Lake Mead and Lake Powell salinity reports

Cathy Lee  
_The Colorado River Water Quality Office_

Steve Gazafy  
_The Colorado River Water Quality Office_

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Memorandum

Chief, Colorado River Water Quality Office

The subject reports have been reviewed and following are our comments.

General

As noted in the memorandum accompanying the reports, they are not considered "polished" documents. They do, however, provide some useful information.

The report by Cathy Lee is very short and does not contain sufficient data and analysis to support the conclusions reached.

The report by Steve Gazafy is done much better and provides more detailed information (except that the isopleths are poorly and incorrectly drawn). Apparently, the long-term trend of increasing salinity in Lake Powell was slowed or reversed in the first half of 1978. It would be well to follow this trend in future years.

Data for Lake Mead are inconclusive because of insufficient sampling stations in the lake, plus a lack of understanding of the influence of Lake Powell on Lake Mead salinity.

Recommendations

1. The data collection program for Lake Powell should be examined to determine if it is providing the information required to adequately assess salinity trends. Obviously the program should be continued in some form. Perhaps a sensitivity analysis of the number of sampling sites and frequency of collection could improve the current program.

2. The current data collection program for Lake Mead appears to be deficient and should be upgraded as resources become available.

3. The two reservoirs should not be viewed only as separate entities but also as parts of an integral system. Future studies should consider their interrelationship.
4. An understanding of the mechanisms controlling salinity in Lake Powell and Lake Mead is essential for control of salinity in the Colorado River. Careful consideration should be given to a long term program of data-collection and interpretation that will further understanding of the physical and chemical reactions occurring in these water bodies. The task will not be easy.

5. Short term, the following actions should be considered as aids in interpreting existing data:

a. A computer program should be developed that will transform sampling results into average salinity concentrations for the entire reservoir as well as segments. This was done by Gazafy and reported on figure 3. Similar results could be routinely prepared for each set of data.

b. Once the average salinity is available from (a), the tons of salt in solution could be determined. This would allow a true salt balance to be calculated for the reservoir to determine if significant quantities of salt are precipitating.

c. Also, a computer program could be developed to prepare isopleths much faster (and more accurately) than by hand.

Specific Comments: Salt Load Balance of Lake Powell and Lake Mead

Page 1, 2nd paragraph - How were salinity loads obtained for Dirty Devil River for months prior to 1971?

Page 1, 3rd paragraph - The "salt balance" defined by the first sentence fails to account for changes in salt storage in the reservoir associated with changes in water storage. How much of the increase resulted from water storage in the lake?

Page 2, last paragraph - The conclusion "that tremendous salt precipitation is occurring in Lake Powell" is unsupported and probably false. Gazafy's report contends that salt is being stored in the solution phase. Data tend to support Gazafy's conclusion. Furthermore, it would be beneficial to put the "8 million tons of salt" into perspective. How much salt enters the lake each year? What error is associated with measurements of salinity and quantity?

A reference should be given for the "previous salt load balance."

We support the recommendation in the last sentence.

Page 3, 3rd paragraph - Again, changes in water storage may account for most of the changes in salt storage. What is the significance of the "value for the base salt load" and how was it determined?

Page 3, 4th paragraph, last sentence - Probably true.
Specific Comments: An Analysis of Salinity in Lake Mead and Lake Powell

Page 1, 1st line - Is it true that "all available" TDS data were analyzed?

Page 1, 2nd paragraph - The use of such terms as "very dense saline flows," "highly saline water," and "dense saline underflows" is probably overstating the case.

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Page 1, 2nd paragraph, last sentence - Suggest rewriting as: Further data are needed to support this hypothesis.

Page 2, 1st paragraph - The changes noted may only reflect the impacts of annual runoff and operation of the reservoirs.

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Figure 3 - The diagrams and tables shown here are very good means of summarizing data and communicating information.

How does the increase in salt depicted here compare with the increase in salt load computed by inflow minus outflow?

Volume units reported as million acre-feet do not agree with corresponding numbers on figure 4.

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<td>11,340</td>
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Page 17 - It appears that opposing conclusions are presented depending on the period of data considered. The first sentence here states that "salinity levels are definitely on the rise," while the second paragraph reports that "presently, this behavior is allowing * * * an overall decrease in total and bottom reservoir salinity." Apparently, more time is required to determine whether the March to June 1978 decrease is but a temporary decrease in a generally increasing trend.

Kenneth O. Kauffman

Copy to: D-700
       D-720
       D-750

RSchaefer:cfr (5/15/79)
Memorandum

TO: Chief, Plans Coordination and Reports Branch

THROUGH: Chief, Hydrology Branch

FROM: Head, Water Quality Section

SUBJECT: Review of Salinity Study Reports of Lake Mead and Lake Powell

The reports were reviewed by D-752 (Lane) and D-754 (Shaffer and Thomas).

General Comments

As noted by the memorandum accompanying the reports, they are not considered "polished" documents. They do, however, provide some useful information.

The report by Cathy Lee is very short and simplistic and her conclusions are at best, unsupported and at worst, false.

The report by Steve Gazafy is much better done and provides more detailed information (except that isopleths are poorly and incorrectly drawn). Apparently, the long term trend of increasing salinity in Lake Powell was slowed or reversed in the first half of 1978. It would be well to follow this trend in future years.

