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major element geochemistry
of lake powell

**R. C. REYNOLDS, JR.
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LAKE POWELL RESEARCH PROJECT BULLETIN

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IN THE LAKE POWELL REGION

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MAJOR ELEMENT GEOCHEMISTRY OF LAKE POWELL

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October 1974

LAKE POWELL RESEARCH PROJECT

The Lake Powell Research Project (formally known as Collaborative Research on Assessment of Man's Activities in the Lake Powell Region) is a consortium of university groups funded by the Division of Environmental Systems and Resources in RANN (Research Applied to National Needs) in the National Science Foundation.

Researchers in the consortium bring a wide range of expertise in natural and social sciences to bear on the general problem of the effects and ramifications of water resource management in the Lake Powell region. The region currently is experiencing converging demands for water and energy resource development, preservation of nationally unique scenic features, expansion of recreation facilities, and economic growth and modernization in previously isolated rural areas.

The Project comprises interdisciplinary studies centered on the following topics: (1) level and distribution of income and wealth generated by resources development; (2) institutional framework

for environmental assessment and planning; (3) institutional decision-making and resource allocation; (4) implications for federal Indian policies of accelerated economic development of the Navajo Indian Reservation; (5) impact of development on demographic structure; (6) consumptive water use in the Upper Colorado River Basin; (7) prediction of future significant changes in the Lake Powell ecosystem; (8) recreational carrying capacity and utilization of the Glen Canyon National Recreational Area; (9) impact of energy development around Lake Powell; and (10) consequences of variability in the lake level of Lake Powell.

One of the major missions of RANN projects is to communicate research results directly to user groups of the region, which include government agencies, Native American Tribes, legislative bodies, and interested civic groups. The Lake Powell Research Project Bulletins are intended to make timely research results readily accessible to user groups. The Bulletins supplement technical articles published by Project members in scholarly journals.

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ABSTRACT

Chemical studies of Lake Powell indicate that its waters are moderately saline (500 ppm T.D.S.), and that their composition is controlled by the relative proportions of contributions from the Green, San Juan, and Colorado Rivers. Ionic species are present in the proportions $SO_4 > Ca \sim Na > Alkalinity > Mg > Cl \gg K$. Surface waters are oversaturated with respect to calcium carbonate, and salt flux calculations and comparisons of pre- and post-dam bicarbonate concentrations of river water at Lee's Ferry suggest precipitation of calcium carbonate in Lake Powell. Tentative values for salinity reduction due to this process are 19 to 29 ppm.

Physical studies of the lake, based on turbidity and conductivity measurements, show that it can be classified as warm monomictic; but it possesses meromictic tendencies inasmuch as convective mixing to the bottom does not occur. Despite the lack of deep convective mixing, the bottom waters have not become anaerobic because they are periodically replaced by cold, saline, advective flows from the input at Hite. This phenomenon and the operation of other advective processes indicate that the lake still possesses much of the character of a river reach in which the water has a long residence time.



MAJOR ELEMENT GEOCHEMISTRY OF LAKE POWELL

INTRODUCTION

The amounts and distribution of the major chemical species dissolved in Lake Powell have been studied during a 3-year period by a combination of standard limnological methods. Electrical conductivity, temperature, turbidity, dissolved oxygen, and pH were measured in the field. Water samples were collected periodically from various depths and locations and were analyzed in the laboratory for calcium, magnesium, sodium, potassium, alkalinity, sulfate, and chloride. These measurements supplement more comprehensive chemical sampling data obtained by the Bureau of Reclamation which have been made available to us. Chemical analytical data are processed by computer methods which allow estimation of the degree to which the waters are in equilibrium with respect to calcium and the various carbonate species. From these studies, a broad picture has emerged of the descriptive chemistry of the water in Lake Powell, and of the importance of chemical reactions which serve to alter the composition of the water as a result of the impoundment.

DISCUSSION

Water Composition

In Figure 1, a few chemical analyses are shown to illustrate the compositional variations encountered in lake waters.

The analyses, expressed as microequivalents of ion per liter, are plotted against electrical conductivity. Sulfate is the dominant anion; alkalinity, which is mostly composed of bicarbonate, is second; and chloride is third. In order of decreasing abundance, the major cations are sodium, calcium, and magnesium. Potassium has been omitted from Figure 1 since its concentration is relatively low, averaging approximately 100 microequivalents per liter or 4 parts per million (ppm). Calculations of the amount of total dissolved solids from chemical analyses show a variation in salinity from approximately 300 to 800 ppm, with an average value close to 500 ppm.

Figure 1 shows that alkalinity behaves uniquely with respect to salinity. All of the other constituents in the graph follow trends that are essentially ideal with respect to salinity (*i.e.*, a doubling of salinity results in nearly a doubling of concentration), but alkalinity has a slope significantly lower than ideal. This behavior may be caused by the solubility limitations of the carbonate system. At low salinities, detrital carbonate dissolves to produce relatively high concentrations, whereas at high salinities, carbonate precipitates and thus limits the concentration.

