The Effects of impoundments on salinity in the Colorado River

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CHAPTER 27

THE EFFECTS OF IMPOUNDMENTS ON SALINITY IN THE COLORADO RIVER

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INTRODUCTION

The increase in salinity of our western rivers has been identified as one of the most serious water quality problems in the nation [1]. This is of special concern in the Colorado River where salinity has increased from pristine levels estimated at 380 mg/l [2] to present-day levels of 825 mg/l at Imperial Dam [3,4]. Flow depletions, associated with decreased runoff and increased evaporation and diversions, coupled with high salt loading from natural and man-created sources are considered the primary causes for rising salinity in the river [5]. The urban and agricultural development projected to occur in the basin through this century could deplete flows by an additional 2 million acre-feet ($2.5 \times 10^{9}$ m$^3$)/yr [4]. Salinity models indicate that depletions of this magnitude will elevate total dissolved solids concentrations (TDS) to 1150 mg/l at Imperial Dam. Since this would have an enormous economic impact on municipal and agricultural water uses [6], salinity control programs are being implemented in the basin to maintain TDS at or below the 1972 levels.

Historical data for the Colorado River, however, indicate that TDS concentrations are not increasing as rapidly as the models predict. Despite the extensive development and large flow depletions that have already occurred in the basin, TDS concentrations in Grand Canyon and below Hoover Dam have not changed appreciably since monitoring began [4]. Water quality monitoring has recently shown that TDS concentrations throughout the Lower Colorado River Basin have been decreasing since 1972. This is thought to be a transient phenomenon caused by changes in flow patterns, salt routing or possibly inundation of saline sources in the Upper Colorado River Basin following completion of Lake Powell and other impoundments during the 1960s [7]. This might also reflect more permanent reductions in TDS due to changes in
chemical processes operating in the impoundments.

The U.S. Geological Survey (USGS) has monitored ion and TDS concentrations in the inflows and outflow of Lake Mead and Lake Powell since early impoundment. The purpose here is to present results of our analysis of the USGS salinity data and describe how these large impoundments have historically influenced ion and TDS concentrations in the Colorado River. The implications of these findings are discussed relative to current efforts to control salinity in the Colorado River Basin.

**SALINITY STUDIES DURING EARLY IMPOUNDMENT**

Large impoundments, like Lake Mead and Lake Powell, are generally thought to have a detrimental effect on salinity. This view stems from the observation that TDS concentrations in the impoundment outflow exceed those in the inflows. Concentration of salt by evaporation is considered a primary cause for this increase in TDS [1]. Evaporation in Lake Mead ranged as high as 900,000 acre-feet ($1.1 \times 10^9 \text{ m}^3$)/yr during early impoundment [8, 9]. Howard [10] noted that this caused a slight increase in TDS below Hoover Dam. Evaporation in Lake Powell has been estimated at about 500,000 acre-feet ($6.2 \times 10^8 \text{ m}^3$)/yr [11] and causes a 16 mg/l increase in TDS below Glen Canyon Dam [12].

Evaporation clearly has an effect on TDS, but it appears to be relatively small by comparison to that caused by salt dissolution processes occurring in the impoundments. The chemical composition of the Colorado River is strongly influenced by the regional geology. Calcium, sulfate and carbonate have historically comprised 60-70% of the TDS. The impoundment of Lake Mead in 1935 further increased calcium and sulfate concentrations in the river [10, 13]. This was derived primarily from dissolution of gypsum deposits which were prevalent in the Muddy Creek geologic formations in Las Vegas Bay and Virgin Basin [14]. The U.S. Bureau of Reclamation [15] estimated that there were only 22 acres ($8.9 \times 10^6 \text{ m}^2$) of exposed salt outcroppings in the reservoir floor prior to inundation. They predicted that rates of dissolution would be high during early impoundment but then diminish as the outcrops dissolved or became silted over. Subsequent studies have not been conducted to evaluate this prediction, or to determine if similar dissolution processes occur in Lake Powell. However, Gloss et al. [12] noted that there was a slight increase in sulfate concentrations at Lees Ferry after the formation of Lake Powell. They suspected that this was caused by dissolution of gypsum and also predicted that rates would diminish as the impoundment aged.