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Jim Thomas

Copy to:  D-700
         D-750
         D-752
         D-754

Signed: 4/27/77

M. Leon Hyatt
Chief, Hydrology Branch
INVESTIGATIONS WORK REQUEST
and FUND ALLOCATION

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*Allocations contain DL&A, Overhead, ADP, Travel, and other job-related costs:

TOTAL OF ALLOCATIONS: 5/71/79

SUBJECT:
Salinity Study Reports of lake Mead and lake Powell

ACTION REQUESTED:
Please review and comment

FURNISH:
1. Comments to 720 for preparation of reply to Regional Director or Commissioner.
2. Quantity estimates and data to be necessary for preparation of cost estimate by 1/43 by
3. One reproducible, one half-size xerox on Vellum and six half-size blackline prints of all drawings, and Construction Cost Estimate, Form 7-1432.

REFERENCES AND REMARKS:
Reference letter, or memorandum:
Chief, Colo. River Water Quality Office
Memo of 2/17/79

ENCLOSURES:
All Codes: Referenced letter, or memorandum:
Code 750: 1 Copy

COPY TO: 320
705
720

WORK PERFORMANCE REQUESTED:
George H. Schaefer
CHIEF, PLANS COORDINATION AND REPORTS BRANCH

FUND ALLOCATION: Recommended: Approved:
CHIEF, DIVISION OF PLANNING COORDINATION CHIEF, PROGRAM COORDINATION BRANCH

If you have any questions, contact: Dick Schaefer Code: 720 Ext: 3321
Memorandum

To: Regional Director, Salt Lake City, Utah
   Attention: UC-700
   Regional Director, Boulder City, Nevada
   Attention: LC-700

From: Chief, Colorado River Water Quality Office

Subject: Salinity Study Reports of Lake Mead and Lake Powell

The enclosed reports were recently compiled for this office based on current salinity data for Lake Mead and Lake Powell. The reports are not considered "polished" documents for public distribution. However, they are interesting, rough appraisals of general trends that may be very important in our understanding the hydro-salinity system in the Colorado River. I would appreciate any comments or suggestions that you may have regarding these reports, including any recommendations for follow-up studies.

Enclosure

Blind to: D-700 (with enclosures)
D-1000
SALT LOAD BALANCE OF LAKE POWELL AND LAKE MEAD,
COLORADO RIVER BASIN

Prepared by:

Cathy Lee
Rotation Engineer

For: The Colorado River
River Quality Office,
E&R Center

February 1979
Lake Powell Salt Load Balance
January 1967 to December 1976

This report contains the results of a salt load balance performed on Lake Powell for each month from January 1967 to December 1976. These results are shown graphically in Figures 1, 2, and 3. Figure 1 displays the accumulation of monthly increases and decreases in the salt load, while Figure 2 gives net accumulations for each year of the study. Salinity concentrations for each month at the outflow station are contained in Figure 3. This evaluation was done in order to expand the scope of a previous analysis, Lake Powell Salt Load Balance - January 1971 - September 1976.

Gaging stations on the five rivers flowing into Lake Powell provided inflow salt loads. However, some unaccounted for salt inflow should be recognized in more detailed studies. These stations are located on the Green River at Green River, Utah, the San Rafael River near Green River, Utah, the Colorado River near Cisco, Utah, the San Juan River near Bluff, Utah, and the Dirty Devil River near Hanksville, Utah. With the exception of the station on the Dirty Devil River, total dissolved solids (TDS) data used were recorded for all stations in Quality of Water Report, Colorado River Basin. Dirty Devil River data, which were almost nonexistent prior to 1971, came from the Geological Survey's Water Quality Records. Outflowing salt loads were provided by a gaging station on the Colorado River at Lees Ferry, Arizona.

The salt balance was calculated by subtracting the salt load leaving the lake from the salt load entering the lake. These differences were determined for each month and plotted cumulatively in Figure 1, relative to the base value indicated on the graph. Positive changes indicate an increase in salt load while negative changes indicate a decrease. Figure 1 shows an overall increase in salt load for the 10-year period. Total accumulations for each year are given in Figure 2. Increases are evident for every year except 1976.

Although this salt balance reveals greater accumulations of salt for each year than the previous salt balance, the same trends in monthly fluctuations are followed. Each year, with the exception of 1976, pronounced decreases in salt load occur around midyear, during or subsequent to spring flows. As noted in the earlier salt balance, the months were salt outflow exceeds salt inflow could be a result of three factors: (1) Strong spring flows may be overturning high bottom salinity which eventually flows through the dam; (2) Outflow control, which regulates the quantity of water and, in turn, regulates the amount of salt outflow, which determines whether the reservoir as a whole is gaining or losing salt; (3) Peak inflows and corresponding peak salt loads result in higher salinity flowing through the dam several months or years later, which may occur at a time when diminished salt inflows for a particular month would result in a net gain in the reservoir.
Each of the last 6 months of 1976 shows a decrease in salt load, which results in the year, as a whole, decreasing in salt load. In the previous salt balance, it was determined that losses in reservoir salinity depend only on outlet conditions. This seems to be the case in 1976 as a look at total streamflow records at the outlet station reveals that 1976 has the greatest outflow of the 10-year period.