Lake Powell has three main tributaries: the San Juan, Green, and Colorado Rivers. The relationships displayed in Figure 2 illustrate the compositional control that each of these tributaries exerts on the composition of the lake. According to Iorns et al. (1965), 98% of the water and 93% of the salt delivered to Lake Powell come from these three tributaries. Consequently, the mean anion

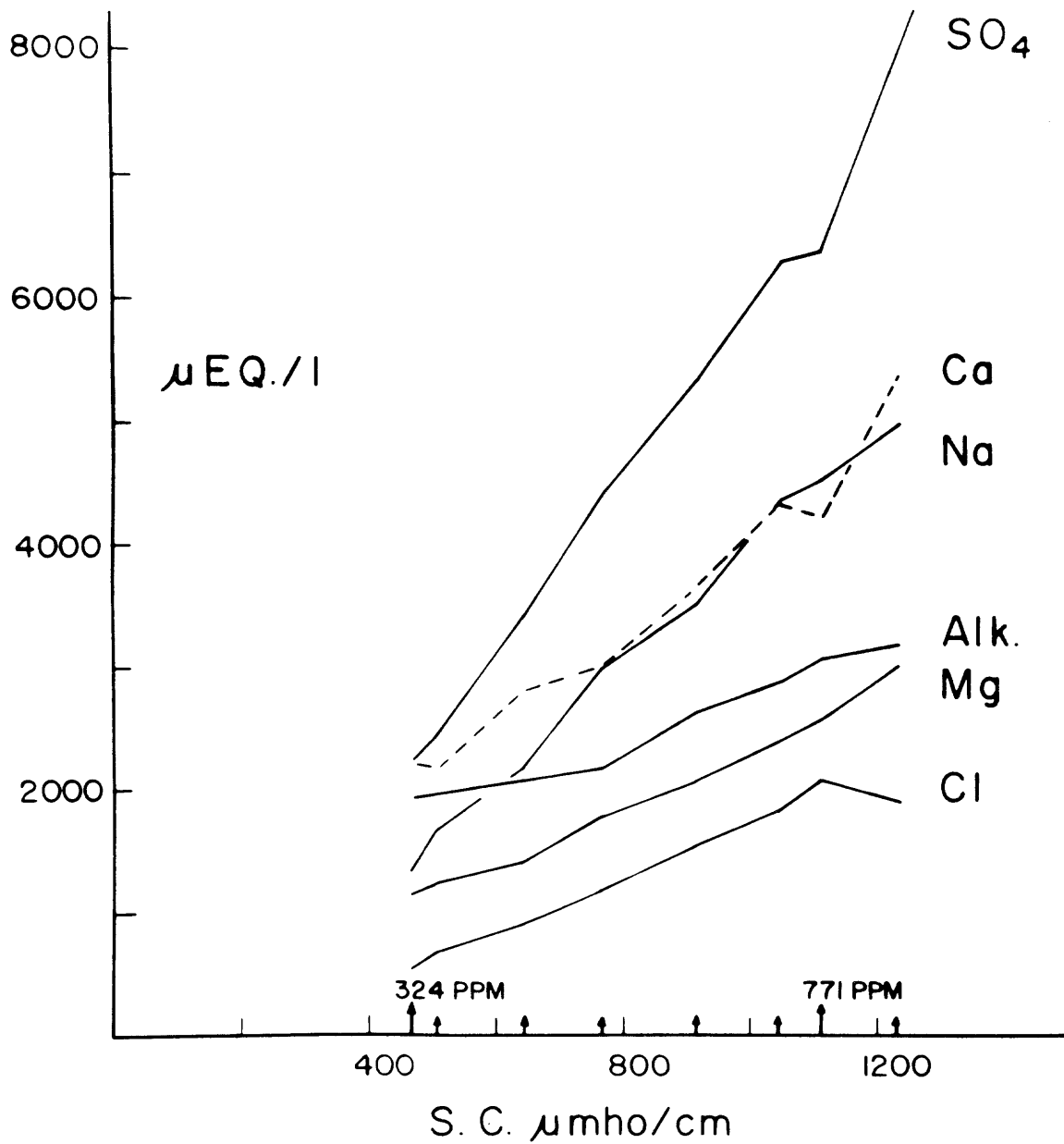


Figure 1: Concentrations of Ions in Lake Powell Waters as a Function of Conductivity (Salinity).

Ion concentration plotted in μEQ./l (micro-equivalents per liter); conductivity plotted as S.C. μmho/cm (specific conductance in micromhos per centimeter).