The increases in TDS caused by evaporation and dissolution appear to be offset to some extent by precipitation of calcium carbonate.
calcium carbonate (calcite) that occurs in the impoundments. Large quantities of calcite were precipitated in Lake Mead during early impoundment [10]. The formation of Lake Powell substantially reduced calcite precipitation in the Upper Basin of Lake Mead, but rates are still high in the Lower Basin [16]. Appreciable quantities of calcite also precipitate in Lake Powell [12,17]. The combined impoundment system may therefore precipitate more calcite than what historically occurred just in Lake Mead. An increase in overall rates of calcite precipitation and/or a decrease in the rates of gypsum dissolution could be possible reasons for recent decreases in TDS observed in the Lower Colorado River Basin.

DATA SOURCES AND METHODS

The U.S. Geological Survey has monitored flow rates, ion and TDS concentrations in the Colorado River and storage in the impoundments for several years. Prior to 1970, the flow rates and storage data were compiled in "Surface Waters of the United States" and ion concentrations in "Quality of Surface Waters of the United States," both of which were published annually in the U.S. Geological Survey Water-Supply Papers, Part 9, Colorado River Basin (1926-1970). These records have since been published in the "Water Resources Data" series of the U.S. Geological Survey Water-Data annual reports for individual states in the Colorado River Basin. In our analyses, we used data from the "Water Resources Data for Arizona", "Water Resources Data for Nevada" and "Water Resources Data for Utah" reports for water years 1970-79.

Flow vs. TDS concentration relationships were evaluated from data collected for various time periods at Lees Ferry, Grand Canyon and below Hoover Dam (Figure 1). Sufficient data were available to evaluate these during pre-impoundment periods of 1926-42 and 1951-60 in Grand Canyon and 1951-60 at Lees Ferry. Data were also available to assess these relationships at Grand Canyon and Lees Ferry during the post-Lake Powell period of 1970-79 and below Hoover Dam during the post-Lake Mead periods of 1935-43, 1951-60 and 1970-79. Flow-weighted average TDS concentrations were computed for individual years within each time period. Changes in TDS concentrations vs. flows were computed between each year in these time periods and used to construct statistical relationships for each location.
Figure 1. Map of Colorado River System.

Ion and TDS budgets were also constructed for Lake Mead during the 1951-60 and 1970-79 periods and for Lake Powell during the 1970-79 period. Annual ion and TDS loads were computed from monthly flow and concentration measurements at
the principal inflows and outflow of each impoundment (Figure 1). Individual ion and TDS data were not available for the Las Vegas Wash inflow to Lake Mead during the 1951-60 period or for the Muddy River inflow during either period. The annual data were used to calculate flow-weighted average concentrations over the 10 yr periods on the combined inflows and outflow of each impoundment.

The effects of evaporation on ion and TDS concentrations could not be evaluated directly. Gross evaporation rates have been measured annually in Lake Mead since 1952, but water inputs from precipitation and ungaged inflows, which are necessary to compute net evaporation, have only been measured during special studies [8,9]. Gross evaporation rates and other variables of the water budget were only measured in Lake Powell during 1973-74 [11]. Water losses from the impoundments, nonetheless, exceed water inputs. In order to assess the effects of this on ion and TDS concentrations, we computed average annual, net rates of water loss for each impoundment and time period using Equation 1.

\[ R = I_g - O_g - O_d - \Delta S \]  

where

- \( R \) = net water loss (precipitation + ungaged inflows) - (evaporation + \( \Delta \) bank storage)
- \( I_g \) = gaged inflows (as in Figure 1)
- \( O_g \) = gaged outflows (as in Figure 1)
- \( O_d \) = diversions
- \( \Delta S \) = change in impoundment storage

The ion and TDS loads computed for the inflows to each impoundment were then divided by the term \( (I_g - R) \) to estimate ion and TDS concentrations expected in the outflow as a result of the net water losses. The net water losses were assumed to be due primarily to evaporation, and we acknowledge that factors like bank storage will have some influence on estimated changes in ion and TDS concentrations for years when lake fluctuations are more severe. However, averages over long term periods should not be largely affected.