Monthly salinity concentrations are plotted in Figure 3. Although the years of 1967 through 1970 show greater differences between high and low concentrations, they still follow the same basic pattern as the later years. That is, peak concentrations occur sometime during spring flows anywhere from March to June. Over the 10-year period, the mean concentration for each year has been gradually decreasing.

The previous salt load balance concluded that a tremendous salt precipitation is occurring in Lake Powell. This study verifies this in that the results indicate more than 8 million tons of salt were retained in the reservoir during the 10 years under consideration. These two investigations are in agreement that most significant decreases in salt load take place during or subsequent to spring flows and salinity concentrations peak out between March and June each year. An in-depth study of streamflow data would be necessary to relate 1976's decrease in salt load to outflow conditions. Moreover, future studies should examine relationship of salt storage and water storage over a long time period.
A 10-year salt load balance performed on Lake Mead gave the results contained in Figures 4, 5 and 6. An accumulation of each month's increase or decrease in salt load for the period from January 1967 to December 1976 is displayed in Figure 4. Figure 5 gives each year's total increase or decrease in salt load. Salinity concentrations for each month are shown in Figure 6. This analysis was performed in the same manner as one done on Lake Powell and some comparisons can be made between the two.

A gaging station on the Colorado River near Grand Canyon, Arizona, and one on the Virgin River at Littlefield, Arizona, provided the major salt loads entering Lake Mead. Outflowing salt loads were supplied by a station located on the Colorado River below Hoover Dam, Arizona-Nevada. *Quality of Water, Colorado River Basin Report* contained all the necessary data from these three stations. The change in salt load was determined by subtracting the total dissolved solids (TDS) leaving the lake from TDS entering the lake for each month. These monthly increases and decreases are plotted cumulatively in Figure 4.

Given a value for the base salt load indicated on Figure 4, the actual salt load for each month could be read from the graph. From this graph, it is evident that over the 10-year period the salt load in the lake is increasing. Figure 5 shows the amount of salt either retained or released each year. Unlike the Lake Powell salt balance, this one shows decreases in salt load for 2 years, 1970 and 1974. A study in a few years might determine if the fact that these decreases occur at 3-year intervals is significant.

This study does not seem to completely follow the trends established in the Lake Powell salt balance. There are periods of anywhere from 1 to 3 years where there are no significant decreases in salt load and there is a buildup of salt of 3,000 to 4,000 tons. These periods are followed by periods where neither increases or decreases are significant. The decreases do occur around midyear as they did in the Lake Powell analysis. Unlike the Lake Powell study where significant decreases lasted only 1 to 2 months, in Lake Mead when salt is released it is over a period of 3 to 6 months. Further study might be able to relate these decreases in salt load to their dependence on outflow conditions.
CHANGE IN SALT LOAD VS TIME (LAKE POWELL)

Fig. 1
YEARLY CHANGES IN STORAGE (LAKE MEAD)

SALT IN $10^3$ TONS

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FIG. 5
AN ANALYSIS OF SALINITY IN LAKE MEAD AND LAKE POWELL,
COLORADO RIVER BASIN

PREPARED BY:

STEVE GAZAFY
CIVIL ENGINEERING TECHNICAN

FOR: THE COLORADO RIVER WATER
QUALITY OFFICE, E&R CENTER

Issued: February 1979
ANALYSIS OF SALINITY IN LAKE MEAD AND LAKE POWELL

Introduction

The purpose of this report is to review and analyze all available total dissolved solids (TDS) data for Lake Powell and Lake Mead. All TDS data are analyzed and displayed in the form of various charts, tables, and graphs to demonstrate general trends and the behavior of the two reservoirs in terms of TDS (salinity) over the past several years. Lake Powell salinity data cover the entire depth profile of the reservoir at seven station locations with the last 2-1/2 years of data readily available for analysis. Salinity data for Lake Mead are very inconsistent and relate to only one station location. The data for this station, however, cover a 10-year period for analysis. Only basic observations concerning Lake Mead data can be made with limited assumptions concerning the entire reservoir.

Summary of Results

In Lake Powell, it was found that over the past several years, the reservoir, in general, is experiencing rapid increases in TDS. The salinity in Lake Powell reached a peak following the drought year of 1977 just prior to the spring flows of 1978. Salinity increased in Lake Powell fairly consistently through 1977 as a result of very little spring inflows. Very dense saline flows entered the reservoir by late 1977 which resulted in a migrating underflow current of highly saline water. A gradual migration of TDS toward the bottom of the reservoir, as a result of the drought combined with the propagation of these dense saline underflows throughout the bottom of the reservoir, resulted in a peak average salinity for the entire reservoir below 3,625 feet of 675 ppm in April of 1978. As illustrated in this report, the reservoir possesses continually circulating advective and convective currents during spring flows and late year return flows. Whether the reservoir retains its high salinity depends on the intensity of these currents. Readings for June of 1978 already showed signs of diminishing pockets and reduced average salinities. A complete "turning over" effect could be in the process due to the tremendous volume of spring runoff entering the reservoir. This would eliminate pockets and reduce average salinities to normally increasing levels. Further data are needed to qualify this assumption.