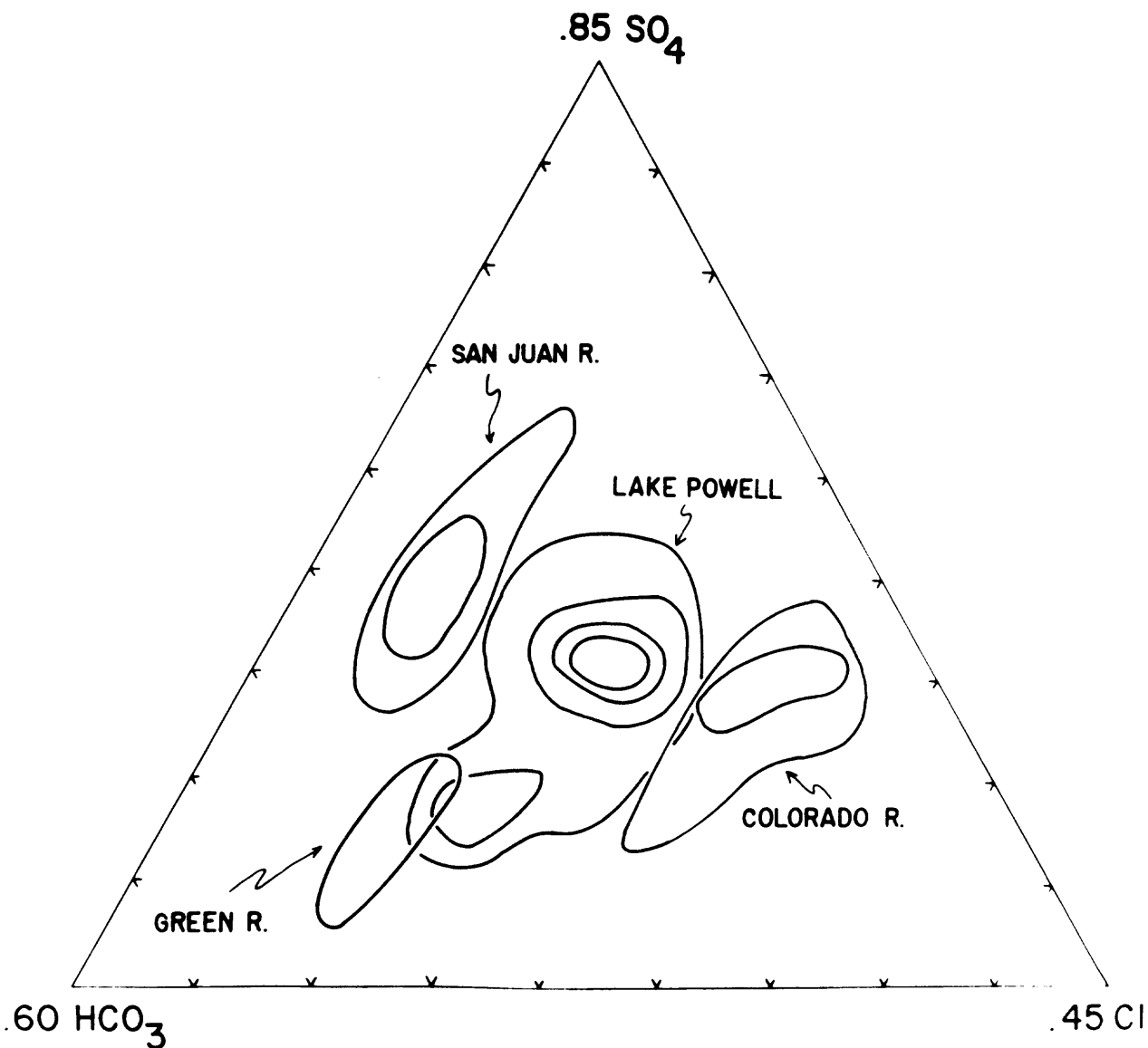


Figure 2: Anion Compositions of Lake Powell and the Green, Colorado, and San Juan Rivers. Data are expressed in ion equivalent percents.

composition of Lake Powell water should be controlled by the discharge-salinity characteristics of these rivers.

Figure 2 shows fields plotted for the variation in anion composition of the

waters from each of the three tributaries. The data for the San Juan and Colorado Rivers were taken from records for the years 1953 through 1960, and for the Green River, the years 1955 through 1960. Annual weighted concentrations were

obtained from the appropriate U. S. Geological Survey Water Supply Papers. The fields are contoured only diagrammatically, but all data are enclosed within the outermost contour. It can be seen that, for the time periods shown, the compositional fields do not overlap, and that, relatively, the Green River is bicarbonate-rich; the Colorado chloride-rich; and the San Juan sulfate-rich. The central field on Figure 2, showing the diagrammatic contours for 150 analyses of Lake Powell water, lies appropriately intermediate with respect to those of the three rivers. A sophisticated analysis would require that relative discharge and salinity be included as variables, but even the first-order consideration shown on Figure 2 shows that the chemical character of Lake Powell water is controlled mostly by these three tributaries. This means that changes in water management procedures in the drainage basins of any of these tributaries could affect significantly the mean composition of Lake Powell water. Implicit also in Figure 2 is evidence that the physical mixing of water masses is achieved somehow within the lake.