Ion budgets, adjusted for net water losses, were used to estimate chemical precipitation and dissolution rates in the impoundments. Calcite precipitation was estimated from molar changes in carbonate (\( = \text{bicarbonate}/2.03 \)) [13]. Gypsum (\( \text{CaSO}_4 \)) and halite (\( \text{NaCl} \)) dissolution were estimated from molar changes in sulfate and chloride.
RESULTS

The various model predictions regarding future TDS levels in the Colorado River are based on the assumption that TDS concentrations will vary inversely with flows. Sufficient data were available to statistically evaluate these relationships at Lees Ferry and Grand Canyon during pre- and post-Lake Powell periods and below Hoover Dam during three post-Lake Mead periods.

The flow vs. TDS concentration relationships developed for these locations are presented in Table I. It was evident that TDS concentrations were inversely related to flows during pre-Lake Powell periods at Lees Ferry and Grand Canyon. The correlation coefficients for these relationships were highly significant at each location (Table I). There was no apparent relationship between TDS concentrations and flows at Lees Ferry or Grand Canyon during the post-Lake Powell period (Table I). A similar situation existed below Hoover Dam (Table I), even though annual flow variations were similar in magnitude to those at Lees Ferry and Grand Canyon during the pre-Lake Powell period. The lack of a relationship, or poor relationship, between TDS concentrations and flows during the post-impoundment periods indicated that other factors were operating in the impoundments to influence TDS.

Table I. Regression Equations and Correlation Coefficients for Relationships Between Changes in Flows (X) and TDS Concentrations (Y) for Various Time Periods and Locations in the Colorado River, (ΔFlow Units as m³ x 10¹⁰ and ΔTDS Concentrations as mg/l) [USGS Data].

<table>
<thead>
<tr>
<th>Location</th>
<th>Time Periods</th>
<th>N</th>
<th>Regression Equations</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lees Ferry</td>
<td>1951-60</td>
<td>9</td>
<td>Y = 0.53-151.712(X)</td>
<td>-.852*</td>
</tr>
<tr>
<td>Lees Ferry</td>
<td>1970-79</td>
<td>9</td>
<td>Y = 4.40-110.844(X)</td>
<td>-.384</td>
</tr>
<tr>
<td>Grand Canyon</td>
<td>1926-42</td>
<td>16</td>
<td>Y = 4.66-211.686(X)</td>
<td>-.786*</td>
</tr>
<tr>
<td>Grand Canyon</td>
<td>1951-60</td>
<td>9</td>
<td>Y = -2.84-172.953(X)</td>
<td>-.494*</td>
</tr>
<tr>
<td>Grand Canyon</td>
<td>1970-79</td>
<td>9</td>
<td>Y = -4.92-42.164(X)</td>
<td>-.208</td>
</tr>
<tr>
<td>Hoover Dam</td>
<td>1935-43</td>
<td>8</td>
<td>Y = -1.28-11.391(X)</td>
<td>-.079</td>
</tr>
<tr>
<td>Hoover Dam</td>
<td>1951-60</td>
<td>9</td>
<td>Y = -2.01-121.480(X)</td>
<td>-.568</td>
</tr>
<tr>
<td>Hoover Dam</td>
<td>1970-79</td>
<td>9</td>
<td>Y = 5.18-6.297(X)</td>
<td>-.011</td>
</tr>
</tbody>
</table>

*S Significant at P (.01)
The ion and TDS budgets for Lake Mead and Lake Powell revealed that the concentrations of certain ions were drastically altered by the impoundments (Figure 2). Lake Mead increased average sulfate concentrations by 63 mg/l during the 1951-60 period which was over 50 mg/l higher than expected due to net water losses (Figure 2). There was a less increase in sulfate during the 1970-79 period in Lake Mead, but concentrations were still 26 mg/l higher than expected (Figure 2). Lake Powell elevated average sulfate concentrations by 24 mg/l in the 1970-79 period which was about 10 mg/l higher than expected (Figure 2).