In contrast to Lake Powell, observations of Lake Mead TDS at one station between the intake towers indicated a decreasing TDS trend from late 1969 to 1975. The last few years have shown a stabilization effect in Lake Mead with only slight increases in 1977.
A comparison of Lake Mead TDS between intake towers and total average salinity of Lake Powell over the past 2-1/2 years indicates that the peak salinity for Lake Powell surpassed the salinity level of Lake Mead attained prior to 1977. This indicates a rapid rate of increase for Lake Powell while Lake Mead is slowly changing to a lower TDS level.
SALINITY ANALYSIS OF LAKE POWELL

Lake Powell Isopleths

Isopleths, or lines of constant salinity, have been plotted for Lake Powell over a 2-1/2-year period from February 1976 through June 1978 and available upon request. These isopleths are analyzed in terms of monthly and yearly variations with consistencies and trends noted for each. Irregularities, such as stratification, pockets, and abrupt increases are examined and an attempt has been made to correlate these observations with various parameters such as incoming stream flow, location of gaging station, and time of year. Locations of all gaging stations are illustrated in Figure 1.

Monthly variations in isopleths show some very interesting trends. There is an overall seasonal increase in salinity through the reservoir from October to April and an overall decrease in salinity from June to October. The bottom of the reservoir particularly increases in salinity from February to March and the head or inlet end of the reservoir increases more intensely from November to February as seen in the December 1977 isopleths at the Hite Station. A very distinct converging of isopleths occurs at Cha Canyon from February to April. After April, the isopleths seem to spread out and become more regular. This is clearly illustrated in the March 29, 1978 and May 25, 1978 sequence of isopleths. Salinity in the upper reaches near the dam stays relatively constant throughout the year. Salinity near the dam face below 3,400 feet increases as the reservoir bottom salinity increases. Three areas of relatively high salinity that fluctuate monthly are the bottom of the reservoir, the head of the reservoir, and the bottom of the dam. One area of low salinity that fluctuates regularly is in the upper reaches of the head of the reservoir at the Hite Station and, to some extent, at Bullfrog. The lowest TDS readings of the year are recorded at Hite near the 3,600-foot level between April and July. The June 21, 1978 isopleths show a low reading of 267 ppm at Hite near 3,600 feet. This area becomes much more saline, however, by the end of the year.

There are some very apparent yearly trends in the behavior of the isopleths. There is an overall yearly increase in salinity at all levels of the reservoir except near the surface for about 100 miles out from the dam. Isopleths form more distinct layers in 1978. In 1976, the isopleths were much more erratic and random. By 1978, a more consistent layered effect seems to occur. A salinity gradient appears to be established with consistently low readings at the top and much higher readings being recorded at the bottom. Pockets become more numerous, obvious, and intense in 1978. There is a migration of higher salinity pockets from the head end and surface of the reservoir to the lower end and bottom of the reservoir. Some isolated pockets continue to persist in the bottom of the reservoir,
LOCATION OF RESERVOIR SALINITY MONITORING STATIONS

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</tr>
<tr>
<td>HITE</td>
<td>155 MILES</td>
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FROM DAM

DIARY DEVIL RIVER
COLORADO RIVER
ESCALANTES CONFLUENCE
SAN JUAN RIVER
LAKE POWELL
OAK CANYON
COLORADO RIVER

FIGURE 1
at the head, and at Cha Canyon. There is a general tendency, as a result of this pocket migration, for isopleths of decreasing salinity to radiate and project outward from the bottom of the dam. The isopleths for March 29, 1978, are a good example of this. The isopleth curves make an abrupt transition from a downward sweeping action to a horizontal projection at about 70-90 miles out around Cha Canyon. In this transition zone are found pockets of high salinity. This transition and pockets of high salinity are probably a result of late-year inflows that are highly saline. This disrupts the isopleths and causes converging isopleths and pockets at Cha Canyon and higher salinity at Hite.

These salinity fluctuations can be attributed to various factors. The bottom salinity fluctuates at specific times of the year. This time of year consistently corresponds to spring flows and late-year return flows. Bottom readings all along the reservoir and along the face of the dam are lower during spring flows. Spring flows through the reservoir result in a less dense, less saline-type of flow that infiltrates the surface waters and forms a wedge-shaped surface current. However, there is evidence, in examining the isopleths, that the spring flows, particularly when heavy, might be providing a strong, underflowing, washing-out type of current. Isopleths consistently become more spread out and salinity diminishes during spring flows. This is especially evident at Cha Canyon where the San Juan River provides fresh inflows. An examination of isopleths from April 12 and July 8, 1977, shows bottom salinities greatly decreased with smoother, more dispersed isopleths in comparing April to July. At the head end of the reservoir near Hite, the Colorado and Green Rivers combine to release a very heavy spring flow into the reservoir around May and June, as evidenced by the low readings in the June 21, 1978 isopleths. Following spring flows, there is an overall decrease in salinity in the reservoir, especially along the bottom and at the inflow areas. Isopleths tend to become more regular and farther apart. This behavior is again illustrated by the March and May 1978 sequence of isopleths.