The field depicting Lake Powell waters in Figure 2 lies near the intersection of the fields for the Colorado and the San Juan Rivers. Yet the relative contributions of salt to Lake Powell (Iorns et al., 1965) are controlled mostly by the Colorado, which provides 49.1%. (The Green provides 31.6% and the San Juan River 11.9%.) The apparent control by the San Juan River probably is the result of chemical change in the lake. If it is assumed that carbonate precipitation is significant in the lake, then the field depicting Lake Powell water has been displaced away from the bicarbonate corner of Figure 2 to its present central

position. The significance of carbonate precipitation will be documented more fully below. But first it is necessary to place the possible chemical reactions in their proper hydrologic framework.

Circulation and Mixing

Lake Powell may be described as a warm monomictic lake. That is, thermal convection at the surface of the lake occurs only once during the year, and that is during the winter cooling period. The records to date show that in Lake Powell such thermal convection is initiated in the late fall (October and November), is fully operative in early winter (November and December), and continues unabated until early spring (February and March). However, at its fullest development the convective mixing zone does not penetrate to the deepest waters of the lake. Lake Powell is by definition, therefore, meromictic. The incomplete convective mixing is indicated by the lack of aeration (*i.e.*, low oxygen content) of the bottom waters. Significantly, the bottom waters of Lake Powell have not become completely anerobic in spite of this condition.

The reason for the absence of completely anerobic conditions is that advective transport and mixing processes dominate the circulation pattern of Lake Powell. The deeper waters of the lake are replenished with oxygen. An underflow density current during the winter period sweeps out the ambient oxygen-depleted bottom water and replaces it with cold, saline, oxygen-saturated water (Figure 3). The evidence to date indicates that the last vestige of "old" bottom water passes through Glen Canyon Dam and out of the lake by late March.

