.

## CONCLUSIONS

Reservoir storage in the Colorado River Basin has in creased to 80 $km^3$ in 1982. The retention time of the system has increased to the range of 4-6 years. This retention time has decreased both the seasonal and annual variability of salinity in the basin. The Colorado River is currently behaving as a mixed reactor system rather than the plug flow system of its natural state.

With the system operating at near capacity, water in excess of demands can no longer be stored by the system. This will increase the average discharge through the Colorado River by approximately 2.5 $km^3$ per year. This excess in flow will effectively dilute the salinity in the Lower Basin. Development in the Upper Basin will eventually reduce the flow through the system and cause an increase in salinity as depletions come online in the future. Until further development occurs, average or wet periods, combined with the reduced capacity to store excess amounts of water, will continue to keep salinity down and periodically cause salinity to drop as it did in 1980.

Development will eventually reduce the flow through the system and cause an increase in salinity as depletions come online. The rate at which salinity increases in the future will, in part, depend on when development actually occurs.

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# Historical Trends in Concentration and Load of Major Ions in the Colorado River System


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## INTRODUCTION

The Colorado River Basin includes 632 000 $km^2$ in the Western United States and northern Mexico (figure 1). Although average unregulated discharge is only 500 to 600 $m^3/s$ [1], the river is an important source of water for more than 12 million people and approximately 1 million ha of irrigated agriculture [2]. Headwaters of the Colorado and its major tributaries, the Green and San Juan Rivers, lie in the high peaks of the Rocky Mountains, where precipitation averages 100 to 150 cm/a. Most of its course, however, crosses the semiarid Colorado Plateau and the Sonoran Desert, where average annual precipitation may be as low as 6 cm [1]. Many of the geologic formations in this part of the basin are of marine origin and contain sodium chloride (halite) and calcium sulfate (gypsum) salts. Natural springs or seeps and man-made wells intercept saline ground waters associated with these formations and discharge into the river system. Soils in much of the basin have developed residually on gypsum-bearing shales. Irrigation water applied to this land promotes weathering and dissolution of salts from the soil and underlying shales and returns to the river with a greater salt load than was diverted [3]. Irrigation also increases dissolved mineral concentrations in the river by depleting streamflow volume. As a result, total dissolved solids (TDS) increase from 50 mg/L at the headwaters to 800 mg/L (1977-1981 average) [1] at Imperial Dam, the final diversion point on the Colorado River in the United States.

During the early 1970's, salinity in the lower Colorado River was recognized as a basinwide problem [3]. TDS standards for lower basin gage locations were adopted by the