Salinity begins to increase again by October. Initially, the salinity buildup occurs at Hite, Bullfrog, and Cha. It is especially noticeable at Hite, with the highest TDS reading recorded at Powell, 1,040 ppm in December 1977. This is explained by the combined inflow of dense, cold, highly saline late-year return flows in the Colorado and Green Rivers. These dense flows cause isolated peaks in salinity at the head of the reservoir as the flows enter, with the rest of the reservoir being affected by February and March as the flows spread out as a bottom-hugging, highly saline current. Pockets of higher salinity form along the bottom of the reservoir as a result of this highly saline current migration. The Cha
Canyon station undergoes a very pronounced stratification toward the end of the year and formation of pockets by March of the following year as the San Juan River provides cold, dense, saline return flows that enter the reservoir and greatly increase bottom salinity while the surface salinity is relatively unaffected. Consequently, this drastic change in salinity causes an increased TDS gradient at mid-reservoir which manifests itself in the form of closely spaced isopleths and isolated pockets of salinity. This is indicated in the March 28, 1978 isopleths.

The isopleths indicate that the entire reservoir is becoming more saline. Isopleths progressively become more distinct and higher in salinity. As the water increases in salinity, there is a corresponding increase in stratification. This stratification becomes increasingly more intense with the formation of distinct layers and isolated pockets of salinity. Pockets become more numerous with the pockets of highest salinity migrating toward the deeper corners of the reservoir. This is shown by highly saline pockets throughout the bottom of the reservoir and along the face of the dam as indicated in the isopleths. By 1978, lines of increasing salinity begin to propagate downward toward the highly saline lower reaches of the reservoir. These isopleths show less abrupt changes in salinity. They become smoother, less fluctuating, and more compressed. This increased stratification is a result of a greater spread in TDS concentration from the top to the bottom of the reservoir. The 1978 isopleths indicate that salinity at the top has been variable but relatively constant in contrast to mid-reservoir and bottom salinity which have increased considerably. In general, the isopleths have shown that the salinity in Lake Powell is increasing throughout most of the reservoir, especially at the bottom, along the face of the dam, and at mid-reservoir. Future projections of reservoir salinity must take into account inflow, outflow, evaporation, and bank storage fluctuations.
LAKE POWELL

TDS vs Time (Constant Elevations)

Figure 2 shows a monthly variation of average total dissolved solids (TDS) at five different levels in the reservoir for a 2-1/2-year period from February 1976 through June of 1978.

The plot shows an overall increase in salinity at all levels over the 2-1/2-year period. There is an increase in salinity at all levels from January to March of each year followed by a dip through the summer months and a rise again by the end of the year. This rise continues into the following year. An exception to this is the drought year 1977 where decreased spring flows caused an increase in salinity through the year. At upper levels, the changes in salinity are more erratic and do not follow as closely the trends apparent at the bottom. The top of the reservoir seems to be more sensitive to changing conditions in terms of inflow and operation of the outlet works. There are similar increases and decreases in salinity although not as pronounced and highly variable. There is, however, an indication of a drastic drop in salinity in June of 1978 probably as a result of heavy spring flows. The lower level curves show a gradual increase in salinity whereas the top curves show a more rapid increase in salinity. This occurrence takes place between February and April of 1978. This is an indication that upper salinity increases are relatively consistent, whereas bottom salinity increases are more erratic and a very high buildup of salinity is present at the bottom of the reservoir by April of 1978.
FIGURE 2

LAKE POWELL SALINITY
TDS (AVE) VS TIME (CONSTANT ELEVATIONS)
LAKE POWELL

TDS vs Incremental Volume

Figure 3 is a time sequence (1976-78) of Lake Powell salinity which indicates the relationship between TDS and incremental water volumes at five different elevations. The numbers for each volume signify the total average yearly TDS for that particular volume.

Comparison of the graph for 1976 and the graph for 1977 indicates some interesting differences. The change in average TDS near the top of the reservoir is very pronounced and increases by almost 100 ppm from 1976 to 1977. This increase is also evidence for volumes at lower elevations. At elevation 3525 feet, the increase is 84 ppm. The salinity increase is less pronounced deeper in the reservoir. At elevation 3225 feet, for example, the increase is only 27 ppm. Obviously, the lesser increase in salinity near the bottom does not result in an overall drastic increase in salinity and total salt loading in the reservoir. The increase in salt load is approximately $2.4 \times 10^6$ tons between 1976 and 1977, as illustrated in Figure 3. The greatest increase in salinity results from changes in the largest incremental reservoir volume (Volume No. 1) and, therefore, results in a higher total salt load for the reservoir. This increase in salinity can be attributed to decreased spring flows in 1977. Typically, fresh spring flows would tend to flush the upper reservoir volumes. Since spring flows did not fully materialize, this was not allowed to happen, and TDS concentration built up. The bottom was affected very little because the previous year did not produce heavy return flows which would ordinarily result in dense heavy pockets of bottom salinity by spring of the following year.