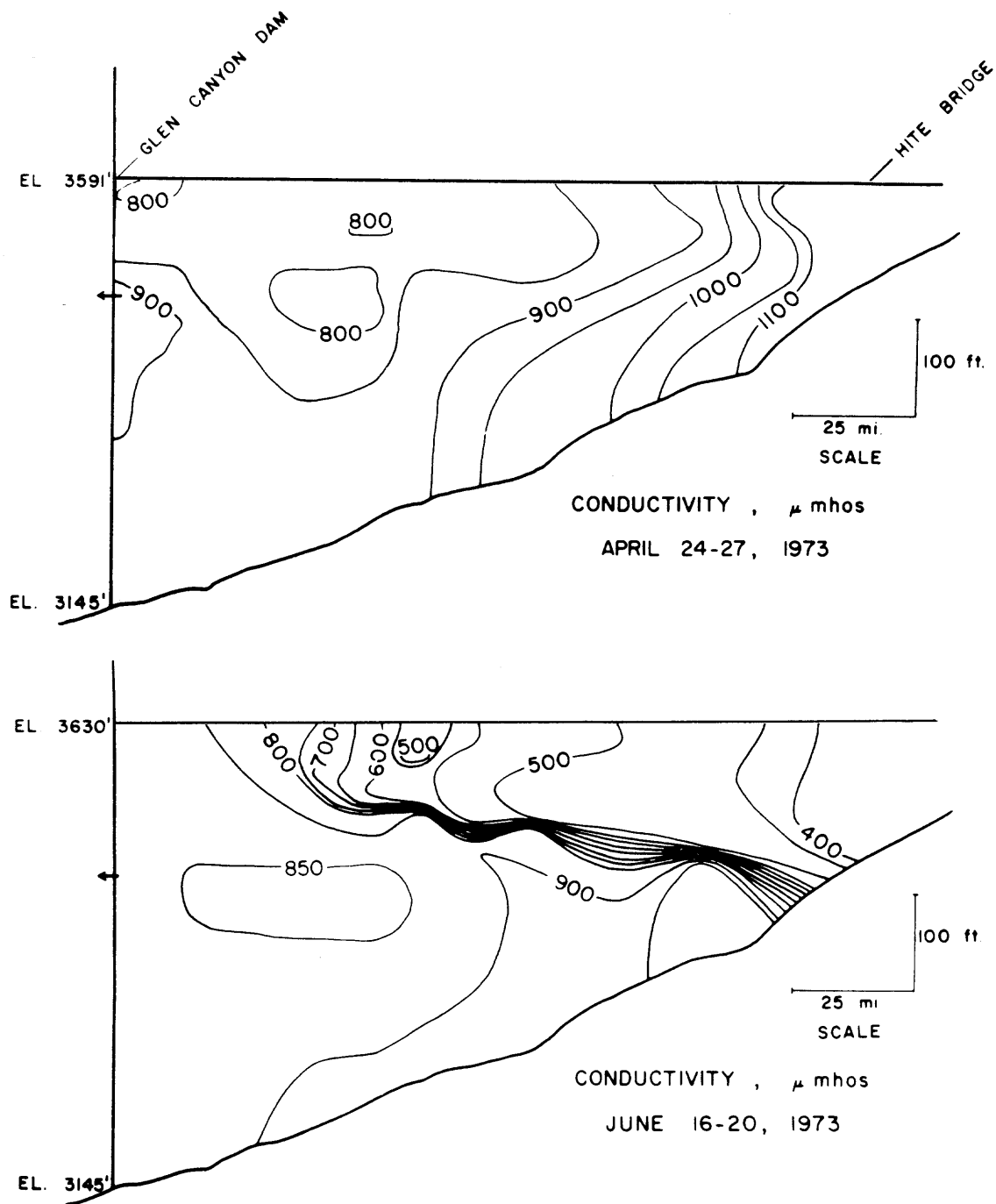


Figure 3: Conductivity (Salinity) Distribution in Lake Powell Before (April) and After (June) the Spring Runoff.

The winter underflow current is derived principally from the Colorado River and Green River tributaries of the lake. Water entering the lake from these tributaries is cold because of the long

transit across a terrain with a harsh winter climate. This water also is saline because it contains water that was left from the preceding dry season on the Colorado Plateau. The result is that very

dense water enters the lake in its upper end and flows down the lake as a bottom-hugging current. Although relatively small in volume, this current exerts a profound effect on the chemical and physical regime of the lake. It is this current which forces an exchange of bottom water in the lake and which prevents anaerobic conditions from being realized.

The second important advective phenomenon in Lake Powell, and one which prevails during the summer season, is a powerful and pervasive overflow density current. This is well illustrated by the conductivity data presented in Figure 3. The existence and extent of this advective process can be delineated by the distribution of heat, salt, and, especially, turbidity during the summer (Figure 4). Snowmelt from the mountain watersheds of Lake Powell first arrives at the lake by late spring (April and May), peaks out by June, and subsequently tapers off to base levels by late summer. Spring floodwater, upon its arrival at the head of the lake, is characteristically warm and fresh, and therefore has a relatively low density. This condition is produced by the combined effects of rapid runoff of snowmelt and surface heating of the water as it travels across the Colorado Plateau. Because of its low density, the spring floodwater overrides lake water and extends its way down the lake in the form of a wedge, with its thin edge pointed downstream. The main thermocline and the chemocline in Lake Powell are established by this mechanism, *i.e.*, the juxtaposition of warm spring floodwater over cold winter water. During the early part of summer, before the warm water has had a chance to be distributed uniformly, the thermocline varies in depth and intensity along the length of the lake and is deepest and most intense at the upper end of the lake. The sea-

sonal thermocline induced by solar radiation is superimposed upon the larger mechanically induced thermocline and chemocline. Overall, the lake tends to mix the various waters that enter it, but not completely. Temporal and/or spatial separation of water masses do exist.

Calcite Precipitation

Figure 5 presents data for the conductivity and the calculated calcite saturation index for the surface waters of Lake Powell during September 1971. The calcite saturation index is given as the ion activity product of free calcium and free carbonate divided by the solubility product constant. Values for $[Ca]$ and $[CO_3]$ were calculated by means of a computer program that takes into account equilibria among the various inorganic carbon species, complex ions, ionic strength, pH, and temperature. The basis for the algorithm is one suggested by Garrels and Thompson (1952) for sea water, but it is more easily applied to Lake Powell waters because the ionic strength of these lie within the range that can be accurately treated by the Debye-Hückel theory.

In Figure 5 it is seen that the surface conductivity of the lake varies in a smooth fashion from the dam to the inflow at Hite along a profile which shows a distinct minimum at the center of the diagram. This minimum in conductivity represents low-salinity spring run-off water pooled at the surface. The high conductivity value of the water at the upper end of the lake is caused by saline inflows which are common by late summer, and the high salinity at the lower end is due to the previous year's partially mixed water not yet being affected by the 1971