The increases in sulfate were offset to varying degrees by reductions in carbonate concentrations (Figure 2). In Lake Mead, carbonate was reduced by 29 mg/l below the expected value during the 1951-60 period (Figure 2). Silica and calcium were also slightly lower than expected. These reductions were not sufficient to offset increases in sulfate, and TDS concentrations rose by 42 mg/l. [TDS concentrations expressed as the sum of constituents do not always agree with TDS measured as residue. Both are reported in Figure 2, but we only refer to sum of constituents.] In the 1970-79 period, average carbonate concentrations were only 9 mg/l lower than expected for Lake Mead (Figure 2). TDS concentrations therefore increased by 57 mg/l which was 15 mg/l higher than the previous period and 12 mg/l higher than expected. Lake Powell reduced carbonate by 14 mg/l which offset nearly one-half the increase in sulfate (Figure 2). TDS concentrations increased by 34 mg/l and were only slightly higher than expected during the 1970-79 period.

The concentrations of other ions were not altered appreciably by the impoundments (Figure 2). There was no measurable change in magnesium and potassium concentrations in Lake Powell during 1970-79 or in Lake Mead during 1951-60. These ions only increased by 4 mg/l in Lake Mead during the 1970-79 period. Sodium and chloride were slightly higher than expected in Lake Powell during 1970-79 and in Lake Mead during the 1951-60 period. However, during the 1970-79 period, sodium and chloride concentrations were lower than expected for Lake Mead (Figure 2), indicating that these ions were being retained in the impoundment. This seemed unlikely because of the conservative nature of both ions. Rather, it appears that sodium and chloride loading to Lake Mead are being underestimated because of a sampling error that developed in Grand Canyon after flows were regulated by construction of Glen Canyon Dam in 1963. We explain this in greater detail in the discussion section of the paper.
Figure 2. Observed and Expected Changes in Ion and TDS Concentrations in Lake Mead During the 1951-60 and 1970-79 Periods and in Lake Powell During the 1970-79 Period. (Carbonate Estimated From Bicarbonate/2.03) [18]. [USGS Data].

Net 1970-79 also une decrease Glen Can have ris Signific in Lake draw dow higher n.

DISCUSS

The have a f flow and impoundn tions of in the r process lution c sulfate caused a chloride reductio ever, th dissolut expected

Table II

Location

Lake Pow
Lake Mea
Lake Mea
Lake Mea

*From Ho
**Includ
Net water losses estimated for Lake Mead during the 1970-79 period were higher than the 1951-60 period. This was also unexpected because evaporation rates in Lake Mead have decreased significantly due to cold-water discharges from Glen Canyon Dam [19,20]. However, water levels in Lake Mead have risen steadily since Lake Powell was formed in 1963. Significant quantities of water are retained in bank storage in Lake Mead when levels increase after extended periods of draw down [9]. This appears to be the principal reason for higher net water losses during the 1970-79 period.

DISCUSSION

The large impoundments on the Colorado River clearly have a significant effect on salinity. The relationships of flow and TDS differed markedly between pre- and post-impoundment periods. The reason for this is that concentrations of sulfate, carbonate and calcium, the principal ions in the river, were altered by dissolution and precipitation processes occurring in the impoundments (Table II). Dissolution of gypsum significantly elevated concentrations of sulfate during all time periods. Halite dissolution also caused slight increases in concentrations of sodium and chloride. Conversely, calcite precipitation caused marked reductions in concentrations of calcium and carbonate. However, this was not sufficient to offset increases caused by dissolution, and TDS concentrations were elevated above expected levels in all time periods.

Table II. Estimated Average Annual Rates of Calcite (CaCO₃) Precipitation and Gypsum (CaSO₄) and Halite (NaCl) Dissolution for Various Time Periods in Lake Mead and Lake Powell. Calcite Precipitation Was Estimated from Molar Changes in Carbonate Ion and Gypsum Dissolution from Molar Changes in Sulfate Ion. Calcium Concentrations Given in Parentheses. [USGS Data].