Comparison of graphs for 1977 and 1978 also shows some interesting trends. In the most significant part of the reservoir (Volume No. 1) the overall increase in TDS is only 4 ppm. Whereas at the bottom of the reservoir, where the volume is small, the increase is 140 ppm. This dramatic increase is due to the accumulation of salinity at the reservoir bottom as a result of late-year return flows and TDS build-up through 1977. The migration of greater salinity toward the bottom does not necessarily indicate a drastic increase in total salinity; however, the increase is, nevertheless, considerable. An examination of Figure 2 shows this sharp increase in bottom salinity and the bottom line of Figure 4 shows the considerable increase in the reservoir as a whole. The increase in TDS is only 4 ppm for the largest volume, primarily because this volume was diluted during spring flows and upper salinity had migrated from the top to the bottom of the reservoir. Since the increase in TDS for the largest volume is not significant, the overall increase in salt load between 1977 and 1978 is only about $1.1 \times 10^6$ tons, which is less than half as much as it was between 1976 and 1977.
LAKE POWELL SALINITY
TDS (AVE.) VS. VOLUME (INCREMENTAL) IN MILLION ACRE-FEET

FIGURE 3
In comparing all three graphs of Figure 3, it is apparent that the salinity, and total salt load increase is much greater between 1976 and 1977 than it is between 1977 and 1978. The latter comparison is not fully representative because all of the 1978 data were not taken into consideration. Records for 1978 were recorded during the first 6 months and at the peak of spring flows. Heavy spring flows for 1978 resulted in decreased salinity despite a peak increase in April 1978 as a result of the previous year's drought. When late saline inflows enter the reservoir through the course of the year and the water is allowed to settle and stratify, more salinity will build up at the top and at mid-reservoir and the salt load increase for 1978 may increase significantly.
LAKE POWELL

TDS vs Total Volume

Figure 4 shows the monthly variation in total reservoir volumes at various elevations with respect to average TDS for those particular volumes. Each curve represents the average monthly TDS for the entire reservoir below the stated elevation.

The graph illustrates a trend of increasing salinity for total volumes at all elevations. The most pronounced change occurs for volume levels closer to the bottom of the reservoir, particularly those at the 3,225, 3,325, and 3,425-foot levels. There is an abrupt increase in TDS from February to June of 1978 at lower reservoir volumes. However, as Figure 3 shows, the volume, and total salt load is small and has a minor impact on the reservoir as a whole. This attenuates the average TDS in the entire reservoir as indicated by the total volume curve (bottom line) of Figure 4. This total volume curve does not show the abrupt fluctuations and increases as do the lower elevation curves because the entire volume is taken into consideration and the low volume highly saline areas are averaged out with the much higher volume less saline upper reaches of the reservoir. The fact that the upper reservoir controls the reservoir's total salinity is illustrated in Figure 1. The TDS values at a constant elevation of 3,625 feet correspond closely to the values for the total volume curve of Figure 2. Despite the relatively small volume of higher salinity water, the reservoir as a whole is becoming more saline as illustrated by the general upward trend of the total volume curve of Figure 2.
LAKE POWELL SALINITY
TDS (AVE) VS TIME (TOTAL VOLUME) IN MILLION ACRE-FEET—FIGURE 4
Analysis of Figures 2, 3, and 4

Figures 2, 3, and 4 show some monthly variations which reinforce the conclusions drawn from the analysis of the isopleths. There is evidence of salinity peaking out immediately preceding spring flows. Bottom salinities peak out around April and decrease from June to October. There is an increase in salinity toward the end of each year, and this increase continues until the beginning of spring flows. An exception is during the year of 1977. The total volume curve of Figure 4 increases throughout the 1977 year, while the other curves decrease slightly at the end of each year. This indicates that the top half of the reservoir maintains a constant increase in salinity through 1977 despite spring flows. As shown in Figure 2, in the lower reservoir elevations average salinity starts to decline in the latter half of 1977, while salinities near the top of the reservoir continually increase throughout the year. Figure 3 also reveals this trend. In 1977, the largest volume, closest to the top of the reservoir, undergoes the greatest increase in salinity. This controls the total reservoir salinity as indicated by the steadily increasing total volume curve of Figure 4.

The primary reason for this constant increase in salinity throughout 1977 instead of the usual decreases following spring flows can be explained in terms of diminished spring flows as a result of the 1976-1977 drought. The drastic effect of the drought can be seen in February to March of 1978 (Figures 2 and 4) where salinity at all levels peaked out with record readings, however, these salinity peaks are being sharply reduced with heavy spring flows for 1978. Decreased spring flows resulted in an overall buildup of salinity throughout the top and middle of the reservoir. This area is typically relieved of any TDS buildup through heavy spring flows; however, this did not occur in 1977, and salinity concentration was allowed to buildup. End of year return flows also contributed greatly to the buildup of salinity, particularly bottom salinity as the flows dispersed throughout the lower reaches of the reservoir by March. This is illustrated by peak bottom readings in March 1978.

According to Figures 2 and 4, bottom salinities decreased both during and after spring flows in 1977. This seems to contradict the preceding paragraph but can be explained in terms of spring flows and surface to bottom undercurrents. In examining the isopleths for April and July of 1977, it is clearly seen that in comparing April to July, the reservoir bottom had become less saline and the reservoir top had become more saline. Spring flows were not heavy enough to induce a drastic decrease in upper salinity, however, they did initiate a slight turning over effect as indicated by the reverse changes in salinity. Apparently, spring flow currents, although lacking in total volume, nevertheless maintained enough
energy and velocity to induce an undercurrent which infiltrated the bottom of the reservoir and caused a subtle movement of saline bottom water toward the surface. This convective motion accounts for a decrease in Figure 2 of the top three curves following spring flows in 1977.