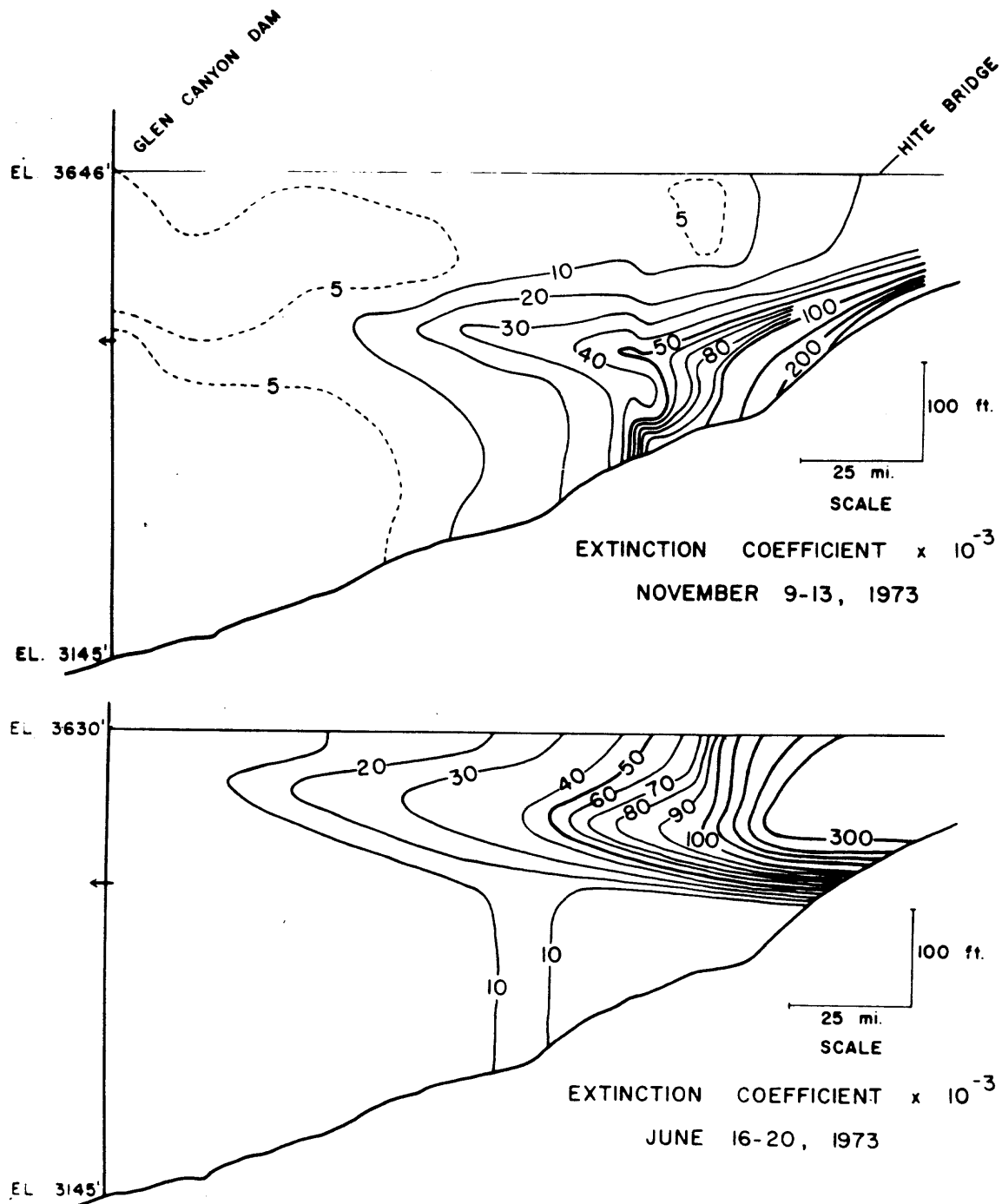


Figure 4: Underflow (November) and Overflow (June) Turbidity Plumes in Lake Powell as Shown by Contours for the Extinction Coefficient.

spring run-off. These relationships are typical for the summer waters of the lake, and they are also evident in Figure 3.

The upper curve of the graph in Figure 5 shows that all surface samples

taken from Lake Powell in September 1971 are oversaturated by at least a factor of five. The saturation index curve generally replicates the conductivity profile because all surface samples showed similar pH values (8.5 to 8.7), and given similar