<table>
<thead>
<tr>
<th>Locations/Time Periods</th>
<th>CaCO₃ (mg/l)</th>
<th>CaSO₄ (mg/l)</th>
<th>NaCl (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Powell/1970-79</td>
<td>23 (9)</td>
<td>16 (5)</td>
<td>5</td>
</tr>
<tr>
<td>Lake Mead/1970-79</td>
<td>15 (6)</td>
<td>37 (11)</td>
<td>-</td>
</tr>
<tr>
<td>Lake Mead/1951-60</td>
<td>48 (19)</td>
<td>75 (22)</td>
<td>3</td>
</tr>
<tr>
<td>Lake Mead/1935-48*</td>
<td>47</td>
<td>123</td>
<td>19**</td>
</tr>
</tbody>
</table>

*From Howard [10], Gould [13].
**Includes potassium.
It appears that significant changes have occurred in the rates of dissolution and precipitation in Lake Mead since early impoundment. Rates of gypsum dissolution decreased from an average of 123 mg/l during 1935-48, to 75 mg/l during 1951-60 and 37 mg/l during 1970-79 (Table II). Average rates of halite dissolution decreased from 19 mg/l during 1935-48 to 3 mg/l during 1951-60. It was not possible to compute rates for 1970-79. The changes observed in the rates of dissolution in Lake Mead seem to confirm predictions made by the USDI [15] that rates would decrease as the salt outcroppings dissolved or became silted over.

The changes in sulfate concentrations in Lake Mead may also have been influenced by the activity of sulfate reducing bacteria. These bacteria convert sulfate ion to hydrogen sulfide under anaerobic conditions. The hydrogen sulfide often combines with iron to form insoluble iron sulfide precipitates that are retained in the sediments [21]. Howard [10] noted that substantial populations of sulfate reducing bacteria were present in Lake Mead sediments. Rates of sulfate reduction have never been measured directly, but sulfate diffusion coefficients were determined for sediments in Las Vegas Bay and Bonelli Bay [22]. It is possible to estimate rates of sulfate reduction from sulfate diffusion coefficients if we assume estimates for Las Vegas Bay are representative of the Lower Basin of Lake Mead and those for Bonelli Bay are representative of the Upper Basin. These calculations indicate that sulfate reduction would decrease sulfate concentrations in the outflow from Lake Mead by 8 mg/l-yr. This functions to offset some of the increase in sulfate concentrations caused by dissolution of gypsum.

Rates of calcite precipitation estimated by Howard [10] indicated that 47 mg/l were precipitated annually in Lake Mead during 1935-48 (Table II). Those measured by Pretki et al. [16] were considerably lower during this period. Rates of calcite precipitation in Lake Mead decreased from an average of 48 mg/l during the 1951-60 period to 15 mg/l during the 1970-79 period (Table II) which does agree with changes measured in Lake Mead sediments and those expected as a result of decreased phytoplankton productivity [16].

The reductions in phosphorus loading that occurred after Lake Powell was formed [23] caused productivity in the Upper Basin of Lake Mead to decrease from an average of 4612 mg C/m²·day to 503 mg C/m²·day [16,24]. Increased phosphorus loading from sewage effluent discharges into Las Vegas Bay increased productivity in the Lower Basin from 937 mg C/m²·day to 1582 mg C/m²·day [24]. However, this was not sufficient to offset the decreases that occurred in the Upper Basin, and reservoir-wide productivity in Lake Mead decreased by 73% after Lake Powell was formed in 1963. Reservoir-wide calcite precipitation decreased from an...
occurred in Lake Mead during the 1970-79 period from an average of 397 \times 10^3 \text{ t/yr} to 180 \times 10^3 \text{ t/yr} over the same period [16]. The greatest decrease occurred in the Upper Basin where rates dropped from 240 \times 10^3 \text{ t/yr} to 28 \times 10^3 \text{ t/yr}. The changes in calcite precipitation were therefore closely related to changes in productivity.

Calcite precipitation in Lake Powell averaged 23 mg/l during the 1970-79 period (Table II). Reynolds [17] demonstrated that polyphenols in the Colorado River inflow to Lake Powell significantly inhibited calcite precipitation in the upper end of the impoundment. The polyphenols are derived from forested regions of the Upper Colorado River Basin, and concentrations vary directly with seasonal flow patterns [12]. During spring, when the river forms an overflow in Lake Powell, polyphenol concentrations are sufficient to inhibit calcite precipitation in the upper one-third of the impoundment. Calcite precipitation is limited primarily to summer months and only occurs in the lower end of Lake Powell where dilution reduces polyphenol concentrations [12,17].