This decreased bottom salinity did not affect the general increase in salinity through the 1977 year because of several factors. The primary one being diminished spring flows resulting in a greater TDS concentration and a general TDS increase for the entire reservoir. Since the bottom volumes are relatively small, total salinity was not influenced by a significant amount. As indicated by Figure 3, the total volume below 3,400 feet comprises just over a fifth of the total volume under consideration. End-of-year saline inflows at Hite initially appear in the upper reaches of the reservoir which have the greatest impact on total salinity. This also accounts for the total reservoir salinity increase despite decreased bottom salinity. At the end of 1977, these inflows remain at mid-reservoir at Hite and somewhat at Bullfrog, and do not appear at the bottom until March of the following year. The minor influence of the bottom volume together with strong spring currents and saline inflows at Hite which infiltrate the largest reservoir volumes account for the overall increase in salinity, particularly mid-reservoir salinity in 1977, despite decreased bottom salinity.

The dramatic increase in overall salinity and especially bottom volume salinity in 1978 is very evident in Figures 1, 2, and 3. This is due to the higher buildup of salinity throughout the drought year of 1977, and the gradual migration of this salinity toward the bottom of the reservoir during the course of the year. This buildup is enhanced by late-year return flows which are cold, dense and highly saline. This is shown by the isopleths for December of 1977. There is a great increase in salinity at the Hite station at all levels where the Colorado and Green River flows enter the reservoir. In examining isopleths for December of 1977 and March of 1978 it is seen that this concentrated highly saline area which has its initial effect at Hite gradually disperses itself and begins to propagate outward through the reservoir. By March 29 of 1978, it begins to manifest itself in the corner of the reservoir. This manifestation is also due to delayed dense cold flows at Cha Canyon, fed by the San Juan River. This, together with an overall increase in salinity through the entire reservoir and migration of this salinity toward the bottom accounts for the dramatic increase in bottom reservoir salinity in April of 1978. Figure 3 shows this bottom buildup in terms of corresponding volumes. The graphs for 1977 and 1978 indicate an increase of 140 ppm from 1977 to 1978 for the bottom
incremental volume of the reservoir. However, the largest incremental volume (Volume No. 1) increased by only 4 ppm. Despite the minor impact of the bottom volume and the small TDS increase in the upper volumes, the increase in TDS was, nevertheless, so dramatic in the bottom volume that the entire reservoir increased significantly in salinity. Average reservoir salinity has dropped considerably after April of 1978 due to heavy spring flows which entered the reservoir by May of 1978. Bottom salinity particularly is being diluted and pockets are becoming more dispersed. Further data covering the rest of the year must be secured and examined to determine if these pockets continue to diminish in intensity as a result of strong underflowing currents and a turning over effect of the reservoir. Whether the reservoir continues to decrease in salinity and follow trends of the past must also be determined.
SALINITY ANALYSIS OF LAKE MEAD

This analysis will review a 9-year period of record of TDS levels at various elevations between the intake towers near Hoover Dam at Lake Mead. Unfortunately, this analysis only takes into consideration one station near the outlet works of the reservoir. Data from other stations must be carefully considered before generalizing the conclusions of this report as applied to the entire reservoir. Throughout this report, reference to Lake Mead will actually pertain to Lake Mead between the intake towers.

No emphasis is placed on an indepth analysis of monthly variations, explanations of increases or decreases in salinity, or description of various yearly fluctuations. Overall, general trends are pointed out with no emphasis on detail. More data are needed to justify any other type of analysis.
LAKE MEAD: TDS BETWEEN INTAKE TOWERS

TDS vs Time (Constant Elevation)

In general, the salinity in Lake Mead from 1968 to 1977 has decreased slightly after having peaked out in late 1969 as shown by Figure 5. This decrease has been highly variable and fluctuating, though there is a definite downward trend. The highest salinities seem to be located near the surface. The curves for surface levels and the 125-foot level are more consistently the highest salinity values located on the graph. The graph clearly indicates that the lower average salinities between the intake towers are located near the bottom of the lake, whereas the higher salinities are located near the top of the lake.