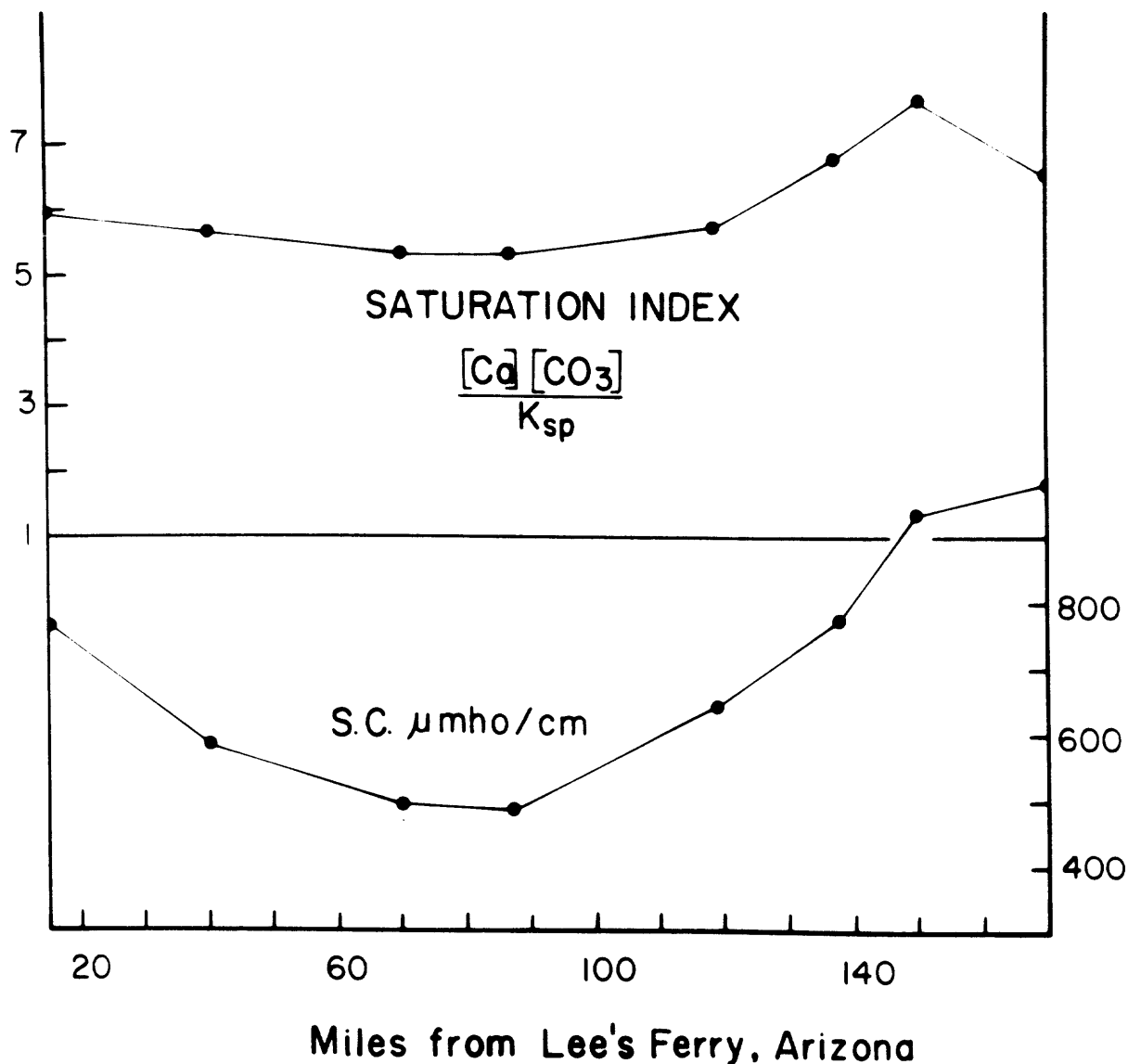


Figure 5: Calcite Saturation Index and Conductivity (Salinity) of Surface Waters of Lake Powell in September 1971. Conductivity plotted as S.C. $\mu\text{mho/cm}$ (specific conductance in micromhos per centimeter). K_{sp} is the solubility product constant.

pH, the calcium-carbonate activity products increase with increasing alkalinity and calcium ion concentration. The high degree of oversaturation of these waters is almost certainly due to the photosynthetic withdrawal of carbon dioxide by phytoplankton. This withdrawal results in an attendant increase in pH. In this regard, the data point to the extreme

right of Figure 5 is significant. It represents water entering the north end of the lake at Hite. Here, much of the river's detrital load is still suspended (Figure 4), the euphotic zone consequently is thin, and algal activity is proportionately reduced. These factors best explain the relatively low calcite-saturation index at the upper end of the lake.

The region with the highest saturation index tends always to be at the lower end of the lake near Glen Canyon Dam. During the summer months, the lower part of the lake is not greatly influenced by the overflow current. Before the fresh water arrives here, the fall mixing season has already begun. During the cold season, vertical mixing continuously maintains the high surface salinities. Consequently, the surface salinities are high near the dam throughout the year. When the pH rises during the summer months, this portion of the lake probably is the site of maximum carbonate precipitation.

Given proper nucleation conditions, the high saturation index of the summer surface water in Lake Powell must cause carbonate precipitation. The driving force for this condition is the algal photosynthesis which is facilitated by clarification of Colorado River water due to precipitation of sediment during its impoundment in the lake. Direct evidence of carbonate precipitation is provided by the data in Table 1. Note that the mean bicarbonate content of water at Lee's Ferry (Irelan, 1971) is considerably higher for the pre-dam as opposed to the post-dam period. This factor must be directly controlled by the lake itself, inasmuch as 97% of the water and 97% of the salt flux measured at Lee's Ferry pass by the site of Glen Canyon Dam (Iorns et al., 1965). Furthermore, there was no significant difference discernible among the bicarbonate concentrations for the pre- and post-dam periods for any of the three major tributaries (U.S. Bureau of Reclamation, 1971). The diminution in bicarbonate concentration is almost certainly caused by precipitation of carbonate in the lake. The relatively poor statistical basis for this argument is strengthened somewhat by the last two en-

tries in Table 1. These entries show that, for the years considered here, the maximum yearly post-dam bicarbonate concentration is significantly less than the minimum yearly pre-dam concentration.