Rates of calcite precipitation in Lake Powell during the 1970-79 period were roughly one-half as high as those estimated for Lake Mead during the 1935-48 and 1951-60 periods (Table II). This could reflect differences in factors influencing solubility (temperature) or possibly indicate that polyphenol inhibition was not as high in Lake Mead when it received runoff directly from the Upper Colorado River Basin. Ratios of autochthonous organic carbon sedimentation to autochthonous calcite precipitation indicate that inhibition was, and still is occurring in the Upper Basin of Lake Mead [16]. These ratios did not change appreciably after Lake Powell was formed indicating that polyphenols are still being supplied to Lake Mead either via export from Lake Powell or possibly from inputs in the Grand Canyon. Thus, even though rates of calcite precipitation were relatively high in Lake Mead during early impoundment, it is likely that they would have been even higher were it not for the inhibition that appears to be caused by polyphenols.

The inhibition of calcite precipitation that occurs in both impoundments, and decreases that occurred in Lake Mead after Lake Powell was formed, reduce the combined effectiveness of the impoundments for calcite removal. However, the two impoundments still removed an average of 38 mg/l of calcium carbonate during the 1970-79 period (Table II) which is extremely significant from the standpoint of salinity control. Lake Powell increased sulfate concentrations by 16 mg/l, but rates of gypsum dissolution have decreased considerably in Lake Mead. The combined impoundment system now contributes 53 mg/l calcium sulfate to the river, but this is still considerably lower than what occurred in Lake Mead.
during the 1935-48 and 1951-60 periods (Table II). This has a pronounced effect on TDS because sulfate alone comprises nearly one-half the TDS in the Colorado River. The changes in rates of gypsum dissolution may, therefore, be an important factor in causing the decrease in TDS observed in the Lower Colorado River Basin during recent years.

Accuracy of Ion Budgets

Precipitation and dissolution estimates based on mass balance calculations have been questioned in a recent salinity study [25]. Messer et al. [25] contend that salinity decreases attributed to calcite precipitation [10] can often be accounted for by salt storage in the impoundments. Sufficient data are rarely available to accurately estimate salt storage, and it was excluded from our calculations. It is unlikely, however, that this introduced errors in the ion budgets.

Salt storage is a function of salt loads in the inflows and outflows (discharge and diversions). Salt concentrations, however, can only vary with changes in inflow salt concentrations or evaporation, if precipitation or dissolution processes are not occurring in the impoundment. The expected outflow concentrations, estimated from 10 yr flow-weighted average inflow concentrations, adjusted for net water losses, differed significantly from measured concentrations for several ions (Figure 2). Outflow concentrations of carbonate were consistently lower and sulfate consistently higher than expected. These differences simply cannot be explained by salt storage since the estimates encompass roughly three flushings of the impoundments. The stoichiometry was not exact in that calcium lost by calcite precipitation did not balance that derived from gypsum dissolution (Table II). This probably reflects the influence of sediment diagenesis processes (e.g. sulfate reduction) [22], but the net effects of such processes on ion concentrations are unknown. There is, nonetheless, little doubt that calcite precipitation is a major loss, and gypsum dissolution a major source, of salinity in the Colorado River.

It was not possible to estimate halite dissolution in Lake Mead during the 1970-79 period. The observed decreases in sodium and chloride concentrations were nearly 5 mg/l lower for each ion than those expected due to net water losses (Figure 2). This did not occur in Lake Mead during the 1951-60 period or in Lake Powell during the 1970-79 period, indicating that it was not caused by retention of sodium chloride in the impoundment. Rather, this appears to be caused by sampling problems that developed in Grand Canyon after flows were regulated by Glen Canyon Dam.