There does not seem to be any obvious consistent yearly variation from year to year. However, there seems to be a slight increase in salinity at the end of each year and fluctuating decreases during mid-year. The basic trend is an overall increase in salinity at all levels up to late 1969. From 1969 to mid-1970, there is a sharp downward trend at all levels followed by a distinct increase in late 1970. Hereafter, there is a very pronounced downward trend with a leveling off in salinity from 1975 through 1977 in the upper levels of the reservoir and a continued downward trend in the lower levels.
LAKE POWELL: TDS AT WAHWEAP STATION

**TDS vs Time (Constant Elevation)**

In order to provide a comparison between corresponding salinity monitoring stations, Figure 6 indicates the relationship between TDS and time at various elevations over a 2-1/2-year period at Wahweap at Lake Powell (roughly equivalent to Intake Station on Lake Mead). There is a definite trend of increasing salinity at all levels at Wahweap. In contrast to Lake Mead, the more drastic increases are at the bottom of the reservoir and slight increases at the top. The TDS seems to peak out around May of 1978, with a downward trend thereafter, although more data are needed to justify this. Each level downward is progressively more saline than the level above it. The least saline level is at the top of the reservoir, the most saline level is at the bottom. These trends are exactly opposite those observed at Lake Mead between the intake towers. Pockets seem to have accumulated at the bottom of the reservoir while a more consistent salinity is observed at the top. This is evidenced by the sharp breaks in the curves at the top, and the smooth transition in the curves at the bottom. There are definite consistencies for each year. Salinities at all elevations seem to peak out every year from January through March and consistently decrease after April.
LAKE POWELL SALINITY AT WAHWEP
TDS (AVE) VS TIME
FIGURE 6
A COMPARISON OF LAKE MEAD AND LAKE POWELL SALINITIES

Figure 7 is a time plot of the average TDS from 1969 through 1977 between the intake towers at Lake Mead. The bottom curve (dashed line) is a plot of the total average TDS in Lake Powell for the entire reservoir below 3,600 feet from 1976 through June of 1978.

The two curves show some basic differences. Based on limited data, Lake Mead is more saline than Lake Powell. It is an older reservoir which has been subjected to greater salt loading. The basic trend that this graph illustrates is that while Lake Mead has been stabilizing with gradual decreases in salinity between the intake towers, Lake Powell as a whole has abruptly increased in salinity in the past 2-1/2 years. This change has been so abrupt that the average salinity in Lake Powell has increased by almost 200 ppm in only 20 months. The average salinity for Lake Powell had almost surpassed the salinity between the towers at Lake Mead in April 1978. Lake Mead has increased only slightly during this time. A downward trend is evident at Lake Powell following this peak reading in June 1978, however, more data are needed to qualify this further. Lake Powell seems to reflect radically any changes in inflow and TDS while these effects are buffered and not as obvious at Lake Mead. Lake Mead, being an older, more mature and slightly larger reservoir appears to have a greater assimilative capability, than does the younger, more erratic Lake Powell.
**Figure 7**

**Comparison of Lake Mead and Lake Powell Salinities**

TDS (AVE.) VS. TIME

**Legend**

- × × × Lake Mead: Between Intake Towers
- ○ ○ ○ Lake Powell: Total Volume (16790 AC. FT.)
Conclusions and Recommendations

Lake Powell salinity levels are definitely on the rise. As the previous graphic trends have suggested, Lake Powell as a whole is becoming more saline over the past 2-1/2 years despite fluctuating tendencies and seasonal variability. These tendencies can be explained in terms of yearly spring flows passing through the reservoir, end of year return flows emitted from the Colorado, Green and San Juan Rivers, and depleted inflow conditions due to the drought years of 1976 to 1977. The drought resulted in a drastic increase in TDS throughout the reservoir, particularly toward the bottom of the reservoir. This effect completely manifested itself in March of 1978 when peak readings were recorded at the bottom of the reservoir. This effect was due primarily to the drought and also to the return flows and overall bottom migration of salinity through the entire reservoir. Depleted inflow conditions resulted in an increase in TDS concentration through the entire reservoir.

The "turning over" effect which was illustrated to have occurred to some extent during spring flows of 1977 is also evident to a much greater degree during spring flows so far recorded in 1978. Bottom TDS readings for May and June are much less than readings for March of 1978, while TDS readings in the upper reaches have increased slightly. Average salinity for the entire reservoir has decreased considerably from March to June of 1978. The "turning over" effect of 1977 did not diminish the increasing total salinity experienced by the reservoir throughout the year as a result of diminished spring flows and increased return flows. Massive spring flows for 1978 are diluting high salinity concentrations and lowering salinities at all levels. Strong spring flows are resulting in undercurrents that are decreasing bottom salinities in the form of convective surfacing currents which raise highly saline bottom water. This surfacing salinity will eventually run through the dam. In this respect, the reservoir, despite its tremendous proportions, is similar in its behavior to a huge river with advective and convective currents continually moving masses of water through it. Presently, this behavior is allowing the dispersion of bottom pockets and an overall decrease in total and bottom reservoir salinity. Generally speaking, the reservoir will retain a certain amount of the peak salinity it attained as a result of the drought. However, full development of convective and advective currents is expected to turn the reservoir over and greatly relieve this salinity buildup. Further data analysis at all levels and all stations is necessary to determine if the reservoir does completely turn over and to determine how much the reservoir recovers from the salinity buildup it experienced as a result of the drought.

Lake Mead salinity between the intake towers is taking on a reverse effect. The reservoir at this particular station has higher average salinities than Lake Powell. Since late 1969, the salinity has
decreased and has evidently stabilized over the past couple of years, with slight increases observed through 1977. The data, however, only reflect conditions between the intake towers. Additional monitoring at more than one station is needed to determine salinity conditions in Lake Mead.

References

LAKE POWELL

ELEVATION IN FEET

RIVER MILES ABOVE LEES FERRY

OEC. 22 1977