The flux of bicarbonate through the Lake Powell system was calculated for the years 1963 through 1968. The input was computed by summing the total amounts delivered by the San Juan, Green, and Colorado Rivers (U.S. Bureau of Reclamation, 1971), and dividing by 0.93 to account for the fact that 93% of the salt delivered to Lake Powell is derived from these three rivers (Iorns et al., 1965). The output from Lake Powell was estimated by the bicarbonate flux at Lee's Ferry for these years (Irelan, 1971) multiplied by 0.97, because the Colorado River increases in salinity by 3% between the Glen Canyon Dam and Lee's Ferry (Iorns et al., 1965). The amount of bicarbonate in storage was computed by multiplying the volume of water in the lake at the end of 1968, plus the water estimated to be in bank storage, by mean bicarbonate concentrations at Lee's Ferry for 1951-1962, (pre-dam) and for 1965-1970 (post-dam). By utilizing these

Table 1: Bicarbonate Concentrations Measured at Lee's Ferry, Arizona, Before and After Completion of Glen Canyon Dam in 1963

Measurement Period	Concentration (microequivalents per liter of bicarbonate)
1951 through 1962	3,160
1965 through 1970	2,663
1959 (Minimum, Pre-Dam)	3,000
1968 (Maximum, Post-Dam)	2,762

Source: Data from Irelan (1971)

two numbers as probable limits for an upper and a lower bicarbonate concentration in stored water, and by recourse to the equation

$$\text{Input} = \text{Output} + \text{Storage}$$

results were obtained that indicate between 8 and 12% reduction in bicarbonate concentration of the Colorado River water. This is equivalent to a salinity reduction of 19 to 29 ppm, assuming that the bicarbonate loss occurs as a result of calcium carbonate precipitation. These values are only tentative. They will be refined as the passage of more water years reduces the weight of the bank storage term in the salt flux budget.

CONCLUSIONS

Lake Powell is a sulfate-bicarbonate-chloride lake with an average salinity of approximately 500 ppm total dissolved solids. The composition of the waters is controlled primarily by the contributions from the Green, Colorado, and San Juan Rivers, but is modified by the precipitation of calcium carbonate.

The thermal regimen and convective mixing characteristics of Lake Powell are adequately described as warm monomictic in the vernacular of conventional limnology. In addition, however, Lake Powell is meromictic to the extent that seasonal convective mixing does not carry to the bottom. At its present volume and configuration, the circulation of Lake Powell is dominated by advective transport and mixing. In this context, Lake Powell is still very much a river despite the impressive volume of water impounded in the form of a lake. Advective flows of cold saline waters have, to date, effectively forestalled the development of an

anaerobic condition in the bottom waters.

Calcium carbonate precipitation is probably most intense in the lower reaches of the lake. Total precipitation may be responsible for lowering of the total salinity by 19 ppm to 29 ppm.

ACKNOWLEDGMENT

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GLOSSARY

algorithm	a rule of procedure for solving a recurrent mathematical problem		current; at constant temperature it is proportional to the total dissolved salts in the water
advection	horizontal transport	extinction coefficient	see definition of turbidity
anaerobic	absence of free oxygen	euphotic zone	the upper layer of a body of water characterized by significant light penetration
carbonates	salts that contain the anion radical CO_3	limnology	the study of lakes
chemocline	a vertical gradient of salt concentration	meromictic	a lake characterized by convective mixing at the surface, but not at the bottom
convection	vertical transport	monomictic	a lake characterized by one convective mixing interval during one annual cycle
Debye-Hückel Theory	a theory of electrostatic ion interaction in solution. The theory provides the mathematical basis for evaluating the effective ionic concentration when that quantity is altered from the true concentration because of the effects of other ions in moderately concentrated solutions	pH	the negative logarithm of the hydrogen ion activity; approximately equal to the negative logarithm of the free hydrogen ion concentration in moles per liter
detrital	fragments of rock or mineral transported into the basin of sedimentation	ppm	parts per million
dissolved oxygen	molecular oxygen (O_2) dissolved in water	precipitation	the growth of crystalline matter from dissolved chemical species, so that the final crystal size is sufficient for settling-out of the crystalline material from the water column
electrical conductivity	a measure of the ability of a solution to conduct electrical		

T.D.S. total dissolved solids
in water

thermocline a layer of water in
the middle elevations
of a lake, which shows
a temperature gradient
from top to bottom

turbidity a measure of the in-
ability of light to
penetrate water be-
cause of suspended
solid material.
Turbidity is often ex-
pressed as the extinc-
tion coefficient κ ,
which has the meaning

$$I_{\tau} = I_0 e^{-\kappa\tau},$$

where I_{τ} is the inten-
sity of light that has
penetrated a thickness
 τ of water, I_0 is the
initial light inten-
sity, and τ is the
thickness of water ap-
plicable to the
measurement

water year a period of time be-
ginning on October 1
and extending through
September 30

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