The Little Colorado River enters the main stem Colorado
This has comprises of an increase in mass salinity that salina- tion [10] can produce. The estimates of salt concentrations in the inflows to Blue Springs derived from surface runoff, which is highly variable seasonally, and a nearly constant base flow of 223 CFS (6.3 m³/sec) from several springs and seeps, collectively referred to as Blue Springs [26]. Blue Springs contribute about 550,000 tons of salt per year to the Colorado River [4]. Comparison of flow-weighted average ion concentrations during the 1970-79 period at Lees Ferry and Grand Canyon (Table III) indicate that the Blue Springs input is comprised primarily of sodium and chloride.

Table III. Flow-weighted Average Ion and TDS Concentration at Lees Ferry and Grand Canyon During the 1970-79 Period. [USGS data].

<table>
<thead>
<tr>
<th>Location</th>
<th>Ca</th>
<th>Mg</th>
<th>Na</th>
<th>K</th>
<th>CO₃</th>
<th>SO₄</th>
<th>Cl</th>
<th>Si</th>
<th>TDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lees Ferry</td>
<td>72</td>
<td>25</td>
<td>76</td>
<td>3.9</td>
<td>79</td>
<td>238</td>
<td>52</td>
<td>8.2</td>
<td>554</td>
</tr>
<tr>
<td>Grand Canyon</td>
<td>75</td>
<td>26</td>
<td>96</td>
<td>4.1</td>
<td>84</td>
<td>243</td>
<td>81</td>
<td>8.5</td>
<td>618</td>
</tr>
<tr>
<td>A</td>
<td>29</td>
<td>5</td>
<td>5</td>
<td>0.3</td>
<td>64</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Sum of constituents

Concentrations of these ions in Grand Canyon will vary inversely with river flows. Glen Canyon Dam stabilized seasonal flows but resulted in extreme variations in hourly flows. It is common for daily flows to vary from 2000 CFS (57 m³/sec) to over 20,000 CFS (566 m³/sec). USGS sampling in Grand Canyon has almost always been conducted at the beginning of each month, but the actual time of sampling varies from month to month. Sampling conducted when flows are high will cause more dilution of sodium and chloride concentrations and result in underestimates of loading to Lake Mead. This appears to be the case during the 1970-79 period which accounts for the unusual discrepancy observed in the sodium and chloride budgets.

This illustrates the kind of problems that can develop where sampling is conducted below a point source tributary in a regulated river. Grand Canyon is an extreme case due to the unique nature of the Little Colorado River, but a similar situation could exist in the Green River, which is regulated by Flaming Gorge Dam. The USGS gaging station in the Green River at Green River, Utah is located below the Price River which is a significant TDS point source [4]. At these locations, it seems that composite, rather than grab, sampling should be conducted to insure that flow-induced variations in ion concentrations are adequately represented by the sample.

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Implications for Salinity Control

Congress authorized the U.S. Department of Interior (Bureau of Reclamation) to proceed with construction of four salinity control projects under Title II of the "Colorado River Basin Salinity Control Act" (PL 93-320) of 1974. These included: the Grand Valley and Paradox Valley units in Colorado, the Las Vegas Wash unit in Nevada and the Crystal Geyser unit in Utah [3]. The Crystal Geyser unit has since been dropped from further consideration, but implementation of the others is proceeding on schedule. Collectively, these salinity control projects will decrease TDS concentrations at Imperial Dam by 65 mg/l [4]. Numerous other projects are in the planning or feasibility stage, and, if all are implemented, these would reduce TDS by 130 mg/l at Imperial Dam [4].

Control of point sources is obviously an effective method of reducing TDS concentrations, and this approach appears to be warranted in view of predictions that TDS could increase to 1150 mg/l by year 2000 [4]. These predictions, however, are based on models that assume TDS concentrations are inversely related to flows. This was the case during pre-impoundment periods, and the assumption is perhaps still valid for extreme variations in flow. However, flow vs. TDS relationships have been highly modified by the large impoundments. The concentrations of principal ions in the Colorado River are now altered significantly by mineral dissolution and precipitation and evaporation processes occurring in Lake Powell and Lake Mead. Rates of calcite precipitation are closely linked to rates of phytoplankton productivity. Inhibition of calcite precipitation occurs to varying degrees in both impoundments. Rates of gypsum and halite dissolution have been decreasing in Lake Mead since early impoundment and will probably decline even more in the future. A similar trend has been predicted to occur in Lake Powell [12]. Although net water losses in Lake Mead were higher, apparently due to increased bank storage during the 1970-79 period, evaporation rates appear to have been reduced considerably by cold-water discharges from Glen Canyon Dam [19,20]. It is estimated that this has reduced average TDS concentrations by 9 mg/l [20]. The impoundments have thus caused numerous changes in ion and TDS concentrations that cannot be modeled by simple flow vs. TDS relationships. Rates of calcite precipitation, mineral dissolution, and evaporation must be incorporated into the models, if they are expected to have any predictive value.

Moreover, the whole concept of controlling TDS point sources seems illogical in view of the natural ion composition of the river and the effect that these have on various beneficial uses. Sulfate comprises nearly one-half the TDS in the Colorado River, and its concentration is often appreciably lower than that observed in other river basins. Sulfate is typically used as an indicator of water quality because it is one of the few ion commodities that is expected to be restored by the rehabilitation of the Colorado River.
of Interior Construction of four the "Colorado the Crystal Gey- has since been ammation of rively, these concentrations or projects are all are imple- Imperial Dam effective its approach is that TDS These predici- me TDS concen- tration is per- ow. However, modified by the principal ions in- tly by mineral processes of calcite phytoplankton precipitation occurs to gypsum and e Mead since ver e in the Lake a Mead were age during the ave been redu- duced average dments have concentrations relationships. lution, and els, if they mg TDS point l ion composite on various -half the TDS in the Colorado River. Studies conducted on a variety of irrigation waters by the FAO [27] show that sulfate has no appreciable effect on agricultural uses. In fact, gypsum is often applied to agricultural soils to maintain calcium at levels sufficient to avoid permeability or toxicity problems that develop where irrigation waters are high in sodium [27]. Sulfate also appears to have little effect on municipal uses, even though concentrations in the Lower Colorado River Basin are slightly higher than the first tier drinking water standards of 250 mg/L.

There are no drinking water standards on calcium and carbonate, but it is well known that these are the principal hardness agents responsible for severe scaling problems in municipal water systems of Colorado River water users. Kleinman and Brown [6] estimated that $240,500 in economic damages were incurred per mg/L TDS by municipal users in the Lower Colorado River Basin. These estimates would probably be considerably higher if they were expressed per mg/L calcium carbonate. Lake Powell and Lake Mead collectively removed an average of 38 mg/L of calcium carbonate per year over the 1970-79 period. This has greatly reduced the economic damages to municipal water systems. Moreover, rates of calcite precipitation in the impoundments would be even higher were it not for polyphenol inhibition. Similarly, calcite precipitation in Lake Mead would probably increase significantly if phytoplankton productivity could be restored to pre-Lake Powell levels.

Sodium and chloride are the only other ions that make up a significant fraction of the TDS in the Colorado River. Dissolution of halite and evaporation in the impoundments caused a slight increase in concentrations of these ions. Sodium, via the effect it has on sodium adsorption ratios, is especially harmful to agricultural crops [27]. Based on the FAO recommended guidelines, sodium adsorption ratios are approaching levels at Parker and Imperial Dams that could present a problem for agricultural users (Paulson unpubl. data). This may warrant some form of control in the future, which could probably best be achieved by controlling point source sodium and chloride inputs, rather than TDS.

Based on information presented by USDI [4], and USGS data collected in rivers near salinity control projects, it appears that the Las Vegas Wash and Grand Valley sources are primarily sulfate salts. Implementation of these projects would decrease TDS by 4 mg/L and 43 mg/L, respectively, but this would probably have little effect on beneficial uses because the salts are primarily sulfate. However, the salts originating from the Paradox Valley area appear to be comprised primarily of sodium and chloride. Similarly, Glenwood and Dotsero Springs in Colorado, which are being considered for salinity control, are comprised primarily of
sodium and chloride [4]. Implementation of these projects could be extremely effective in reducing impacts on agricultural uses.

Selective control of specific ions, coupled with enhancement of natural salinity control processes, like calcite precipitation, seem to constitute a more cost effective approach to salinity management than indiscriminate control of TDS point sources. We are hopeful that results of this paper will stimulate a move in that direction.

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REFERENCES


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